# Mapping Spatial Synergies and Trade-Offs: A Geographically Weighted Analysis of Ecosystem Services and Carbon Sequestration in Southern Italy

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**Abstract.** Moving toward climate neutrality calls for spatially explicit planning frameworks that reflect territorial diversity and land-use change processes. Within this conceptual framework, this study has the objective of identifying and discussing spatially explicit planning approaches that can support the transition to climate neutrality in different regional spatial contexts. Therefore, a methodological framework is introduced and applied, designed to support climate neutrality through spatial planning strategies. Carbon sequestration (CS) serves as a key metric to evaluate both the current state and the temporal evolution of this process, examined in connection with the provision of specific ecosystem services (ESs) within the relevant spatial setting. The work is structured as follows. An approach is developed to define the provision of ESs. Drawing on previous research and assessments of environmental, landscape, and socio-cultural features, the study considers the following ESs: quality of habitat to sustain the life cycles of species valuable to humans; regulating climate by mitigating land sur-face temperature; agricultural and forestry production; and nature-based recreational opportunities. Moreover, spatial relationships between CS capacity and ES provision are examined through geographically weighted regressions, allowing comparisons across Basilicata, Campania, and Sardinia, regions in Italy forming the Italian Mezzogiorno. The multifunctional characteristics of ES supply contribute to optimizing CS capacity and advancing climate neutrality goals. In all regional contexts, high values of CS capacity elasticity are recognized in relation to habitat quality and ground temperature mitigation, and very low elasticity conditions as regards the supply of recreational ESs and agricultural and forestry production.

**Keywords:** Carbon sequestration · Climate neutrality · Ecosystem services · Geographically weighted regression (GWR) · InVEST model · Spatial planning

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## 1 Introduction

One of the biggest threats to global stability today is climate change (CC), which is having a rising impact on both rural and urban areas by affecting people's health, physical well-being, and general quality of life [1]. The evident consequences of global warming necessitate urgent action to meet the Paris Agreement target of limiting warming to 1.5 °C above pre-industrial levels. Achieving this objective requires a long-term balance between greenhouse gas emissions and removals, a pursuit often referred to as climate neutrality. Consequently, the European Union has committed to a 55% reduction in emissions by 2030 and full climate neutrality by 2050.

A third of the potential biological productivity of the global carbon cycle has been utilized by human activities, especially the use of fossil fuels and land clearing, which have fundamentally disturbed the cycle. In the Italian context, this pressure is manifested in increasing land consumption and urban sprawl, leading to biodiversity loss and heightened environmental risks such as floods and heat islands [2, 3]. Within this framework, regulating ecosystem services (ESs), specifically Carbon Capture and Storage (CCAS), are vital for mitigation and adaptation. CCAS is a natural phenomenon, primarily driven by photosynthesis, through which terrestrial ecosystems remove $CO_2$ from the atmosphere and store it in biomass and soil [4]. Natural ecosystems provide a multifunctional supply of services that interact in complex ways. While the principle of multifunctionality suggests that a single area can provide multiple benefits, certain functions may be mutually conflicting, leading to trade-offs where the enhancement of one service (e.g., carbon storage) may negatively affect another (e.g., biodiversity or agricultural production). Conversely, synergies occur when multiple services improve simultaneously.

Multiple studies such as Früh-Müller et al. [5] and Bateman et al. [6] document trade-offs and synergies between CCAS and other services. Viglizzo et al. [7] provide a comprehensive regression-based analysis, to examine how carbon sequestration partitions with water-flow, soil and climate regulation. Although regression analysis is commonly used to analyze relationships among multiple ESs [7, 8], these relationships are analyzed in a stationary way. This study seeks to go beyond the limitations of stationary regression analysis by studying non-stationary relationships in Mediterranean landscapes using a geographically weighted regression (GWR).

From this perspective, this work aims to analyze the relationship between CCAS and multiple ESs, such as quality of habitat (QOHA), land surface temperature mitigation (LOHM), agricultural and forestry production (AFPL), and nature-based outdoor activity potential (NOAP) using a GWR model, in order to determine and critically examine geographically delineated planning methodologies capable of facilitating the progression toward climate neutrality across heterogeneous regional territorial configurations. A GWR-based approach is preferred over ordinary regression models in ES studies for its ability to handle spatial non-stationarity, where relationships vary across locations.

The study employs a methodological framework aimed at promoting climate neutrality through spatially oriented planning policies. CCAS is employed as a central indicator to assess both the existing conditions and the dynamic progression of sequestration processes, analyzed in relation to the supply of selected ESs, with two main steps. First

step is the assessment of four ESs and the second is the investigation of the spatial interdependencies between CS potential and ES distribution using a GWR model, enabling comparative analyses among the selected Italian regions.

The paper is structured as follows. Section two outlines the case studies and methods. Section three presents the results obtained, which are then discussed in section four. Finally, section five concludes with final remarks and future research directions.

