Carbon Sequestration and Provision of Ecosystem Services: Evidence from Campania Region, Italy

Federica Isola, Francesca Leccis, Federica Leone(✉), and Corrado Zoppi

Department of Civil and Environmental Engineering and Architecture, University of Cagliari, Cagliari, Italy
{federica.isola,francescaleccis,federicaleone,zoppi}@unica.it

Abstract. A methodological approach is implemented here that aims to study the relationships between climate neutrality and the supply of ecosystem services (ESs), with reference to regional spatial contexts. The measure of carbon sequestration (CS) is taken as a reference to estimate the status and evolutionary dynamics of this phenomenon, which is analyzed and evaluated as associated with the supply of certain types of ESs, in relation to the reference spatial context. The study is developed as follows.

First, the spatial framework of the CS is characterized through density maps, using the "Carbon Storage and Sequestration" model of the InVEST suite. Second, a methodology for characterizing the supply of ESs is identified. Based on in-depth analyses of environmental, landscape and cultural contexts, the supply of ESs in relation to the Campania regional territory is characterized in this study by the following types: preservation of habitat quality; regulation of the local climate through mitigation of land surface temperature; production of agricultural and wood crops; protection and enhancement of the attractiveness of spatial contexts in relation to recreational and cultural activities; and preservation and enhancement of landscape values that ground regional identity.

Finally, the correlations between the spatial taxonomies of CS and ESs supply with regard to the regional context of Campania are analyzed to assess how the characteristics and specificities of ESs supply can be used to foster climate neutrality. These correlations allow, also, to identify specific recommendations related to plan policies, finalized to improve the quality of life of local communities.

Keywords: Carbon Sequestration · Climate Neutrality · Ecosystem Services

1 Introduction

In this study, a methodological approach that aims to implement climate neutrality through spatial planning policies is defined and applied. The measure of carbon sequestration (CS) is taken as a reference to estimate the status and evolutionary dynamics of this phenomenon, analyzed and evaluated as associated with the supply of certain types of ecosystem services (ESs), in relation to the reference spatial context.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2026
O. Gervasi et al. (Eds.): ICCSA 2025 Workshops, LNCS 15890, pp. 122–139, 2026.
https://doi.org/10.1007/978-3-031-97606-3_9

Climate change is affecting both rural and urban areas with increasing intensity, compromising well-being and quality of life. Its consequences, which are now evident, call for urgent action, especially to meet the Paris Agreement target of limiting global warming to 1.5 °C by 2030. The European Union (EU) has initiated several mitigation and adaptation strategies, including the Green Deal and the "Ready for 55" package, aimed at climate neutrality by 2050 and a 55% reduction in emissions by 2030 compared to 1990 levels. These actions are based on the European Climate Act, which obliges Member States to fulfil their commitments. The strategies are implemented at the national, regional and local scales.

In order to effectively integrate CS issues into policies and strategies at different planning levels, a thorough understanding of this process and the aspects that most contribute to achieving climate neutrality, including in terms of multiple provision of ESs, is required. Natural ecosystems provide multiple services that mutually influence each other, positively or negatively. In order to define effective planning choices, it is necessary to fully exploit the potential of nature by considering the existing relationships between different ESs in terms of synergies and trade-offs, since, if not properly studied and implemented, measures aimed at increasing CS in habitats could have negative effects on biodiversity and other services produced by the same ecosystem.

The study is developed as follows.

First, the spatial framework of the CS is characterized through density maps, using the "Carbon Storage and Sequestration" model of the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) suite, which estimates the amount of carbon stored in spatial units of reference using raster maps of land cover. The model estimates the state of CS, also allowing for appreciation of its variation over time. The spatial context targeted by the implementation of the methodology is Campania, an administrative region in southern Italy.

Second, a methodology to characterize the supply of ESs is identified. Based on previous studies and in-depth analyses of environmental, landscape, and socio-cultural contexts, the supply of ESs in relation to the regional territory of Campania is characterized, in this study, by the following types: preservation of habitat quality levels suitable for sustaining the life cycles of wild plants and animals that can be useful to humans; climate regulation through mitigation of land surface temperature; production of agricultural and wood crops; protection and enhancement of the attractiveness of spatial contexts in relation to nature- and natural resource-based recreational and cultural activities; preservation and enhancement of landscape values that ground the regional identity.

Finally, the correlations between the spatial taxonomies of CS capacity and ESs supply with regard to the regional Campanian context are detected and analyzed, in order to assess how the characteristics and specificities of the multifunctional supply of ESs can be effectively used in order to maximize CS capacity, and, thus, the contribution of the Campania Region to the improvement of global climate neutrality. The identification of these correlations makes it possible, also, to identify specific recommendations in terms of plan policies in order to improve the quality of life of local societies in Campania.

2 Materials and Methods

This section is organized as follows. First, the regional context of Campania is presented, as regards its features as for supply of CS and the other ESs which are involved in this study. Secondly, the methodology used to detect the spatial taxonomy of the provision of CS and of the other ESs is described, which is implemented through the identification of the spatial taxonomies of CS capacity, levels of habitat quality, land surface temperature (LST) mitigation, agricultural and forestry production, landscape value and outdoor recreation features. Finally, a multiple regression is estimated, in order to detect spatial correlations between CS and the ESs supply.

2.1 Campania Region

Campania, located in Southern Italy, covers about 13,700 square kilometers and borders Latium, Molise, Apulia, Basilicata, and the Tyrrhenian Sea. The Region's geography is predominantly hilly and mountainous, with 51% of its surface being hills and 35% mountains. The plains, mostly alluvial, cover only 14% of the area. Campania features coastal plains like the Campana and Sele Plains, as well as ancient lake basins between mountainous regions such as the Matese, Sannio, Irpinia, and Alburni Mountains. The Region also has volcanic areas, such as Vesuvius and Phlegraean Plain.

