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Nature-Positive Cities: Adaptive Spatial Planning in Italy for an Ecological Urban Transition

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ISSN 2191-530X ISSN 2191-5318 (electronic)
SpringerBriefs in Applied Sciences and Technology
ISSN 2282-2577 ISSN 2282-2585 (electronic)
PoliMI SpringerBriefs
ISBN 978-3-032-06616-9 ISBN 978-3-032-06617-6 (eBook)
https://doi.org/10.1007/978-3-032-06617-6

This work was supported by Politecnico di Milano.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Contents

Role of Spatial Planning in Addressing Climate Challenges: A Study Concerning the Functional Urban Area of Cagliari

Sabrina Lai and Corrado Zoppi

Keywords Ecosystem services · Urban planning · Carbon sequestration and storage · GIS · Inferential models

1 Introduction

The capacity for carbon sequestration (CSC) enhances the absorption of carbon in natural environments, whereas disposal methods inhibit carbon dioxide (CO_2) from returning to the active carbon cycle. These techniques are typically organized according to the Earth system component they aim to influence: land-based CSC, marine CSC, and geological storage [1]. Land-based CSC utilizes photosynthesis to transform atmospheric CO_2 into organic matter and soil-based carbon stocks, offering co-benefits like enriched soil fertility, higher agricultural productivity, and cleaner water resources [2].

Given that CO_2 is the principal greenhouse gas accelerating climate change, a range of engineering and ecological strategies has been introduced to curb its emissions and maintain stable concentrations in the atmosphere. Among these, natural CSC boosts the capacity of ecosystems such as woodlands and soils to capture and retain carbon [3]. Strengthening these natural carbon sinks should thus be a central consideration in planning land use.

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A. De Toni et al. (eds.), *Nature-Positive Cities: Adaptive Spatial Planning in Italy for an Ecological Urban Transition*,
PoliMI SpringerBriefs, https://doi.org/10.1007/978-3-032-06617-6_10

This research defines and applies a methodological framework aimed at achieving climate neutrality through spatial planning mechanisms. CSC is employed as a core analytical concept to meet this aim, grounded in an array of ecosystem services (ESs). The study unfolds in several stages. Initially, the spatial dimensions of CSC are assessed using CSC density mapping through the "Carbon Storage and Sequestration" module from the InVEST toolset [4], which calculates carbon reserves across land units based on land cover data [5].

In the next phase, the relationship between CSC and various ESs is modeled and spatially evaluated, focusing on services such as sustaining biodiversity by ensuring viable habitats for flora and fauna beneficial to humans; moderating climate by lowering land surface temperature (LSTE); controlling water runoff; and providing areas for recreational activities in natural settings.

Lastly, spatial correlations between CSC metrics and ES categories are examined within the Functional Urban Area (FUA) of Cagliari, situated in Sardinia, an island in Southern Italy. This analysis aims to determine how ES provision can be strategically optimized to enhance CSC performance while refining the spatial arrangement of ESs. The findings contribute to place-sensitive policy guidance for improving environmental quality through better ES delivery in FUAs.

2 Methodologies and Materials

2.1 The FUA of Cagliari

The FUA of Cagliari (Fig. 1), located in Sardinia, Italy, spans approximately 2000 km^2, includes 32 municipalities, and has a population of 475,170 as of 2023. To calculate the model variables detailed in Sect. 2.3, a vector-based grid of ~200,000 cells, each measuring 100 $\times$ 100 m, was developed to cover the FUA.

2.2 CSC Definition and Spatial Taxonomies of ESs

CSC is in this study was analyzed alongside four additional ESs relevant to the FUA: nature-based recreation, pluvial runoff regulation, habitat quality, and LST regulation. Table 1 lists the spatial datasets and sources used to evaluate the density of carbon stored in carbon sinks (CSCD) and the other ESs.