## 2 Materials and Methods

### 2.1 Study Area

The study area comprises three regions of the Italian "Mezzogiorno": Basilicata, Campania, and Sardinia (Fig. 1). Basilicata covers an area of approximately 10,000 km$^2$ [9] which is predominantly hilly, with 10% constituting plains and mainly concentrated along the Ionian coastline, and its landscape is predominantly agricultural, with extensive farming practices and high biodiversity [10]. Concerning land covers, according to the latest CORINE data [11], around 57% of the region is agricultural, 41% is forests and semi-natural vegetation, and only 1.6% is artificial. Campania extends over 13,700 km$^2$ [9] with mainly hilly and mountainous territory, while alluvial plains account for about 14% of the surface. The main mountain systems include the Matese Mountains and the Cilento Massif. Volcanic landforms are a distinctive feature of the region. Around 55% of the region is agricultural, around 37% is covered by forests and semi-natural vegetation, and 7.5% is artificial. Sardinia is the second-largest island in the Mediterranean Sea and has a landmass of approximately 24,000 km$^2$. The regional territory is predominantly hilly and characterized by numerous isolated mountain groups, including Gennargentu, Sette Fratelli, and Limbara [13], and coastal wetlands constitute a distinctive landscape feature. Around 46% of the region is agricultural, around 50% is covered by forests and semi-natural vegetation, and only 3% is classed as artificial. As of 1 January 2025, the population is 530,005 in Basilicata, 5,582,337 in Campania, and 1,562,381 people in Sardinia [12].

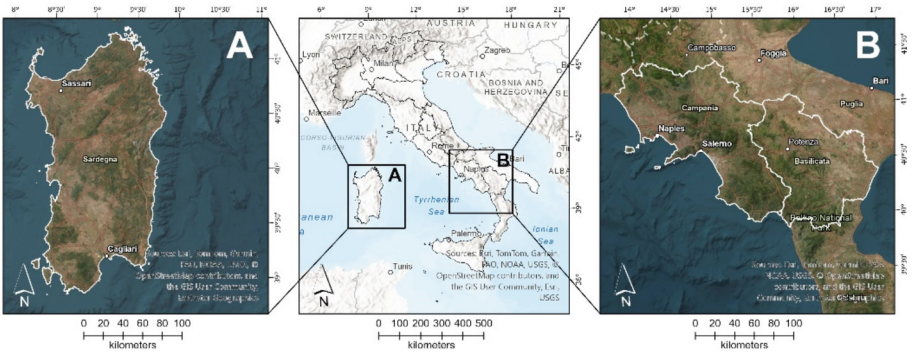


**Fig. 1.** Study areas: Sardinia (panel A), Basilicata, and Campania (panel B).

### 2.2 ESs Assessments

The methodology employed for assessing CCAS, QOHA, LOHM and NOAP is explained in Table 1 below.

**Table 1.** Data sources used for ESs assessments

| ES | Method | Input/Parameter | Source |
|---|---|---|---|
| CCAS | InVEST Suite carbon storage and sequestration model | Land cover map | Corine Land Cover 2018 |
| | | CSV table showing carbon density values | NASA'S ORNL DAAC<br>National Inventory of Forests and Carbon Pools in Italy<br>ISPRA<br>AGRIS Sardegna |
| QOHA | InVEST Habitat Quality model | Land cover map | Corine Land Cover |
| | | Threat maps | Geofabrik Download Server |
| | | Sensitivity table | Habitat classification and related parameters defined by Sallustio et al. [14] were adopted in this study. |
| LOHM | Land Surface Temperature (LST) | Satellite images | USGS Earth Explorer |
| NOAP | ESTIMAP Recreation model [15] | Degree of naturalness (Hemeroby index) | ISTAT 2019 for Sardinia,<br>ISTAT 2023 for Basilicata and Campania<br>livestock density<br>Forested areas |
| | | Protected and natural sites | National and regional parks<br>Ramsar sites<br>Natura 2000 sites |
| | | Attractiveness of coastal zones | (i) distance from the coastline, modeled via an inverse logistic function; (ii) coastal geomorphology, using the Eurosion dataset; and, (iii) bathing water quality, based on European Bathing Water Directive data |

(*continued*)

**Table 1.** (*continued*)

| ES | Method | Input/Parameter | Source |
|---|---|---|---|
| AFPL | overlay of the land cover map with the agro-forestry value map | Average monetary values per unit area for agricultural lands | (i) the national agricultural land value database produced by the Council for Agricultural Research and Economics (CREA) |
| | | mean land values for forestry areas | (ii) the dataset issued by the National Revenue Agency (NRA) |