2.2 Provision of Ecosystem Services

This subsection reports synthetic descriptions of the six ecosystem services whose influence on CS is assessed and, therefore, whose impact on climate neutrality is analyzed. The description includes the measurement methods and spatial taxonomy of ES provision.

Land Surface Temperature
LST is an important climate variable to identify phenomena related to thermal emissions that are produced between the Earth's surface and the overlying atmosphere. This temperature directly affects air temperature and is one of the main parameters in physics of processes occurring between land and surface, both on regional and global scales. The methodological approach to LST mapping and assessment implemented here provides the identification of temperature anomalies and peaks in the study area, and it is applied as follows.

LST is obtained from the satellite images through the United States Geological Survey (USGS)'s Earth Explorer interface, specifically utilizing the Landsat 2 - Level 2 collection (Landsat 8–9 OLI/TIRS C2 L2)[1], which provides 30-m LST raster maps[2]. The LST variable was detected during Summer 2023, the date range was set from the last week of June (June 25, 2023) to the first week of September (September 2, 2023), with a maximum cloud cover threshold of 6%. Specifically, the information utilized is

[1] The Landsat collection 8-9 incorporates the Operational Land Imager (OLI) and Thermal Infra-Red Sensor (TIRS) sensors.

[2] Earth Explorer by U.S. Geological Survey. Available from https://earthexplorer.usgs.gov/. [Accessed: 2025.03.26].

derived from the Landsat B10 thermal band, which provides data on the Earth's surface temperature. To obtain the mean values in Celsius degrees (°C), the scale factor provided by the USGS Guide is utilized using the digital number (DN) values in raster images:

$$0.00341802 * DN + 149.0 - 273.15 \left(^{\circ}C\right) \quad (1)$$

Satellite scenes do not cover the whole Campania Region; to create a complete map, therefore, several raster images are required. Different scenes' merged raster images are needed. Merged images with high mean values are selected to compose the LST map.

Habitat Quality

Habitat quality denotes the ability of a habitat to sustain species survival and population persistence [1], nevertheless, it is increasingly imperiled by anthropogenic land-use transformations. These alterations fragment the landscape and reduce its connectivity, thereby undermining ecosystem health and their capacity to deliver crucial services [2].

The InVEST Habitat Quality model is acknowledged as a reliable and efficient tool for assessing habitat quality. This GIS-based software maps the distribution of habitats while accounting for their degree of degradation, using habitat quality and rarity as proxies for biodiversity.

The model computes the Habitat Quality Index (HQI) by incorporating five essential factors: (i) Land Use Land Cover (LULC), (ii) threats and their corresponding impacts, (iii) habitat proximity to threats, (iv) habitat suitability, and (v) habitat sensitivity [3]. Mandatory inputs encompass the land cover data; threat raster layers, the threat table detailing the maximum impact distance, impact intensity, spatial decay function, and storage path for each threat raster; the sensitivity table indicating habitat suitability and relative sensitivity to each threat, and the half-saturation constant.

Habitat quality is mapped and measured using a dimensionless index ranging from 0 to 1. Although not a direct biodiversity metric, this score enables comparative evaluations. Higher values indicate superior habitat quality in relation to surrounding areas, whereas lower scores highlight areas with poor habitat quality. Results are visualized in a habitat quality gradient map, which illustrates the spatial distribution of habitat quality and the extent of habitat degradation across the Region.

Value of Agricultural and Forestry Production

Agricultural and forestry production qualifies as a provisioning ES. Provisioning ESs are material goods such as food, fresh water, timber, fiber, and energy resources. There are multiple methodological approaches that can be implemented to assess this ES.

The method used in this study assesses agricultural and forestry production (VAFP) based on location, altitude, morphology, and orography, by means of two datasets: the National Dataset for agricultural areas, which shows the land monetary value per unit area, provided by the National Research Council of Agriculture and Agricultural Economics (CREA); and, the National Dataset for forestry areas, which shows the mean values (MVs) per unit area, provided by the National Revenue Agency (NRA). The data

on agrarian regions are reported in the "List of agrarian regions associated to municipalities, subdivided by region, province and elevation zone", related to the CREA's Land values Database[3].

Subsequently, correspondences between the 2018 CORINE Land Cover classes and the types of agricultural crops defined by CREA for the agricultural value, and the taxonomy of the NRA for the forestry value were established. Finally, to analyze spatial distribution of mean agricultural and forestry land values, a land cover vector map to be overlaid on the agroforestry value vector map. This allows the value of agricultural and forestry production to be identified for each spatial unit of land cover.

Landscape Value

Landscape value is strictly associated to individual perception and personal experience, yet various methodologies have been developed, and different indicators have been defined to objectively assess landscape quality, on the assumption that consensus on landscape quality perception is shared among individuals [4]. Scenic beauty assumes a crucial aesthetic role as it serves as a measurable indicator of landscape beauty, determining whether its visual qualities inspire human admiration [5]. Scenic beauty, a fundamental aesthetic measure, is positively influenced by natural elements such as vegetation and water features, which elevate perceived value [6]. In contrast, anthropogenic infrastructure such as wind turbines and solar farms, commonly diminishes its perceived quality. These principles are operationalized by the InVEST Scenic Quality model, which measures visual disamenities to determine landscape quality. It creates viewshed maps from observer perspectives and calculates the visibility of landscape detractors while taking topography and terrestrial curvature into consideration. These viewsheds are defined using the region's Digital Elevation Model (DEM) and geospatial markers of visually impactful features. They reflect the unobstructed 360-degree area visible from an observation site.

Landscape quality is mapped and quantified with integer Impact Values (IV) ranging from 0 to 4. This score is unitless and does not correspond to any specific measurement of landscape quality; instead, it serves as a relative index of visual quality within the landscape studied. Higher values indicate higher visual impact, and, consequently, diminished visual quality in relation to surrounding areas, whereas lower scores indicate a reduced visual impact, and, consequently, superior visual quality. Locations completely unaffected by visual disamenities are assigned a score of 0.

