A Methodological Approach for Identifying Hotspots of Regulating Ecosystem Services: Insights from Campania and Sardinia, Italy

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Abstract. The assessment of ecosystem services (ESs) plays a vital role in spatial planning and land-use decision-making. While ecosystems provide both tangible and intangible benefits essential for sustaining life, land-use changes driven by spatial planning influence the distribution and health of ecosystems, thereby affecting ES provision. To effectively identify priority areas for ES supply, it is essential to analyze ES hotspots, i.e., clusters of areas where individual ESs or bundles of ESs are delivered at high levels. Within this context, this study introduces a methodological approach for delineating ES hotspots. The first step involves a biophysical assessment of ESs, which here focuses on three regulating ESs: habitat quality, reflecting ecosystems' capacity to provide niches and nurseries for wildlife; carbon storage and sequestration, indicating their role in climate mitigation; and land surface temperature, serving as a measure of local temperature regulation by vegetation and unsealed soils. In the second step, various spatial statistical techniques for hotspots identification are integrated to reduce the sensitivity associated with relying on a single method. The proposed approach is applied in the Italian regions of Campania and Sardinia, revealing significant differences in the extent and the spatial distribution of areas that serve as hotspots for all three ecosystem services. The proposed approach to ES delineation can be readily applied in any context where ES biophysical assessments are available. Besides aiding the identification of key areas for ES supply, it provides planners and decision-makers with robust, easily communicable information that can be effectively understood by a broader audience.

Keywords: Carbon storage and sequestration · Habitat quality · Land surface temperature · Regulating ecosystem services · Hotspots

1 Introduction

Ecosystem services (ESs) are defined as the benefits that humans receive from natural and semi-natural ecosystems [1, 2]. Specifically, regulating ESs are those provided by the regulation capacity of ecosystem processes [3], including the moderation of natural

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phenomena, such as carbon sequestration and regulation of local climate [4]. The prerequisite for these functions is the very existence of suitable habitats for wild plants and animals, which enables the maintenance of biological and genetic diversity [2].

Research shows that, along with climate change, changes in land use land cover (LULC) are one of the primary causes which affect ESs [5, 6]. These in turn alter location and persistence of ES hotspots [7, 8], thus potentially impacting the effectiveness of sustainable conservation programs [9]. Mapping and assessing ESs is therefore essential for achieving biodiversity objectives and informing sustainable policies [10]; however, it is the identification of ES hotspots that is particularly crucial for spatial planning, as it enables the prioritization of conservation areas [11].

Initially, the term "hotspot" was exclusively referred to areas exhibiting rich variety of species [12, 13]; nowadays, an ES hotspot can be either interpreted as the areas with high levels of supply of one particular ES [14, 15], or as the areas where multiple ESs simultaneously present high levels of supply [16, 17]. When defining the second type of ES hotspots, it is crucial to ascertain the presence of synergistic interactions among the analyzed ESs, as this influences the purpose of the identified areas. Indeed, where synergies are absent or positive these areas can be valuably designated for conservation, whereas, the presence of negative interactions may lead to conflicts, thus necessitating integrated management to address trade-offs effectively [18].

This study refers to both current definitions and focuses on regulating ESs. It firstly maps the regulating ES hotspots of carbon storage and sequestration (CSS), habitat quality (HQ), and land surface temperature (LST) in the Italian regions of Campania and Sardinia; next, regional hotspots that simultaneously provide the three ESs examined are identified, leading to the identification of areas that could be targeted as priority sites for conservation.

The study unfolds through the following three stages. First, the regulating ESs of CSS, HQ, and LST are biophysically assessed and mapped. Second, hotspots for each single ES are identified. Third, multi-service hotspot cores, representing the spatial overlap of core hotspot areas for CSS, HQ, and LST, are delineated. Following this introduction, the materials and methods section provides information on the two case studies and illustrates the methodological approach developed to assess the three regulating ESs and identify ES hotspots. Finally, the results are presented and discussed, and conclusions are drawn.

2 Materials and Methods

This section is organized into three subsections. The first provides some information on the two case studies, i.e. the Italian regions of Campania and Sardinia; the second, further subdivided into three paragraphs, briefly describes how the three selected regulating ESs were assessed; finally, the third explains the methodological approach allowing for the identification of ES hotspots.