### 2.3 Geographically-Weighted Regressions

The relationship between CCAS capacity and the supply of the four ESs selected for the study proposed here was investigated using a GWR model, according to the formalization proposed by [16]. The model assesses the non-stationary relationship between CCAS (dependent) and ES supply (explanatory) variables, building upon a spatially stationary multiple linear regression that assumes constant coefficients across Basilicata, Campania, and Sardinia formulized as:

$$\mathrm{CCAS} = \alpha 0 + \alpha\ 1\ \mathrm{LOHM} + \alpha 2\ \mathrm{QOHA} + \alpha 3\ \mathrm{AFPL} + \alpha 4\ \mathrm{NOAP} \quad (1)$$

where CCAS is the density of carbon capture and storage capacity ($Mg/m^2$); LOHM is the heat mitigation reference, i.e., the land surface temperature (LST) with values in °C.; QOHA measures the level of habitat quality, and takes values ranging from 0 and 1; AFPL is the value of agricultural and timber production (€/ha); NOAP measures the potential for nature-based outdoor activities, and takes values ranging from 0 to 1.

The estimated coefficients of the explanatory variables show the marginal impacts of these covariates on the CCAS. The regression model is typically used when no prior assumptions can be made about the functional relationships between the variables [17–20]. Significance tests for the estimated coefficients are usually assessed using p-values, and the adjusted R-squared is the reference for evaluating the goodness of fit.

The GWRs model replaces the linear regression model when relationships vary spatially across large, non-homogeneous datasets—like the tens of thousands of records in Basilicata, Campania, and Sardinia—where coefficients are location-specific and not stationary. For each of the points in three spatial contexts, the regression estimate was implemented by assuming that the influence of the explanatory variables on the dependent variable decreases when distance increases, by introducing a Gaussian weighting scheme. According to the detailed and analytical discussion of the model [16], the value of *b*, called bandwidth, must be chosen in such a way as to account for the trade-off in terms of unbiasedness and reliability of the GWR estimate. It is therefore very important, for the GWRs model, to identify the bandwidth that balances minimizing the variance and the bias of the estimate of the dependent variable CCAS ($x_i$, $y_i$). The search for the

value of the bandwidth *b* that solves the minimization problem can be carried out, as suggested by [16], by applying the golden section share algorithm.

With regard to the goodness-of-fit of the GWRs estimate, the following statistics are important: (i) the adjusted R-squared which measures the variance of CCAS, explained by the GWRs estimate, purifying this measurement from the increase in the coefficient linked to the number of explanatory variables; (ii) the adjusted critical value of pseudo-t statistics, used to verify the statistical significance of the estimated coefficients using a two-tailed t-test, at a significance level of 5%; while checking in the family-wise error rate (FWER). The resulting vector, $\hat{a}(x_i,y_i)$, locally characterizes the correlations between CCAS $(x_i,y_i)$ and the four ES availability variables.

## 3 Results

### 3.1 Carbon Capture and Storage

The CCAS taxonomy is intrinsically linked to the biophysical characteristics of the territory, with particular reference to land cover, especially with forest types. The spatial distribution of this ES supply is highest in forest-covered soils, varying by type, while lower values are found in sparse vegetation, and, in built-up areas.

The CCAS assessment yields that in all three regions highest capacity is observed in forests (Fig. 2). Campania exhibits the highest density at 23.82 kg/m$^2$, followed by Basilicata at 21.21 kg/m$^2$, both observed in broad-leaved forests, whilst Sardinia's maximum value is 17.75 kg/m$^2$, noted in the coniferous category. In all three regions, forests represent the primary carbon pool. However, average forest productivity varies significantly. Campania's forests range from 15.07 to 17.40 kg/m$^2$, followed by Basilicata (12.88–14.76 kg/m$^2$) and Sardinia (10.99–12.65 kg/m$^2$). Spatially, high-density clusters are correlated with mountainous and protected areas, and the eastern/southwestern massifs in Sardinia. Intermediate storage levels (7.77–10.54 kg/m$^2$) are found in shrublands and marshes, while artificial areas and water bodies consistently yield the lowest results. Moreover, these regions act as natural reservoirs: Campania as high-capacity tank, Basilicata as a well-distributed network of medium basins, and Sardinia as a specialized reservoir where coniferous forests are more efficient than others.

