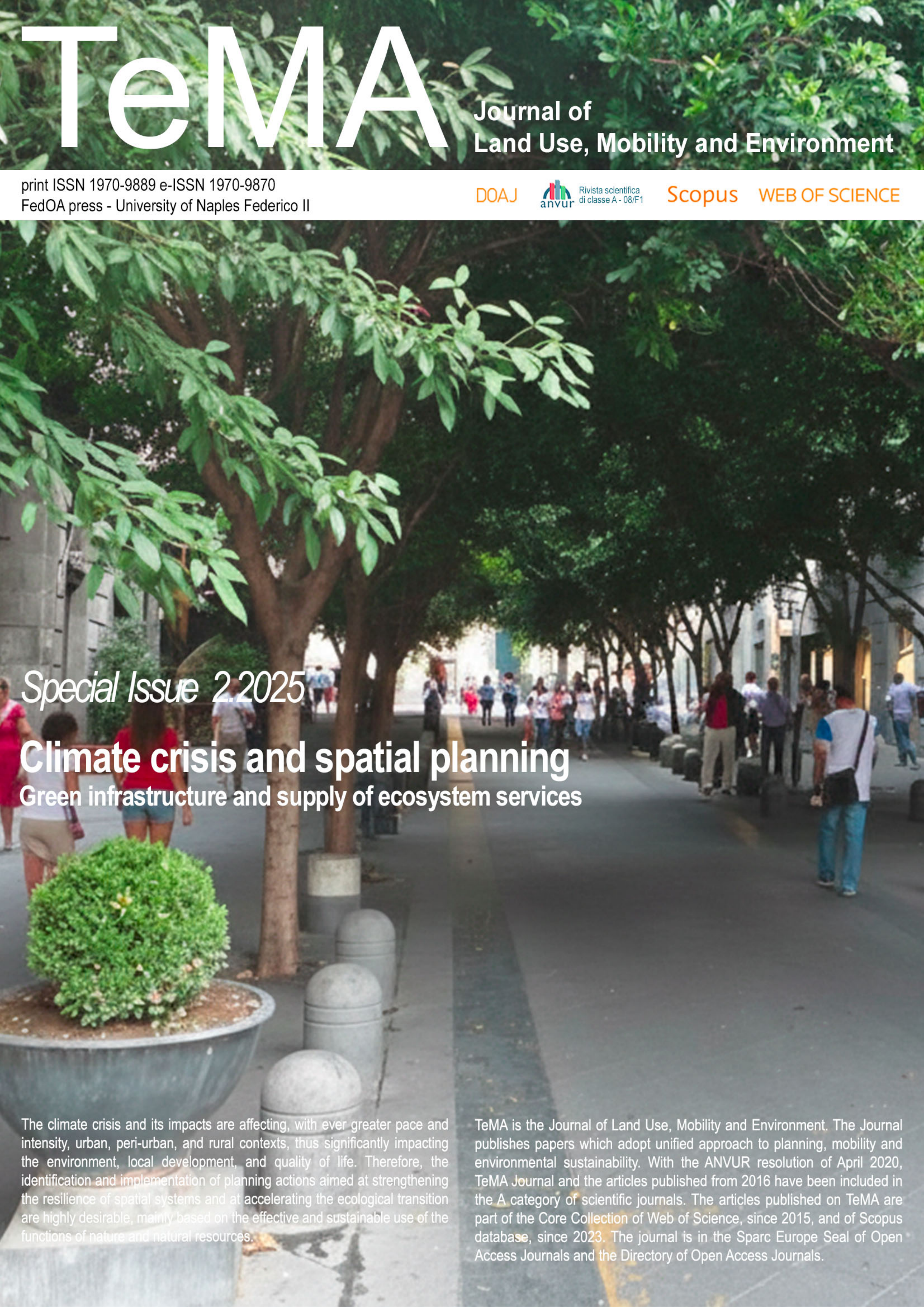

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Special Issue 2.2025

Climate crisis and spatial planning
Green infrastructure and supply of ecosystem services

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

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

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Carbon sequestration and ecosystem services. Evidence from the functional urban area of Cagliari, Italy

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Abstract

Carbon sequestration and storage, i.e., the process whereby carbon dioxide is removed from the atmosphere by plants and stored in natural reservoirs such as soil or water pools, is a key regulating ecosystem service (ES) that contributes to mitigating climate change and its impacts. Its positive and negative relationships with other ESs, i.e., respectively, synergies and trade-offs, are yet to be fully understood, especially at the urban level. Therefore, this study proposes a methodological approach that integrates ES modeling and mapping with inferential models, with a view to identifying and assessing the relationships between carbon sequestration and storage and other ESs. The implementation of the proposed approach in the context of the Functional Urban Area of Cagliari (Italy) puts in evidence a positive and significant relationship between carbon sequestration and storage and other regulating ESs, i.e., pluvial flood retention, local temperature regulation, and habitat quality; to the contrary, a negative but quantitatively negligible relationship is unveiled as far as the potential supply of nature-based recreation is concerned. Relevant planning implications are identified based on these outcomes, which highlights the significance and usefulness of the proposed approach for planners and policy makers.

Keywords

Carbon sequestration and storage; Pluvial flood retention; Land surface temperature; Habitat quality; Nature-based recreation

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1. Introduction

Since carbon is the building block of complex molecules like proteins and DNA, it is fundamental to all biological processes and essential for life on Earth; as such, terrestrial life could not exist or continue without it (NOAA, n.d; Zehnder, 1982; Olah et al., 2011).

The continuous process of carbon transforming into different forms and traveling across the Earth is known as the carbon cycle (Fung, 2003). The carbon cycle on Earth controls the levels of carbon dioxide (CO_2) in the atmosphere, which influences global temperatures and affects the various processes that regulate the cycle (Hain et al., 2025). Carbon (C) cycle is generally divided into key components such as marine or oceanic C cycle, terrestrial C cycle, atmospheric C cycle, geologic (Fung, 2003), and anthropogenic C cycle (Olah et al., 2011). The marine C cycle is crucial for regulating atmospheric CO_2 levels, with the ocean serving as the largest carbon reservoir (Lal, 2008).

The global C cycle supports ecosystem services (ESs) through carbon sequestration in terrestrial ecosystems, aiding in climate change adaptation (CCA) while providing direct benefits to humanity and protecting against risks to Earth's stability and human wellbeing (Raupach, 2013).