Recreational Service Supply

Recreational services are a sub-category of cultural ESs [7], including activities like walking and cycling, and provide non-material benefits that enhance mental, physical, and social well-being. Accessibility, landscape features, and proximity to nature are key factors in making these services attractive and beneficial.

The assessment of recreational service value (RECVA) relies on ESTIMAP (Ecosystem Service Mapping Tool), a GIS-based model developed in 2013 by a group of the

[3] Documentation on agricultural regions is available online at: https:// www.crea.gov.it/documents/68457/0/Regioni+agrarie+indagine+MF+INEA.xlsx/8019a0cb-f3d4-dcd9-6639-d178e9f2e89e?t=1561366035978 (Accessed: 2025.03.26).

Joint Research Centre (JRC) of the European Commission. The ESTIMAP recreation model helps assess how ecosystems support outdoor activities and contact with nature. In this study, only the first part of the original ESTIMAP model, developed by Vallecillo et al. [8] and Barton et al. [9] is applied to evaluate the recreational potential of Campania Region, based on Isola et al. [10].

The methodological approach follows three key phases. The first phase examines the availability of natural areas for recreation, considering their degree of naturalness, measured using the hemeroby index (HI) [11]. HI determines how much human activity has altered an ecosystem. HI ranges from 0 (completely natural) to 9 (highly artificial) [10]. The second phase studies the presence of protected areas and landscape assets, assigning scores based on conservation objectives [12]. Areas are classified according to IUCN categories, and their importance is reflected in a raster map, where higher values indicate greater recreational potential. The third phase focuses on coastal elements, considering three factors: proximity to the coastline [12], which influences attractiveness; coastal geomorphology, based on geological classifications; and bathing water quality. Once all these elements are analyzed, the final step is to combine the results from the three phases. The outcome is a detailed raster map that highlights the potential for nature-based recreational activities in Campania (Table 1).

Table 1. Selected ecosystem services: list, definition, and data sources.

Variable	Definition and unit of measurement	Input data	Data sources
LST_Cmax	Maximum land surface temperature in a census tract [°C]	Landsat, Collection 2-Level 2 imagery (Landsat 8–9 OLI/TIRS C2 L2)	USGS Earth Explorer
HAQUA	Habitat quality index [0–1]	2018 CORINE Land cover	Copernicus land monitoring service
		Threat rasters	Open Street Map
		Threat table	Sallustio et al. [13]
		Sensitivity table	Sallustio et al. [13]
		Half saturation constant	Model's default value
VAFPR		2018 CORINE Land cover	Copernicus land monitoring service
	Land monetary value per unit area [€/ha]	National Dataset for agricultural areas on the land monetary value	"National Research Council of Agriculture and Agricultural Economics" (CREA)

(*continued*)

Table 1. (*continued*)

Variable	Definition and unit of measurement	Input data	Data sources
	Mean agricultural value (MAV) per unit area [€/ha]	National Dataset for forestry areas concerning MAV	National Revenue Agency (NRA)
LANVA	Classes of landscape value [0–4]	Area of Interest	ISTAT
		Aesthetic detractors	Global Energy Monitor [14]
		Digital Elevation Model	Copernicus GLO-30
		Refractivity coefficient	Model's default value
RECVA	Values of recreational service provision [0–1]	Hemeroby index	ISTAT National Livestock Database[a]
			Map of potential natural vegetation[b]
		CORINE land cover map	Copernicus Land Monitoring Service
		Protected areas and landscape assets	Italian national geoportal[c]
			Campania - Regional geoportal[d]
			European Environment Agency[e]
		Coastal geomorphology	European Environment Agency – Eurosion. Coastal erosion and defense[f]
		Bathing water quality	European Environment Agency – Bathing Water Directive. Status of bathing water[g]

[a]Data are available online at: https://www.vetinfo.it/j6_statistiche/#/, last accessed 2025/03/30.
[b]Data are available online at: https://land.copernicus.eu/en/products/corine-land-cover/clc2018, last accessed 2025/03/30.
[c]Data are available online at: https://gn.mase.gov.it/portale/wfs, last accessed 2025/03/30.
[d]Data are available online at: https://sit2.regione.campania.it/content/decreti-ministeriali-art-136, last accessed 2025/03/30.
[e]Data are available online at: https://www.eea.europa.eu/en/datahub/datahubitem-view/6fc8ad2d-195d-40f4-bdec-576e7d1268e4, last accessed 2025/03/30.
[f]Data are available online at: https://www.eea.europa.eu/en/datahub/datahubitem-view/ba6d7fe6-c79f-48c7-b738-f78260730538?activeAccordion=1090218, last accessed 2025/03/30.
[g]Data are available online at: https://www.eea.europa.eu/en/datahub/datahubitem-view/c3858959-90da-4c1b-b9ca-492db0e514df, last accessed 2025/03/30

2.3 Multiple Regression Model

The multiple linear regression model implemented here allows the spatial distribution of CS to be associated with the taxonomies of the five identified ESs. The model operationalizes as follows.

$$CASQT = \beta_0 + \beta_1 LSURT + \beta_2 HAQUA + \beta_3 VAFPR + \beta_4 LANVA + \beta_5 RECVA + \beta_6 CSLAG \quad (2)$$

Measurements of the CS variable and related covariates are related to a four-hectare square cell:

- CASQT is the carbon sequestration per unit area (Mg/m^2);
- LSURT is the LST, which is a reference for urban heat variation and, therefore, for the measure of its variation, which, if it were decreasing, would put in evidence an improvement in the quality of life of local communities (°C);
- HAQUA is the measure of the level of habitat quality, and takes decimal values between 0 and 1, as described in Subsect. 2.2;
- VAFPR measures the value of agricultural and forestry production (€/ha);
- LANVA measures the value of landscape, and takes decimal values between 0 and 1, as described in Subsect. 2.2;
- RECVA is the measure of recreational value, and takes decimal values between 0 and 1, as described in Subsect. 2.2;
- CSLAG is a spatially-lagged control variable for the spatial autocorrelation of CASQT (Mg/m^2).