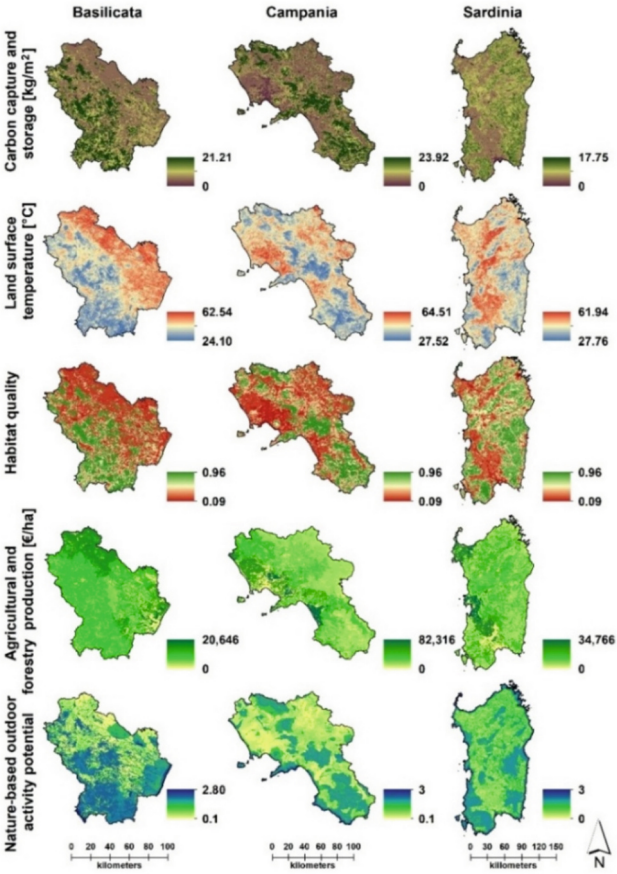


**Fig. 2.** Spatial distribution of the five ecosystem services in the three study areas.

### 3.2 Quality of Habitat Analysis

The analysis of QOHA, represented as HQ scores, shows consistent contrasts between high values characterizing natural areas and low values found in urban and intensive agricultural areas. Human infrastructures are recognized as major sources of degradation, reducing HQ scores according to their proximity and their threat level.

Sardinia records the highest average HQ (0.54) and the greatest proportion of high-quality habitats (40.86%). Basilicata follows with an average score of 0.51, but with the highest percentage of low-quality habitats (44.45%). Campania reports the lowest average HQ (0.49) and the smallest share of high-quality habitats (31.43%). In all regions, the best habitats are forested areas; broadleaved forests exhibit the highest mean scores (ranging from 0.85 to 0.86), followed by grasslands and wetlands. Conversely, artificial surfaces and impervious areas score near zero (0.09) across all regions, with open urban fabric and intensive arable land also exhibiting very low values (0.21–0.25).

The biophysical characteristics across three regions - are decisive in identifying the HQ level. First, through their influence on threat classification linked to agricultural use and soil permeability, which are influenced by human activities and infrastructure, highlighting radical differences between threats related to green and gray infrastructure.

### 3.3 Regulating Local Climate: Land Surface Temperature Mitigation

In Campania, LST ranges from about 27.5 to 64.5 °C (Fig. 2), with the highest values concentrated in densely urbanized and artificial areas. Lower temperatures occur where mountainous and hilly landscapes dominate. Overall, thermal patterns align with land-use intensity, with cooler conditions in vegetated and high-elevation zones. In Sardinia, LST ranges from around 27.8 to 61.9 °C (Fig. 2). The highest temperatures occur mainly in agricultural zones, while cooler values characterize mountainous, forested, and protected. The highest temperatures are observed in agricultural fields and discontinuous urban fabric (both 61.9 °C), whereas the highest mean values are observed in artificial areas. Water bodies and forests remain the coolest (32–40 °C). Basilicata's LST ranges from 24.1 to 62.5 °C (Fig. 2). Higher values occur in industrial, commercial, and agricultural areas of the northeast, including the Bradano basin, Vulture Hills, and the urban zone of Matera etc. Cooler temperatures characterize the Lucanian Apennines. CLC data indicates the highest means of LSTs in irrigated and mixed agriculture and artificial surfaces, and the lowest in water bodies, forests, and rocky areas.

In the three regions, the highest temperatures are consistently found in intensive agricultural areas, in urbanized areas with high building density, and in peri-urban areas characterized by scattered settlements with marked fragmentation of the spatial continuity of permeable soils and habitats. The relationship between the territorial distribution of LST and spatial biophysical characteristics is evident from the above results since across all regions lowest temperatures in the mountainous areas or areas in proximity to or inclusion of wetlands, waterways, lakes, woods, and forests.

### 3.4 Agricultural and Forestry Production

The 2023 AFPL map for Campania reveals a highly uneven spatial configuration, with values ranging from zero, where no agricultural or forestry classification is present, to a maximum of EUR 82,316/ha (Fig. 2). About 22.08% of the region records a null value, while the mean reaches EUR 12,552/ha. Over half of the territory (52.11%) shows values below EUR 10,000/ha, mainly in the eastern Campanian Apennines and the Cilento area, while the highest AFPL values occur in the coastal hills of Naples and the Sorrento Peninsula, characterized by high-value arable and horticultural production.

A similar distribution emerges in Sardinia, where the 2023 AFPL values range from zero to EUR 34,766/ha (Fig. 2). Around 17.41% of the region falls below EUR 1,000/ha, with an overall mean of EUR 5,091/ha. Values above EUR 10,000/ha are concentrated in fertile plains such as Campidano di Cagliari, Oristano, and Nurra, areas typically dedicated to vineyards, orchards, citrus groves, and horticultural crops. Peaks exceeding EUR 30,000/ha occur in the coastal hills of Sarrabus, in the Lower Tirso plain, and in the Campidano of Serrenti.

