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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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Global climate crisis and regional contexts. A study on ecosystem services related to Sardinia, Italy

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Abstract

Global climate change threatens human health, impacting both physical and psychological well-being. Mitigating these effects requires balancing the carbon cycle, as carbon dioxide regulates Earth's temperature through its role in greenhouse gases. In line with the Paris Agreement's goal of climate neutrality by century's end, the objective is to limit global warming to 1.5 °C by balancing carbon emissions and removals. Yet, existing atmospheric carbon could still add about 0.6 °C of warming, even if emissions ceased today. Achieving net-zero emissions is therefore crucial and underscores the need to understand ecosystems' capacity for carbon storage and sequestration. This study proposes a methodological framework to support climate neutrality through spatial planning policies, using the Carbon Capture Capacity (CCC) indicator to assess current conditions and trends. CCC is examined alongside five ecosystem services (ESs): heat mitigation, habitat quality, crop and timber production, scenic quality, and potential for outdoor activities (POA). Focusing on Sardinia, spatial correlations between CCC and these ESs are analyzed to assess how multifunctional ecosystems enhance carbon sequestration and contribute to global climate goals. CCC mapping, based on the InVEST "Carbon Storage and Sequestration" model, reveals strong positive correlations with heat mitigation and habitat quality, while POA shows moderate influence. Weaker links with production and scenic quality stress the need for careful siting of renewable energy to preserve landscape integrity.

Keywords

Carbon sequestration; Climate neutrality; Ecosystem services

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1. Introduction

Climate change (CC) is expected to place significant strain on human health, affecting both physical well-being and mental health in diverse and far-reaching ways (Driga & Drigas, 2019). To mitigate the risks associated with CC, maintaining a balanced carbon cycle is crucial, given that carbon dioxide is a fundamental component in regulating the planet's surface temperature through its influence on atmospheric greenhouse gas concentrations. In accordance with the Paris Climate Agreement, which seeks to achieve climate neutrality by the latter half of this century, a target of limiting global warming to 1.5 °C has been established to maintain a balanced carbon cycle, reducing CC impacts through a long-term balance between emissions and removals. This process is challenging because the carbon dioxide already in the atmosphere will cause an additional warming of approximately 0.6 °C over the next century due to the greenhouse effect (Riebeek, 2011), even if emissions stop immediately; therefore, achieving net zero carbon emissions is essential to limit global warming to the set target and avoid exceeding it, highlighting the critical importance of understanding the carbon storage and sequestration capacity of natural systems.

Human activities, particularly the burning of fossil fuels and land clearing, are causing significant disruptions to the carbon cycle. Land use changes, along with the intensification of agriculture to produce more food on less land and similar trends, have led to increased emissions and a reduced capacity for carbon sequestration. Currently, human activity affects over 70% of ice-free land and utilizes up to a third of its potential biological productivity for food, energy, and materials, underscoring both its ecological importance and vulnerability (IPCC, 2023).

In the European context, Italy has experienced increasing land consumption, especially in agricultural and natural areas, leading to urban sprawl, biodiversity loss, and environmental risks such as floods and heat islands (Mussinelli et al., 2024). Sardinia emerged as the Italian region with the highest increase in artificial land cover in both 2023 and 2024, recorded as +0.57% in the latest year. This trend highlights persistent pressures on ecosystems and the urgent need to align climate adaptation strategies with ecosystem service (ES) preservation to advance toward climate neutrality (Munafò, 2023; SNPA, 2024). Land-based strategies aimed at CC and achieving climate neutrality require integrating diverse adaptation and mitigation actions that simultaneously enhance ecosystem health and the delivery of multiple ESs (IPCC, 2023).

Within this conceptual framework, the study aims to propose and apply a methodological approach for the implementation of climate neutrality through spatial planning policies. The Carbon Capture Capacity (CCC) measure is taken as a reference to estimate the status and evolutionary dynamics of this phenomenon, analyzed and evaluated as associated with the supply of five ESs, Heat Mitigation (HM), Habitat Quality Level (HQL), Crop and Timber Production (CTP), Scenic Quality (SCQ), and Potential for Outdoor Activities (POA). Specifically, the correlations between the spatial taxonomies of CCC and the supply of the five ESs, with reference to the regional context of Sardinia, are detected and analyzed in order to assess how the characteristics and specificities of the multifunctional supply of ESs are effective in maximizing CCC, and, thus, the contribution of the Sardinian Region to the improvement of global climate neutrality. In particular, the spatial configuration of CCC is delineated through the generation of density maps, employing the "Carbon Storage and Sequestration" model from the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) toolset. This model quantifies the stock of carbon retained within defined spatial units, based on raster data derived from land use/land cover classifications in relation to four carbon pools, aboveground and belowground biomass, dead organic matter and soil.

The study is organized into five main sections. Section two outlines the selected case study and details the methodologies employed for the evaluation and spatial representation of the five ESs, as well as their relationship with CCC. Section three presents the empirical findings, while section four offers a critical interpretation and discussion of the results. Finally, section five summarizes the key conclusions and proposes avenues for future investigation.

2. Materials and methods

This part is structured in the following way. Initially, the regional context of Sardinia is introduced, focusing on its characteristics concerning the provision of CCC and the other essentials that are part of this research. Secondly, the approach utilized to identify the spatial taxonomy of CCC provision and other ESs is outlined, which is executed by recognizing the spatial taxonomies of CCC capacity, HQL, land surface temperature (LST) mitigation, crop and timber production, scenic quality, and potential for outdoor activities. In conclusion, a multiple regression is conducted to identify spatial correlations between CCC and the supply of ESs.