The coefficient estimates of the covariates and the spatially-lagged variable express the marginal effect of these variables on CASQT. Multiple linear regression is generally used when there is evidence of the impossibility of priors regarding correlations between dependent and explanatory variables.

The multiple linear regression model represents the equation of a plane, tangent to a surface of unknown shape, in an n-dimensional spatial domain consisting of the variable associated with the CS, the five explanatory variables and the control variable. Around the tangency point, the linear relationship linking the seven variables, expressed by the estimate of model (2), effectively approximates the unknown surface equation above.

The control variable, CSLAG, is the spatially-lagged variable whose distribution is related to the spatial distribution of CS, and allows control of the phenomenon of spatial autocorrelation. This distribution is identified through the methodology proposed by Anselin [15].

The significance of the coefficient estimates of the explanatory and control variables is assessed by the p-value test.

3 Results

This section is organized as follows.

First, the spatial taxonomies related to the regional spatial context of Campania are presented as for the variables associated with CS and to the covariates of model (2). Secondly, the correlations implied by the estimates of the coefficients of the covariates of regression (2) are shown, so as to detect evidence concerning the association of CS to the explanatory variables.

3.1 Spatial Taxonomies of Ecosystem Services

Carbon Sequestration

Figure 1, panel A, displays the carbon storage values in the Campania Region, which range from 0 to 21.55 megagrams per 900 square meters. The highest values are distributed in distinct clusters, with two large ones located in the central and southern parts of the Region, while smaller clusters are found in the northern areas. The southern part of the Region, particularly the National Park of Cilento and Vallo di Diano, also holds substantial carbon storage values. The areas with medium-low values concern: in the north-west, the Metropolitan City of Naples, characterized by an almost totally urbanized land and the Volturno-Litorale Domizio Plain, characterized by a rural landscape that includes both specialized arboreta and arable land.

Land Surface Temperature

A total of 21 satellite images from Summer 2023 were analyzed, with only those from the same date merged into three sets. The merged images' mean values were compared, and those with the highest means were selected. The LST map is created using four Landsat images, two related to July 17, 2023 (scene 189), and two related to August 25, 2023 (scene 190).

In the Campania Region, the LST values are within the range of 27.5–64.5 °C (see Fig. 1, panel B). 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. These areas include the Campana Plain, the Phlegraean Plain and the coastal hills of Naples, as well as the areas in the crown of the Vesuvius Volcano. A concentration of elevated LST values is observed in the north-eastern portion of the provinces of Avellino and Benevento as well, specifically within the agrarian regions of Alto Tammaro and Alto Fortore. The lowest LSTs are observed in the green belt extending along the Dorsale Appenninica from the north-eastern border of the Region, in areas characterized by widespread mountains and hills.

Habitat Quality

Figure 1, panel C displays the habitat quality values in the Campania Region, where the average value is 0.49. Specifically, 40.61 percent of the Region comprises low-quality habitats ($0 < HQ \leq 0.33$), 27.96 percent consists of medium-quality habitats ($0.33 < HQ \leq 0.66$), while the remaining 31.43 percent exhibits high-quality habitats ($0.66 < HQ \leq 1$). The highest values are concentrated in green areas, particularly in forested regions, frequently safeguarded by parks and reserves. In contrast, the lowest values

occur in large urban zones and areas characterized by intensive agriculture. 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. Higher mean values are found in "inland unvegetated or sparsely vegetated areas" (aggregated from CLC 332, 333, 334, 335) with a mean of 0.53.

Value of Agricultural and Forestry Production

Four types of elevation zones can be identified: hills, mountains, coastal hills, and plains. The spatial layout of agrarian regions and elevation zones through the spatial layout of municipalities in Campania are detected, based on agrarian regions identified with groups of contiguous municipalities. Regarding forestry areas, a preliminary correspondence is established between the taxonomy of the NRA and that of the subclasses of the second level of 2018 CORINE Land cover forestry classes (3.1 - Forests and 3.2 - Areas characterized by shrub and/or herbaceous vegetation). The final step is to aggregate the data referring to VAFPR. Figure 1, panel D shows the spatial distribution of the VAFPR for the Region related to 2023 in thousands €/ha. The value ranges from zero, in case the areas were not classified as agricultural or forestry, to a maximum value of 82,316 €/ha. VAFPR is zero as for 22.08% of the Region; the average land value is 12,552 €/ha. 52.11% of land values are less than 10,000 €/ha and are concentrated in the eastern mountainous areas of the Campanian Apennines and in the Cilento area. The peaks are observed in the agrarian regions of the coastal hills of Naples and in the coastal regions of the Sorrento Peninsula, characterized by the crops "Arable and horticultural crops."

Landscape Value

Figure 1, panel E illustrates the landscape quality values in the Campania Region, indicating a regional average value of 1.33. Specifically, over half of the Region (54 percent) maintains areas with unaffected landscape quality (VI = 0), 17 percent consists of landscapes with moderate quality (VI = 2), 18 percent includes areas of low landscape quality (VI = 3), while the remaining 11 percent exhibits poor landscape quality (VI = 4). The highest values of VI are predominantly concentrated in agricultural areas. However, agricultural areas in the Province of Salerno are an exception, where landscape values commonly range from low to unaffected, with only small portions of the territory displaying poor visual quality. Protected areas are not immune from visual degradation. While landscape quality remains largely unaffected in the Cilento National Park, the Guardaregia-Campochiaro Natural Oasis, and the Roccamonfina – Foce Garigliano Regional Park, this pattern deviates in the Taburno-Camposauro Regional Park, the Monti Picentini Regional Park, and the Partenio Regional Park, where extensive areas exhibit poor visual quality. Preserved landscapes persist in the southern part of the Region, in the Province of Salerno.