In Basilicata, AFPL values range from zero to EUR 20,646/ha (Fig. 2). Approximately 9.86% of the Region shows a null value, while 11.44% falls below EUR 1,000/ha. The average value is EUR 5689/ha. Higher AFPL values, above EUR 20,000/ha, are found in the Metapontino Plain near the river mouths of the Sinni, Agri, Cavone, Basento, and Bradano, where agricultural production is dominated by orchards and vineyards. Even in the case of AFPL it is clear that supply is closely linked to the biophysical characteristics of the territory in all three regions considered in which the highest values are found where there are flat or hilly, arable soils characterized by vegetable crops, olive groves, vineyards, and citrus groves.

### 3.5 Nature-Based Outdoor Activity Potential

The assessment of NOAP in all regions reveals significant spatial heterogeneity driven by naturalness and coastal proximity. Values range from 0.1 to 2.8 in Basilicata and 0.1 to 3.0 in Campania, while Sardinia covers the full 0 to 3 scale with a mean of 1.21 (Fig. 2). A common geographical trend emerges, represented by high-value clusters predominantly located along coastal strips, such as the Tyrrhenian and Ionian coasts in Basilicata and the Campania coastline, and within mountainous protected areas in Sardinia. Statistical analysis of CLC classes confirms that natural and semi-natural areas provide the highest service levels such as salt marshes, beaches, and water bodies. Conversely, the lowest values are systematically associated with anthropized environments, including industrial units, urban fabrics, and intensive agricultural plains. These results emphasize that NOAP is intrinsically linked to environmental conservation and the presence of significant landscape features. Moreover, the biophysical characteristics of the territory align in a clear and homogenous way with the spatial taxonomy of the ES.

### 3.6 Geographically Weighted Regressions

To run the GWR, a vector layer composed of one-kilometer square polygons arranged in a regular grid was created. For each polygon, the average values of CCAS, LOHM, QOHA, AFPL, and NOAP were calculated from the ES maps described in Sects. 3.1–3.6 and shown in Fig. 2, using zonal statistics.

Prior to the GWR, an ordinary least squares regression was performed to check for global multicollinearity. All variables had a Variance Inflation Factor lower than four, and therefore below ten, a commonly used threshold for multicollinearity [21]. Subsequently, the GWR model in which the dependent variable CCAS is locally regressed against the four explanatory variables was implemented by using the tool "Geographically Weighted Regression (GWR) (Spatial Statistics)" in ESRI ArcGIS Pro 3.6.0 separately for each of the three study areas [22]. Table 2 provides the mean statistics of the coefficients $\alpha_1$, $\alpha_2$, $\alpha_3$, $\alpha_4$, as well as of the local coefficient $R^2$, for Basilicata, Campania, and Sardinia, respectively.

**Table 2.** GWR: mean statistics of the coefficients of the models presented in Eq. (3) for Campania, Basilicata, and Sardinia.

| Region | Explanatory Variable | Coefficient Mean Value | % Significant Records at 0.95 Level |
|---|---|---|---|
| Basilicata | LOHM | −0.1541 | 87.35 |
| | QOHA | 10.0357 | 99.88 |
| | AFPL | 0.0003 | 79.83 |
| | NOAP | 0.928 | 62.43 |
| Campania | LOHM | −0.2787 | 96.78 |
| | QOHA | 12.3032 | 100.00 |
| | AFPL | 0.00004 | 62.01 |
| | NOAP | −0.0876 | 38.14 |
| Sardinia | LOHM | −0.0377 | 70.84 |
| | QOHA | 7.9304 | 100.00 |
| | AFPL | 0.0001 | 38.75 |
| | NOAP | −0.3321 | 45.54 |

Table 2 shows QOHA as the most significant variable, nearly always at the 0.95 level. LOHM ranks second, with 0.95 ranging from 71% to 97% of the records in Sardinia and Campania, respectively. Regarding AFPL and NOAP, significant estimates are high in Basilicata (AFPL $\simeq$ 80% and NOAP $\simeq$ 62%) and low in Sardinia (AFPL $\simeq$ 39% and NOAP $\simeq$ 46%), intermediate in Campania (AFPL $\simeq$ 62% and NOAP $\simeq$ 38%). Figs. 3, 4, 5 show the spatial distribution of the coefficients of the GWR model for the three case studies, with red indicating negative values and blue indicating positive.

