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Special Issue 2.2023

Burn or sink
Planning and managing the land

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University of Naples Federico II

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Cover photo by Giuseppe Mazzeo. Rising wheat fields on the hills of Conza della Campania, Irpinia. January 31, 2023.

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Factors affecting the supply of urban regulating ecosystem services. Empirical estimates from Cagliari, Italy

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Abstract

This study aims at analyzing the relationships between supply of ecosystem services, features of green areas and characteristics of settlements in urban contexts, by taking the Italian city of Cagliari as study area. The services offered by the urban ecosystems that are identified as the most relevant in association with the spatial framework of green areas in urban environments are heat mitigation, carbon capture and storage, and runoff control, with particular reference to flood-related events. The features of green areas are identified with reference to the height of vegetation, by distinguishing between grasslands, shrubby cover, and trees and woodland cover. Finally, we characterize the urban settlement through the building and population densities, and through the education level, as a proxy for the residents' social statuses. The assessment of performances of the urban ecosystem services shows negative correlations with the intensity of urbanization, whereas the size of the enhancement in the supply of ecosystem services can be associated with different types of green areas. In terms of policy implications, the outcomes of the study show that there is plenty of room for improvement in the ecosystem services performance based on fine-tuning measures which involve building and population densities and vegetation cover.

Keywords

Ecosystem services; Urban vegetation; Carbon capture and storage; Urban runoff control; Urban heat mitigation.

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1. Introduction

According to figures available from the World Bank, around 56% of the world's population is presently concentrated in urban areas, whereas the population living in cities is forecast to grow up to nearly 70% by 2050[1]. The increasing urban expansion trend generates radical transformations in city landscapes, which entail, for example, decrease in urban biodiversity that causes destruction of habitats and widespread development of alien invasive species, loss of habitats and addition of new habitats, increase in vegetated land cover fragmentation (Tratalos et al., 2007; Warren et al., 2021; Davis, 1978), decrease in agriculture production, increase in air temperature (Donovan et al., 2005; Bonan, 2000), loss of carbon storage and capture potential (Floris & Zoppi, 2020), and increase in flood risk due to the growing trend of soil sealing (Isola et al., 2023).

A well-grounded approach to mitigation of negative impacts of intensive urbanization on natural ecosystems is represented by the paradigm of the "compact city" (Bibri et al., 2020), which aims at minimizing land-taking processes by concentrating city services in the central locations of urban fabrics (UN-Habitat, 2015; UN-Habitat, 2014a; UN-Habitat, 2014b; UN-Habitat, 2014c; UN-Habitat, 2011). By doing so, decrease in urban sprawl and important ecological and social positive impacts are implemented in the long run, so as to boost living quality in urban, periurban and rural environments (Guida, 2022; Hofstad, 2012; Jenks & Jones, 2010).

A less investigated profile is represented by the effects of intensive urbanization processes on the areas where such processes take place, with reference to ecosystem services endowment and provision (Gaglione & Ayiine-Etigo, 2021; Geneletti et al., 2019; Zucaro & Morosini, 2018; Tratalos et al., 2007).

For this purpose, three ecosystem services are identified in this study, which are particularly important as regards city environments, such as carbon capture and storage (CCS), runoff control (ROC) and heat mitigation (HEM).

CCS through biotic processes can be identified with photosynthesis, which takes place in ecosystems such as forests, woodlands, shrubs, garrigues, natural grasslands, and heathlands. Photosynthesis eliminates carbon dioxide from the air, and stores carbon in soil and biomass (Lal, 2008) while releasing oxygen in the atmosphere. Soil and air composition, and their interactions, significantly contribute to global climate regulation, and are heavily related to land covers and their transitions (Jobbagy & Jackson, 2000). Thus, green areas and soil play key roles in carbon cycle processes at the global level by supplying the CCS ecosystem service (European Commission, 2012; Millennium Ecosystem Assessment, 2003). Soil is the largest carbon terrestrial pool (Lal, 2004), since the carbon quantity stored in the soil is quite larger than in the biomass located overground (EEA, 2012). That is why even low changes in carbon concentration in the soil may generate relevant effects on the aerial concentration of carbon dioxide and on the temperature at the global level (Muñoz-Rojas et al., 2013; Arrhenius, 1897). Climate and soil show a mutual connection. On the one hand, climate changes influence geophysical and geomorphological conditions and environmental processes related to soil; on the other hand, soil transitions generate important effects on the terrestrial climate (Molinaro, 2020; EEA, 2012). The identification of the relation between climate change and the quantity of organic carbon stored in the soil is a fundamental point of reference to mitigate the negative impacts of climate changes (Yigini & Panagos, 2016). Since the global mean surface temperature (GMST) in the period 2011-2020 already shows an increase of 1.09 °C with respect to the preindustrial reference point (1850-1900)[2] and a growing trend thereof, the Protocol of Kyoto and the Paris Agreement state that the signatory parties will work to reach a world peak in greenhouse gas emissions (GHGEs) in the very short run and a virtuous balance between decrease in GHGEs and increase in CCS, so as to limit the increase in GMST to 1.5 °C by 2100 (World Meteorological Organization, 2018; United Nations, 2016). In this perspective, urban planning policies should play a relevant role as regards conservation and enhancement of the CCS ecosystem service provided by soils,

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[1] https://www.worldbank.org/en/topic/urbandevelopment/overview#:~:text=Today%2C%20some%2056%25%20of%20the,people%20will%20live%20in%20cities.

[2] https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-2/.

which entails the implementation of specific and effective measures aimed at improving its capacity of storing carbon (European Commission, 2012).