2.1 Study Areas: Sardinia and Campania

The region of Campania, located in southern Italy (Fig. 1, panel A), covers a total area of 13,700 square kilometers [19]. As of January 1, 2025, the total population of Campania

was 5,575,025, making it the third most populous region, with Napoli, the regional capital, accounting for 908,082 inhabitants [20]. The region is bordered by Lazio to the northwest, Molise to the north, Apulia to the northeast, and Basilicata to the east, with the Tyrrhenian Sea to the south and west. The region's landscape is mostly made up of hills (51%) and mountains (35%), while the plains, covering 14% of the area, are alluvial and were formed in ancient times by the two main rivers, Volturno and Sele. The Campanian landscape is characterized by a diverse range of relief features, including limestone mountains such as the Matese, Sannio, Irpinia, and Alburni ranges, clay-based hills prone to landslides, and the dormant Vesuvius volcano, all of which are subject to seismic activity. Average altitude is 322 m [21]. A GIS analysis considering the first-level 2018 Corine Land Cover (CLC) classes reveals that slightly less than 40% of the regional territory is covered by woodland and semi-natural environments.

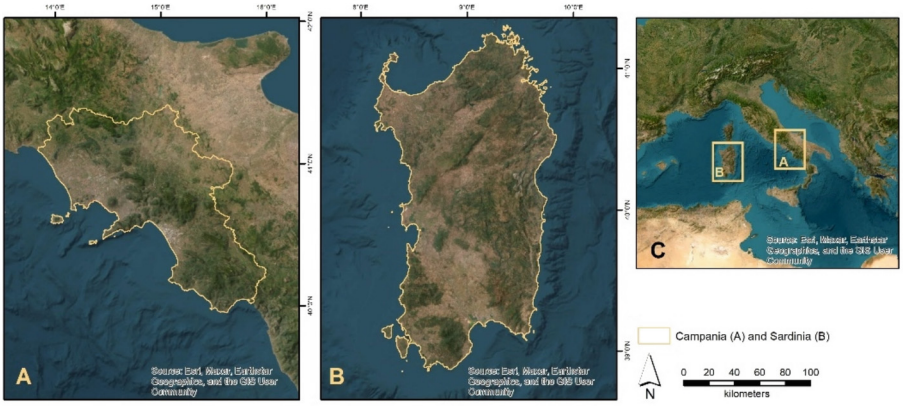

Fig. 1. Study areas: Campania (panel A) and Sardinia (panel B) in the Italian context (panel C).

The region of Sardinia, also situated in southern Italy (Fig. 1, panel B), is an island spanning a total area of 24,100 square kilometers [19]. The total number of inhabitants was 1,581,339 as of January 1, 2025 [20], and the capital city of the region is Cagliari with 146,627 inhabitants [20]. The island is bordered by the Tyrrhenian Sea to the east and south, and the Mediterranean to the west. The region is largely mountainous, characterized by several isolated mountain ranges, including Gennargentu, Sette Fratelli, and Limbara, along with hilly terrains, plateaus, and a few plains [22]. The average altitude is 300 m [23]. Major rivers like Coghinas, Tirso, and Flumendosa, which follow tectonic fractures and have carved deep valleys due to past uplifts, exhibit a predominantly torrential flow reflecting the island's dry summers and limited rainfall [22]. Considering the first-level CLC classes, around 49% of the total regional land area is occupied by woodland and semi-natural environments.

2.2 Ecosystem Service Mapping

Carbon Storage and Sequestration. The assessment of CSS was conducted using the Carbon storage and sequestration model of the InVEST (the Integrated Valuation of

Ecosystem Services) suite, a free and open-source modeling tool created by the Natural Capital Project [24] to map and assess ESs. InVEST helps compare alternative land use scenarios by evaluating their environmental impact [25] and integrates data on the often-overlooked, intangible benefits of ecosystems into decision-making processes, especially for local and regional planning [26]. In particular, the CSS model estimates total carbon storage across four carbon pools: aboveground and belowground biomass (within the top 30 cm of soil), dead organic matter, and soil organic matter. According to the InVEST User Guide, above-ground biomass (AGB) includes all living plant material above ground, while below-ground biomass (BGB) refers to the living roots of AGB. Dead organic matter (DOM) consists of leaf litter and dead wood. Soil organic matter (SOM), the largest carbon pool, includes organic material within the soil.

The CSS model has been applied in a variety of studies around the world. For instance, García-Ontiyuelo et al. [27] use it to estimate carbon sequestration in the coastal forests of southern Galicia to support sustainable forest management. Rachid et al. [28] evaluate the CSS benefits provided by urban greening in Nador for climate action. The CSS model is instrumental in studying how land use changes impact on carbon storage in the Sariska Tiger Reserve in India [29]. Moreover, the CSS model is useful to evaluate biodiversity and ES changes [30], to analyze the economic value of carbon sequestration [31], and to assess hurricane-related carbon and timber losses [32]. Other applications include examining urban development impacts, as in the Changzhutan area [33], and evaluating how land-use policies affect carbon storage in mixed-use landscapes [34].