For CSCD, InVEST's [4] "Carbon Storage and Sequestration" module generates a raster map representing carbon density per pixel, calculated as the sum of carbon stored in four pools: aboveground biomass, belowground biomass, dead organic matter, and soil organic carbon. This output is derived from a land cover dataset and a corresponding look-up table assigning carbon values to each land cover type. Due to the absence of data on belowground biomass, the model was run using only the

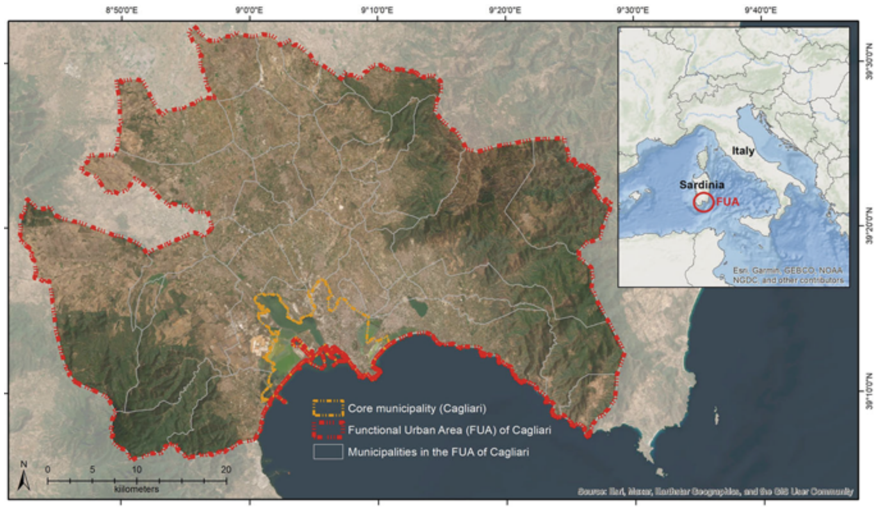

Fig. 1 Study area: the functional urban area of Cagliari and its core municipality

remaining three pools. Carbon values were sourced from the 2005 Italian forest and carbon sink inventory and supplemented by field data collected through a regional pilot initiative led by two Sardinian agencies specializing in rural development and agricultural research.

RCTR was evaluated using InVEST's [4] "Urban Flood Risk Mitigation" model, which requires the following inputs: i., a land cover dataset; ii., a soil hydrologic group map based on USDA-NRCS's [16] classification; iii., a biophysical table linking curve numbers to each land cover–soil group combination; iv., rainfall depth; and v., watershed boundaries for spatial aggregation. The model outputs a raster map of runoff retention, where water retained per pixel is determined by rainfall and runoff, both influenced by land use and soil permeability. All input data were sourced from regional repositories.

HAQU was assessed using InVEST's [4] "Habitat Quality" model, which evaluates ecosystem integrity based on degradation caused by the presence and intensity of biodiversity threats and considering institutional protection, which may limit exposure. The model uses a raster land cover map to represent habitat distribution, supplemented by a table assigning habitat suitability scores to each land cover type (ranging from 0 to 1). In this study, the CORINE 2018 land cover dataset was employed. Threat data were obtained from the Natura 2000 standard data forms and the regional geoportal. Two expert-informed tables were developed: one defining the severity and spatial influence of each threat, and another assigning suitability values and sensitivity scores to each land cover type.

LSTE was derived from raster maps of LST, used as a proxy for ecosystems' temperature-regulating capacity. Landsat Collection 2, Level 2 imagery (May–October 2023) was sourced from the USGS, excluding scenes with over 10% cloud

Table 1 Data used to map the variables used in this study

Variable	Data requirements	Source
CSCD	Land cover map	Sardegna Geoportale [6]
	Reference table linking land cover categories to carbon pools data	Sardegna Geoportale [6, Inventario Nazionale delle Foreste e dei serbatoi forestali di Carbonio [National Inventory of Forests and forest Carbon pools] 7]
RECA	Land cover map	Urban Atlas [8]
	Vector map of census tracts Table linking census tract identifiers to population data	Dati per sezione di censimento [Data by Census Tract] [9]
RCTR	Land cover map	Sardegna Geoportale [6]
	Map outlining watershed regions	Sardegna Geoportale [6]
	Map of soil permeability characteristics	Sardegna Geoportale [6]
	Table mapping land cover types to curve number values	Carta del curve number regionale [Regional Curve Number Map] [10]
	Data on rainfall	Idrologia e Idrometria [Hydrology and Hydrometry] [11]
HAQU	Land cover map (CORINE 2018)	CORINE Land Cover [12]
	List and geographic datasets of environmental threats	Sardegna Geoportale [6, Natura 2000 Viewer 13]
	Table with information on threats	Lai and Leone [14]
	Table indicating sensitivity to various threats	
	Accessibility to threats	Sardegna Geoportale [6]
LSTE	Satellite imagery Landsat C2L2	EarthExplorer [15]

cover. The image with the highest mean temperature, dated July 30, 2023, was selected for analysis.