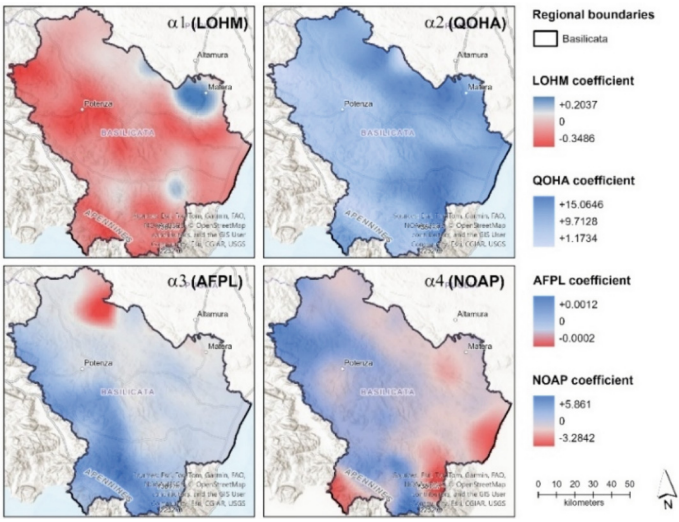


**Fig. 3.** GWR coefficients in Basilicata.

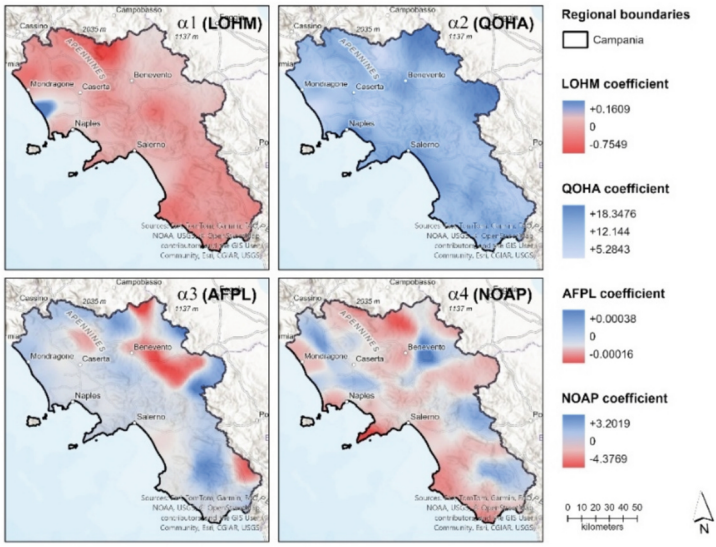


**Fig. 4.** GWR coefficients in Campania.

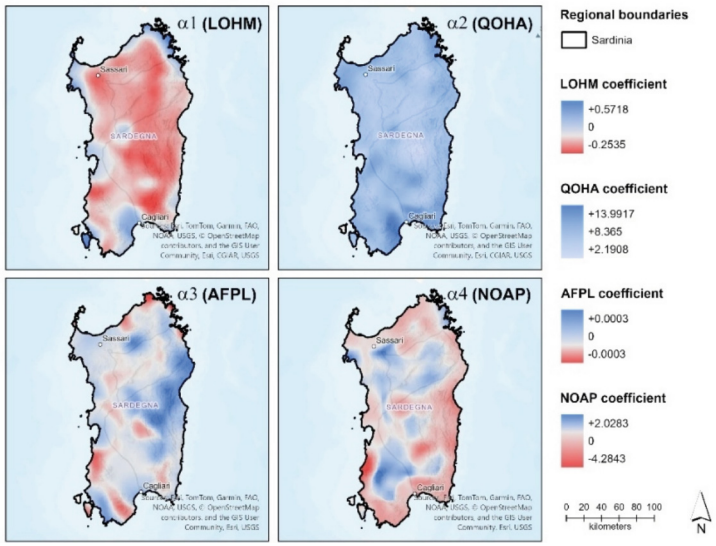


**Fig. 5.** GWR coefficients in Sardinia.

For LOHM, the mean values in Table 2 are negative, as seen as red shades in Figs. 3, 4, 5, indicating that higher LOHM generally decreases CCAS and vice versa; a 1 °C LST increase decreases CCAS by 0.17 kg/m$^2$ in Basilicata, 0.30 in Campania, and 0.05 in Sardinia. This association is more pronounced in Basilicata and Campania, whereas

in Sardinia positive (blue) values are mainly distributed along the coastline and in some inland clusters, with very low absolute magnitudes. Most settlements show negative coefficients (red), except for Matera (Fig. 3) where the significance of correlation is low and Cagliari, where positive coefficients (blue) likely reflect its location within coast and wetlands.

QOHA is the only explanatory variable whose coefficients in Table 2, in addition to being relatively high, are always positive across the three regions. This pattern is clearly illustrated in Figs. 3, 4, 5, which display only varying shades of blue and no red tones, signaling that an increase in QOHA is consistently associated with an increase in CCAS. A 10% increase in QOHA raises CCAS by 1.12 kg/m$^2$ in Basilicata, 1.37 in Campania, and 0.88 in Sardinia, roughly a 10% change in all cases. Although the coefficient is always positive, lower values tend to correspond to main settlements and transport infrastructures. While in Basilicata and Campania, the darker shades are generally associated with hilly landscapes, in Sardinia (Fig. 5) the darker shades are found in a flat, low-elevation area in the southeastern part of the island.