The CSS model requires two key input datasets: i., a csv table with carbon density values assigned to each land cover class for at least one carbon pool, expressed in megagrams per hectare (Mg ha^{-}1), and, ii., a land cover map. In this study, three carbon pools were analyzed within InVEST, with belowground biomass incorporated in the final phase by overlaying the NASA Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) map onto the InVEST results and aggregating the values. The carbon density values for the csv table were derived from multiple sources, including NASA's Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) [35], which provides the Global Carbon Map for AGB and BGB pools. Additional sources include the 2015 National Inventory of Forests and Carbon Pools [36], datasets from ISPRA, the Italian Institute for Environmental Research and Protection [37], data from the Regional Agricultural Research Agency of Sardinia [38], and classifications from the CLC map [39]. Data inputs are summarized in Table 1.

Habitat Quality. The InVEST Habitat quality model was used to assess HQ, informed by the work of Sallustio et al. [40], who provide expert-based data on threats, sensitivity, and habitat suitability. The model requires four key inputs: i., a land cover map (TIFF); ii., a folder of threat maps (TIFF); iii., a sensitivity table (CSV); and, iv., a threats table (CSV). Data inputs are summarized in Table 1. Habitat types in the study area were classified based on the 2018 CLC map: the existing categories were grouped into 12 broad categories based on [40], with an additional "mixed forest" category included to account for this specific type in Sardinia, hence totaling 13 categories.

The parameters needed for the threats table include maximum influence distance (MAX_DIST), indicating the extent of a threat's impact (km); relative weight (WEIGHT), ranking threats from 0 (low) to 1 (high); and decay parameter (DECAY),

Table 1. Data inputs and sources (last access date for all sources: 2025/04/07).

Ecosystem service	Data input	Data source
Carbon storage and sequestration	CSV table with carbon density values assigned to each land cover class	Aboveground biomass • ORNL DAAC (https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1763) • INFC2015 (https://www.inventarioforestale.org/it/il-contenuto-di-carbonio-della-vegetazione-carbon-stock-in-the-aboveground-living-biomass)
		Belowground biomass • ORNL DAAC (https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1763)
		Dead organic matter • INFC2015 (https://www.inventarioforestale.org/it/il-contenuto-di-carbonio-della-vegetazione-carbon-stock-in-the-aboveground-living-biomass)
		Soil organic carbon • INFC2005 (https://www.sian.it/inventarioforestale/jsp/dati_carquant_tab.jsp?menu=3) • ISPRA (https://www.mase.gov.it/sites/default/files/archivio/normativa/linee_guida_ISPRA_implementazione_RED_II.pdf) • AGRIS Sardegna (http://www.sardegnaportalesuolo.it/opendata/carta-della-distribuzione-del-carbonio-organico-del-progetto-cut-alla-scala-150000.html)
	Land cover map	Copernicus - Corine Land Cover 2018 (https://land.copernicus.eu/en/products/corine-land-cover/clc2018)
Habitat quality	Threats table	Sallustio et al. (2017) [40]
	Sensitivity table	Sallustio et al. (2017) [40]

(*continued*)

Table 1. (*continued*)

Ecosystem service	Data input	Data source
	Threat maps	Geofabrik. OpenStreetMap Data Extracts – Italy (https://download.geofabrik.de/europe/italy/Geofabrik)
	Land Cover map	Copernicus - Corine Land Cover 2018 (https://land.copernicus.eu/en/products/corine-land-cover/clc2018)
Land surface temperature	Landsat 8–9 OLI/ TIRS Collection 2, Level 2	USGS Earth Explorer (https://earthexplorer.usgs.gov/)

describing whether a threat's effect diminishes linearly or exponentially over space. While other values follow Sallustio et al. [40], the decay parameter was here assumed to be linear due to data limitations, therefore providing a conservative worst-case estimate of the threat's impact.

The sensitivity table lists habitat types and their sensitivity scores to each threat, with values derived from [40]. For the newly added "mixed forest" category, the score was calculated as the average of the "broadleaved" and "conifers" categories.

Land Surface Temperature. As per the Global Climate Observing System (GCOS) [41], LST is a key parameter for assessing land surface conditions and land-atmosphere exchange thermal emissions processes. The analysis of LST provides a solid base for spatial prioritization within sustainable spatial planning strategies aimed at climate regulation through LST mitigation [42]. In this subsection, the identification of areas where LST take on significantly high or low values in Campania and Sardinia is presented. Despite their differing geographical characteristics, both regions have experienced a marked increase in the frequency and intensity of heat waves in recent years [43].