Carbon sequestration (CS) is the long-term storage of carbon in the land, underground, or oceans to slow or reduce the buildup of CO_2 in the atmosphere. This can involve supporting natural processes or using new methods to manage and store carbon (Kambale et al., 2010). This could be geologic or biologic. Biologic CS can be described as the storage of atmospheric carbon in soils, vegetation, wood products, and aquatic ecosystems. Geologic CS, on the other hand, involves storing carbon in geological formations, a process that incorporates engineering approaches.

CS increases carbon uptake in natural systems, while disposals prevent CO_2 from re-entering the active carbon cycle. Techniques are generally categorized based on the part of the Earth system that needs to be managed: terrestrial sequestration, ocean sequestration, and geologic disposal (Dilling et al., 2003). Terrestrial carbon sequestration relies on photosynthesis to convert CO_2 into biological and soil carbon pools, offering benefits such as improved soil quality, enhanced agricultural efficiency, and better water quality (Lal, 2008). Thus, it plays a crucial role in enhancing biodiversity and supporting ESs.

Italy is within the top three CO_2 emitters in Europe, according to 2019 figures (European Parliament, 2024). However, it also plays a significant role in net carbon removals from the Land Use, Land-Use Change, and Forestry (LULUCF) sector, alongside Romania, Sweden, Spain, Poland, and France, which together account for nearly 87% of the EU's total LULUCF sink, although the European Environment Agency anticipates a decrease in these removals over the next decade (EEA, 2024).

As the primary greenhouse gas driving global warming, various technical solutions have been proposed to lower CO_2 emissions and stabilize atmospheric CO_2 levels, including natural carbon sequestration, which enhances the ability of ecosystems like forests and soils to absorb and store carbon (Ghommem et al., 2012). Improving the capacity of natural sequestration reservoirs to capture and store CO_2 should therefore be a significant aspect of land use planning.

Given the alarming rate of land use conversion, preserving existing trees and encouraging the planting of more, especially fast-growing species capable of absorbing significant amounts of CO_2 and storing carbon in new wood, could be the most intelligible way for carbon sequestration (Kambale et al., 2010). However, more comprehensive measures that consider long-term sustainability should be adopted for effective climate adaptation strategies. To address future global warming, substantial amounts of both anthropogenic and natural CO_2 emissions need to be sequestered (Ghommem et al., 2012). Implementing effective land use practices and following adequate soil and plant management strategies can improve the retention of photosynthetic carbon in both terrestrial and marine ecosystems, resulting in improved environmental quality (Lal, 2008).

A methodological approach is defined and applied in this study, which aims at implementing climate neutrality through spatial planning policies. CS is taken as a comprehensive reference to pursue this objective, based on a set of ESs. The study develops as follows. First, the spatial framework of CS is characterized through CS density maps, by using the InVEST suite (NCP, n.d.) "Carbon Storage and Sequestration" model which estimates the quantity of carbon stored in land parcels using land cover raster maps (Liquete et al., 2015).
Secondly, a methodology to feature the relations between CS and ESs is implemented, which models, and spatially assesses, such relations with reference to the following ESs: preserving levels of habitat quality that are suitable to support life cycles of wild plants and animals that can be useful to people; climate regulation through mitigation of land surface temperature (LST); runoff control; areas suitable for outdoor recreational activities.
Finally, correlations between the spatial taxonomies of CS capacity and ESs are detected and analyzed as for the Functional Urban Area (FUA) of Cagliari, located in Sardinia, an insular Region of Southern Italy, in order to assess how the supply of ESs can be effectively addressed to maximize CS capacity, while improving the spatial framework of the ESs. This leads to identifying place-specific policy recommendations to improve the environmental quality based on ESs supply in FUAs.

2. Materials and Methods

This section is organized as follows. First, the FUA of Cagliari is described. Second, the methodology used to detect the spatial taxonomy of CS and ESs supply is presented. Finally, a linear multiple regression is described, which estimates the spatial correlations between the ESs taxonomy and the spatial layout of CS.

2.1 Study area

The FUA of Cagliari (Fig.1) is chosen as study area for this research; according to EUROSTAT data[1], it has a size of nearly 2,000 km^2 and a resident population of 475,170 people as of 2023, and it comprises 32 municipal authorities, including Cagliari.

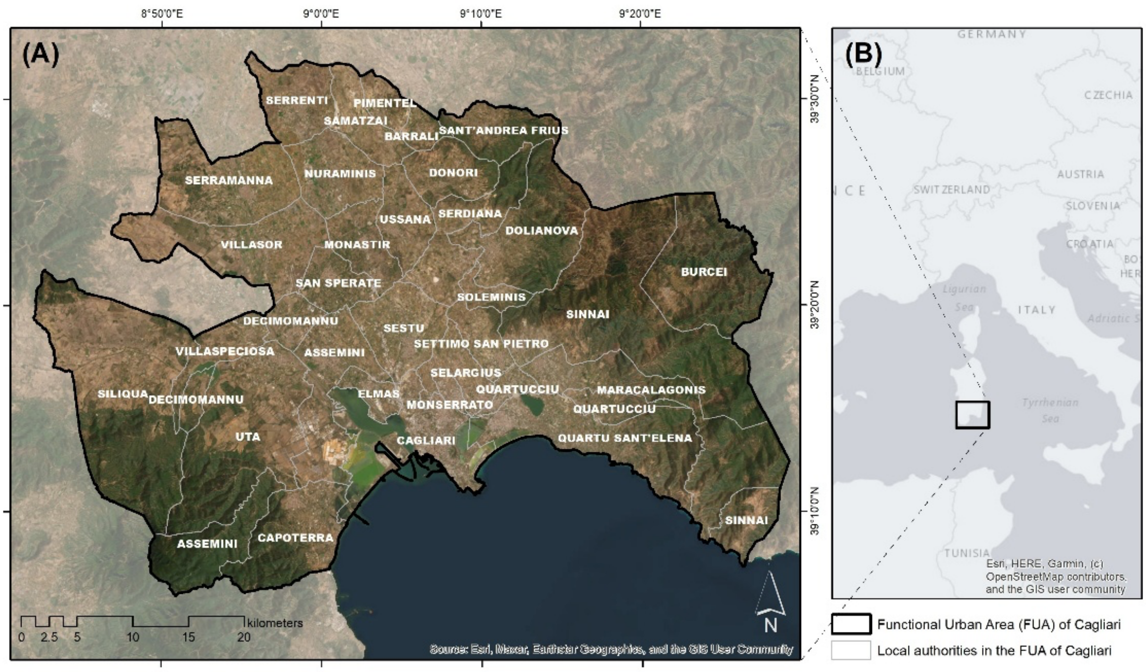

Fig.1 The functional urban area of Cagliari with its municipalities (A) within the Mediterranean context (B)

[1] https://ec.europa.eu/eurostat/databrowser/view/URB_LPOP1/default/table?lang=en. Accessed May 6, 2025.