ROC is related to regulation of flood events, which can be operationalized through shaping and maintenance of river courses and floodplains so as to implement effective drainage and adequate runoff, underground aquifers recharge and generation of groundwater tanks to be used in case of drought as well. Soil permeability is fundamental as regards regulation of flood flow rates and related runoff speed, and, that being so, it represents a key factor in the provision of the ROC ecosystem service, which entails a reduction in sediment downstream flows as well. Permeability makes agricultural areas perform quite well as ROC ecosystem service providers (Bridgewater, 2018; Patekar et al., 2021). Effective management of forests, as well as of other wooded and tree areas, provides an adequate ROC in case of flood events, especially through the implementation of appropriate drainage and runoff into floodplains (Pede et al., 2022; EEA, 2021). Forest management coupled with effective ROC is also very important with reference to reduction of the share of polluted wastewater from industrial and agricultural productive activities which flows downstream through waterways (Mysiak et al., 2019). Nature-based solutions aimed at conveying surface waters into underground aquifers are very effective in maximizing the positive impacts of the ROC ecosystem service (EEA, 2021). ROC can be appropriately implemented in urban contexts through rainwater collection and storage, like for instance raingardens, swales and bioswales, green roofs and walls, and collection tanks (UNaLab, 2019; Berland et al., 2017). Another relevant paragon is represented by the realization of roads, parking lots, pedestrian paths and playgrounds, covered with porous, water-permeable materials, aimed at regulating runoff (Wild, 2020; Bridgewater, 2018), and, in so doing, at conveying a relevant rainwater share into the groundwater aquifers, which would constitute important reserves in case of drought, and, at the same time, would reduce flood flow rates, which often generate dramatic events in urban environments (Du et al., 2019). Moreover, rainwater flows through porous pavements are associated with a filtering action which entails an important enhancement in the quality of the underground aquifers (Depietri & McPhearson, 2017).

In this study, land surface temperature (LST) is targeted as a key point of reference to address the issue of HEM. In other words, decrease in LST is taken as a proxy for the provision of the HEM ecosystem service. As per Hulley et al. (2019), LST is a fundamental climate-related and biological factor which influences the ecosystems viability at different geographical scales. In particular, LST can be assumed as a measure of the thermal radiance generated by the interaction between the land surface, or the canopy in case of tree areas, and the sun power (Echevarria Icaza et al., 2016; Salata et al., 2016). Furthermore, as per the NASA Earth Observatory[3], LST can be considered as the temperature felt to the contact and can be identified by the temperature of what you can see from a satellite by looking through the atmosphere, be it the soil surface or the canopy of an urban woodland; thus LST is different from air temperature. Under this perspective, it is evident that the spatial taxonomies of land cover and LST are interrelated, and that land cover transitions influence climate change trends (Alfraihat et al., 2016; Li et al., 2016). Several studies are available in the current literature related to these issues. Landsat TM/OLI images concerning 1999, 2009 and 2019 are used by Al Kafy et al. (2020) to detect land cover transitions in Rajshahi (Bangladesh). The association between LST changes and land cover transitions in Pune City (India) is analyzed by Gohain et al. (2021), with reference to the 1990-2019 period, by means of a mixed GIS-remote sensing approach. A three-phased methodology is used by Tran et al. (2017) to identify relations between LST and land covers in the Hanoi metropolitan area (Vietnam), which develops from the use of the normalized built-up and vegetation indices to characterize each land cover and detect the relations which connect LST, vegetated areas, anthropic characteristics and agricultural zones, through the identification of the relation between heat islands and land cover transitions by means of hot spot and urban landscape analyses, to assess future scenarios related to urban climate based

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[3] This definition is available on the NASA Earth Observatory's website: https://earthobservatory.nasa.gov/global-maps/MOD_LSTAD_M.

on a non-parametric regression. The relations between vegetated areas and LST transitions are investigated by Akinyemi et al. (2019) with reference to the Caborone (Botswana) urban semi-arid environment, through LST detected during the day and the night provided by MODIS and the Normalized difference vegetation index (NDVI), in the 2000-2018 time period. The relations between LST and land cover transitions were assessed in a number of studies concerning Italian urban contexts. Among many, Zullo et al. (2019) assess the effects of urbanized zones on LST as regards the Po River Valley during the 2001-2011 time period. The relations concerning NDVI, normalized difference built-up index (NDBI) and LST are analyzed by Guha et al. (2018) with reference to Naples and Florence, whereas urban and landscape morphology effects on LST are investigated by Scarano & Sobrino (2015). Four Italian urban environments, located in Basilicata, Campania, Molise and Apulia, are analyzed by Stroppiana et al. (2014), as regards the association of LST, topography, land cover transitions and radiation from the sun.

The three ecosystem services described so far are generated through peculiar characteristics of highly urbanized contexts and work as relevant factors related to the quality of life in cities. The provision of CCS, ROC and HEM is associated with urban land cover, and it basically depends on two intertwined aspects. First, as discussed above, the three ecosystem services are supplied by unsealed soils, therefore the building density structure, which identifies the urban taxonomy of sealed and unsealed soils, is a focal point to detect if, and to what extent, urban environments can be providers of such ecosystem services. Second, the intrinsic characteristics of urban unsealed soils play a fundamental role in the effectiveness of the provided ecosystem services. In other words, to detect the correlations between provision of ecosystem services and urban land cover characteristics is highly important. Such correlations can lead to relevant implications in terms of planning policies aimed at increasing the provision of urban ecosystem services and at improving the living quality of urban communities.