The analysis was performed on satellite imagery; LST was mapped by using Landsat 2-Level 2 collection (Landsat 8–9 OLI/TIRS C2 L2 with a spatial resolution of 30 m, see Table 1) satellite images [44] retrieved from the United States Geological Survey (USGS) Earth Explorer platform. The image search was limited to the Summer of 2023 (time frame from June 25, 2023 to September 2, 2023) with a 6 percent maximum threshold on cloud cover. LST values were calculated using the Landsat B10 thermal band. Due to limitations in the spatial coverage of satellite imagery, multiple raster images from different acquisition scenes were collected. Among the retrieved images, those with the highest mean LST values were selected to generate the final composite LST maps.

As regards the Campania region, a total of 21 satellite images were retrieved; because no single-date images covering the whole region were available due to the configuration of satellite images, three sets of three/four images were used to fully cover the region. Once the raster images belonging to the same scene and date were merged, those with the highest mean values were subsequently selected. The final LST map for Campania was constructed using four Landsat images, as detailed in Table 2.

Regarding Sardinia, the same selection criteria (time frame and cloud cover) yielded 51 satellite images. Five of these images were required to ensure complete coverage of the region, as illustrated in Table 2.

Table 2. Selected Landsat images to create LST map for Campania and Sardinia Regions.

Region	Image code	Scene	Date
Campania	LC09_L2SP_189031_20230717_20230719_02_T1_ST_B10	189	July 17, 2023
	LC09_L2SP_189032_20230717_20230719_02_T1_ST_B10	189	July 17, 2023
	LC09_L2SP_190031_20230825_20230827_02_T1_ST_B10	190	August 25, 2023
	LC09_L2SP_190032_20230825_20230827_02_T1_ST_B10	190	August 25, 2023
Sardinia	LC08_L2SP_192033_20230730_20230805_02_T1_ST_B10	192	July 30, 2023
	LC08_L2SP_192032_20230730_20230805_02_T1_ST_B10	192	July 30, 2023
	LC09_L2SP_193033_20230814_20230817_02_T1_ST_B10	193	August 14, 2023
	LC09_L2SP_193032_20230814_20230817_02_T1_ST_B10	193	August 14, 2023
	LC09_L2SP_193031_20230814_20230817_02_T1_ST_B10	193	August 14, 2023

2.3 Hotspot Mapping

Various methods have been used in the literature for hotspot detection; according to Bagstad et al. [45], they can be grouped in three categories as follows: i., based on local spatial autocorrelation-based indices; ii., ES quantile-based; iii., area-based. Moreover, different approaches for identifying multi-service areas, which serve as hotspots for a plurality of ESs, have been proposed; for a classification of such approaches, the reader can refer to Schröter and Remme [18]. Both [45] and [18] show how different methods yield different hotspots. In this regard, Anselin [46, ch. 17.5], who focuses on approaches based on spatial statistic indexes, argues that "interesting locations" are those that remain detected as clusters regardless of the method or of the criteria used. Therefore, four methods were applied and integrated in this study to identify hotspots for each single ES: Local Index of Spatial Autocorrelation (LISA), median LISA, Getis-Ord (G*), and, finally, top-richest cells (i.e., quantile-based segmentation).

LISA, as per Anselin's definition, is an umbrella term for any statistics that "for each observation gives an indication of the extent of significant spatial clustering of similar

values aggregation around that observation" [47, p.94], and for which a proportionality link between the sum of LISAs for all observations and a global indicator of autocorrelation exists. As implemented in GeoDa [48], LISA consists of a local application of Moran's index of spatial autocorrelation (I), by using a moving window that centers in a spatial unit and whose size and shape depend on the contiguity criterion in use. The result is a cluster map that, at assigned significance levels, categorizes clusters into four groups (HH, or hotspots; LL, or coldspots; HL and LH, spatial outliers) depending on whether the values in the observed spatial unit and in its surrounding area, as defined by the contiguity criterion, are higher (H) or lower (L) than the average. An extension of the traditional LISA, also implemented in GeoDa [48], is the median LISA statistics, which operates in a similar manner, but uses the median value instead of the mean, therefore reducing the impact of outliers.

The third statistic here used is the local G* proposed by Getis and Ord [49, 50] and widely used in cluster analysis. Similarly to LISA, local G* uses a moving window centered in the spatial unit being observed; it is defined as the ratio of the sum of the values within the window to the sum of values in the entire dataset. In contrast to LISA, local G* only yields hotspots and coldspots, but not spatial outliers [46, ch. 17.4].

For all the three above-mentioned local statistics, in this study, the queen criterion at the first level of contiguity was used.

The fourth method applied in this study is the quantile-based method, with a cut-off value set at the 90th percentile, hence focusing on the top 10% of grid cells with the highest values.