Around 46 percent of the FUA consists of non-artificial land covers, i.e., green and blue spaces, mainly coinciding with inland wetlands that surround the built-up area of the core city and are shared with the adjacent municipalities. Agricultural and natural land covers, that potentially contribute the most to capturing and storing carbon, make up around 42 percent of the FUA. A vector fishnet, hereafter termed "grid," was developed to carry out the methodological procedures detailed in the following sections. This grid is composed of about 200,000 square units, each measuring 100 meters in width, and extends across the entire FUA. It serves as the foundational spatial reference for calculating the variables that feed into the model presented in Section 2.3.

2.2 CS and ESs assessment and mapping

To develop a methodological approach for identifying recommendations that help local planners and policymakers enhance environmental quality based on ES supply, spatial data on the distribution of CS and a selected set of ESs is essential. Besides CS, which is itself an ESs included by the Common International Classification of Ecosystem Services (CICES) within class 2.2.6.1 "Regulation of chemical composition of atmosphere and oceans" (CICES, 2018), the following four ESs were chosen for their significance in the FUA.

- Opportunities for nature-based recreational activities, class 3.1.1.1 "Characteristics of living systems that enable activities […] through active or immersive interactions";
- Pluvial runoff retention, class 2.2.1.3, "Hydrological cycle and water flow regulation (including flood control […])";
- Habitat quality, as an indicator of ecosystems' capacity to support life, class 2.2.2.3 "Maintaining nursery populations and habitats";
- LST, as an indicator of ecosystems' cooling capacity, class 2.2.6.2 "Regulation of temperature and humidity […]".

Variable (label)	Input Data	Data Sources
C_SEQ	Land use/land cover map	Regional geoportal (RAS, n.d.a)
	Lookup table associating land cover types with data on carbon sinks (above ground, dead organic matter, organic soil)	Italian inventory of forests and forest carbon sinks (INFC, n.d.) Regional geoportal (RAS, n.d.b)
RECR_ARE	Land cover map	Copernicus land monitoring service (Urban Atlas, 2018)
	Census tracts (vector map) Lookup table associating census tract codes with resident population	ISTAT – Italian national census (ISTAT, 2025)
ROFF_CTR	Land cover map	Regional geoportal (RAS, n.d.a)
	Watershed boundaries	Regional geoportal (RAS, n.d.c)
	Soil permeability map	Regional geoportal (RAS, n.d.d)
	Lookup table associating land cover types with curve number values	Regional environmental agency (ARPAS, 2019)
	Precipitation data	Regional hydrologic annals (RAS, n.d.e)
HABT_QUA	Land cover map (CORINE 2018)	Copernicus land monitoring service (CLC, 2018)
	Threats list and spatial layout	Natura 2000 standard data forms (EEA, n.d.) Regional geoportal (RAS, n.d.f)
	Threats table	Expert survey (Lai & Leone, 2017)
	Sensitivity table	
	Accessibility to threats	Regional geoportal (RAS, n.d.g)
SUR_TEMP	Landsat Collection 2, level 2 imagery	Earth Explorer (USGS, n.d.)

C_SEQ: carbon storage and sequestration; RECR_ARE: opportunities for outdoor recreational activities; ROFF_CTR: pluvial runoff water retention; HABT_QUA: habitat quality; SUR_TEMP: land surface temperature

Tab.1 CS and the four other ESs: input data and sources

Tab.1 provides a list of the input data used to spatially assess both CS and the other four ESs, as well as their sources. C_SEQ, ROFF_CTR, and HABT_QUA were mapped using InVEST (v. 3.14.1), a freely available suite of open-source models to assess and map ESs. This suite is widely used in the academic community because it relies on scientifically sound models, thoroughly explained in its user's guide; it has a neat interface which makes it comparatively easy to use, and it comprises standalone modules for the ESs being assessed. However, as with other spatial models, the outputs heavily depend on the quality of input data, in terms of both spatial and thematic resolution. As for C_SEQ, the InVEST tool "Carbon Storage and Sequestration" returns a raster map of carbon density (Pilogallo et al., 2019), i.e., the amount of carbon stored in a pixel, which is calculated as the sum of four contributions, namely, carbon densities stored in four carbon pools: aboveground biomass, belowground biomass, dead organic matter, and organic topsoil. The raster map of C_SEQ was produced based on a land cover map and on a look-up table that associates, to each land cover type, the amount of carbon that is stored in each of the four carbon sinks. Because no data was available on carbon stored in the belowground biomass, the model was run with only three carbon pools, for which data were retrieved from the 2005 Italian inventory of forests and forest carbon sinks, as well as from on-site surveys carried out within a regional pilot project by two regional agencies operating in Sardinia in the fields of rural development and of research and innovation in agriculture (Floris & Zoppi, 2020).

The second ES modeled through InVEST is ROFF_CTR. The InVEST tool "Urban Flood Risk Mitigation" makes use of the following input data: i., a land cover map; ii., a map of the soil hydrologic groups classed in accordance with the USDA-NRCS (2009) standards; iii, a biophysical associating curve number data to each combination of land cover type and soil hydrologic group; iv., the rainfall depth; v., a vector map of the areas of interest, corresponding to watersheds, over which the results are aggregated. The model returns a raster map with runoff retention values, where the volume of water retained in each pixel is a function of rainfall depth and runoff levels; because the latter ultimately depend on land covers and soil permeability (Cialdea et al., 2022), the retention value works as an indicator of the capacity of ecosystem to regulate floods. In this study, all of the input data required were retrieved from the regional geoportal and from regional reports; specifically, we used i., the 2008 Sardinian 1:10,000 land cover vector map; ii., a table providing curve numbers for each soil hydrologic group and land cover type listed in the regional map; iii., the regional permeability map to obtain the spatial layout of the soil hydrologic groups; iv., the regional hydrologic annals to retrieve the highest recorded precipitation value over a ten-year time span in the study area; v., the regional DTM to delineate watersheds.

The third ES for which the InVEST suite, namely the tool "Habitat Quality", was used is HABT_QUA. The assumption of the model is that ecosystems' health and conservation status depend on their degradation, hence on two factors. The first is presence and significance, in terms of both impact and distance, of threats to biodiversity; the second is protection levels which might regulate accessibility thus providing barriers against threats. The model relies on a raster land cover map as a proxy of the spatial distribution of habitats; to this end, a table scoring the suitability of each land cover type as habitat, where scores range from 0 (not suitable) to 1 (fully suitable), is also required. In this study, the CORINE 2018 land cover map was used, together with data on threats from the standard data form of Natura 2000 network and from the regional geoportal, while expert-based judgments were used to build the two tables concerning: i., the significance and decay distance of each threat and, ii., the scores expressing the suitability of each land cover as habitat and each land cover's sensitivity to each threat.