2.1 Sardinia Region

The Sardinia Region (see Fig.1), Italy's second-largest island, spans 24,100 km² (ISTAT, 2024) and features a predominantly hilly and mountainous terrain with significant geological diversity. Its rivers follow a torrential regime, and despite limited freshwater lakes, the island hosts numerous coastal lagoons. Sardinia includes national and regional parks, 131 Natura 2000 sites (EEA, 2024a), and extensive agricultural areas. It plays a key role in Italy's livestock farming and has a growing renewable energy sector, mainly wind and solar.

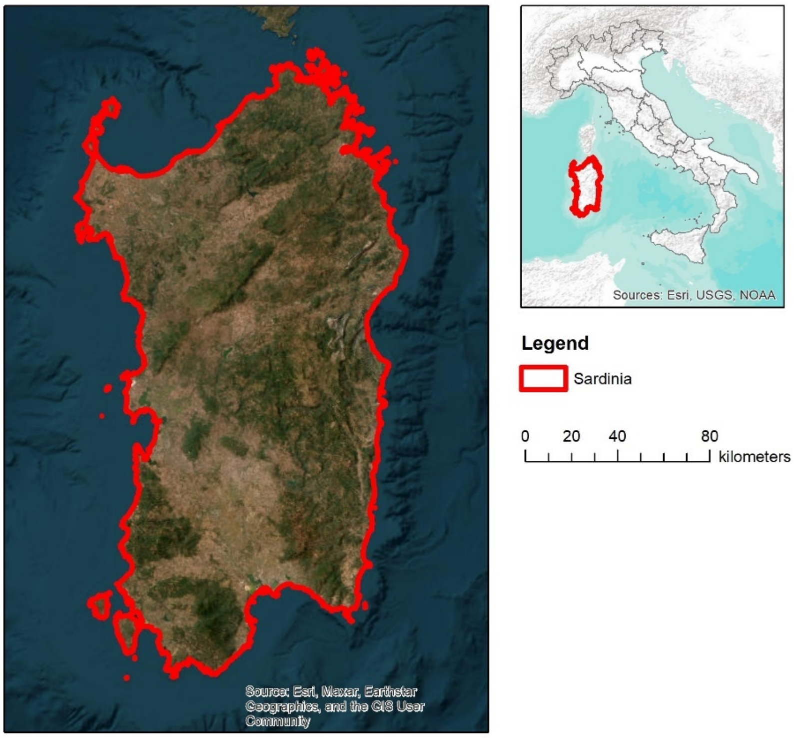

Fig.1 Location of the study area

2.2 Ecosystem service supply

This subsection presents synthetic summaries of the five ecosystem services that are evaluated for their effect on CCC and, consequently, whose role in climate neutrality is examined. The description entails the measurement techniques and spatial classification of ecosystem service supply.

Heat mitigation

Heat mitigation is a vital ES that affects quality of life on earth. In this study it is measured through satellite images provided by the United States Geological Survey (USGS)'s Earth Explorer[1]. The relevant information is

[1] Earth Explorer by U.S. Geological Survey. https://earthexplorer.usgs.gov/ (last accessed:20/06/2025).

extracted using Band 10 of the "Landsat 8-9 OLI/TIRS C2 L2" imagery where Band 10 corresponds to the thermal infrared range which captures LST data. The search criteria included a maximum cloud cover level of 6% and a date range of the final week of June (25/06/2023) to the first week of September (02/09/2023) in order to cover the summer season with the highest temperatures. The method involves comparing all available satellite images within the selected threshold and selecting the imagery with the highest mean value, while accounting for potential anomalies that may influence the mean; these anomalies were identified by analyzing the percentile rank distribution of raster values, using turning points in the curve to determine the thresholds for valid minimum and maximum values. The USGS Guide[2]'s scale factor is applied to raster images' digital number (DN) data to determine the mean values in Celsius degrees (°C):

$$0.00341802 * DN + 149.0-273.15\ (°C) \tag{1}$$

In the case of Sardinia, 5 satellite images were used to cover the whole region.

Habitat quality level

HQL refers to the capacity of an area to support the flora and fauna to thrive as well as maintain ecological processes and is closely linked to biodiversity. It can be measured by analyzing spatial patterns by examining land use and land cover (LULC) maps along with threats to the habitat of species. This study uses InVEST Habitat Quality[3] model is to map HQL. The model requires information on habitat types corresponding to a LULC map, threats and habitat suitability scores which are informed by Sallustio et al. (2017). Their study defines 8 threats and 12 habitat types, the habitat type "mixed forest" is added in the case of Sardinia totaling up to 13. 8 threats are defined as follows:

1. Roads 1: Motorways; Trunks; Primary roads.
2. Roads 2: Secondary and tertiary roads.
3. Roads 3: Residential and service roads.
4. Roads 4: Tracks and bridleways.
5. Railways
6. Intensive agricultural lands
7. Extensive agricultural lands
8. Buildings and other artificial areas or imperviousness soils

13 habitats are as follows:

1. Beaches, Dunes, and Sands
2. Water Bodies
3. Wetlands
4. Grasslands
5. Shrublands
6. Broadleaves Forests
7. Conifers Forests
8. Inland Unvegetated or Sparsely Vegetated Areas
9. Intensive Agricultural Lands
10. Extensive Agricultural Lands
11. Buildings and Other Artificial Areas or Impervious Soils

[2] U.S. Geological Survey. (2024). Landsat 8-9 Collection 2 (C2) Level 2 Science Product (L2SP) Guide. https://www.usgs.gov/media/files/landsat-8-9-collection-2-level-2-science-product-guide (last accessed:20/06/2025).
[3] The Natural Capital Project (n.d.) InVEST User's Guide. Habitat Quality. Stanford University. https://releases.naturalcapitalproject.org/invest-userguide/latest/en/habitat_quality.html (last accessed:20/06/2025).