A four-step approach was applied in this study. The first step involved creating a vector grid composed of square cells with 200-m sides and covering the two study areas; for each cell, the mean values of the three selected ESs were calculated through zonal statistics and assigned to the cells as attributes. In the second step, the four selected methods for hotspot delineation were applied to the three ES maps in the two study areas; as a result, four hotspot maps were obtained for each ES. In the third step, for each ES the four corresponding hotspot maps were intersected, with a view to identifying those cells that remain identified as hotspot cores regardless of the method. Finally, in the fourth step a further intersection was applied so as to identify the cells that perform simultaneously as hotspot cores for CCS, HQ, and LST.

3 Results

This section is organized into four subsections. The first three sections describe the spatial distribution of the three selected ESs in Campania and in Sardinia, whereas the fourth accounts for ES hotspots in the two study areas.

3.1 Carbon Storage and Sequestration

Figure 2, panel A illustrates the distribution of carbon storage across the Campania Region, with values ranging from 0 to 21.55 megagrams per 900 square meters. The highest carbon storage values are grouped in distinct clusters, particularly in the central and southern parts of the region. These high values are mostly located within protected

natural areas, like Regional Park of Roccamonfina - Garigliano Outfall, Matese Regional Park, area of Trebulani Mountains, Taburno-Camposauro Regional Park, and Partenio Regional Park in the north-west; Vesuvius National Park, Natural Reserve of Tirone Alto Vesuvius, Lattari Mountain Regional Park, Picentini Mountain Regional Park and Natural Reserve of Eremita-Marzano Mountains in the central area; and, finally, National Park of Cilento and Vallo di Diano in the south. In contrast, medium to low carbon storage values are found in more urbanized or cultivated zones, such as the Metropolitan City of Naples and the surrounding plains and hills. The data also shows that broad-leaved (CLC 311), coniferous (CLC 312), and mixed forests (CLC 313) have the highest average carbon storage, whereas artificial areas and watercourses show the lowest levels.

Carbon storage values in Sardinia vary from 0 to 16 megagrams per 900 square meters. All four carbon pools exhibit the same spatial pattern, with the largest concentrations occurring in the mountainous and forested areas of eastern and southwestern Sardinia, as seen in Fig. 2, panel B, including Sette Fratelli and the Gennargentu mountain chain as well as the two National parks of Asinara and of La Maddalena, and the three Regional Natural Parks of Porto Conte, Tepilora, and Gutturu Mannu. The land cover classes with the highest mean carbon storage values are coniferous and mixed forests (CLC 312 and 313), with averages of 11.4 and 11.1 megagrams per 900 square meters, respectively. Conversely, in every pool, the average values of broadleaved forests (CLC 311) are consistently lower than those of the other forest types in this region, the total average value being 9.9 megagrams per 900 square meters. Inland water bodies, artificial surfaces (CLC 111, 112, 121, 122, 123, 124, 131, 132, 133, 422, 511, 512, 521, 522, 523) have the lowest carbon storage values with values lower than 2 megagrams per 900 square meters, followed by agricultural areas (CLC 211, 212, 213, 241) with mean values below 4 megagrams per 900 square meters and vineyards, fruit trees and complex cultivation patterns (CLC 221, 222, 223, 242) below 5 megagrams per 900 square meters.

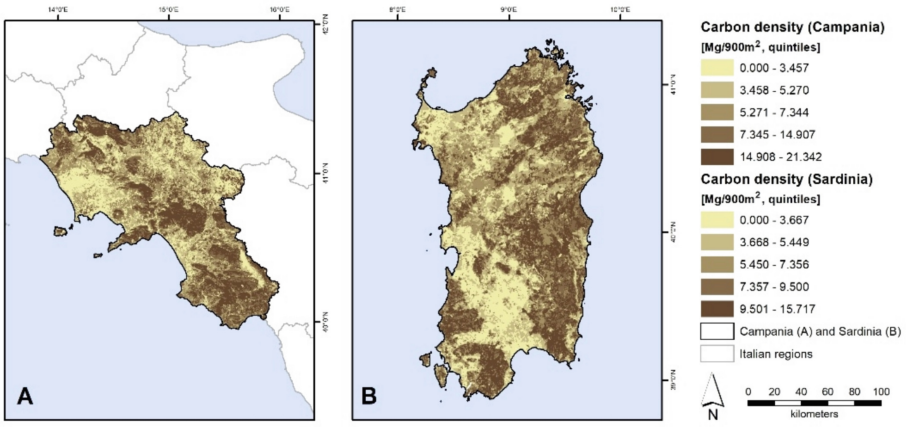

Fig. 2. Carbon storage and sequestration in Campania (panel A) and Sardinia (panel B).

3.2 Habitat Quality

The spatial distribution of habitat quality values is depicted for the Campania Region in Fig. 3, panel A, and for the Sardinia Region in Fig. 3, panel B.