AFPL takes an average positive, but very small value in the three regions, The dominance of blue shades in Figs. 3, 4, 5 indicates that the coefficients are mostly positive, with negative (red) values clustering in a distinct area in northeast Basilicata and in a few isolated clusters in Campania, whereas in Sardinia several negative clusters are spread across the island. An increase in AFPL of one euro, on average, does not produce any changes in CCAS in Campania, and an increase of only 0.1 g/m$^2$ in Sardinia and 0.3 in Basilicata.

Finally, as for NOAP, the coefficients are the highest after those of QOHA, and their spatial distribution varies considerably across the three regions. An increase in NOAP of one unit, on average, is associated with an increase of CCAS by 1.03 kg/m$^2$ in Basilicata and a decrease by 0.1 kg/m$^2$ in Campania, and 0.37 in Sardinia. In Basilicata, the mean value reported in Table 2 is positive; accordingly, the prevalence of blue shades in Fig. 3. Conversely, in Campania the mean value is negative, shown in red shades in Fig. 4, with four notable positive (blue) agglomerations in inland areas, largely coinciding with natural protected areas. In Sardinia the mean value is also negative. Moreover, values are less clustered than in the other two regions and are predominantly negative (red) (Fig. 5), observed in natural lands covers such as the Gennargentu-Supramonte massifs, while positive (blue) clusters appear inland, similar to the patterns in Campania.

## 4 Discussion

Regarding habitat quality, as seen in the figures and Table 2, the GWR results for all three regions consistently show that increases in QOHA correspond to increases in CCAS at its mean level. The positive correlation between CCAS and the habitat quality level is consistent with several studies available in the current literature concerning this issue such as the findings of Spohn et al. [23], which suggest that plant species richness can enhance soil organic carbon sequestration by improving the quality of organic inputs rather than their overall quantity, indicating that t management practices aimed at recovering plant diversity can promote greater soil organic carbon (SOC) sequestration. Schittko et al. [24] show that the quality of habitats has a consistently positive impact on both soil multifunctionality and soil organic carbon stocks. Structural equation modeling indicates

that these effects are largely mediated by an increase in the diversity of soil-dwelling organisms.

Furthermore, a comparison of the spatial distribution of the GWR coefficients of QOHA and LOHM shows a significant association between growth in carbon capture and storage capacity, improvement in habitat quality, and a decrease in LST, and therefore a positive correlation between the latter two variables. In other words, in all three regional cases examined, where carbon storage capacity is higher, habitat quality is also comparatively higher and LST is lower. This result is supported by the study by Hu et al. [25], in the context of China, showing that higher levels of LST are associated with lower habitat quality values, thus with opposite spatial patterns. Furtjermore, a study by Müllerová and Šiffel [26], conducted in Czech Republic, shows that areas with better vegetation conditions and greater water availability tend to have lower LSTs, while areas with more or less pronounced vegetation cover degradation show higher LSTs, thus revealing a negative correlation.

Regarding the local climate mitigation, in all three regions, GWR estimates show that decreasing LOHM increases average CCAS. This relationship is roughly proportional in Basilicata (89% elasticity) and Campania (150%), but significantly lower in Sardinia (2%). This different pattern can be explained by the significant presence of wetlands in the Sardinian coastal areas, which are much more widespread than in Basilicata and Campania and distributed over much longer stretches of coastline: the coastline of Sardinia is almost 1900 km long, that of Campania about 500 km, and that of Basilicata about 70 km. As Zhang et al. [27] point out with regard to Bohai Bay, China, the spatial distribution of SOC is associated with environmental variables that include various climatic factors, with areas of higher SOC corresponding to areas with higher temperatures, which favor carbon input into wetland soils. The inland areas of Sardinia, on the other hand, offer a spatial pattern very similar to those of Basilicata and Campania, characterized by a generalized positive correlation between CCAS and decrease in LOHM. This result finds numerous and consistent confirmations in the current literature such as the results proposed by Hartley et al. [28], where they analyze over 9000 soil profiles located in the five continents, yielding the result that stored organic carbon decreases sharply with an increase in average annual temperature, thus finding that lower soil temperatures are associated with higher amounts of organic carbon.