Recreational Service Supply

Figure 1, panel F displays the distribution of recreational service provision across Campania, with values ranging from 0.1 to 3, indicating that no area has the lowest potential value of 0. The highest values are concentrated along the coastline, with the exception of the area within the administrative boundaries of the Metropolitan City of Naples.

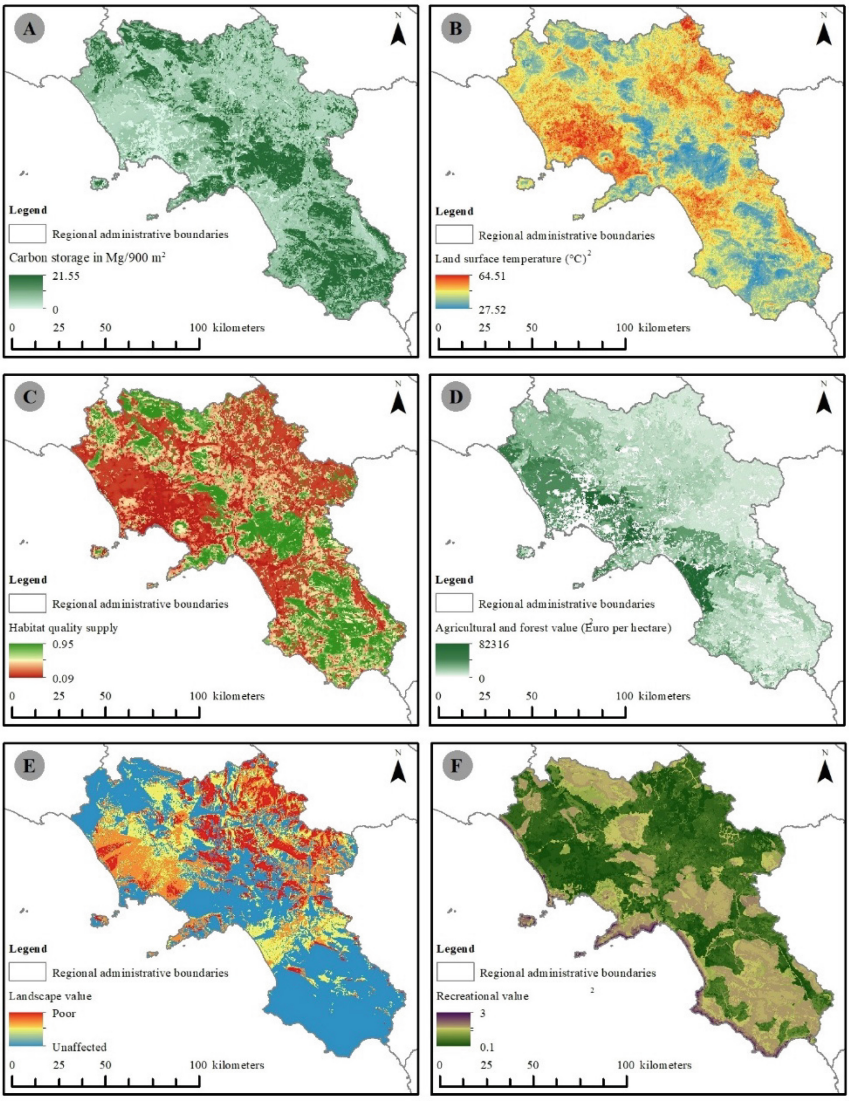


Fig. 1. Spatial distribution related to Carbon storage (panel A), Land surface temperature (panel B), Habitat quality supply (panel C), Agricultural and forest values (panel D), Landscape value (panel E), and Recreational value (panel F) in the Campania Region (Regional boundaries retrieved from: https://www.istat.it/statistiche-per-temi/ambiente-e-territorio/territorio-e-cartografia/).

Medium to high values are found in several key parts of the Region. In contrast, areas with the lowest recreational service values are located in the northeastern and northwestern parts of the Region. These areas show a lower potential for providing recreational services due to their agricultural use and less natural landscape features. These data are confirmed by the mean values that each land cover class assumes. Natural cover classes,

such as salt marshes, beaches, water bodies, bare rock, water courses and coastal lagoons have the highest mean values, from 2.79 to 1.80. Conversely, the lowest mean values, between 0.23 and 0.96, are associated with agricultural and artificial land cover types.

3.2 Multiple Regression Model

The results of the estimates of model (2) are described, in the following, as shown in Table 2, which reports the marginal effects related to CS as for a unitary increase in the variables associated to the five ESs and spatially-lagged variables, and the p-value significance tests, that account for the reliability of these estimates.

Table 2. Regression outcomes.

Variable	Coefficient	t-Statistic	p-Value	Mean of the explanatory variable	Elasticity at the mean values of CASQT and expl. Var's [(Δy/y)/(Δx/x)]
Dependent variable: Carbon sequestration (CASQT)					
LSURT	−0.39144	−44.47850	0.00000	42.47074	−0.18892
HAQUA	75.20223	308.71536	0.00000	0.49840	0.42593
VAFPR	0.00023	114.84450	0.00000	16484.56641	0.04279
LANVA	0.84426	10.948531	0.00000	0.33133	0.00318
RECVA	−10.18535	−50.90622	0.00000	0.31506	−0.03647
CSLAG	35.24651	508.05586	0.00000	0.08111	0.03249
Mean and Standard deviation of dependent variable: 87.9987, 56.2533 - Adjusted R-squared: 0.92109					

The outcomes of model (2) should be read taking account that the positive sign of an estimated coefficient implies that a growth in the availability of the associated ES corresponds to a growth in the CS and vice versa. An exception is the case of LANVA, the variable expressing landscape value, in which the availability of the corresponding ES increases as the value of the covariate decreases. All estimated coefficients, as shown in Table 2, have highly significant p-values. The estimated values of the coefficients are, therefore, reliable in identifying the relationships between CS and the supply of the ESs corresponding to the covariates. The absolute values of the elasticities are always less than unity and, therefore, configure an inelastic behavior of the CS availability with respect to the covariates, although significant differences between them are evident.