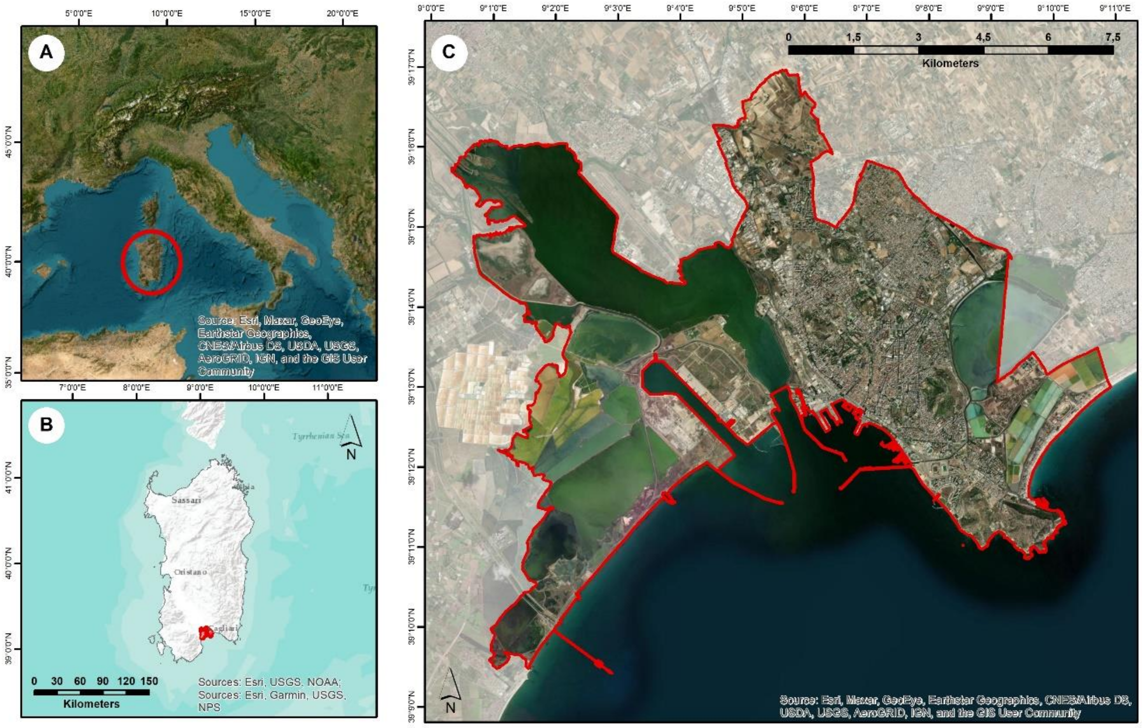
The research question that this study aims at addressing is, therefore, identified as follows: how and to what extent is the endowment of sealed and unsealed areas related to the supply of ecosystem services in intensively urbanized urban areas?

The study develops as follows. In the second section, the spatial data used to identify urban land cover characteristics and building structure are presented, and the approach to derive them is explained, with reference to the city of Cagliari, the regional capital city of Sardinia, Italy, which is taken as the urban context for the implementation of this study. Moreover, the methodology used to identify the correlations between ecosystem services supply and urban characteristics is described. The third section assesses the outcomes of the correlation analysis and of the estimates of the regression models. In the fourth section, such outcomes are discussed in the context of the current literature, and as regards their implications for future research. The concluding section remarks the value added of the study, with particular reference to planning policy implications.

2. Materials and methods

2.1 Study area

The area chosen for this study is Cagliari (Fig.1), the regional capital of Sardinia, an Italian region and a Mediterranean island. Hosting notable remains of the Phoenician and of the Roman settlements, the inner and pluri-stratified part of the town much owes to the medieval urban morphology. As many medieval towns, it was (and partly still is) surrounded by defensive walls and fortified bastions, which constrained the urban growth and spurred soil sealing and densification within the walled settlement; it is therefore not surprising that the historic districts host only a few tiny green areas. The parts of the city that surround the old districts are also characterized by a dense urban fabric; however, some large green areas and parks can be found therein, and larger roads are often lined with rows of trees. The outer, and most recent, districts are characterized by a larger share of green areas, and host, for instance, scattered houses or multi-story residential buildings with private gardens and courtyards, as well as public green areas. This reflects on the uneven spatial pattern of the residential density: as of December 2022, Cagliari's resident population was around 150,000 people and the population density was 1,751, with peaks of nearly 19,000 residents/km^2 in the most central districts (Comune di Cagliari, 2023). Therefore, the complex and variegated urban morphology and uneven endowment of green areas make the city of Cagliari a good case study to investigate the relationship between sealed/unsealed areas and the supply of ecosystem services in an urban context.



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Sources: Esri, USGS, NOAA; Sources: Esri, Garmin, USGS, NPS

Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Fig.1 Study area: Location of Sardinia (A), location of Cagliari within Sardinia (B), administrative boundaries of Cagliari (C)

2.2 Spatial data

As per the introduction, factors concerning the urban settlement that might influence the provision of the selected urban ecosystem services can be grouped into three main classes: land cover types; aspects related to the built environment; socio-economic characteristics of the resident population.

Spatial references for each factor are the 1,285 census tracts in which the municipality of Cagliari is divided for statistical purposes, shown in Figure 2[4]. Census tracts are highly homogeneous in terms of urban fabric characteristics, and represent subdivisions of the 31 districts that make up the city. While all the factors were mapped across the whole municipality of Cagliari, the correlation analysis and the regression model next described in section 2.3 were implemented by looking only at the 1,114 census tracts inhabited at least by ten residents (blue hashed in Fig.2).

The indicators for the three selected urban ecosystem services are listed in Tab.1, together with their definition and data sources. The following paragraphs provide a synthetic account of how each indicator was mapped across the study area.

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[4] Boundaries of census tracts can be retrieved from: https://www.istat.it/storage/cartografia/basi_territoriali/Sezioni-Censimento-kmz.zip.