For the fourth ES (SUR_TEMP), raster maps with LST values, chosen as indicator of ecosystems' capacity to mitigate local temperatures (Lai et al., 2020), are freely available from the USGS website. Such raster maps have a 30-m resolution, much finer than those provided by other sources. For instance, Sentinel Hub[2] makes

[2] https://docs.sentinel-hub.com/api/latest/data/planet/planetary-variables/land-surface-temp/. Accessed October 20, 2025.

100-m and 1-km LST raster images available; similarly, the Copernicus Land Monitoring Service[3] provides 5-km raster datasets, whose coarser resolution is, however, compensated by its much higher temporal frequency. In this study, the full dataset of Landsat satellite imagery (Collection 2, Level 2) ranging from May to October 2023, was therefore analyzed, and images with cloud cover exceeding 10 percent were excluded from consideration. Among the thirteen remaining images, the one having the largest mean temperature value, dating July 30, 2023, was selected.

The indicator chosen for the fifth ES, RECR_ARE, accounts for two aspects of nature-based recreation: the first is the potential supply, i.e., availability of green and blue spaces suitable for outdoor recreation (Mobaraki, 2024) while the second is the potential demand (Pantaloni et al., 2024), i.e., the number of potential daily beneficiaries of the ES, identified in residents who live within a 500-meter distance from ES providing areas. The calculation of the indicator involved determining the proportion of green and blue spaces within each cell in the grid and multiplying this value by the number of residents residing within a 500-meter radius of the respective cell. For a full explanation of the methodological approach, the reader can refer to Isola et al.'s (2024) work. Concerning providing areas, in this study the identification of spaces suitable for nature-based recreational activities within the FUA was conducted utilizing the 2018 Urban Atlas land cover dataset, whereas, as far as population data are concerned, the most recent national census dataset, dating back to 2021 and comprising both the map of census tracts and a table with residents per tract, was used.

Once all the raster maps representing the spatial layout of C_SEQ and of the other four ES were obtained, their mean values within each cell of the 100-m grid were calculated through zonal statistics.

On land, the largest carbon pool is soil (Smith, 2019), whose presence, everything else being equal, is associated with largest values of C_SEQ. A control variable (LAND_CAP) accounting for this relationship was therefore introduced in the regression explained in Section 2.3, and a binary indicator based on land capability classes was used. Specifically, LAND_CAP equals 1 in case of arable soils, belonging to classes I-IV, whereas it equals 0 in case of non-arable soils, belonging to classes V-VIII, following Klingebiel and Montgomery's (1961) classification. To map this control variable in the FUA, Aru et al.'s (1991) soil map, which provides land capability classes in Sardinia, was reclassed and, through zonal statistics, the value of LAND_CAP was assigned to each cell in the grid.

Finally, a second control variable, CS_LAGGD, was introduced to account for the autocorrelation of C_SEQ. Representing the spatial lag of C_SEQ, CS_LAGGD was calculated using Moran's I test in GeoDa (Anselin et al., 2006) on the 100-m vector grid, where C_SEQ was one of the attributes, and the weight matrix was built based on first-order contiguity, queen criterion.

2.3 Regression model

The correlations between the spatial taxonomy of CS and the supply of the selected ESs are estimated through a linear regression, which develops as follows:

$$C\_SEQ = \alpha_0 + \alpha_1 REC\_ARE + \alpha_2 ROFF\_CTR + \alpha_3 HABT\_QUA + \alpha_4 SUR\_TEMP + \alpha_5 LAND\_CAP + \alpha_6 CS\_LAGGD \quad (1)$$

The dependent and explanatory variables are identified as follows, which refer to a one-hectare square cell:

- C_SEQ is carbon sequestration density (Mg/(100 m2));
- REC_AREA is the share-part of the area available for outdoor recreation multiplied by the population residing in a cell 500-meter neighborhood (percentage value multiplied by the number of residents);

[3] https://land.copernicus.eu/en/products/temperature-and-reflectance. Accessed October 20, 2025.

- ROFF_CTR is the volume of water from precipitation that can be retained, and which, therefore, does not become surface runoff (m3);
- HABT_QUA is habitat quality (this variable ranges in the interval 0-1; the identification of habitat quality is described in Section 2.2);
- SUR_TEMP is land surface temperature (LST), which is taken as the reference measure for the containment of urban heat phenomenon (°C);
- LAND_CAP is a variable which controls for the arability of soils (this is a dichotomous variable, equal to 1 if the soil is arable and equal to 0 otherwise; the identification of arable soil conditions is described in Section 2.2);
- CS_LAGGD is a covariate which controls for spatial autocorrelation of the dependent variable.

The estimated coefficients of the explanatory variables identify the quantitative correlations between the spatial taxonomies of CS and of the distributions of ESs supply and of the control variables. Regression models are routinely used when a priori assumptions about relationships among variables representing complex phenomena are not available (Zoppi et al., 2015; Sklenicka et al., 2013; Stewart & Libby, 1998; Cheshire & Sheppard, 1995).

In this conceptual framework, the regression estimate of model (1) represents a linear equation in an n-dimensional space, that is, a hyperplane tangent to a surface, of unknown equation, associating the dependent variable, in this case CS, with the four covariates and the three control variables. The hyperplane constitutes, therefore, a linear approximation of the n-dimensional surface in a neighborhood of the tangency point, then, in the neighborhood of this point, its infinitesimal trace, on a surface of unknown equation, defined in an eight-dimensional domain (Wolman & Couper, 2003; Byron & Bera, 1983).

The control variable LAND_CAP is related to the arability of the soil. In fact, arable soils, other things being equal, have lower CS capacity than other permeable soils, mainly due to losses of this capacity related to organic carbon mineralization, as described and discussed by Anuo et al. (2024).

The second control variable, CS_LAGGD, the spatially lagged variable derived from the spatial configuration of CS, controls for spatial autocorrelation of such dependent variable. CS_LAGGD is identified through the methodology implemented by Zoppi & Lai (2014), based on Anselin's studies (2006; 2003).

The model estimation is completed by p-value significance tests of the coefficients of the covariates and control variables.