In the Campania region, the average habitat quality value is 0.49. Specifically, 40.61% of the region consists of low-quality habitats ($0 < HQ \leq 0.33$), 27.96% exhibits medium-quality habitats ($0.33 < HQ \leq 0.66$), and the remaining 31.43% is comprised of high-quality habitats ($0.66 < HQ \leq 1$). These highest values are predominantly concentrated in green spaces, especially forested areas, frequently protected by parks and reserves. Conversely, the lowest values are observed in extensive urban areas and those dominated by intensive agriculture. Although 13 habitat types were intended for analysis, mixed forests were not found within the boundaries of the Campania region. Among the analyzed habitats, broadleaved forests showed the highest average quality (mean = 0.85), closely followed by grasslands (mean = 0.80). In contrast, the lowest mean score, approaching zero, is recorded in buildings and other artificial areas or impervious soils (aggregated from CLC 111, 112, 121, 122, 123, 124, 131, 132, 133) with a score of 0.09. The second-lowest values are observed in open urban areas (aggregated from CLC 141, 142) and intensive agricultural lands (aggregated from CLC 211, 212, 213, 221, 222, 223), with mean values of 0.22 and 0.24, respectively.

Figure 3, panel B, depicts the spatial distribution of HQ values across the Sardinia region. The average habitat quality value is 0.54. When examining the distribution of habitat quality across the region—categorized as low (values ranging from 0 to 0.33), medium (0.33 to 0.66), and high (0.66 to 1)—it emerges that 31.05% of the area is characterized by low-quality habitats. Medium-quality habitats account for 28.06% of the region, whereas high-quality habitats represent the largest share, covering 40.86% of the total area. The highest values are concentrated on forest areas scattered around the eastern part of the island. The highest mean habitat quality values are observed in broadleaved forests (CLC 311), with an average value of 0.85. This is followed by mixed forests (CLC 313) at 0.78, grasslands (CLC 321) at 0.77, and coniferous forests (CLC 312) at 0.75. Conversely, the lowest mean value, 0.09, is associated with artificial surfaces (CLC 111, 112, 121, 122, 123, 124, 131, 132, 133), followed by open urban areas (CLC 141 and 142). These results suggest that urban green spaces make a limited contribution to the provision of this type of ecosystem service.

3.3 Land Surface Temperature

In Campania, the LST values are within the range of 27.8–64.5 °C, as shown in Fig. 4, panel A. The highest LST values are observed in urban and artificial areas in the north-western part of the region, with reference to the Metropolitan City of Naples and in the north-eastern sectors of the provinces of Avellino and Benevento. The lowest LSTs are found in the green belt along the "Dorsale Appenninica" from the northeastern border, in mountainous and hilly areas. Regarding CLC classes, the highest mean values (47.6–53.3 °C) are associated with artificial surfaces, specifically continuous and discontinuous urban fabrics (CLC 111, 112). An exception is represented by urban green areas (CLC 141), which exhibit lower mean temperatures. The lowest mean values (34.3–39.4 °C)

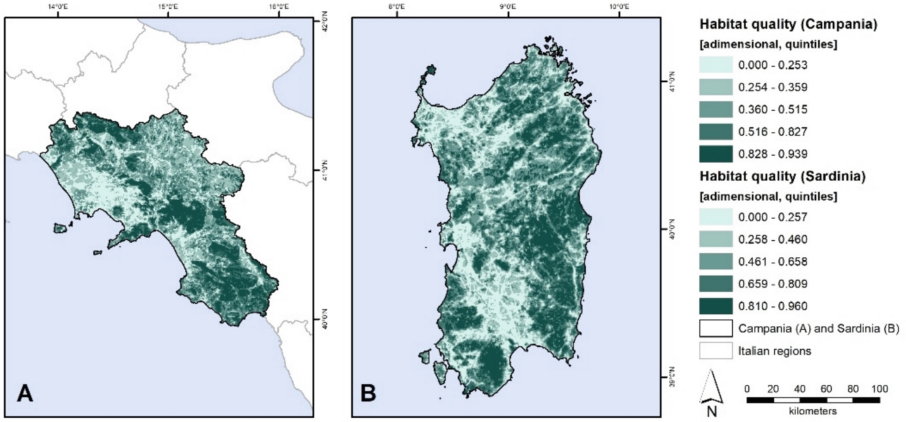

Fig. 3. Habitat quality in Campania (panel A) and Sardinia (panel B).

are observed in coastal wetlands and water bodies (CLC 521 and 512), forests (CLC 311, 312, 313), and areas covered by scrubs and herbaceous vegetation (CLC 323, 324).