12. Open Urban Areas
13. Mixed Forest

In total, four inputs are required: LULC map, threat maps, a sensitivity table and a threats table. CORINE Land Cover[4] 2018 is utilized as LULC in tiff format with 13 values corresponding to the habitat types, threat maps are created using OSM Geofabrik[5] , sensitivity and threats table are derived from the same study, using the average between "broadleaved" and "conifers" for the added 13th category. The model generates two final maps, one of which demonstrates the HQL on scale from 0 to 1, a unitless score representing the relative level of habitat quality within the area.

Crop and timber production

Provisioning ESs including goods such as food, freshwater, timber, fiber, and energy, represent one of the four ES categories defined by the Millennium Ecosystem Assessment (CICES, 2022; MA, 2003). Agricultural and forestry production are key examples within this category, particularly significant in Italy's diverse landscapes characterized by extensive agricultural activities and rich biodiversity (ISPRA, 2020). In line with the EU Common Agricultural Policy (CAP) reforms (COM(2017)713), aligned with the Paris Agreement[6] and 2030 Sustainable Development Goals[7], efforts focus on enhancing sustainability and rural development through technical and financial measures (National Strategic Plan 2023-2027). Economic valuation of provisioning ESs is increasingly integrated into strategic environmental assessments to guide land-use planning and ecosystem conservation (Santolini & Morri, 2017).

The valuation of crop and timber production (CTP) employs land monetary value as a proxy, refined by geographic and environmental factors such as location, altitude, morphology, and orography (Isola et al., 2022). This approach utilizes two primary datasets: CREA's national land value[8] dataset for agriculture and the National Revenue Agency's (NRA) forestry land values (2023). Data on agrarian and forestry regions are organized by municipality, province, and elevation zone, facilitating spatial analysis. Correspondences between 2018 CORINE Land Cover classifications and crop taxonomies from CREA and NRA allow spatial overlay mapping, enabling estimation of CTP per spatial unit.

Scenic quality

The InVEST scenic quality model is used to assess scenic quality (Sharp et al., 2018). The model evaluates overall scenic quality by combining topographic data and beauty detractors (Singh et al., 2020). To map their visibility and create viewshed maps, it employs the Digital Elevation Model (DEM) and a point vector layer representing visual disamenities (Griffin et al., 2015; Sieber & Pons, 2015). It also accounts for terrestrial curvature and atmospheric refraction of visible light (Singh et al., 2020).

Whole numbers between 0 and 4 are assigned by the model based on the Visual Impact (VI) that visual detractors have on the landscape. These dimensionless numbers, which are inversely correlated with levels of scenic quality, allow comparisons between the different areas of the landscape (NatCap, n.d.). In comparison to the surrounding areas, higher values imply greater visual impact and, therefore, diminished scenic quality, whereas lower values indicate less visual deterioration and, thus, higher scenic quality. Locations completely unaffected by visual disamenities are assigned a score of 0 (Ibid.).

[4] European Environment Agency (2020). CORINE Land Cover 2018 (vector), Europe, 6-yearly – version 2020_20u1, May 2020 [Data set]. Copernicus Land Monitoring Service. https://doi.org/10.2909/71c95a07-e296-44fc-b22b-415f42acfdf0.
[5] Geofabrik (2024). OpenStreetMap data for Italy - Isole. Geofabrik GmbH. https://download.geofabrik.de/europe/italy/isole.html (last accessed: 20/06/2025).
[6] UN (Unite Nations). Paris Agreement 2015. Available online: https://unfccc.int/sites/default/files/english_paris_agreement.pdf (last accessed: 20/06/2025).
[7] The 17 Goals. Available online: https://sdgs.un.org/goals (last accessed: 20/06/2025).
[8] National Research Council of Agriculture and Agricultural Economics (Italian acronym: CREA).

Since Renewable Energy Sources (RES), such as solar farms and wind turbines, are acknowledged for degrading landscape aesthetics (Saganeiti et al., 2020; Zardo et al., 2023), they are classified as aesthetic detractors within this study. Their locations are sourced from the database provided by the Global Energy Monitor (GEM, 2024a; 2024b), the DEM is obtained from the European Space Agency's Copernicus DEM at 30m resolution, and the refractivity coefficient is established as the default value of 0.13.

Potential for outdoor activities

The ESTIMAP (Ecosystem Service Mapping Tool) model is a GIS-based framework designed to spatially quantify and map potential for outdoor activities. This study employs the first part of the ESTIMAP model, as adapted by Vallecillo et al. (2019) and Barton et al. (2019), and implemented by Isola et al. (2022), to assess the potential provision of recreational services. The approach is divided into three phases. Phase A evaluates the availability of areas that support recreation based on the degree of naturalness, using the hemeroby index, which reflects anthropogenic influence (Paracchini & Capitani, 2011). The resulting raster output classifies areas in a range from [0] to [1]. Phase B considers the presence of recreationally relevant landscape features, such as protected areas and assets of landscape interest. Each area is assigned expert-based scores according to its IUCN classification, reflecting its recreational value, following approaches by Zulian et al. (2013) and La Notte et al. (2017). The resulting raster output classifies areas as [0] for no value, [0.8] for moderate, and [1] for high recreational value. Phase C incorporates coastal components, assessed through three indicators: proximity to the coastline, coastal geomorphology, and bathing water quality. The integration of these three phases enables the spatial representation of the potential for recreational service provision in coastal and inland areas. The resulting raster output classifies areas within the range [0-1]. The POA is obtained by summing the values of the outputs of phases A, B and C.