RECA captures the flow of nature-based recreational opportunities. Supply was measured as the availability of green and blue spaces, while demand was estimated as the number of residents within 500 m of these areas. The indicator was computed by multiplying the share of recreational land within each grid cell by the local population within a 500-m radius. Recreation-suitable areas were identified using the 2018 Urban Atlas, and population data were obtained from the 2021 national census, including tract boundaries and resident counts. For detailed methodology, see [17].

After generating the raster maps for CSCD and the other four ESs, mean values for each 100-m square cell were computed using zonal statistics.

To control for the effect of soil presence and consistency, a variable named LCAP was introduced in the regression model; it equals 1 for arable soils (classes I–IV) and 0 for non-arable soils (classes V–VIII), following a classification by USDA [18] and using as input a regional soil map of Sardinia, reclassified and aggregated to the grid level via zonal statistics. An additional control variable, CSCL, was included to account for spatial autocorrelation in CSCD. Defined as the spatial lag of CSCD, CSCL was computed using Moran's I in GeoDa [19], applying a first-order queen contiguity weight matrix to the 100-m vector grid.

2.3 Linear Regression

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

$$\text{CSCD} = \beta_0 + \beta_1\text{RECA} + \beta_2\text{RCTR} + \beta_3\text{HAQU} + \beta_4\text{LSTE} + \beta_5\text{LCAP} + \beta_6\text{CSCL} \quad (1)$$

The dependent and covariates are the following, which relate to a cell of 100 × 100 m:

- CSCD is CSC density (Mg/(100 m^2));
- RECA is the percentage of recreational areas for outdoor activities times the residents located within a 500-m radius around a cell (% times residents);
- RCTR is the amount of precipitation that can be absorbed or held, and thus does not contribute to surface runoff (m^3);
- HAQU is habitat quality (this variable takes rational values between 0 and 1; see Sect. 2.2);
- LSTE is taken as a proxy for heat mitigation size (°C);
- LCAP is a Boolean variable which has value 1 for arable soils and 0 otherwise; for the definition see Sect. 2.2);
- CSCL is a control variable related to spatial autocorrelation of CSCD.

Linear regression is used to assess the relationship between CSC spatial patterns and selected ESs supply. Predictive models based on regression are commonly applied in situations where prior knowledge about the interconnections between variables describing intricate systems is lacking [20, 21]. Coefficients quantify links between CSC distribution, ESs provision, and control factors. LCAP, reflecting soil arability, accounts for CSC reductions in arable soil due to organic carbon loss [22]. Spatial autocorrelation in CSC is addressed using the spatial lag variable CSCL, following Anselin's approach [19, 23]. Model significance is tested via p-values for all variables.

3 Results

3.1 CSC Definition and Spatial Taxonomies of ESs

Figure 2 presents the spatial distribution of CSCD, RECA, and RCTR. As for CSCD (panel A), the highest values, falling within the top two deciles, are primarily located along the FUA edges, where extensive forest cover and protected natural areas dominate. These include major Natura 2000 sites and regional parks. In contrast, the urban core of Cagliari and adjacent wetlands consistently show the lowest CSCD values, while agricultural zones register intermediate levels. Concerning RECA (panel B), the highest decile values are concentrated in the central FUA, particularly in urbanized areas where green and blue spaces are accessible within 500 m of residential zones. To the west, medium-to-high values appear in low-density areas near the "Sette Fratelli" forest. Conversely, a prominent low-value cluster in the east is due to the absence of nearby settlements. The lowest RCTR values (panel C) correspond to impervious surfaces primarily concentrated in and around the FUA's urban core and other settlements. Conversely, the highest values (ninth and tenth deciles) are located along the FUA's western and eastern boundaries. Moderate-to-high retention values (sixth and seventh deciles) are mainly found in permeable agricultural zones.