In Sardinia, LST values range from 29.8 to 61.9 °C, as illustrated in Fig. 4, panel B. The highest values are observed in agricultural areas on the eastern part of the island as seen in three big clusters. Low values are observed in areas characterized by mountains, forests, and regional parks such as Mounts Limbara and Sulcis-Iglesiente, Gennargentu massif and Sette Fratelli. Regarding the corresponding CLC classes, agricultural areas (CLC 211, 212, 221, 222–231, 241–244) generally exhibit high mean LST values (46.9-51.5 °C). However, the category with the highest mean value is recorded in artificial areas (CLC 111, 112, 121–124, 131–133, 141, 142), reflecting the urban heat island effect. Urbanized areas show high values (44.4–54.0 °C) except for the "sports and leisure facilities" class (CLC 142), showing a mean value of 42.1 °C. The lowest mean values are observed in water-related classes (CLC 512, 521–523) with mean values ranging from 32 °C to 36 °C, and in forest areas (CLC 311–313) with the average LST ranging between 39.1 and 40.2 °C, possibly due to shading and evapotranspiration.

3.4 Ecosystem Services Hotspot

Core areas of the hotspots, defined here as cells that simultaneously exhibit high values across all three ESs (i.e., above the 90th percentile in each distribution) and that are consistently identified as cluster cores with a confidence level of 95% regardless of the spatial statistics applied, are presented in Fig. 5 for Campania (panel A) and Sardinia (panel B). The smaller panels (A1-A3 and B1-B3) provide the spatial layout of hotspots identified for each ES.

Cells that perform as hotspots simultaneously for the three regulating ESs assessed in this study make up a total of 643.68 km^2 in Campania and 208.6 km^2 in Sardinia, thus 4.7% and 0.08% of their land masses, respectively. Furthermore, the exclusion of small hotspots, i.e., those measuring less than 20 hectares, results in a reduction of the total

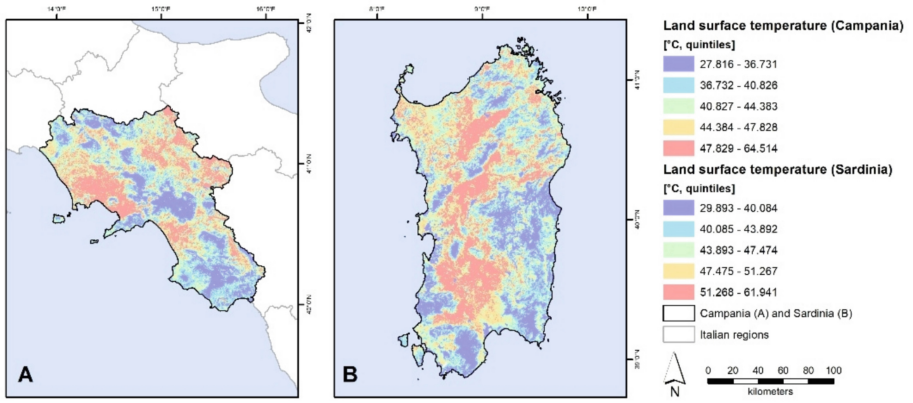

Fig. 4. Land surface temperature in Campania (panel A) and Sardinia (panel B).

area interested by hotspot cores to 606.20 km^2 in Campania and 149.4 km^2 in Sardinia, therefore equaling 4.4% and 0.06% of the two regions.

As clearly visible in Fig. 5, hotspots in panels A and B tend to be much larger in size in Campania than in Sardinia, with average sizes of 0.78 km^2 and 0.18 km^2, respectively; this feature reflects i., the spatial aggregation of individual ES hotspots, and, ii., higher levels of synergy between the three ESs; both aspects are more significant in Campania than in Sardinia (panels A1-A3 and B1-B3). Moreover, notable differences concern their spatial layout: while in Campania large hotspots form a sort of north-west to south-east inner belt, in Sardinia smaller and scattered hotspots are mostly found in the eastern and southern parts of the region.

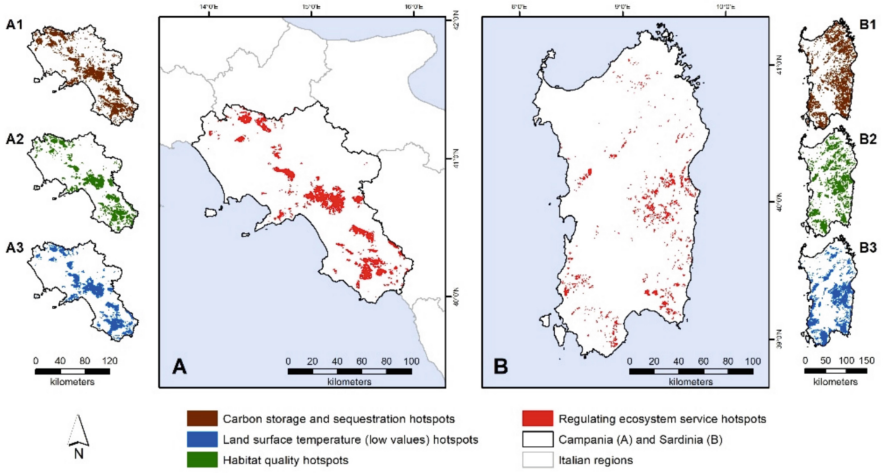

Fig. 5. Regulating ecosystem services hotspots in Campania (panel A) and Sardinia (panel B).