The results posit that a 1% increase in the LSURT covariate, i.e., an average gradient of just over 0.4 °C, corresponds to an average decrease in CS of about 0.17 Mg/ha, or just under 0.2%. It should be emphasized, in this regard, how the temporal trend, on an annual basis, of thermal gradients is generally smaller than this value and, therefore, how the association of CASQT and LSURT, consistent with the results of several scientific

articles available in the literature, indicates a reduced and, in any case, significant impact of LST on CS.

Of particular note is habitat quality, whose associated variable, HAQUA, shows the highest value among elasticities, at about 43%. This implies that a 1% increase in this covariate is associated with a 0.43% increase in CS, or about 0.38 Mg/ha. Since habitat quality can be significantly improved in relation to land policies geared toward direct or indirect protection of areas, especially in relation to mitigation of threats, it is evident that the HAQUA variable emerges as the most important one with regard to what concerns the establishment of land policies geared toward contributing to overall climate quality.

As for the variable representing agricultural and forestry production, the elasticity value associated with it is positive and rather low, at about 4%, thus about one-tenth of the elasticity related to habitat quality. This implies that only changes in VAFPR of the order of 10%, or about 1.650 €/ha, or more, are associated with changes of some significance in CS, amounting to about 0.35 Mg/ha, thus of the order of magnitude of those associated with habitat quality or with decreasing LST.

With regard to landscape value, which is related to the significance of scenic views in relation to aesthetic detractors such as, for example, wind turbines and photovoltaic installations, the positive and significant value of the coefficient estimated through model (2) indicates how an increase in CS is associated with a decrease in landscape value, i.e., scenic significance. The value of the elasticity is, however, very low at about 3‰. This outcome highlights a substantial indifference of CS with respect to landscape value, although it implies, as well, a strong indication in the direction of avoiding, as much as possible, the location of energy production plants in areas of particular scenic importance.

The value of the ES representing the supply of nature-based services behaves similarly to the landscape value, but with a significantly larger elasticity of about 3.6%. In this case, a 10% decrease in RECVA supply is associated with an increase in CS of about 0.30 Mg/ha. The negative correlation can be attributed to the fact that recreational potential is closely linked to the accessibility of areas available for outdoor activities, thus to the presence, albeit with limited extent, of mobility infrastructure.

4 Discussion

The discussion developed in the following subsections is based on the implications of model (2), with reference to the relationships between the supply of CS and the availability of the other ESs.

4.1 Carbon Sequestration and Land Surface Temperature

The link between CS and LST, evidenced by the use of the methodology presented here in the regional spatial context of Campania, is supported by multiple research in the literature. Momo and Devi [16] examine the trends in LST and CS over ten years (2011–2021), focusing on the western district of Imphal, which is the capital of the Indian State of Manipur. They compare the results achieved through different methodologies based on satellite data, showing how they converge, both qualitatively and quantitatively, and demonstrate that the steady decrease in CS is associated with an equally steady increase

in LST. Similar results, albeit with different methodological approaches, are presented and discussed by Wang et al. [17], with reference to the metropolitan context of Shenzen, located in a subtropical area of China, by Dibaba [18], regarding the urban contexts of Nekemte and Jimma, in western Ethiopia.

4.2 Carbon Sequestration and Habitat Quality

There are many studies showing a positive relationship between CS and habitat quality, covering a wide range of spatial scales including continental, regional, and local contexts, as well as different definitions of the spatial distribution of ESs associated with habitat quality. Based on Bayley [19], in the context of the Falkland Islands, a link emerges between improved habitat quality and increased CS capacity. The research by Hua et al. [20] focuses on the Xiamen metropolitan area, located in the Min Delta Region of China. In addition, two articles are significant, that of Del Vecchio et al. [21] on the progress of dune vegetation along the Veneto coast of northeastern Italy, and that of Zullo et al. [22] on the coastal area of Abruzzo, in eastern Italy.

4.3 Carbon Sequestration and Value of Agricultural and Forestry Production

Many studies highlight the connection between CS and VAFPR. Al Kafy et al. [23] examined the influence of changes in land use and land cover on CS capacity in forest ecosystems in the Chittagong Hill Tracts Region (Bangladesh) using remote sensing techniques. This study, conducted for the years 1996 to 2021, revealed a loss of 21.65 $\times$ 10^6 Mg of CS due to a 21% reduction in vegetation cover.

Regarding agricultural areas, Paris et al. [24] and Frank et al. [25] have evidence that agricultural and forestry techniques contribute to ecological intensification of productivity. This is demonstrated in a recent research on olive groves in the Umbria Region of Italy [26] which indicates how significant portion of soil carbon is concentrated in the top 30 to 60 cm of agricultural land. Maintaining olive grove cultivation is a key strategy for protecting soil organic carbon and minimizing atmospheric carbon release due to land use change or intensive soil management.

4.4 Carbon Sequestration and Landscape Value

CS and landscape value are very strongly intertwined such that scholars identified Agroforestry systems of High Nature and Cultural Value (HNCV) [27], where CS and landscape aesthetics are mutually enhanced. Specifically, agroforestry systems of high nature value are defined as areas characterized by the prevalence of semi-natural habitats and trees that typically support rich biodiversity [28] and provide numerous services, including CS [29], while simultaneously offering pleasant landscapes [30]. However, Renewable Energy Source (RES) infrastructures, such as the here examined wind turbines and solar farms, often disrupt the scenic views that characterize these landscapes, sacrificing their aesthetic value in the name of green energy supply.