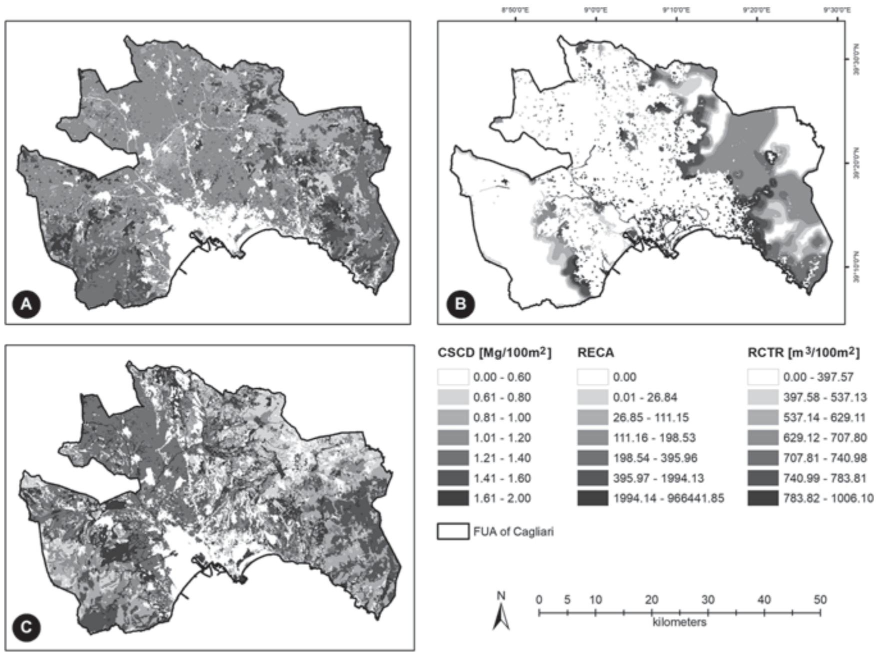

Fig. 2 Spatial layout of CSCD (panel A), RECA (panel B), and RCTR (panel C) in the FUA

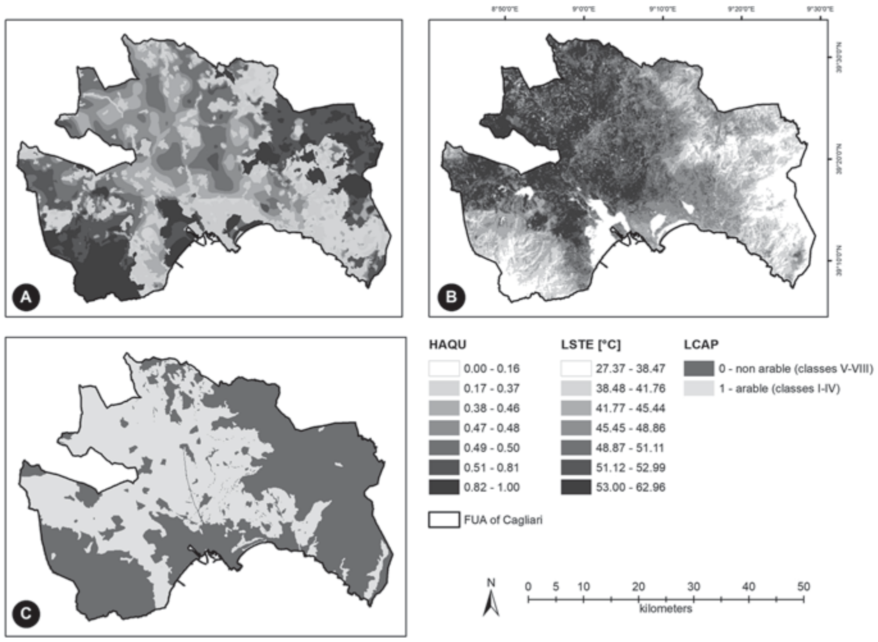

Fig. 3 Spatial layout of HAQU (panel A), LSTE (panel B), and LCAP (panel C) in the FUA

Figure 3 shows the distribution of HAQU, LSTE, and LCAP. As for HAQU (panel A), the highest scores, in the top two deciles, appear not only along the forested and protected western and eastern margins, but also near the urban core and its surroundings. This pattern reflects the significant biodiversity and legal protections of two large Natura 2000 wetlands. Areas in the lowest decile generally correspond to artificial land covers, while rural zones display a gradient from low to medium–high values. Concerning LSTE (panel B), the spatial variation of LST recorded on the hottest summer day of 2023 is shown. LSTE indicates ecosystems' ability to moderate local temperatures, where higher LST values correspond to reduced regulating capacity. The coolest temperatures are found in inland water bodies (first decile), followed by elevated terrain (second and third deciles). The highest temperatures occur across the agricultural Campidano Plain. The Cagliari core and adjacent areas show moderate values, likely influenced by the sea and the two wetlands.