3. Results

This section shows the obtained results of the methodology proposed in the previous section and implemented with reference to the Cagliari FUA. The spatial distributions of the CS and the four ESs is presented, followed by the outcomes of the estimation of model (1), whose coefficients define the framework of the correlations between CS and the supply of ecosystem services in urban areas.

3.1 Spatial taxonomies of CS and ES

Fig. 2A illustrates the spatial distribution of the variable C_SEQ. The highest values, corresponding to the ninth and tenth deciles, are concentrated along the outer edges of the FUA, where forests and several natural protected areas are prominent. These areas include large Natura 2000 sites that extend partially into the FUA from both the east and west, as well as the Gutturu Mannu Regional Park to the west and the "Sette Fratelli" public regional forest to the east. In contrast, the inner part of the FUA that includes the core urban area of Cagliari, as well as two extensive wetlands, consistently exhibits the lowest carbon density. Agricultural areas generally tend to show intermediate values.

Fig.2B depicts the spatial pattern of the indicator selected for ecosystem-based recreation opportunities. Areas falling within the tenth and ninth deciles are mostly located in the inner part of the FUA, corresponding to built-up areas where residents have access to green and blue spaces within 500 meters of their homes. To the west, a large green cluster with medium-to-high values is characterized by low-density development and by proximity to the previously mentioned "Sette Fratelli" forest. In contrast, to the east, a large yellow cluster devoid of green spaces overlaps with the Gutturu Mannu Regional Park; this area exhibits low recreational opportunity values due to the absence of resident population.
Fig.3A shows the spatial distribution of ROFF_CTR. Areas in the first decile are characterized by built-up surfaces and other impermeable soils, including the wetlands' bottoms; as a result, they are concentrated within and around the core city of the FUA, as well as in other urban settlements. In contrast, the highest values, corresponding to the ninth and tenth deciles, are clustered along the western and eastern edges of the FUA. Medium-high values, falling within the sixth and seventh deciles, are predominantly distributed across permeable agricultural areas in the Campidano Plain.

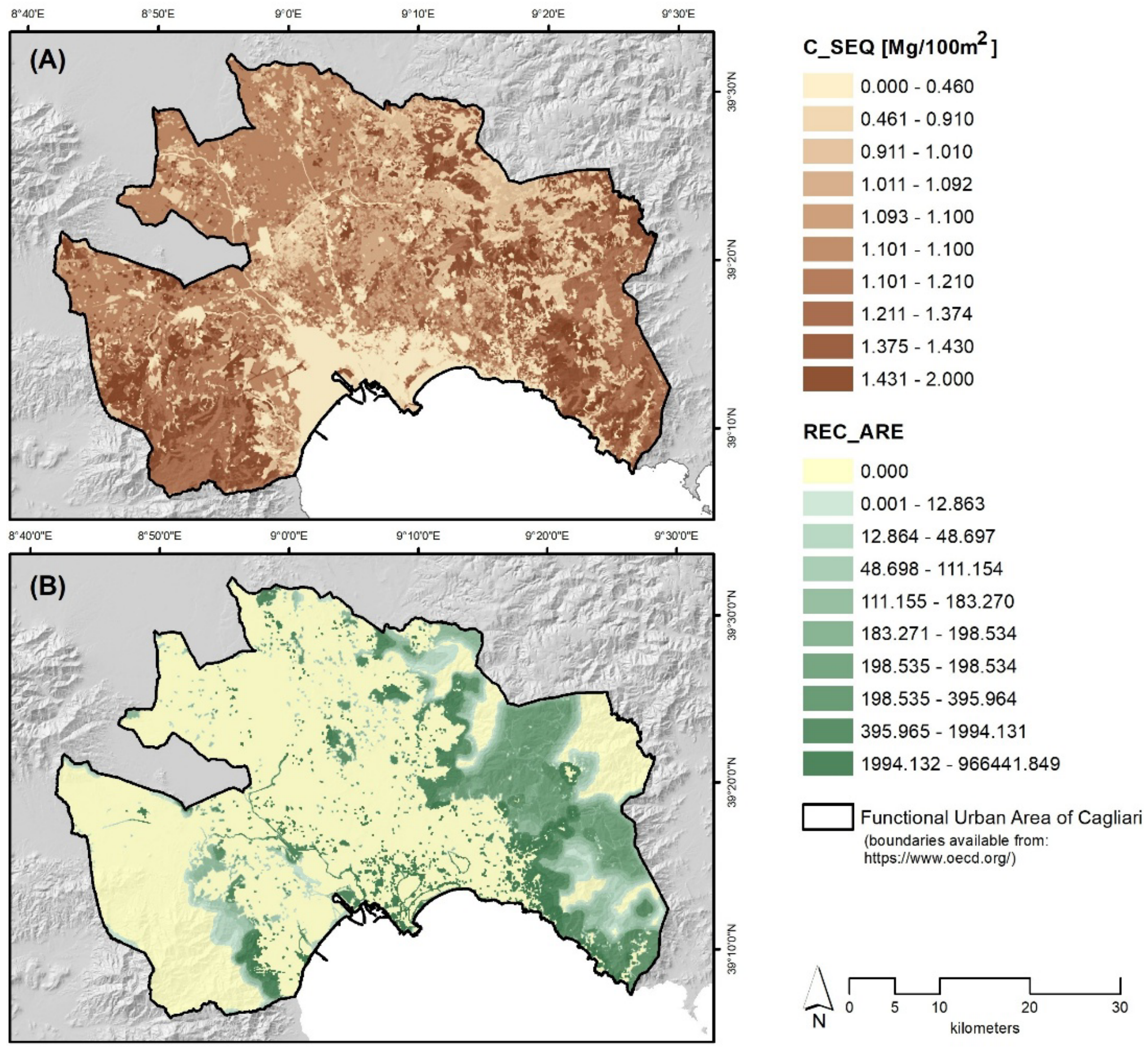

Fig.2 Spatial distribution of indicators for (A) C_SEQ and (B) REC_ARE, both classified by deciles

Fig.3B illustrates the spatial layout of HAB_QUA. The highest values, in the ninth and tenth deciles, are concentrated not only along the western and eastern edges of the FUA, encompassing the forested and protected areas of Gutturu Mannu and Sette Fratelli, but also around the core urban area of Cagliari and its hinterland. This counterintuitive pattern is due to the presence of two large wetlands, rich in biodiversity and relatively safeguarded from threats under existing legal protection frameworks, as both are part of the Natura 2000 network, with one also designated as a regional park. Conversely, areas in the first decile mostly correspond to artificial land covers. Rural areas, whether agricultural or natural, exhibit a range of values from low to medium-high, depending on their proximity and exposure to degradation sources.