4.5 Carbon Sequestration and Recreational Service Supply

The results point to a negative correlation between RECVA supply and CS, potentially associated with issues related to the accessibility of such areas for recreational activities. Costanza [31] describes recreational services as "user movement related," highlighting accessibility as one of the three core elements of recreational services, alongside ecosystem functions and the spatial distribution of potential demand. Moreover, according to Paracchini et al. [32], one key factor influencing a place's attractiveness is its proximity. When it comes to everyday recreational activities, people tend to favor locations within approximately 8 km of their residence. High CS values are associated with wooded areas, which are very often located in natural and semi-natural areas far from built-up areas.

5 Conclusions

This study proposes a methodological itinerary aimed at identifying the association between climate neutrality conditions, represented by CS capacity, and ESs supply, structured through a spatial system consisting of two regulating ESs, namely LST control and habitat quality, one provisioning ES, such as agricultural and forestry production, and two cultural ESs, namely landscape value and outdoor recreation. The methodology was experimentally implemented with reference to the regional context of Campania.

There are two significant profiles that characterize the study. First, the definition and application, in a single interpretative model, of different methodological approaches, based on current scientific and technical literature, concerning the identification of the spatial supply of some ESs, typical of spatial, urban, peri-urban and rural contexts, and their integration in a single model that configures their association with the global climate situation, represented by CS capacity. In this way, the spatial configuration of this situation is read and interpreted with reference to an integrated supply of ESs and not only in relation to the impacts of the individual ES. The results, with reference to Campania, indicate how habitat quality is the most relevant ES in relation to the impact on climate neutrality, how, likewise, effects of medium importance are found with regard to LST control, agricultural and forestry production, and nature-based recreation, and how, finally, the influence of landscape value is significantly less significant, although, in the latter case, the model estimate identifies a relationship between the provision of this ES and climate neutrality that signals the need for special attention of the location of renewable energy production facilities as environmental detractors of landscape scenic value.

Secondly, the model's easily readable and interpretable outcomes allow, with regard to the results just mentioned, to recognize implications for regional and local planning policies based on the integration of enhancing the supply of different services provided by natural ecosystems. The ecosystem approach represents, certainly, a highly innovative conceptual horizon, probably still revolutionary today, for the practice of spatial planning.

Authors' Contributions. Federica Isola (F.I.), Francesca Leccis (F.L.), Federica Leone (F.Le.) and Corrado Zoppi (C.Z.) collaboratively designed this study. Individual contributions are as follows: F.Le. And C.Z. collaboratively wrote Sects. 1; F.Le. Wrote Sect. 2.1, Subsections "Recreational service supply" in Sects. 2.2 and 3.1, and Sect. 4.5; F.I. wrote Subsections "Land surface temperature" and "Value of agricultural and forestry production" in Sects. 2.2 and 3.1, and Sect. 4.3; F.L. wrote Subsections "Habitat quality" and "Landscape value" in Sects. 2.2 and 3.1, and Sect. 4.4; C.Z. wrote Sects. 2.3, 3.2, 4.1, 4.2 and 5.

Acknowledgments. This study was carried out: i. within the RETURN Extended Partnership funded by the European Union – NextGenerationEU (National Recovery and Resilience Plan – NRRP, M4, C2, In-VESTment 1.3 – D.D. 1243 2/8/2022, PE0000005); ii. Within the NRRP, M4, C2, In-VESTment 1.1, Call for tender no. 1409 published on 14.9.2022 by the Italian Ministry of University and Research (MUR), funded by the European Union – NextGenerationEU – Project Title "Definition of a guidelines handbook to implement climate neutrality by improving ecosystem service effectiveness in rural and urban areas" – CUP F53D23010760001 – Grant Assignment Decree no. 1378 adopted on September 1, 2023, by MUR; iii. Within the research grant CUP F73C23001680007 for the project "Geodesign for climate change mitigation and adaptation in the Mediterranean region," funded in 2022 by Fondazione di Sardegna.

Disclosure of Interests. The authors declare no competing interests.

References

1. Hall, L.S., Krausman, P.R., Morrison, M.L.: The habitat concept and a plea for standard terminology. Wildlife Soc. Bull. (1973–2006), **25**, 173–182 (1997). https://www.jstor.org/stable/3783301
2. Lorilla, R.S., Poirazidis, K., Kalogirou, S., Detsis, V., Martinis, A.: Assessment of the spatial dynamics and interactions among multiple ecosystem services to promote effective policy making across Mediterranean island landscapes. Sustainability **10**, 3285 (2018). https://doi.org/10.3390/su10093285
3. Yang, S., et al.: Nature-based solution for climate change adaptation: coastal habitats restoration in Xiamen Bay, China. Forests**15**(11), 1844 (2024). https://doi.org/10.3390/f15111844
4. Bader, P.: Understanding landscape change. The. Environment **3**, 16–18 (2020)
5. Mundher, R., et al.: Aesthetic quality assessment of landscapes as a model for urban forest areas: a systematic literature review. Forests **13**, 991 (2022). https://doi.org/10.3390/f13070991
6. Zhang, N., Zheng, X., Wang, X.: Assessment of aesthetic quality of urban landscapes by integrating objective and subjective factors: a case study for riparian landscapes. Front. Ecol. Evol. **9** (2021). https://doi.org/10.3389/fevo.2021.735905
7. MA (Millennium Ecosystem Assessment): ecosystems and human well-being: a framework for assessment. Island Press: Washington, DC, USA (2003). https://wedocs.unep.org/bitstream/handle/20.500.11822/8768/Ecosystem_and_human_well_being_a_framework_for_assessment.pdf?sequence=3&amp%3BisAllowed=, Accessed 30 Mar 2025