4 Discussion

This study focuses on the spatial identification of hotspots capable of simultaneously providing three regulating ESs: global climate regulation through carbon storage and sequestration, local climate regulation through LST measurement, and habitat provision through habitat quality assessment.

Several studies have addressed the issue of hotspot identification by considering different ESs. Although some authors, including [3] and [51, 52], consider all four ES groups as classified by MA [3] (provisioning, regulating, supporting and cultural), others [53–57] concentrate on regulating services, as in this study. For example, Nardella et al. [57] focus on the identification of hotspots for the provision of four regulating ESs (PM_{10} removal, O_3 removal, mitigation of the urban heat island effect, and urban flood risk mitigation) in order to assess the synergies and trade-offs between the four ESs in seven coastal Italian metropolitan cities. Moreover, according to Zheng et al. [58], the interactions between various regulating ecosystem services can vary significantly, depending on which services are considered, the scale at which they are analyzed, and the methods used for their assessment.

Our analysis shows that hotspots capable of simultaneously providing the three regulating ESs represent 4.4% of the regional territory in Campania and 0.06% in Sardinia. This different percentage is due to the fact that in Sardinia patches showing the highest values are scattered and not clustered as in the case of Campania. In Campania major hotspots create an internal corridor stretching from north-west to south-east. These areas correspond to the forested areas inside some protected areas, starting from the Matese Regional Park in the north to the Cilento and Vallo di Diano National Park in the south. This result is consistent with the results provided by Lin et al. [53], who identified hotspots related to the provision of six ESs, including carbon storage and habitat quality, and show that hotspots related to carbon storage and habitat quality are located in forested areas. This is also valid in the case of Sardinia, where the hotspots, although not corresponding to protected areas, in many cases concern forested areas, whose altitude exceeds 900 m. Furthermore, a strong synergy between habitat quality and carbon storage and sequestration values is evident in both Sardinia and Campania. This result is in line with the results reported in the study by Lee and Lautenbach [59], who analyze pairwise relationships between different typologies of ESs based on a review of the existing literature in order to promote synergies between the ESs themselves; they show that the strongest synergistic relationships concern the group of regulating ESs, and in particular, the relationship between habitat provision and most regulating ES. This is consistent with de Groot et al.'s [2] assertion, as they define habitat provision as a basic element for the provision of the other services. On the other hand, as pointed out in other studies, the relationship between regulating ESs can change in relation to other factors, such as vegetation and soil type, or human-environment interactions expressed in terms of land uses and socio-economic factors [59, 60].

5 Conclusions

The methodological approach proposed in this study enables the identification of hotspots of three key regulating ESs, i.e., areas having high ecological values. This information is of relevance to planners and decision-makers for two reasons. First, the outcomes highlight the need for the protection and conservation of regulating ES hotspots, as these areas are rich in natural resources that might be subject to increasing pressure. Targeted conservation measures are therefore needed to ensure the long-term sustainability of their ecosystem functions, in the context of rapid land use and land cover changes driven, for instance, by increasingly intense urbanization processes. Second, the identification of areas characterized by high levels of ES supply provides a significant foundation for policies aimed at enhancing these regulating ESs by improving the ecosystem's functional capacity to deliver ESs. In this context, enhancement refers to the implementation of strategies to improve the management and performance of natural ecosystems that possess high biophysical value and deliver considerable benefits to humans.

A potential future direction for this research involves the broader application of the proposed framework to identify ES hotspots, by introducing further key regulating ESs. This would be of particular importance, for example, in areas that have undergone substantial soil sealing, where remaining patches of unsealed soil and vegetated areas play a crucial role in addressing hydrogeological hazards or climate-related phenomena such as land degradation, desertification, or drought. In such areas, identifying ES hotspots and implementing spatial strategies aiming at their conservation, enhancement, and expansion can contribute to mitigating pressures from growing urbanization and can effectively foster climate adaptation. Finally, the proposed methodology is adaptable and could be applied to other contexts with different biophysical characteristics, as well as to other regions, provided that similar input datasets are available.

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