In terms of agricultural and forestry production, the consistently positive but very small AFPL coefficients in Table 2 show that increases in AFPL are associated with only modest increases in CCAS at mean values. Overall, the impact of AFPL on CCAS is quite weak, and less significant than that of QOHA and LOHM, particularly in Sardinia, where significance occurs for only about 38% of observations. This limited effect may reflect the heterogeneous and sometimes contradictory evidence from the literature. Aryal et al. [29] identify the trade-off between crop production and carbon or climate services as the most frequently studied relationship between 2005 and 2020. Such trade-offs have been observed in Quebec, Canada [30], and the Beijing area, China [31], Conversely, some studies report synergistic relationships between food production and carbon sequestration or storage [32]. For forested areas, most studies report a positive association with carbon sequestration; however, as with agriculture, effective management is essential [33] to ensure the synergistic effect: timber harvesting can either increase or decrease

carbon storage depending on management strategies [34]. Moreover, the inner hilly and mountain landscapes in all three regions are characterized by traditional Mediterranean grazing practices, with livestock living on natural pastures and wooded grassland [35] and, in the case of sheep and goats, even on mediterranean maquis and garrigue or forest undergrowth [36]. While these practices are not only culturally and socially rooted but also generally sustainable due to their low intensity, long-term grazing is associated with reductions in carbon stocks, as shown in other studies such as [37].

As for nature-based recreation, Table 2 indicates that GWR results differ across the three regions. An increase in NOAP is associated with higher CCAS values at the mean level in Basilicata, whereas it corresponds to modest decreases in Campania and Sardinia. The estimated supply elasticity of CCAS at the mean level is approximately 13% in Basilicata, −1% in Campania, and − 5% in Sardinia; in the latter two regions, fewer than 50% of the records are statistically significant. A clear pattern emerges from the spatial distribution of the negative coefficients along coastal areas across all regions, indicating that increased recreation is associated with reduced CS. The recreation potential in coastal areas is high due to the combined presence of natural ecosystems such as sandy beaches, proximity to water, and protected areas [38]. This pattern is intuitive and consistent with empirical evidence worldwide, which confirms the popularity of coastal areas for daily recreation due to the abundance of recreational opportunities and high environmental quality [39, 40]. On the other hand, CS tends to be lower in arid regions such as Mediterranean coastlines, driven by the relatively limited forest cover and by calcareous and acidic soils [41], and in spite of the presence of coastal wetlands acting as carbon sinks [42]. This suggests a trade-off in these regions, where enhancing recreation may reduce carbon storage, requiring a balance. This balance could be supported through the adoption of sustainable tourism and land-use policies, which have been shown to mitigate environmental impacts while maintaining economic and recreational benefits in Mediterranean contexts [43]. By contrast, positive coefficients are observed in Basilicata and large inland areas of Campania and Sardinia, likely due to the forests and other vegetated areas that simultaneously support carbon storage and outdoor recreation. Proximity to urban settlements is a key determinant of daily recreation. Hence, from a policy perspective, increasing recreational opportunities through afforestation in inland areas near human settlements could also lead to enhanced CCAS.

## 5 Conclusions

This study establishes a comprehensive methodological framework for analyzing the functional relationships between CCAS, assumed as the reference ES for evaluating the role of regional spatial contexts in achieving global climate neutrality, and the provision of four additional ESs: QOHA and LOHM (regulating ESs); AFPL (provisioning ES); and NOAP (cultural ES) in the contexts of Basilicata, Campania, and Sardinia. The core of the analysis involves correlating the spatial distribution of each of these four ESs with the taxonomy of CCAS in urban, peri-urban, rural, and natural areas.

Since these relationships are not stationary in the spatial contexts of reference, they are analyzed by employing a GWR, run on 1-km grid cells, adopting a Gaussian-based weighting approach, and choosing bandwidths that are optimized through the golden

search selection method. QOHA consistently showed a strong positive relationship with CCAS, indicating that areas with higher ecological integrity tend to support greater carbon stocks. Conversely, LOHM shows negative associations, confirming that cooler microclimatic conditions are associated with higher carbon stocks. AFPL shows a negligible association with CCAS, which can be positive or negative, depending on management strategies. Similarly, NOAP displays spatially variable results, negative correlations in coastal areas, and synergistic relationships in forested inland regions.

GWR maps reveal spatially varying ES correlations, enabling identification of leverage areas, where local coefficients are higher and targeted interventions (e.g., habitat restoration) would yield the greatest synergistic co-benefits (e.g., CCAS), as well as the delineation of zones of inevitable trade-offs, where conflicting ES priorities, such as tensions between coastal tourism and CCAS, must be negotiated. By making these spatial asymmetries explicit, GWR provides a direct, evidence-based foundation for differentiated regional planning, supporting targeted measures that maximize synergies and balance competing demands, priority-setting, and context-sensitive policy design that cannot be derived from non-spatial models.

Despite its innovative contribution, the proposed methodology has some limitations. First, it relies on proxy-based estimations from secondary sources, which may affect accuracy. Second, ES assessments based on expert judgment (e.g., HQ) may introduce subjectivity. Third, it does not explicitly account for the influence of human infrastructure on ES trade-offs. Future research could expand the range of ESs considered and extend the framework to include climate change mitigation scenarios, dynamic land-use modeling, and applications in other geographical contexts to explore long-term synergies and trade-offs.

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