3.2 *Linear Regression*

Model (1) estimates, shown in Table 2, reveal how CSCD responds to changes in four ES supply and control variables. Each coefficient indicates the marginal effect on CSCD per unit increase in the respective variable, with significance confirmed via p-values.

A positive coefficient means that higher ES supply increases CSCD, and vice versa. All estimates are statistically significant, making them reliable indicators of the relationships analyzed. The strength of each effect is expressed, in sign and size, through elasticity, calculated as the ratio of percentage changes in CSCD to those in each variable. Table 2's final column presents these elasticity values, related to the mean values of the covariates. Since all values are below 100%, CSCD is generally inelastic to changes in ES supply, though variation exists, in size and sign, across ESs.

According to model (1), despite significance, the four ESs affect CSCD differently. A 5% increase in LSTE (about a 2.5 °C rise) leads to a ~1% drop in CSCD, indicating a weak negative effect due to LSTE's typically small temporal variation.

HAQU shows a smaller positive elasticity than LSTE's negative one, suggesting improvements in habitat quality have limited effect. For instance, a 10% HAQU increase, related, for example, to a relevant decline in the size of threats to habitat quality in the FUA of Cagliari, yields under 1% CSCD growth.

RECA negatively affects CSCD but has a very low elasticity (~0.4%). However, as for the definition of RECA delivered in Sects. 2.2 and 2.3, a 10% drop in buffer-zone population could result in a ~10% CSCD increase, implying a substantial negative elasticity (~100%). Still, since population shifts are minimal over time, the short- to medium-term effect is weak.

RCTR has the strongest positive influence on CSCD, with an elasticity close to 50%, despite CSCD's overall inelasticity.

LCAP negatively impacts CSCD; a 10% rise in arable land (~5% of the total) reduces CSCD by ~0.2%.

Table 2 Regression results

Explanatory variable	Coefficient	t-statistic	p-value	Mean of the explanatory variable	Elasticity at the mean values of CSCD and expl. var's, related to a 10% increase in expl. var's [(Δy/y)/(Δx/x), %]
RECA	−2.0E−6	−66.7691	0.000	2074.3821	−0.3897
RCTR	0.0008	220.3108	0.000	628.7480	48.2439
HAQU	0.2265	86.5215	0.000	0.4571	9.7642
LSTE	−0.0047	−31.5592	0.000	46.4666	−20.7214
LCAP	−0.0527	−29.57889	0.000	0.4781	−2.3771
CSCL	0.3136	35.8959	0.000	0.2568	7.5937

Dependent variable: CSCD: Mean: 1.0604 Mg/(100 m^2); Standard deviation: 0.3270 Mg/(100 m^2); Adjusted R-squared: 0.2986

Finally, CSCL confirms significant spatial autocorrelation, reinforcing spatial dependency in CSC distribution.

4 Discussion

The relationship between CSC and LSTE, as shown through the spatial analysis of the Cagliari FUA, is consistent with numerous studies. Momo and Devi [24] analyzed LST and CSC trends over 2011–2021 in Imphal's West District, India, using various satellite-based methods. Their findings showed consistent declines in CSC and rising LST. Likewise, Wang et al. [25] studied subtropical Shenzhen, China, where urban heat islands led to lower CSC levels, especially in dense urban cores compared to peripheral areas.

Many studies also highlight the positive link between CSC and habitat quality across spatial scales, local to continental. CSC is considered a key structural aspect of habitat quality, actively enhancing environmental health. Bayley et al. [26], for example, found improved CS tied to forest restoration on the Falkland Islands. In urban Xiamen, Hua et al. [27] introduced a model assessing trade-offs from urban growth, showing how services like CSC, water regulation, habitat quality, and soil stability change in coordinated ways.

A negative correlation between CSC and population density is also widely observed. Kinnunen et al. [28] note that dense urban areas contribute little to CSC, with declining capacity linked to building density. Gao and O'Neill [29] emphasize that population growth and urban sprawl increase CO_2 emissions and reduce high-value natural carbon sinks. Riparian zones and wetlands still serve as strong carbon sinks. Pan et al. [30] point out that forest root systems enhance CSC and water retention, aiding flood control. Kumar et al. [31] observe this effect in western India, where afforestation improves both CSC and hydrological resilience. In cities, green roofs provide similar benefits, improving both stormwater control and CSC through vegetative root systems [32].