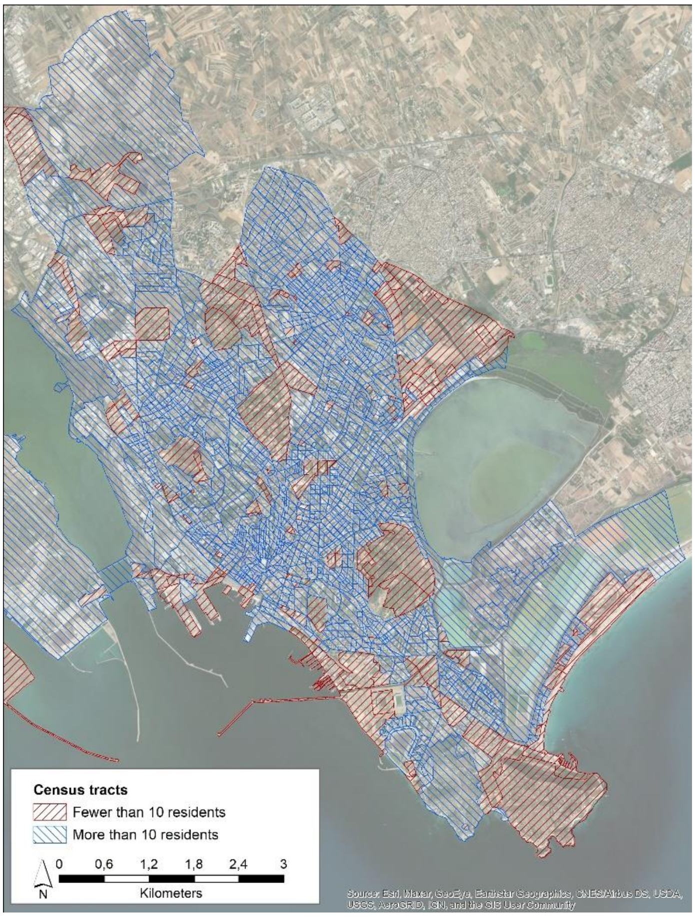

Fig.2 Census tracts in the study area

Variable	Definition and unit of measurement	Data sources
C_Stor	Average density of carbon capture and storage in a census tract [Mg/hectare]	Regional land cover map (https://www.sardegnageoportale.it/index.php?xsl=2420&s=40&v=9&c=14480&es=6603&na=1&n=100&esp=1&tb=14401) 2005 National Inventory of Italian Forests (https://www.sian.it/inventarioforestale/) Regional pilot project on land units and soil capacity in Sardinia (https://www.sardegnageoportale.it/index.php?xsl=2420&s=40&v=9&c=14481&es=6603&na=1&n=100&esp=1&tb=14401)
LST_Cmax	Maximum land surface temperature in a census tract [°C]	Landsat Collection 2 Surface Temperature (available from https://earthexplorer.usgs.gov/)
Dens_Ret	Density of runoff retention in a census tract [m^3/m^2]	City of Cagliari's 2021 land cover dataset (not published) Sardinian Hydrological Annals as for rainfall depth (https://www.sardegnaambiente.it/index.php?xsl=611&s=21&v=9&c=93749&na=1&n=10) Permeability map of Sardinian substrates (https://www.sardegnageoportale.it/index.php?xsl=2420&s=40&v=9&c=94083&es=6603&na=1&n=100&esp=1&tb=14401) Curve number table, tailored to Sardinia (https://www.sardegnageoportale.it/documenti/40_615_20190329081206.pdf)

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

Concerning CCS, the InVEST "Carbon Storage and Sequestration" model, which is a part of the InVEST suite, was used. This model focuses on carbon stored in four terrestrial pools: above-ground biomass, below-ground biomass, dead organic matter, and soil, i.e., the top 30-cm layer. INVEST estimates the amount of carbon stored in the area of interest through a land cover map and a lookup table that provides carbon density values for each land cover type and for each carbon pool for which data are available from on-site surveys, inventories or literature. The result is a carbon density map, measured in megagrams (Mg) of carbon per pixel, where the carbon stored in each pool is aggregated as per equation (1):

$$TC_{LCk,i,j} = TSC_{LCk,i,j} + DMC_{LCk,i,j} + BGC_{LCk,i,j} + AGC_{LCk,i,j} \tag{1}$$

where, for each cell denoted as the cell i, j and whose land cover type is LCk,

- TC is the total carbon density;
- TSC, DMC, BGC, AGC are the carbon densities stored, respectively, in: top-soil layer, dead organic matter, below-ground biomass, above-ground biomass.

No information is available regarding below-ground biomass in the study area; therefore, the InVEST model was applied solely focusing on the three remaining carbon pools: above-ground biomass, soil organic content, and dead organic matter. The total carbon density values for each pool were determined using data from the 2005 National Inventory of Italian Forests and a regional pilot project that examined land units and soil capacity in Sardinia. Through zonal statistics, the total carbon density stored in each census tract (C_Stor) was calculated.

As for LST, raster maps are currently available off-the-shelf from the United States Geological Survey (USGS) through its Earth Explorer service, which makes it possible to retrieve Landsat Collection 2 Level-2 products, including 30-m land surface temperature raster maps, by selecting the area of interest, a time range and, optionally, other parameters such as maximum cloud cover. A four-month interval, from June to September 2022, was selected. Among the twenty LST maps retrieved from Earth Explorer, the one having the highest LST mean value across the study area (once the wetlands were removed) was selected, having unique identifier LC09_L2SP_192033_20220719_20220723. Through zonal statistics, the variable LST_Cmax was calculated as the maximum LST in each census tract.

Finally, ROC was mapped using the tool the InVEST "Urban Flood Risk Mitigation" model, which enables to estimate both runoff levels and the water volume retained by permeable soils and green areas, hence providing an assessment of the flood regulation ecosystem service. The model requires the following input data: the area of interest (vector map); the rainfall depth; a raster map of the soil hydrologic group; a land use/land cover raster map; a biophysical table.