8. Vallecillo, S., La Notte, A., Zulian, G., Ferrini, S., Maes, J.: Ecosystem services accounts: valuing the actual flow of nature-based recreation from ecosystems to people. Ecol. Model. **392**, 196–211 (2019). https://doi.org/10.1016/j.ecolmodel.2018.09.023
9. Barton, D.N., et al.: Discussion paper 10: recreation services from ecosystems (2019). https://www.researchgate.net/publication/333263149_Recreation_services_from_ecosystems, Accessed 30 Mar 2025
10. Isola, F., Lai, S., Leone, F., Zoppi, C.: Green infrastructure and regional planning. An operational framework. FrancoAngeli, Milan, Italy (2022)
11. Paracchini, M.L., Capitani, C.: Implementation of a EU Wide Indicator for the Rural-Agrarian Landscape. Publications Office of the European Union, Luxembourg (2011)
12. Zulian, G., Paracchini, M.L., Maes, J., Liquete, C.: ESTIMAP: ecosystem services mapping at European scale. JRC (European Commission – Joint Research Centre – Institute for Environment and Sustainability) Technical Report EUR 26474 ENG. Publications Office of the European Union: Luxembourg (2013). https://doi.org/10.2788/6436
13. Sallustio, L., et al.: Assessing habitat quality in relation to the spatial distribution of protected areas in Italy. J. Environ. Manage. **201**, 129–137 (2017). https://doi.org/10.1016/j.jenvman.2017.06.031
14. GEM (Global Energy Monitor): global solar power tracker, global energy monitor and TransitionZero, June 2024 release. https://globalenergymonitor.org/projects/global-solar-power-tracker/, Accessed 30 Mar 2025
15. Anselin, L., Syabri, I., Kho, Y.: GeoDa: an introduction to spatial data analysis. Geogr. Anal. **38**(1), 5–22 (2006). https://doi.org/10.1111/j.0016-7363.2005.00671.x
16. Momo, M., Devi, T.T.: Assessment of land surface temperature and carbon sequestration using remotely sensed satellite data in the Imphal-West district, Manipur, India. J. Earth Syst. Sci. **131**, 229 (2022). https://doi.org/10.1007/s12040-022-01944-8
17. Wang, J., Xiang, Z., Wang, W., Chang, W., Wang, Y.: Impacts of strengthened warming by urban heat island on carbon sequestration of urban ecosystems in a subtropical city of China. Urban Ecosyst. **24**, 1165–1177 (2021). https://doi.org/10.1007/s11252-021-01104-8
18. Dibaba, W.T.: Urbanization-induced land use/land cover change and its impact on surface temperature and heat fluxes over two major cities in Western Ethiopia. Environ. Monit. Assess. **195**, 1083 (2023). https://doi.org/10.1007/s10661-023-11698-5
19. Bayley, D.T.I., Brickle, P., Brewin, P.E., Golding, N., Pelembe, T.: Valuation of kelp forest ecosystem services in the Falkland Islands: a case study integrating blue carbon sequestration potential. One Ecosyst. **6**, e62811 (2021). https://doi.org/10.3897/oneeco.6.e62811
20. Hua, Y., Yan, D., Liu, X.: Assessing synergies and trade-offs between ecosystem services in highly urbanized area under different scenarios of future land use change. Environ. Sustain. Indicat. **22**, 100350 (2024). https://doi.org/10.1016/j.indic.2024.100350
21. Del Vecchio, S., Rova, S., Fantinato, E., Pranovi, F., Buffa, G.: Disturbance affects the contribution of coastal dune vegetation to carbon storage and carbon sequestration rate. Plant Sociol. **59**(1), 37–48 (2022). https://doi.org/10.3897/pls2022591/04
22. Zullo, F., Montaldi, C., Di Pietro, G., Cattani, C.: Land use changes and ecosystem services: the case study of the Abruzzo Region coastal strip. ISPRS Int. J. Geo Inf. **11**, 588 (2022). https://doi.org/10.3390/ijgi11120588
23. Al Kafy, A., et al.: Integrating Forest cover change and carbon storage dynamics: leveraging google earth engine and In-VEST model to inform conservation in hilly regions. Ecol. Indicat. **152**, 110374 (2023). https://doi.org/10.1016/j.ecolind.2023.110374
24. Paris P., et al.: Agroselvicoltura ed intensificazione ecologica. Forest@ **16**, 10–15 (2019). https://doi.org/10.3832/efor3053-016
25. Frank, S., Lessa Derci Augustynczik, A., Havlík, P., et al.: Enhanced agricultural carbon sinks provide benefits for farmers and the climate. Nat. Food **5**, 742–753 (2024). https://doi.org/10.1038/s43016-024-01039-1

26. Bateni, C., Ventura, M., Tonon, G., Pisanelli, A.: Soil carbon stock in olive groves agroforestry systems under different management and soil characteristics. Agrofor. Syst. **95**, 951–961 (2021). https://doi.org/10.1007/s10457-019-00367-7
27. Beaufoy, G., BaldocK, D. E ClarK, J.: The nature of farming. Low intensity farming systems in nine European countries Report IEEP/WWF/JNCC, London, Gland, Peterborough (1994). https://ieep.eu/wp-content/uploads/2023/01/TheNatureOfFarming_1994_.pdf, Accessed 25 Mar 2025
28. Andersen E., et al.: Developing a high nature value indicator. Report for the European Environment Agency, Copenhagen (2003)
29. Rolo, V., et al.: Challenges and innovations for improving the sustainability of European agroforestry systems of high nature and cultural value: stakeholder perspectives. Sustain. Sci. **15**, 1301–1315 (2020). https://doi.org/10.1007/s11625-020-00826-6
30. Moreno, G., et al.: Agroforestry systems of high nature and cultural value in Europe: provision of commercial goods and other ecosystem services. Agroforest Syst. **92**, 877–891 (2018). https://doi.org/10.1007/s10457-017-0126-1
31. Costanza, R.: Ecosystem services: multiple classification systems are needed. Biol. Cons. **141**(2), 350–352 (2008). https://doi.org/10.1016/j.biocon.2007.12.020
32. Paracchini, M.L., et al.: Mapping cultural ecosystem services: a framework to assess the potential for outdoor recreation across the EU. Ecol. Ind. **45**, 371–385 (2014). https://doi.org/10.1016/j.ecolind.2014.04.018