Variable	Description	Data	Source
CCC	Density of carbon in Mg/m^2	Land cover map	Copernicus Land monitoring service (2018)
		Carbon density values for each land cover type in relation to the four pools	ORNL DAAC (2010) (aboveground and belowground biomass) INFC (2015) (aboveground biomass and dead organic matter) INFC (2005) (soil) ISPRA (2022) (soil) AGRIS (2016) (soil)
HMR	Maximum values of Land surface temperature in °C	Landsat, Collection 2-Level 2 imagery (Landsat 8-9 OLI/TIRS C2 L2)	United States Geological Survey though the interface Earth Explorer (https://earthexplorer.usgs.gov/)
HQL	Value of habitat quality in the 0-1 range	Land cover map	Copernicus Land monitoring service (2018)
		Raster map of treats	Geofabrik. OpenStreetMap Data Extracts, Europe, Italy (https://download.geofabrik.de/europe/italy/)
		Treat table	Sallustio et al. (2017)
		Sensitive table	Sallustio et al. (2017)
CTP	Crop and timber production in euro per hectare	Land cover map	Copernicus Land monitoring service (2018)
		Land monetary value per unit area [€/ha].	National Research Council of Agriculture and Agricultural Economics (CREA) (https://www.crea.gov.it/documents/68457/0/Regioni+agrarie+indagine+MF+INEA.xlsx/8019a0cb-f3d4-dcd9-6639-d178e9f2e89e?t=1561366035978)

Variable	Description	Data	Source
		Mean agricultural value (MAV) per unit area [€/ha].	National Revenue Agency (NRA) (https://www.agenziaentrate.gov.it/portale/schede/fabbricatiterreni/omi/banche-dati/valori-agricoli-medi/valori-agricoli-medi-sardegna)
SCQ	Scenic value in the 0-4 range	Interest area	ISTAT (Istituto nazionale di statistica) [National Institute of Statistics] (2024) https://www.istat.it/notizia/confini-delle-unita-amministrative-a-fini-statistici-al-1-gennaio-2018-2/
		Aesthetic detractors	Global Energy Monitor (GEM) (2024b) https://globalenergymonitor.org/projects/global-solar-power-tracker/
		Digital Elevation Model	Copernicus GLO-30 Copernicus DEM - Global and European Digital Elevation Model https://doi.org/10.5270/ESA-c5d3d65
		Refractivity coefficient	Default value of the model
POA	Potential for outdoor activities	Hemeroby index (agricultural areas)	ISTAT (2019)
			National Livestock Database (https://www.vetinfo.it/j6_statistiche/#/)
		Hemeroby index (forestry areas)	Bacchetta et al. (2009)
		Land cover map	Copernicus Land monitoring service (2018)
		Protected areas and landscape assets	Sardinian geoportal (https://www.sardegnageoportale.it/)
		Coastal geomorphology	EEA (2004)
		Bathing water quality	EEA (2024b)

Tab.1 CCC and the five selected ESs: Information and data sources

2.3 Linear regression

As in many studies on correlations between spatial variables, a regression model is used because no preliminary hypothesis seems plausible regarding the effect of the explanatory variables on the dependent variable (Cheshire & Sheppard, 1995; Sklenicka et al., 2013; Stewart & Libby, 1998; Zoppi et al., 2015). Therefore, a surface, characterized by an unknown equation, representing a spatial phenomenon characterized by n (6, in this particular case) factors, is approximated, in an infinitesimal neighborhood of one of its points, by its tangent hyperplane. The infinitesimal area shared by the hyperplane and the surface is identified by the known equation of the tangent hyperplane, i.e., by the linear relationship between the variables.

This linear relationship locally approximates the unknown surface. That being the case, the multiple regression model estimates the trace of a six-dimensional hyperplane on a six-dimensional surface whose equation is unknown (Byron & Bera, 1983; Wolman & Couper, 2003), showing the linear correlations between CCC and the five dependent variables.

Through a linear regression the spatial taxonomy of CCC is correlated with the five spatial distributions of the ESs described in section 2.2. The model develops in the following manner.

$$CCC = \alpha_0 + \alpha_1\ HMR + \alpha_2\ HQL + \alpha_3\ CTP + \alpha_4\ SCQ + \alpha_5\ POA \qquad (2)$$

where measures of the CCC dependent variable and related explanatory variables are associated with a basic spatial unit of 200x200 square meters, and the variables are identified as follows (units of measurement are given in parentheses):

- CCC is the density of carbon capture capacity (Mg/m^2);

- HMR is the heat mitigation reference, namely LST, which serves as a measure for urban heat fluctuation and, consequently, for assessing its changes; if it were to decline, it would highlight an enhancement in life quality for users of the local environments (°C);
- HQL measures the habitat quality level, and holds rational values ranging from 0 to 1, as described in section 2.2;
- CTP is the value of crop and timber production (€/ha);
- SCQ is the value of scenic quality, and holds rational values ranging from 0 to 1, as described in section 2.2;
- POA measures the potential for outdoor activities, and holds rational values ranging from 0 to 1, as described in section 2.2.