For each pixel *i*, the runoff retention volume (RRV) is expressed by equation (2):

$$RRV_i = (1-\frac{Q_{RFD,i}}{RFD}) \cdot RFD \cdot A_i \cdot 10^{-3} \tag{2}$$

where:

- RRV is the runoff retention volume [m^3];
- RFD is the rainfall depth [mm];
- *i* is a pixel, whose area is A_i [m^2];
- Q is the runoff (in mm), which is null if RFD is not enough to initiate runoff ($RFD \leq \lambda \cdot PR_i$); otherwise, it takes the form in equation (3).

$$Q_{RFD,i} = \frac{(RFD - \lambda \cdot PR_i)^2}{RFD + (1-\lambda) \cdot PR_i} \tag{3}$$

where:

- PR_i is the potential retention [mm] in pixel *i*, and it is related to soil characteristics and land cover types through the curve number CN as per equation (4):

$$PR_i = \frac{25400}{CN_i} - 254 \tag{4}$$

- CN is an empirical and dimensionless parameter introduced by the Unites States Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS, 2004). CN depends on soil characteristics and land cover types, and it represents the runoff potential of an area of land, ranging from 30 to 100 (where CN=100 signals no retention capacity), after a rainfall event;
- $\lambda \cdot PR_i$ is the "initial abstraction", i.e., the amount of rainfall required to initiate runoff (in mm), where λ can be taken as 0.2 (USDA-NRCS, 2004, p. 4).

RFD represents a measure of the amount of rain associated with a rainstorm, without considering the temporal dynamics of the event (Quagliolo et al., 2021). In this study, the 2012-2021 Sardinian hydrological annals were scrutinized to identify the day in which the largest rainfall depth was recorded in the study area. In Cagliari, in the ten-year timeframe examined, the largest amount of rain fallen in 24 hours was recorded on November 13, 2021, and it amounted to 101.8 mm[5].

As for soil hydrological groups (SHG), the model requires a map where the groups are classed using the four-category classification (A, B, C, D) of the United States soil, ranging from soil type A, having low runoff potential and high infiltration rates, to type D, having high runoff potential and low infiltration rates, whereas B and C represent intermediate situations (USDA-NRCS, 2007). A 1:25,000 vector permeability map of Sardinian substrates was used, which classes infiltration levels into five groups (low-mid-low, medium, mid-high, high) that were reclassed into the four SHG groups; the map was next rasterized to feed into the model.

The land cover municipal map, already mentioned in reference to vegetation, was used coupled with a biophysical table that associates each land cover in the map to four curve numbers, each corresponding to one soil group type (A-D). To fill in this table, a report produced by the Regional Agency for the environment (ARPAS, 2019) was used, which details the four curve numbers needed for each Corine four-level land cover type present in Sardinia.

By using the delineation of the census tracts as area of interest, the retention volume associated with a 101.8 rainfall depth in each tract (Dens_Ret) was obtained.

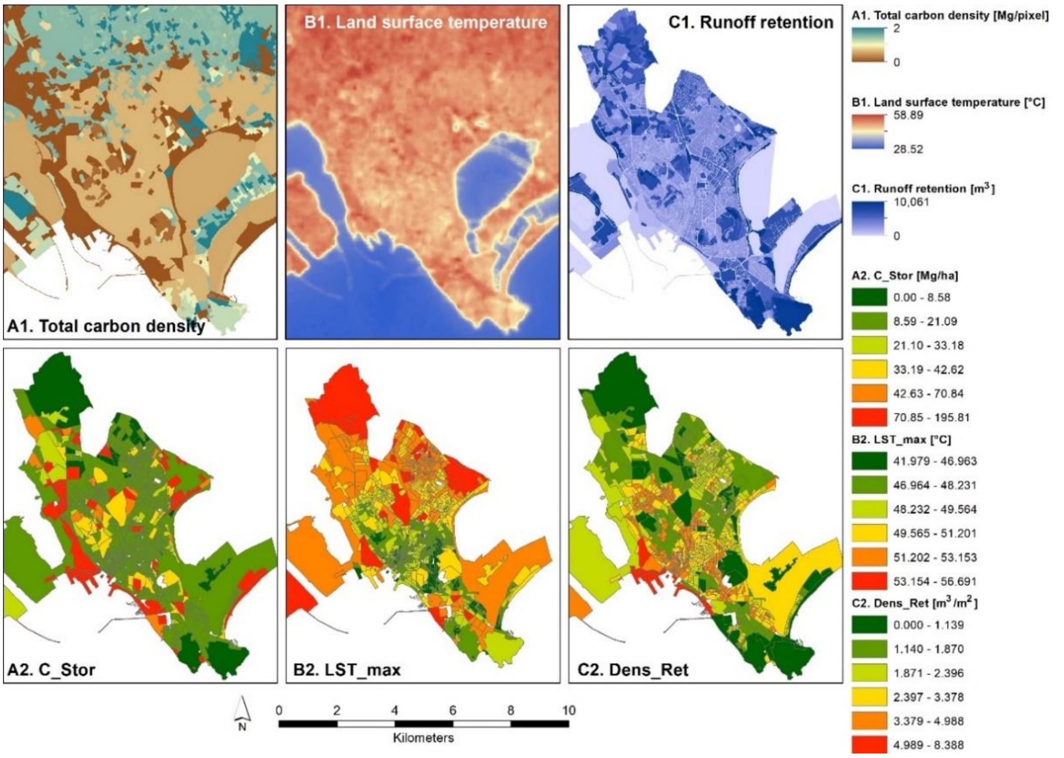

Fig.3 Spatial layout of the selected ecosystem services (A1-B1-C1) and corresponding indicators within census tracts (A2-B3-C2)

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[5] The reader can refer to the 2021 regional hydrological annal (https://www.sardegnaambiente.it/documenti/21_393_20220729125359.pdf), label "Cagliari RF", pages 119 and 123.

Finally, for each of the three variables representing as many ecosystem services (C_Stor, LST_Cmax, and Dens_Ret) their spatially lagged variables (C_Stor_lag, LST_Cmax_lag, and Dens_Ret_lag) were assessed to control for their spatial autocorrelation. Anselin's approach (Anselin, 1988; 2003) was followed, as implemented in the freeware GeoDA[6] (Anselin et al., 2006), by taking census tracts as the minimum spatial units and by considering the first-order queen contiguity to determine weights.

The spatial distribution of the three selected proxies for CCS, HEM, and ROC, together with their indicators within each census tract, is shown in Fig.3.

Factors that can affect the provision of the three selected urban ecosystem services are listed in Tab.2, together with their definition and data sources. The following paragraphs provide a synthetic account of how such factors was mapped across the study area.