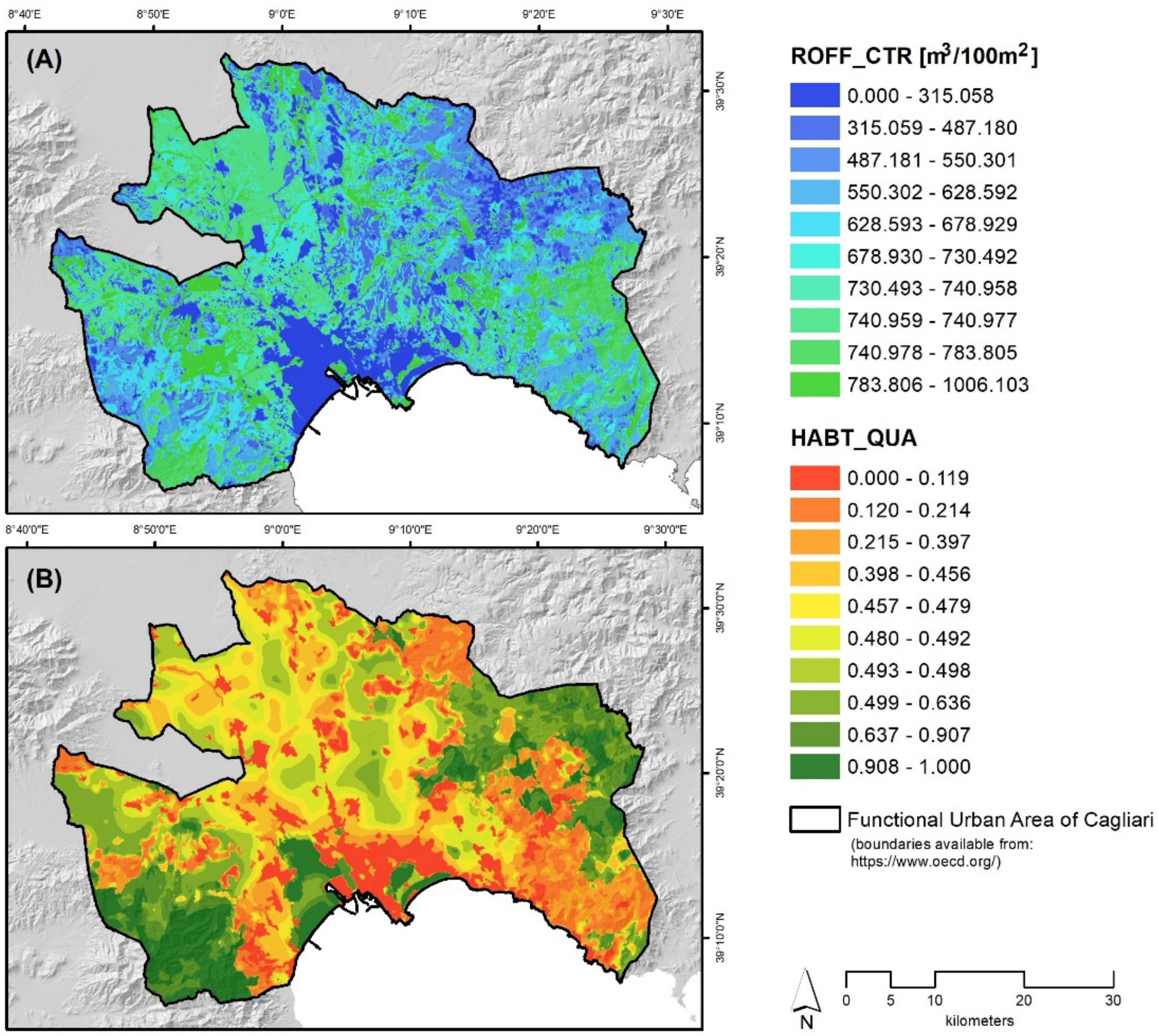

Fig.3 Spatial distribution of indicators for (A) ROFF_CTR and (B) HABT_QUA, both classified by deciles

Fig.4A provides the spatial variation of SUR_TEMP across the FUA, representing LST as recorded on the hottest day of summer 2023 in the FUA. This variable serves as an indicator of ecosystems' capacity to mitigate local climate conditions: the higher the LST, the lower the provision of this regulating ES. As expected, the lowest temperatures are observed in inland water bodies (first decile), followed by hilly and mountainous areas (second and third deciles).

The highest temperatures are concentrated in the Campidano Plain, encompassing both urban settlements and agricultural areas. The core city of Cagliari and its hinterland exhibit moderate values, possibly due to their proximity to wetlands and the coastline, as well as to a well-known phenomenon studied in arid regions, which in summer tend to exhibit higher temperature in rural areas than in urban ones (Marando et al., 2022). Finally, Fig.4B depicts the spatial pattern of LAND_CAP.