The estimated coefficients of the explanatory and control variables show the marginal impacts of such covariates on CCC.

The significance tests concerning the estimated coefficients is evaluated using the p-values.

3. Results

This part is structured in the following manner. Initially, the spatial classifications pertaining to the regional spatial context of Sardinia are introduced regarding the variables linked to CCC and the explanatory variables of model (1). Secondly, the relationships suggested by the coefficient estimates of the regression model (1) are presented to uncover indications related to the association of CCC with the covariates.

3.1 Carbon capture capacity

The spatial distribution of CCC (Fig.2, panel A) across Sardinia indicates that the highest contributions originate from wooded areas which are concentrated in the central and eastern parts of the island, where mountainous areas more prevalent, including Gennargentu ranges, Sulcis mountains and regional parks. Notably, the mean values associated with coniferous forests are higher than those of broadleaved forests. The areas exhibiting the lowest contribution to CCC are predominantly water bodies, urban and artificial surfaces, as exemplified by the Cagliari Metropolitan Area, as well as agricultural zones, located in the western parts of the island. Compared to other land cover types, shrublands and areas characterized by transitional vegetation demonstrate an above-average capacity, whereas agro-forestry areas exhibit a below-average capacity.

3.2 Heat mitigation

The region shows LST values between 27.7-61.95 °C (See Fig.2, panel B). In the western parts of the island, which coincide with agricultural areas, the greatest temperatures are recorded except rice fields. Lowest temperatures are observed in water areas, mountainous areas with high altitudes, hills and forests including regional parks. Mean LST values are consistently high in agricultural areas, with the highest maximum temperatures recorded particularly in the land-use types classified as 'Non-irrigated arable land' and 'pastures.' However, the highest mean temperature is observed in artificial surfaces, reflecting the urban heat island effect, especially in 'construction sites,' which exhibit a mean temperature of 54 °C. Additionally, dump sites and airports also display very high mean temperatures exceeding 50 °C. Mean temperatures in water-related areas range from 32 to 36 °C, while forested areas show a narrower range of 39.14 to 40.24 °C.

3.3 Habitat quality level

Consistent with earlier ESs, the highest HQ levels (see Fig.2, panel C) are observed in forested areas, predominantly located in the eastern part of the island, whereas the lowest levels occur in urbanized zones, followed by intensively cultivated agricultural lands. In Sardinia, broadleaved forests have a slightly higher HQL (scoring 0.85) than coniferous forests (0.75). The lowest values, approaching zero, are observed in artificial areas and impervious surfaces, with a score of 0.09. Similarly, areas classified as 'open urban areas' contribute minimally, with a score of 0.21, representing the second lowest HQL after artificial surfaces. The difference between intensive and extensive agricultural practices considering the HQL is also evident as intensive agricultural lands score 0.23 while extensive agricultural lands score 0.43. The average HQL in the island is 0.54, and 40.86 % of the territory exhibits high levels with scores exceeding 0.66.