Variable	**Definition and unit of measurement**	**Data sources**
Perc_Tree	Share of a census tract occupied by tall trees [%]	Public green areas and tree lined roads from the City of Cagliari's geoportal (https://geoportale.comune.cagliari.it/) City of Cagliari's 2021 land cover dataset (not published) Sentinel-2 Copernicus satellite imagery (https://dataspace.copernicus.eu/)
Perc_Bush	Share of a census tract occupied by medium-height shrubs [%]	
Perc_Lowveg	Share of a census tract occupied by low-height vegetation [%]	
Vol_Dens	Built volume density (i.e., built volume per unit of land) within a census tract [m^3/m^2]	Geotopographic dataset of Sardinian urban centers and inhabited areas (https://www.sardegnageoportale.it/index.php?xsl=2420&s=40&v=9&c=95648&es=6603&na=1&n=100&esp=1&tb=14401)
Sup_Nvp	Share of sealed area within a census tract [%]	Public green areas and tree lined roads from the City of Cagliari's geoportal (https://geoportale.comune.cagliari.it/) City of Cagliari's 2021 land cover dataset (not published) Sentinel-2 Copernicus satellite imagery (https://dataspace.copernicus.eu/) Geotopographic dataset of Sardinian urban centers and inhabited areas (https://www.sardegnageoportale.it/index.php?xsl=2420&s=40&v=9&c=95648&es=6603&na=1&n=100&esp=1&tb=14401)
Dwel_Dens	Density of housing units (i.e., number of dwellings per unit of land) within a census tract [no./m^2]	2011 National Census dataset (https://www.istat.it/storage/cartografia/variabili-censuarie/dati-cpa_2011.zip)
Res_Dens	Population density within a census tract [residents/hectare]	
Perc_Degr	Share of residents holding a college degree within a census tract [%]	

Tab.2 Factors that can affect the supply of the selected urban ecosystem services: list, definition, and data sources

As well as the boundaries of census tracts, spreadsheets are available from the National Census website providing several data related to the built environment and to resident population at the tract level; this made it possible to retrieve the variables Dwel_Dens, Res_Dens and Perc_Degr within each census tract.

As for the built volume, a dataset available from the regional geoportal and termed "Geotopographic dataset of Sardinian urban centers and inhabited areas" was used. The dataset, having nominal scale 1:2000, was released in 2021; it derives from aerial photogrammetric restitution of data acquired in 2006-2008 flights and contains also more recent elements integrated by the regional office in charge of cartography and geographic information systems. From this dataset, the layer "ST02TE01CL01PLG" that describes elementary building units was used as it provides information on the elevation at the building's eaves (attribute A02010101) and base (attribute A02010102), hence making it possible to calculate the volume for each building unit and, through simple geoprocessing operations, the total built volume per census tract.

Concerning the three types of vegetation (tall trees, medium-height shrubs, low vegetation), no spatial dataset having appropriate temporal resolution and minimum mapping unit (MMU) provides such information for the

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[6] Version 1.20 was used, retrievable from: http://geodacenter.github.io/index.html.

Cagliari area. The 2018 Corine Land Cover map produced within the framework of the Copernicus Land Monitoring Service coordinated by the European Environment Agency, for instance, has an MMU of 25 hectares[7], while the 2008 regional land cover map produced by the Regional Government of Sardinia, having an MMU of 0.5 hectares within urban settlements[8], is now more than 15 years old. Useful information is provided by the municipal geoportal, which maps road tree lines, public greenery, urban parks, and agricultural periurban areas. Moreover, a municipal land cover map has recently been produced within the ongoing revision of the municipal masterplan; this map basically takes urban blocks as minimum polygons and classes land covers by detailing the traditional three-level Corine nomenclature up to the fourth level. Both data available from the city geoportal and the municipal land cover map, therefore, neglect private green areas that are included within single blocks (for instance, secluded courtyards) or interspersed between blocks (for instance, front or back gardens or lawns). For this reason, the available data sources were complemented with an NDVI raster map to detect small green areas included within polygon classed as "artificial land covers" within the municipal land cover map. To produce the NDVI map, 10-meter resolution Sentinel-2 satellite images were retrieved from the Copernicus Data Space Ecosystem; a six-month timeframe (January to June 2022) was chosen so as to include the spring period, when vegetation is in its full potential in Sardinia. For each satellite image, its corresponding NDVI map, having cell size ten meters, was produced, using the well-known equation (5) (among the first studies that used this index: Rouse et al., 1973; Tucker, 1979; Dave, 1980):

$$\mathrm{NDVI}=\frac{\mathrm{NIR}-\mathrm{RED}}{\mathrm{NIR}+\mathrm{RED}} \tag{5}$$

where NIR and RED represent the spectral reflectance measurements captured within the near-infrared and the red (visible) spectrums. For Sentinel-2 data, equation (5) takes the form provided in equation (6):

$$\mathrm{NDVI}=\frac{\mathrm{B8}-\mathrm{B4}}{\mathrm{B8}+\mathrm{B4}} \tag{6}$$

where B8 and B4 are, respectively, the NIR and the RED bands.

Among the January-June 2022 images retrieved, the NDVI map obtained from the March 9, 2022 Sentinel-2 image[9] was selected, as this was the one with the highest mean value of the NDVI across the study area, hence potentially allowing for the best detection of vegetation within built-up areas. The latter was identified as the parts of the blocks classed as "artificialized" in the municipal land cover map that were not occupied by the building footprints and for which the NDVI was larger than 0.18. Such threshold was selected after checking approximately 1,500 control points (classed into seven groups: barren land, buildings, lawns, roads, shrubs, trees, water) across the study area and it is consistent with findings from previous literature (e.g., Akbar et al., 2019; Bondarenko et al., 2021; Aryal et al., 2022). While the threshold differentiating green areas from buildings, roads and barren land was quite straightforward, the analysis of control points showed some overlap between low-vegetation areas (such as lawns or gardens), bushes, and threes. Therefore, cautiously, all the green spots within built-up areas were classed as "low-height vegetation".