5 Conclusion

This study has presented a novel method combining geospatial analysis and modeling to examine links between CS and other ESs in the Cagliari FUA, focusing on runoff retention, temperature regulation, habitat quality, and nature-based recreation.

Quantifying these relationships supports evidence-based urban planning for permeable soils and green spaces. Key urban strategies include soil desealing, afforestation, and green space expansion, primarily in public areas, where private property regulations should encourage maintaining unsealed surfaces and appropriate vegetation. In agricultural areas, however, management practices are often more critical than planning policies for enhancing carbon sequestration and related

ESs. This approach is notable for its simplicity and adaptability, using standard inferential models on publicly available biophysical spatial data. Data limitations, such as missing belowground carbon and coarse soil maps, pose challenges; therefore, future work could consider using more detailed datasets. Moreover, the range of ESs studied could be broadened to better inform planning and policy decisions.

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

Authors' Contributions Sabrina (S.L.) and Corrado Zoppi (C.Z.) collaboratively designed this study. Individual contributions are as follows: C.Z. wrote Sections 1, 2.3, 3.2 and 4; S.L. wrote Sectios 2.1, 2.2, 3.1 and 5.

Disclosure of Interests The authors declare no competing interests.

References

1. Dilling L, Doney SC, Edmonds J, Gurney KR, Harriss R, Schimel D, Stephens B, Stokes G (2003) The role of carbon cycle observations and knowledge in carbon management. Annu Rev Environ Res 28(1):521–558. https://doi.org/10.1146/annurev.energy.28.011503.163443
2. Lal R (2008) Carbon sequestration. Philos Trans R Soc B 363(1492):815–830. https://doi.org/10.1098/rstb.2007.2185
3. Ghommem M, Hajj MR, Puri IK (2012) Influence of natural and anthropogenic carbon dioxide sequestration on global warming. Ecol. Modell. 235–236:1–7. https://doi.org/10.1016/j.ecolmodel.2012.04.005
4. What is InVEST. https://naturalcapitalproject.stanford.edu/software/invest. Accessed 20 May 2025
5. Liquete C, Kleeschulte S, Dige G, Maes J, Grizzetti B, Olah B, Zulian G (2015) Mapping green infrastructure based on ecosystem services and ecological networks: a pan-European case study. Environ Sci Policy 54:268–280. https://doi.org/10.1016/j.envsci.2015.07.009
6. SardegnaGeoportale. https://www.sardegnageoportale.it/. Accessed 20 May 2025
7. Inventario Nazionale delle Foreste e dei serbatoi forestali di Carbonio [National Inventory of Forests and forest Carbon pools]. https://www.inventarioforestale.org/en/. Accessed 20 May 2025
8. Urban Atlas. https://land.copernicus.eu/en/products/urban-atlas. Accessed 20 May 2025
9. Dati per sezione di censimento [Data by Census Tract]. https://www.istat.it/it/archivio/285267. Accessed 20 May 2025
10. Carta del curve number regionale [Regional Curve Number Map]. https://www.sardegnageoportale.it/documenti/40_615_20190329081206.pdf. Accessed 20 May 2025
11. Idrologia e Idrometria [Hydrology and Hydrometry]. https://www.sardegnaambiente.it/index.php?xsl=611&s=21&v=9&c=93749&na=1&n=10. Accessed 20 May 2025