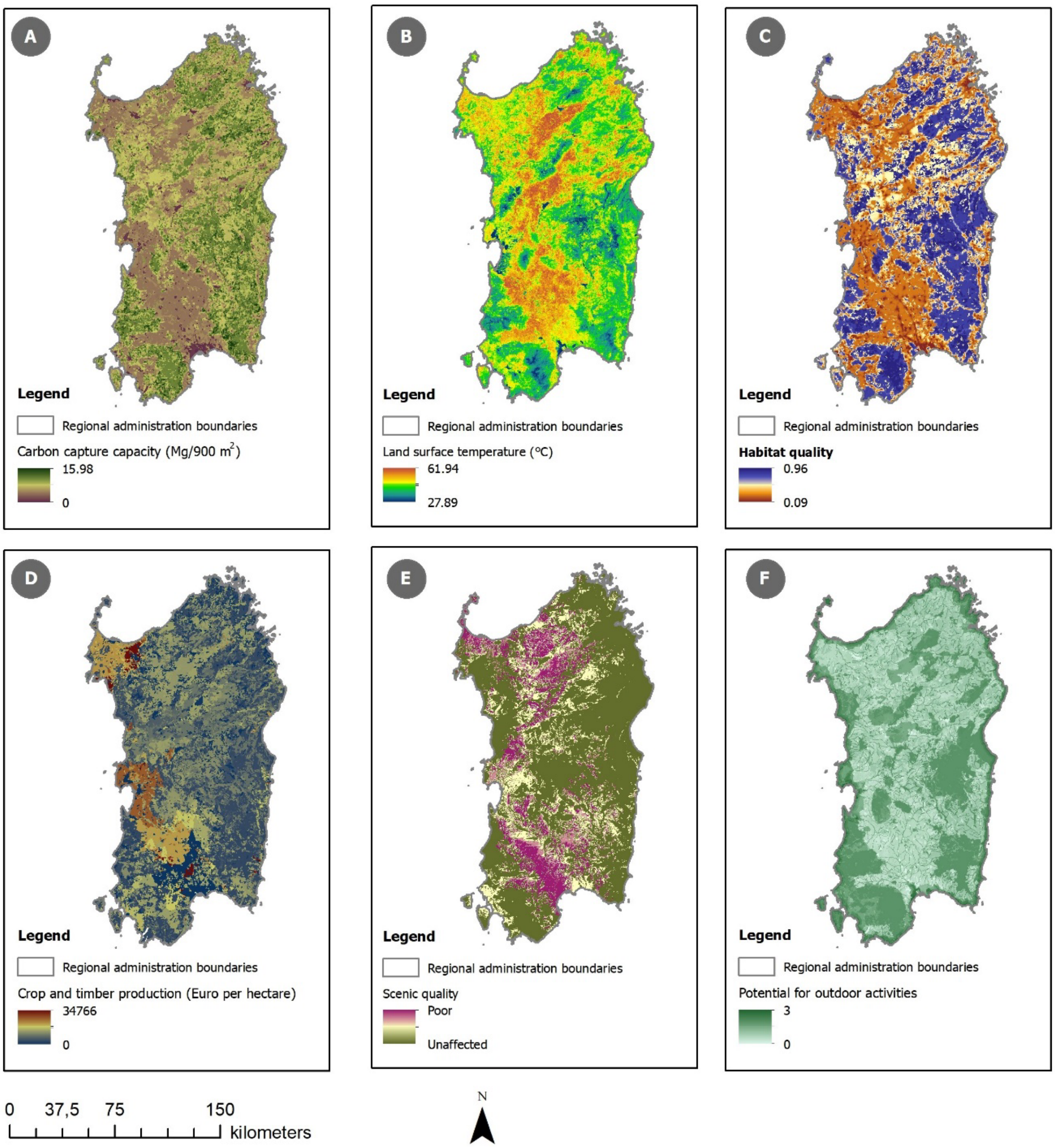

Fig.2 Spatial distribution of Carbon Capture capacity in Mg/900 m² (panel A), Land surface temperature in C° (panel B), Habitat quality (panel C), Crop and timber production in Euro per hectare (panel D), Scenic Value (panel E) and potential for outdoor activities (panel F)

3.4 Crop and timber production

The CTP value, representing the economic worth of agricultural and forestry land, was mapped across the region for 2023 (€/ha). The analysis reveals a heterogeneous distribution (see Fig.2, panel D): values range from 0 to 34,766 €/ha, while 17.41% shows values below €1,000/ha. The average value stands at €5,090.62

/ha. Higher valuations, exceeding €10,000/ha, are concentrated in fertile plains such as Campidano di Cagliari, Campidano di Oristano, and Nurra, typically associated with vineyards, orchards, citrus groves, and horticulture. Exceptional values, surpassing €30,000/ha, are in the coastal hill areas of Sarrabus, particularly within the municipalities of Villaputzu and San Vito, in the plain agrarian region of the Lower Tirso in the province of Oristano, and in the agrarian region of the Campidano of Serrenti.

3.5 Scenic quality

Fig.2, panel E, depicts the spatial distribution of scenic quality values across the Sardinia Region. The average scenic quality value is 0.97. When examining the distribution of scenic quality across the Region it emerges that unaffected landscapes (VI=0) are admirable in 66% of the Sardinian Region, while medium values (VI=2) are found in 16% of Sardinia's territory. In contrast, low scenic quality (VI=3) characterizes 7% of the Region, whereas poor scenic quality areas (VI=4) account for 11% of Sardinia. The highest VI is primarily observed in agricultural areas, where solar farms and wind turbines are frequently installed. Nonetheless, adjacent areas are also affected by RES presence, which degrades the scenic quality to medium or low values. Conversely, scenic quality is largely preserved in designated protected areas, although visual degradation is noted in some Sardinian national and regional parks.

3.6 Potential for outdoor activities

Fig.2, panel F illustrates the spatial pattern of the supply of potential for outdoor activities in Sardinia, with values ranging from 0 to 3 (average: 1.21). Although the full spectrum is represented, zero values are limited to marginal zones. Higher scores cluster along coastal areas, due to the added influence of aquatic elements, and within forested mountain systems, especially when overlapping protected zones such as regional parks or Natura 2000 sites. Notable examples include Gutturu Mannu Park, Monte Arcosu, Monte Limbara, Supramonte, and Monti del Gennargentu. These areas benefit from combined effects of high ecological integrity and distinct landscape features. Additional moderate-to-high values emerge in hilly forest regions and conservation zones, linked to naturalness or scenic attributes. In contrast, agricultural lowlands, such as Campidano, Nurra, Flumendosa, Cedrino, Coghinas valleys, and unprotected hilly interiors show lower scores due to ecological disturbance from farming, grazing, and vegetation alteration.

3.7 Linear regression

The outcomes of the linear regression (1) are presented in Tab.2, whose coefficients describe the marginal impacts, expressed in terms of the change in the dependent variable CCC, associated with a one-unit increase in the variables representing the supply of the five ESs under consideration, and whose p-values allow us to assess the significance of the results of the coefficient estimates themselves.