To sum up, the vegetation map for the study area was developed by using the city's land cover map and the city's map of green areas as primary sources of information, by reclassing the vegetation types into three types: trees, shrubs, and low-height vegetation, of which the latter was complemented with green spots within built-up areas, identified through the NDVI raster map.

Once the vegetation map was built, the variables Perc_Tree, Perc_Bush, and Perc_Lowveg could be calculated, as well as the variable Sup_Nvp, which represents the share of the census tract that is sealed, i.e., non-vegetated.

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[7] https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=metadata.

[8] https://www.sardegnageoportale.it/index.php?xsl=2420&s=40&v=9&c=14480&es=6603&na=1&n=100&esp=1&tb=14401.

[9] Unique identifier: S2A_MSIL2A_20220309T100841_N0400_R022_T32SNJ_20220309T134626.SAFE.

2.3 Methods

In this study, unsealed areas in highly urbanized contexts are identified through three types of land covers, as follows: tall vegetated cover, such as in wooded and tree areas; medium-height shrubby cover; and, ground cover, such as garrigues, natural grasslands, heathlands and sparsely vegetated or bare soils. Sealed zones are featured by built-up blocks, roads, sidewalks, and the like. In order to represent such zones, the following characteristics are used: built-up volume; number of households; number of houses; and, the size of the area not covered by vegetation.

The relationships between the supply of ecosystem services in intensively urbanized environments, and the presence and quantity of sealed and unsealed areas, are analyzed and assessed through correlation analysis and regression models, as described in the following sections.

Correlation analysis

The associations of the distributions of the supply of the three selected ecosystem services (CCS, ROC, and HEM) with the distributions of the variables which represent land covers concerning sealed and unsealed areas can be identified through correlation analysis, which makes it possible to associate the distributions of two variables with each other so as to detect if, and to what extent, the two phenomena show similar trends.

The Spearman's rank correlation coefficients (SRCCs) are estimated to detect correlations between the distributions of the variables, related to census tracts, associated with CCS, ROC and HEM, that is, density of CCS (C_Stor), density of runoff retention (Dens_Ret) and maximum land surface temperature (LST_Cmax), and the distributions of those representing sealed and unsealed areas. Unsealed areas are associated with the following: percentage share of a census tract covered with: i. tall plants (Perc_Tree); ii. medium-height shrubs (Perc_Bush); or, low-height vegetation (Perc_Lowveg). Sealed zones area associated with the following: population density (Res_Dens), built volume density (Vol_Dens), density of housing units (Dwel_Dens), and percentage share of sealed area (Sup_Nvp). Since the forms of the distributions are unknown, SRCC can be identified as the most reliable measure to detect the presence and size of correlations between the variables at stake (Schober *et al.*, 2018). The assessment of the results of the SRCCs estimates as regards the expectations on such estimates is based on three items, that is, the sign, the size, and the related *p*-values. The detail of such results is presented and discussed in section 3.1.

Regression model

Three linear regression models are implemented to identify the correlations between the variables associated with the provisions of CCS (C_Stor), ROC (Dens_Ret) and HEM (LST_Cmax) ecosystem services, and the covariates associated with vegetated (Perc_Tree, Perc_Bush) and sealed (Sup_Nvp) land covers. Among the variables related to land covers, indicated in the previous section, Perc_Lowv in not included in the sets of the explanatory variables of the regression models since it is the complement to 1 of the sum of Perc_Tree, Perc_Bush and Sup_Nvp, and, that being so, it has to be omitted to avoid multicollinearity. As it is shown by the SRCCs results reported in the next section, the variables representing sealed land cover (Res_Dens, Vol_Dens, Dwel_Dens, Sup_Nvp) are strictly correlated with each other and, therefore, just one of them can be included in the set of the explanatory variables. Sup_Nvp is selected among the variables associated with sealed land cover since it is the one most correlated with the three dependent variables (C_Stor, Dens_Ret and LST_Cmax), as it is shown in the next section, which reports the results concerning the estimates of the SRCCs. Moreover, Sup_Nvp identifies sealed soils in the most complete way, since it takes account not only of buildings, dwellings and inhabitants, but also of paved areas such as roads, squares, sidewalks, parking lots, pedestrian paths, playgrounds, and the like.

The three regression models operationalize as follows:

$$\begin{gathered}\{C\_Stor \mid Dens\_Ret \mid LST\_Cmax\} = \\ \beta_0 + \beta_1\, Perc\_Tree + \beta_2\, Perc\_Bush + \beta_3\, Sup\_Nvp + \beta_4\, Perc\_Degr + \\ \beta_5 \{C\_Stor\_lag \mid Dens\_Ret\_lag \mid LST\_Cmax\_lag\}\end{gathered} \tag{7}$$

where labels are associated with dependent and explanatory variables, described and identified in detail in section 2.1., as follows:

- C_Stor is for density of CCS in a census tract;
- Dens_Ret is for density of runoff retention in a census tract;
- LST_Cmax is for maximum land surface temperature in a census tract;
- Perc_Tree is for percentage share of area covered with tall plants in a census tract;
- Perc_Bush is for percentage share of area covered with medium-height shrubs in a census tract;
- Sup_Nvp is for percentage share of sealed area in a census tract;
- Perc_Degr is for percentage share of residents holding a college degree in a census tract;
- C_Stor_lag, Dens_Ret_lag and LST_Cmax_lag are the spatially lagged dependent variables that control for spatial autocorrelation of C_Stor, Dens_Ret and LST_Cmax.

The estimates of the coefficients of the regression models reveal the correlations between the supply of the CCS, ROC and HEM ecosystem services and the presence of vegetated and sealed parcels in census tracts.