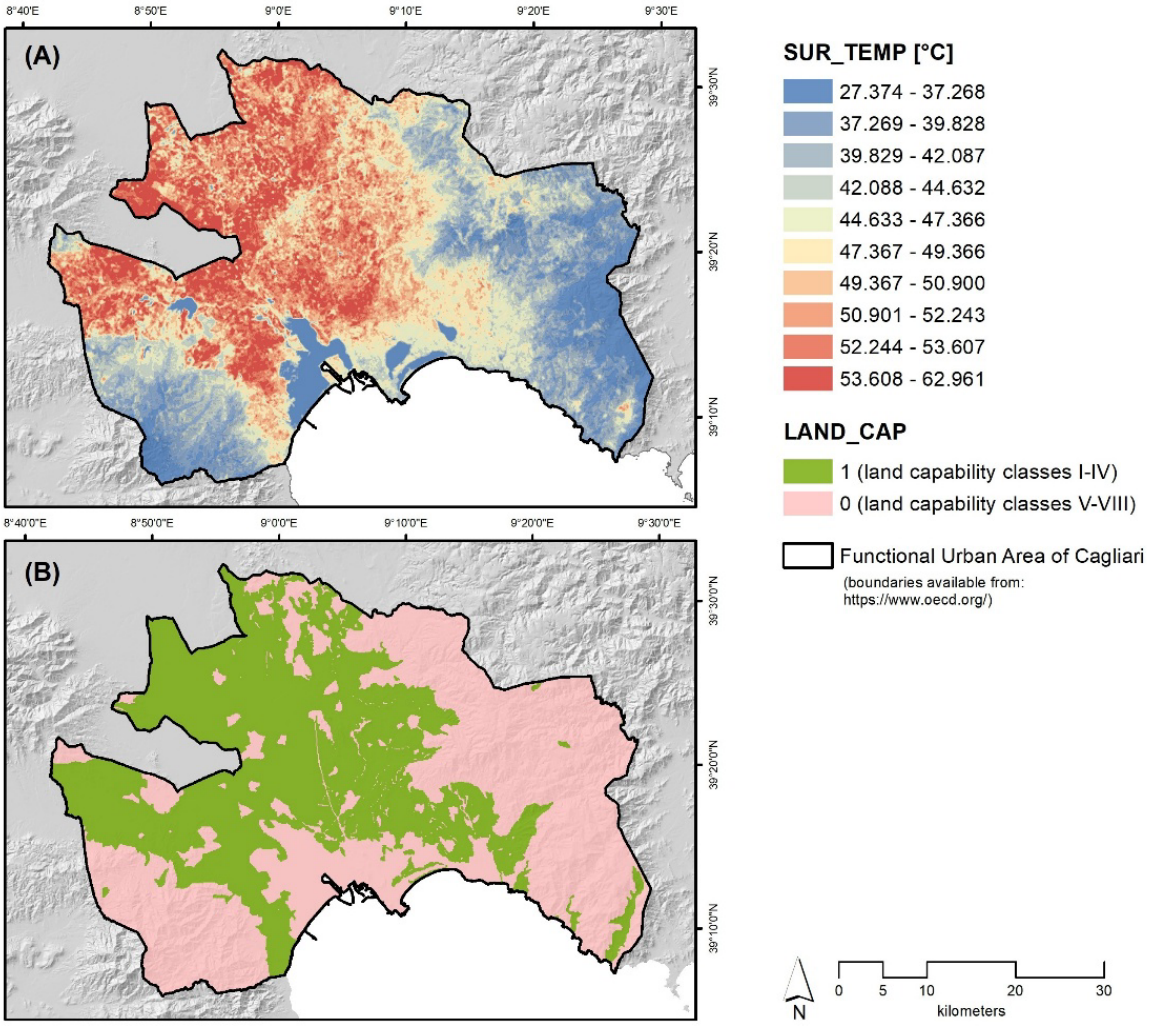

Fig.3 Spatial distribution of indicators for (A) SUR_TEMP, classified by deciles, and (B) LAND_CAP, 1 for arable and 0 for non-arable soils

3.2 Multiple regression model

The coefficient estimates of model (1) are presented, in the following, as reported in Tab.2, which shows, in value and sign, the marginal changes in CS in relation to the unit increase in the supply of the four ESs and control variables, and the values of the p-value significance tests, which allow us to assess the reliability of the regression outcomes.

The results are to be read bearing in mind that estimating a positive value of the sign of a coefficient implies that an increase in the supply of the corresponding ES is associated with an increase in C_SEQ, and the other way around. Such estimates all have significant values in relation to the p-value test. Such estimates, therefore, can be taken as reliable measures of the correlations between C_SEQ and availability of the ESs which are associated with the variables to which the estimated coefficients refer. The magnitude of the impact, positive or negative, is assessed by calculating the elasticities of CS capacity with respect to the supply of the different ESs. The calculation of elasticities is equal to the ratio of the percentage changes, in value and sign, of the dependent variable and the explanatory variables. The last column of Tab.2 reports the elasticities entailed by the coefficient estimates from the multiple linear regression, referred to the mean values of such variables. The values of the elasticities, always lower than 100 percent, configure CS capacity as an essentially inelastic phenomenon with respect to the supply of the targeted ESs, although substantial differences, both in value and sign, are evident.

Explanatory variable	Coefficient	t-statistic	p-value	Mean of the explanatory variable	Elasticity at the mean values of C_SEQ and expl. var's, related to a 10% increase in expl. var's [(Δy/y)/(Δx/x), %]
REC_AREA	-0.0000020	-66.7691210	0.000	2,074.3821441	-0.3896740
ROFF_CTR	0.0008137	220.3107902	0.000	628.7480144	48.2438526
HABT_QUA	0.2265020	86.5215270	0.000	0.4571412	9.7641556
SUR_TEMP	-0.0047290	-31.5592406	0.000	46.4666493	-20.7213618
LAND_CAP	-0.0527197	-29.5788868	0.000	0.4781383	-
CS_LAGGD	0.3135804	35.8959072	0.000	0.2567973	-

Dependent variable: C_SEQ: Mean: 1.0604442 Mg/(100 m^2); Standard deviation: 0.3269716 Mg/(100 m^2); Adjusted R-squared: 0.2985817

Tab.2 Regression results

Although, therefore, the coefficient estimates in model (1) are significant in relation to the p-value test, the impacts on C_SEQ associated with the supply of the four ESs are quite different. It can be seen, then, that a 5 percent increase in the average value of the SUR_TEMP variable, i.e., an average LST gradient of just under 2.5 °C, is associated with an average decrease in C_SEQ of about 1 percent. It should be pointed out in this regard that, in general, thermal gradients in diachronic terms are much lower than this value and, therefore, how the relationship between C_SEQ and SUR_TEMP, although, as discussed in the next section, is in line with the results available in the current literature, points to a rather weak influence of LST on CS capacity.

The positive elasticity with respect to the HABT_QUA variable, which is less than a half of the elasticity related to variable SUR_TEMP, implies that the improvement in habitat quality is a less significant factor, compared to a negative thermal gradient, in enhancing CS capacity. Indeed, a 10 percent increase in the HABT_QUA variable, linked, for example, to a significant decrease in threats to habitats in the spatial context of the Cagliari FUA, is associated with an increase of just under 1 percent.

Regarding the relationship between C_SEQ and the ES supply variable for outdoor recreation, it is shown that the negative impact of RECR_OUT is associated with a very low value of the elasticity of C_SEQ of about 0.4 percent. However, since, as indicated in Section 2.3, RECR_OUT is equal to the share of a cell area available for outdoor recreation times the population residing in a 500-meter buffer of such cell, it should be noted that a 10% decrease in such buffer resident population would be associated with an increase of about 10% in C_SEQ, which identifies an increase of about 0.1 Mg/(100 m^2), with an implied negative elasticity of about 100%. Thus, resident population in buffers of cells characterized by above-average recreational area emerges as an important factor in relation to CS capacity. As in the case of SUR_TEMP, however, the change in such buffer resident population is subject to very low diachronic variations. Therefore, at least in the short and medium run, this implies, as in regard to SUR_TEMP, a weak influence of this variable on CS capacity.