Variable	**Coefficient**	**t-Statistic**	**p-Value**	**Mean of the explanatory variable**	**Elasticity at the average values of CCC and explanat. var's [(Δy/y)/(Δx/x)]**
HMR	-0.54388	-104.71477	0.00000	45.66415	-0.43584
HQL	93.54459	751.61056	0.00000	0.541637	0.88914
CTP	0.00040	71.912244	0.00000	2,483.98915	0.01750
SCQ	-5.95032	-85.414754	0.00000	0.24163	-0.02523
POA	-4.32887	-27.99609	0.00000	0.40475	-0.03075
Mean and Standard deviation of dependent variable CCC: 72.75331, 30.98471 - Adjusted R-squared: 0.66863					

Tab.2 Linear regression estimation

The linear regression estimate (1) should be read bearing in mind that a positive coefficient is associated with an increase in CCC in relation to growth in the supply of the ES corresponding to it, while a negative value of the coefficient is correlated with a decrease in CCC. The only exception is the variable associated with scenic quality, SCQ, whose supply increases as the value of the explanatory variable decreases. It should also be noted how the p-value tests for the estimates of all coefficients signal a generalized reliability of the estimates. The elasticities are always, in absolute value, less than one, configuring, therefore, a generalized inelasticity of CCC supply with respect to the explanatory variables. The values of the elasticities configure, however, rather differentiated correlations, in terms of orders of magnitude. The outcomes report how a 1% growth in HMR, i.e., an average increase in LST of about 0.45 °C, is associated with a decrease in CCC of about 0.32 Mg/ha, thus just about 0.44%. It should be highlighted, in this regard, how annual thermal gradients are, in general, close to this level and, therefore, how the correlation between CCC and HMR shows a statistically significant medium-sized relevance of HMR with respect to CCC.

Particularly important is the impact of HQL on CCC, which shows an elasticity of about 89%, implying that a 1% growth in this variable corresponds to a growth of about 0.64 Mg/ha in average CCC. Since the improvement of habitat quality status is closely dependent on the protection of the areas in which they are located, exercised, directly or indirectly, for the most part with reference to potential threats, it is clear that the implications of the spatial taxonomy of HQL are significantly relevant to the definition and implementation of planning policies aimed at improving the conditions of climate neutrality.

The covariate associated with crop and timber production, CTP, has a positive elasticity, and almost insignificant in quantitative terms, of about one-hundredth the value of that of HQL. This implies that in order to have a quantitatively relevant impact of CTP on CCC, major market fluctuations in crop and forest production of 50% or more would be required, corresponding to increases of at least 1,250 €/ha, and would be associated with growths of 0.63 Mg/ha or more, similar in magnitude to the impact on CCC of HQL.

In relation to the representative variable of scenic quality, SCQ, referring to the presence of visual disturbances that limit the aesthetic quality of landscape views, such as, for example, those generated by wind turbines or photovoltaic installations, the negative estimate of the coefficient of linear regression (1) shows a negative correlation between CCC and scenic quality, as the latter increases as the value of the SCQ variable decreases. The elasticity is, however, almost insignificant, on the order of 2.5%. This outcome highlights a very low significance of the functional connection between SCQ and scenic quality.

The covariate for the supply of the ES associated with the POA has a negative elasticity, as in the case of the SCQ, of about 3.1%, and, therefore, slightly higher. Indeed, in this case, a 10% decrease in POA supply is correlated with a growth of about 0.22 Mg/ha in CCC. The close link between the size of the POA and the accessibility of attractive places for outdoor recreation gives, arguably, reason for this result, since accessibility is linked to the presence, albeit limited, of infrastructure that facilitates transportation, both individual and collective.

4. Discussion

The discussion that unfolds in the subsequent subsections relies on the implications of model (1), regarding the connections between the availability of CS and the accessibility of other ESs.

4.1 CCC and heat mitigation

The correlation between CCC and HMR, i.e., LST, arising from the outcomes of linear regression (1), with reference to the regional spatial context of Sardinia, is in line with what has been presented and discussed in numerous articles in the scientific and technical literature (Cialdea et al., 2022).

Wang et al. (2021) propose a study referring to the Shenzen metropolitan area in subtropical China, in which the effects of heat islands on carbon storage capacity are analyzed, in the context of a territory that discloses varying degrees of urbanization. These findings are consistent with the results offered by Dibaba (2023) who, with reference to the spatial contexts of the Ethiopian cities Nekemte and Jimma, points out that the negative impacts of heat waves, in relation to CCC, are most dramatically manifested in areas of the urban fabric characterized by urbanization- and sealing-oriented land cover transitions (Mobaraki, 2023; Pantaloni et al., 2024). Also, in this scientific and technical perspective is an article by Bounoua (2015), who, through the integration of MODIS and Landsat data, points out, in relation to the United States, evidence of a correlation between the increase in LST, urban sprawl and the decrease in CCC.

4.2 CCC and habitat quality level

According to the results of linear regression (1), the relationship between HQL and CCC is positive, consistent with earlier research (Cardinale et al., 2012; Chaplin-Kamer et al., 2015; Ren et al., 2023). Looking at this correlation, to achieve carbon neutrality, HQL needs to be improved. As it is strongly linked to biodiversity, one effective way to support this is by increasing plant diversity, which enhances CCC in soils (Lange et al., 2015).

Especially in areas with low HQL such as urbanized areas, implementation of urban trees might help achieve carbon balance (Vaccari et al., 2013). Raymond et al. (2013) examine how protecting natural ecosystems, such as mature forests and wetlands, supports HQ, which in turn enhances CCC in urban environments. Therefore, the protection and conservation of biodiversity in regional natural parks and wooded areas in Sardinia is important not only to sustain the high HQL in these areas but also to increase the regional capacity.

4.3 CCC and crop and timber production

The relationship between CCC and CTP are emphasized in several scientific studies on agricultural systems. Evidence from Paris et al. (2019) and Frank et al. (2024) highlights the role of agroforestry and agricultural practices in promoting ecologically sustainable productivity. Legesse et al. investigated how changes in land use and land cover affect the carbon storage capacity of forest ecosystems in Ethiopia's Upper Awash Basin, employing remote sensing methodologies. Their analysis, covering the period from 1993 to 2023, reported a 15% decline in carbon storage, primarily associated with a 27.4% reduction in forest cover and a 41.58% decrease in shrub vegetation.