12. CORINE Land Cover. https://land.copernicus.eu/en/products/corine-land-cover/clc2018. Accessed 20 May 2025
13. Natura 2000 Viewer. https://natura2000.eea.europa.eu. Accessed 20 May 2025
14. Lai S, Leone F (2017) Bridging biodiversity conservation objectives with landscape planning through green infrastructures: a case study from Sardinia, Italy. In: Gervasi O et al (eds) 17th international conference on computational science and its applications (ICCSA 2017), Lecture notes in computer sciences series (LNCS), vol 10409, pp 456–472. Springer, Cham. https://doi.org/10.1007/978-3-319-62407-5_32
15. EarthExplorer. https://earthexplorer.usgs.gov. Accessed 20 May 2025
16. USDA-NRCS (2009) National engineering handbook. Part 630 Hydrology. Chapter 7 Hydrologic soil groups. https://www.hydrocad.net/neh/630ch7.pdf. Accessed 20 May 2025
17. Isola F, Lai S, Leone F, Zoppi C (2024) Urban green infrastructure and ecosystem service supply: a study concerning the functional urban area of Cagliari, Italy. Sustainability 16(19):8628. https://doi.org/10.3390/su16198628
18. Klingebiel AA, Montgomery PH (1961) Land capability classification. https://www.govinfo.gov/content/pkg/GOVPUB-A-PURL-gpo20777/pdf/GOVPUB-A-PURL-gpo20777.pdf. Accessed 20 May 2025
19. Anselin L, Syabri I, Kho Y (2006) GeoDa: an introduction to spatial data analysis. Geogr Anal 38(1):5–22. https://doi.org/10.1111/j.0016-7363.2005.00671.x
20. Sklenicka P, Molnarova K, Pixova KC, Salek ME (2013) Factors affecting farmlands in the Czech Republic. Land Use Policy 30(1):130–136. https://doi.org/10.1016/j.landusepol.2012.03.005
21. Stewart PA, Libby LW (1998) Determinants of farmland value: the case of DeKalb County, Illinois. Rev Agric Econ 20(1):80–95. https://www.jstor.org/stable/1349535. Accessed 20 May 2025
22. Anuo CO, Sleem M, Fossum B, Li L, Cooper JA, Malakar A, Maharjan B, Kaiser M (2024) Land use selectively impacts soil carbon storage in particulate, water-extractable, and mineral-associated forms across pedogenetic horizons. Geoderma 449:116992. https://doi.org/10.1016/j.geoderma.2024.116992
23. Anselin L (2003) Spatial econometrics. In: Baltagi BH (ed) A companion to theoretical econometrics. Blackwell Publishing, Oxford, pp 310–330
24. Momo M, Devi TT (2022) Assessment of land surface temperature and carbon sequestration using remotely sensed satellite data in the Imphal-West District, Manipur, India. J Earth Syst Sci 131:229. https://doi.org/10.1007/s12040-022-01944-8
25. Wang J, Xiang Z, Wang W, Chang W, Wang Y (2021) Impacts of strengthened warming by urban heat island on carbon sequestration of urban ecosystems in a subtropical city of China. Urban Ecosyst 24:1165–1177. https://doi.org/10.1007/s11252-021-01104-8
26. Bayley DTI, Brickle P, Brewin PE, Golding N, Pelembe T (2021) Valuation of kelp forest ecosystem service in the Falkland islands: a case study integrating blue carbon sequestration potential. One Ecosyst 6:e62811. https://doi.org/10.3897/oneeco.6.e62811
27. Hua Y, Yan D, Liu X (2024) Assessing synergies and trade-offs between ecosystem services in highly urbanized area under different scenarios of future land use change. Environ Sustain Indic 22:100350. https://doi.org/10.1016/j.indic.2024.100350
28. Kinnunen A, Talvitie I, Ottelin J, Heinonen J, Junnila S (2022) Carbon sequestration and storage potential of urban residential environment—a review. Sustain Cities Soc 84:104027. https://doi.org/10.1016/j.scs.2022.104027
29. Gao J, O'Neill B (2020) Mapping global urban land for the 21st century with data-driven simulations and shared socioeconomic pathways. Nat Commun 11:2302. https://doi.org/10.1038/s41467-020-15788-7
30. Pan C, Shrestha A, Innes JL, Zhou G, Li N, Li J, He Y, Sheng C, Niles J-O, Wang G (2022) Key challenges and approaches to addressing barriers in forest carbon offset projects. J For Res 33:1109–1122. https://doi.org/10.1007/s11676-022-01488-z

31. Kumar R, Bhatnagar PR, Kakade V, Dobhal S (2020) Tree plantation and soil water conservation enhances climate resilience and carbon sequestration of agro ecosystem in semi-arid degraded ravine lands. Agr Forest Meteorol 282–283:107857. https://doi.org/10.1016/j.agrformet.2019.107857
32. Mihalakakou G, Souliotis M, Papadaki M, Menounou P, Dimopoulos P, Kolokotsa D, Paravantis JA, Tsangrassoulis A, Panaras G, Giannakopoulos E, Papaefthimiou S (2023) Green roofs as a nature-based solution for improving urban sustainability: progress and perspectives. Renew Sust Energ Rev 180:113306. https://doi.org/10.1016/j.rser.2023.113306