With regard to the control of flood phenomena, i.e., the variable ROFF_CTR, associated with runoff control, this presents a positive, significant and rather relevant marginal effect estimate in value, with an elasticity of just under 50 percent. Thus, it is shown that the ES associated with runoff control, although in a general situation of inelasticity of CS capacity, is configured as the one that most influences the C_SEQ variable.

As for the LAND_CAP dichotomous control variable, the coefficient estimate is negative and significant, and that a change in it, if relevant, can lead to a depletion of CS capacity of some importance as well. A 10 percent increase in arable soils, or just under 5 percent of the total, is, in fact, associated with a 0.2 percent decrease in the C_SEQ variable.

Finally, a positive and significant spatial autocorrelation is evidenced by the estimate of the coefficient of the spatially lagged variable CS_LAGGED, related to the dependent variable C_SEQ.

4. Discussion

The relationship between CS capacity and LST, highlighted by the implementation of the methodology proposed here to the spatial context of the Cagliari FUA, is reflected in several studies available in the current literature. Momo and Devi (2022) survey the trends in LST and CS, during a decade (2011-2021), with reference to the West District of Imphal, the capital of the Indian state of Manipur, and compare the results obtained through the implementation of different methodologies based on satellite remote-sensed data, highlighting how the results converge, both qualitatively and quantitatively, and reflect a steady decrease in CS capacity associated with a steady increase in LST. Similar results, albeit with a different methodological approach, are presented and discussed by Wang et al. (2021) with reference to the metropolitan context of Shenzen, located in a subtropical area of China. The study focuses on the impact of urban heat island on CS capacity in relation to different urban ecosystems, and points out that the empirical investigation shows a decrease in CS more pronounced in the central areas of the metropolis, where LST is higher than in the peripheral areas.

Studies that focus on positive correlations between habitat quality and CS capacity are numerous, covering different spatial scales, thus continental, regional, and local levels, and multiple definitions of the spatial arrangement of ecosystem service provision related to habitat quality. Generally, it is noted that CS capacity is regarded as a structural component of habitat quality and how, therefore, it is a feature of it, rather than a related phenomenon. As part of habitat quality, therefore, CS capacity connotes and catalyzes its improvement and enhancement. The improvement of habitat quality and enhancement of CS capacity is found, according to Bayley et al. (2021), in the regional context of the Falkland Islands, where this quality is linked to forest health and, therefore, to policies aimed at forest plantation and restoration. With regard to the urban context, the work of Hua et al. (2024) is significant, in which, with reference to the urban context of Xiamen, a major city in the Min Delta region, located in the southern coast of China, a spatial model is defined for the assessment of trade-offs between urban expansion and decreasing supply of ESs, identified with reference to CS capacity, habitat quality, water conservation and soil retention. These services are considered to be positively correlated with each other, and such that the changes, in value and sign, are structurally consistent with each other

The estimation of the negative correlation between CS capacity and resident population density is also reflected in the current literature. The study by Kinnunen et al. (2022), which proposes a general review of the international technical and scientific debate related to the interaction between the CS phenomenon and the urban residential context in which it occurs, points out that it is acquired, in general terms, that the contribution of highly urbanized contexts to CS is minimal, and structurally decreasing with increasing population density and building volume density. It should, moreover, be recognized, according to the conceptual approach of Gao & O'Neill (2020) how the increase in these densities leads to an increase in CO_2 emissions and a decrease, in situations that are already highly penalized from this point of view, in the areas suitable for storing carbon, especially when the form of urbanization processes is extensive and these are characterized by urban sprawl, that is, by a progressive consumption of natural soils with good CS capacity. Several areas of the spatial context of the river riparian zone, and the wetlands adjacent to it, function as strong carbon sinks. In a review article concerning the identification of synergies and trade-offs of the supply of different types of ESs in relation to forest planting, maintenance, and restoration, Pan et al. (2022) posit how forests, especially through the consolidation of root systems, increase the CS capacity of soils and, at the same time, improve their water retention, thus their runoff control capacity and hydraulic risk mitigation. Thus, a substantial positive interaction between flood control and CS capacity can be seen. The close positive correlation between forestation operations, flood control, and increased CS capacity is described and discussed by Kumar et al. (2020) with reference to an area characterized by troubled and barren orography in western India. Even in urban areas, the effectiveness of runoff control is, generally, associated with the improvement of CS capacity.

With reference to the case of the implementation of the nature-based solution represented by the construction of green roofs, Mihalakakou et al. (2023) point out, again in the context of a review article, how the benefits of these devices consist, in parallel, of the mitigation of flooding phenomena in dense urban building fabrics and of the significant increase in CS capacity, again partly to be attributed to the development and consolidation of root systems.

5. Conclusions

This study has proposed a novel methodological approach that integrates geospatial analysis and inferential modeling to examine the relationships between CS and other ESs. By applying this approach to the FUA of Cagliari, relationships between CS and pluvial runoff control, local temperatures, habitat quality, and outdoor recreation, were analyzed.

In urban planning, identifying these relationships and quantitatively assessing their magnitude and robustness is crucial, as this assessment provides an evidence-based foundation for spatial policies related to permeable soils and green spaces. In urban areas, effective strategies for enhancing carbon storage, reducing temperatures, and mitigating the impacts of heavy rainfall include soil desealing, urban afforestation, and expansion of green space coverage, including the utilization of residual areas.

These measures primarily target public spaces rather than private properties; in the latter, planning codes should focus on maintenance of unpaved and unsealed areas within individual plots and parking spaces, as well as guiding the appropriate selection of vegetation. In agricultural settings, appropriate management practices may play a more significant role than planning regulations in maintaining or enhancing carbon sequestration and its related synergic ESs.

The novelty of the proposed approach lies in its simplicity and adaptability to different contexts, as it applies standard inferential modeling to biophysical ESs assessments grounded on publicly available datasets. Such assessments may seem highly demanding, particularly in terms of required expertise and data collection, since the availability and quality of input data are crucial for ensuring reliable results. Researchers must consider and address issues such as data availability, constraints on spatial or temporal resolution, and the inherent subjectivity in expert-based evaluations. Such data-related challenges can translate into limitations, examples of which in this study include the lack of data on carbon stored in belowground biomass or the spatial resolution of the soil permeability and land capability maps.

Future implementations of this methodological approach could, therefore, explore the possibility of making use of readily available datasets on ESs provision. Moreover, a second direction for future research could involve a different, and maybe wider, selection of ESs included in the set of explanatory variables, to provide a bigger picture of the synergistic or antagonistic relationship between CS and other ESs, with a view to better ground suggestions for planners and policy makers.

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Image Sources

All images were prepared by the Authors.

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