A case study on olive groves in the Umbria Region of Italy (Bateni et al., 2021) further highlights the role of perennial crops in carbon conservation, revealing that a substantial proportion of soil organic carbon is retained within the top 30-60 cm of soil. The continued management of olive cultivation is therefore identified as a strategic measure to enhance soil carbon retention and reduce carbon emissions associated with land use change and intensive soil managing.

4.4 CCC and scenic quality

Numerous studies recognize the link between CCC and scenic quality, with the inverse relationship between the SCQ variable and CCC supporting the expectation that higher aesthetic quality correlates with greater CCC. Lee and Kim (2024), for instance, illustrate how parks and forests are not merely vital in carbon capture and storage but also bestow considerable scenic value. Similarly, Mundher et al. (2022) highlight that urban forests are pivotal for carbon sequestration while concurrently offering significant social, tourism, and aesthetic benefits that enhance human health and well-being. Mitsch (2015) supports this perspective by demonstrating how wetlands simultaneously function as effective carbon sinks and as sources of scenic aquatic landscapes. This is supported by Quevedo and Kohsaka's systematic review of the cultural services provided by blue carbon ecosystems, which revealed that in addition to their essential role in capturing carbon, mangrove forests, seagrass meadows, and saltmarshes provide 14 different types of cultural ecosystem services, including aesthetic value.

4.5 CCC and potential for outdoor activities

The findings reveal an inverse relationship between the provision of POA and CCC, which may be attributed to limitations in the accessibility of high-CCC areas for recreational use. Costanza (2008) characterizes recreational ESs as inherently linked to human mobility, identifying accessibility as one of three fundamental components, alongside ecosystem functionality and the spatial pattern of potential demand. Furthermore, Paracchini et al. (2014) emphasize that proximity plays a pivotal role in determining the appeal of a location, noting that individuals typically prefer recreational sites located within an approximate 8-kilometer radius of their homes for daily use. In addition, the method used to map POA provides a high value to coastal areas, characterized in Sardinia by sparse or sometimes absent vegetation with a low capacity to absorb and stock carbon.

5. Conclusions

The methodology defined and developed in this study is aimed at investigating the functional connections between the CCC, as the reference ES for analyzing and assessing the contribution to the global climate neutrality of regional spatial contexts, and the provision of five ESs, of which: two regulating ESs, heat mitigation, detected through the spatial taxonomy of the LST, and habitat quality; one provisioning ES, crop and timber production; and two cultural ESs, scenic quality and potential for outdoor activities. The regional territory of Sardinia is taken as the spatial context for the application of this methodological approach.

This study offers a conceptual framework that systematizes, in integrated manners, some methodologies aimed at constructing spatial taxonomies of different ESs, which connote environments of the city, conterminous territories and rural areas. The spatial distribution of ESs is associated with the taxonomy of CCC, as an overall indicator of the contribution that the reference spatial system makes to global climate neutrality. This contribution is, therefore, characterized as an expression of a system of ESs that cooperate or conflict with climate neutrality, thus integrating their potential, synergistic or divisive, in a holistic reading of ecosystem factors affecting global climate. The outcomes, referring to the regional territorial context of Sardinia, report that the ESs identified by heat mitigation and habitat quality present the greatest positive impacts in relation to CCC, while POA is lower in quantitative terms, although of some significance. Decidedly less relevant are the impacts found with regard to CTP and scenic quality, although, with regard to the latter, the estimated linear regression signals the need to carefully consider the location of photovoltaic and wind power plants as relevant threats to scenic quality.

The methodological approach proposed in this study demonstrates a high degree of exportability across diverse national and European contexts, while retaining sufficient flexibility to enable the integration of additional ESs as new data and policy needs emerge. On the other hand, the methodological approach presents two problematic aspects. The first concerns the data used. It is evident that the information regarding the supply of ecosystem services related to outdoor recreation, carbon sequestration and storage, as well as habitat quality, does not derive from primary survey observations—which are unavailable—but rather from estimations grounded in secondary data sources. The second issue concerns the individual methods used to assess and map the five ecosystem services. For example, the model used to assess scenic value only considers energy plants as environmental detractors. Furthermore, the method used to assess habitat quality has certain limitations dictated by the choice of threats to be included and the assessments provided by experts.

Since the data base on which the study proposed here is based consists, for the most part, of sources available, at the regional level, with reference to Italy and other European Union countries, as well as to many non-European national contexts, a future development of the research is certainly represented by the export of the methodological approach applied here for the purpose of highlighting similarities and differences in the outcomes, and, therefore, in the resulting spatial policy implications. Another issue, certainly relevant in this perspective, is the expansion of the set of ESs to be considered in the integrated assessment of the impacts they generate in relation to climate neutrality (Pilogallo et al., 2019; Lai et al., 2020), from the five considered in this study. Among these, ESs aimed at hydraulic and landslide hazard mitigation are certainly significant, particularly relevant with reference to Sardinia and other Italian regions.

A final relevant aspect, in terms of future research development, is represented by the implementation, with reference to the same database, of methodologies other than linear regression to analyze and interpret the correlations between the covariates associated with the supply of ESs, such as conjoint analysis, spatially-weighted linear regressions or principal component analysis.

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Image Sources

All images were prepared by the Authors.

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