Multiple regression models are used since there are not any prior hypotheses associated with the relation between dependent and explanatory variables, which is in line with the current literature concerning this issue (Zoppi et al., 2015 Sklenicka et al., 2013; Stewart & Libby, 1998; Cheshire & Sheppard, 1995). In this perspective, a spatial variable related to *n* factors can be associated with a surface, which develops in a space with *n* dimensions, whose equation is not identified. The functional form of such surface can be approximated, in a very small neighborhood of each of its points, by the hyperplane which is tangent at that point (Couper & Wolman, 2003; Byron & Bera, 1983). That is why the linear equations estimated through the multiple regression models (7) are assumed as adequate approximations, in six-dimensional spaces, of the relationships between C_Stor, Dens_Ret and LST_Cmax, and the covariates which identify models (7).

Variable Perc_Degr, which represents the share of graduates within a census tract, is used as a proxy for the residents' economic welfare, since no data on household or personal income are available at the census tract level, which is likely to provide information on such item. This covariate controls for a possible income effect related to the provision of the three ecosystem services at stake. An increase in the income level is expected to be correlated with an increase in the supply of ecosystem services since public goods such as CCS, ROC and HEM ecosystem services should be seen as luxury goods in urban contexts and, in so doing, as drivers of gentrification phenomena (Leccis, 2019; Ferreira & Moro, 2013).

The covariates C_Stor_lag, Dens_Ret_lag and LST_Cmax_lag are associated with the spatially lagged values of C_Stor, Dens_Ret and LST in models (7), and control for their spatial autocorrelation on the basis of the methodological approach by Zoppi & Lai (2014), which develops from Anselin's articles (Anselin et al., 2006; Anselin, 2003).

Finally, the statistical significance of the estimated coefficients of the regression models are tested through their *p*-values.

3. Results

This section reports and discusses the outcomes of the estimates of the SRCCs and the results of the regression models, implemented on the basis of the definitions presented in the previous section. Estimates are related to the urban area of Cagliari. The section develops through two subsections, concerning the SRCCs and the regression findings respectively.

3.1 Spearman’s rank correlation coefficients

The SRCCs estimated with reference to the correlations between the variables associated with the supply of the three targeted ecosystem services (C_Stor, Dens_Ret and LST_Cmax), and the covariates representing the characteristics of sealed and unsealed soils, generally show the expected sign and significant *p*-values, as reported in Tab.3.

Variable	**Coefficient**	**t-Statistic**	***p*-Value**
Carbon capture and storage (C_Stor)			
Perc_Tree	-0.00603	-0.20110	0.84066
Perc_Bush	0.20989	7.15852	0.00000
Perc_Lowv	0.25416	8.76325	0.00000
Vol_Dens	-0.25830	-8.91600	0.00000
Res_Dens	-0.19024	-6.46204	0.00000
Dwel_Dens	-0.21294	-7.26748	0.00000
Sup_Nvp	-0.27868	-9.67642	0.00000
Water retention (Dens_Ret)			
Perc_Tree	0.04398	1.46801	0.14238
Perc_Bush	0.22418	7.67089	0.00000
Perc_Lowv	0.48682	18.58474	0.00000
Vol_Dens	-0.52649	-20.65031	0.00000
Res_Dens	-0.41839	-15.36086	0.00000
Dwel_Dens	-0.46388	-17.46138	0.00000
Sup_Nvp	-0.45443	-17.01156	0.00000
Mitigation of land surface temperature (ref.: Land surface temperature, LST_Cmax)			
Perc_Tree	-0.19263	-6.54632	0.00000
Perc_Bush	-0.02725	-0.90892	0.36359
Perc_Lowv	0.17642	5.97667	0.00000
Vol_Dens	-0.07881	-2.63617	0.00850
Res_Dens	0.02683	0.89487	0.00000
Dwel_Dens	-0.05421	-1.81036	0.00000
Sup_Nvp	0.22581	7.72974	0.00000

Tab.3 Spearman’s correlation coefficients of targeted ecosystem services

As for C_Stor, variable Perc_Tree shows a very low SRCC associated with a high *p*-value, which indicates no correlation between wooded and tree covers and CCS. This is consistent with the features of wooded and tree covers in the highly urbanized urban area of Cagliari, where wooded and tree areas are characterized by tree rows planted in small garden beds with limited soil size. The other SRCCs are in a range between 19% and 28%, with very low and significant *p*-values; moreover, they show the expected correlation signs. Perc_Bush and Perc_Lowv are positively correlated to the supply of CCS, which is consistent with expectations, since unsealed shrubby soils covered with medium-height plants or low-height ground covers generally perform as important sinks for CCS (Yigini & Panagos, 2016; European Commission, 2012). On the other hand, Vol_Dens, Res_Dens, Dwel_Dens and Sup_Nvp are negatively correlated with C_Stor, which is also consistent with expectations, since all of them are measures of the size of the soil-sealing phenomenon. Moreover, such four variables are highly correlated with each other, as reported in Tab.4. These findings are consistent with the

SRCCs estimates associated with the ROC and HEM ecosystem services, as shown below. Therefore, this indicates that the densities of population, built-up volume and housing units, and the size of the unsealed area, can be considered four measures, consistent with each other, of the size of land subtracted from the potential provision of important ecosystem services in the densely urbanized urban context of Cagliari.

Variable	Coefficient	t-Statistic	p-Value
Built volume density (Vol_Dens)			
Res_Dens	0.74078	36.77303	0.00000
Dwel_Dens	0.81686	47.22204	0.00000
Sup_Nvp	0.68789	31.60424	0.00000
Population density (Res_Dens)			
Dwel_Dens	0.94272	94.23846	0.00000
Sup_Nvp	0.58721	24.19157	0.00000
Mitigation of land surface temperature (ref.: Land surface temperature, LST_Cmax)			
Sup_Nvp	0.66033	29.32140	0.00000

Tab.4 Spearman's correlation coefficients of variables associated to sealed soil

With reference to Dens_Ret, the three variables associated with unsealed soil are positively correlated with the supply of the ROC ecosystem service, and the estimated SRCCs are highly significant in terms of *p*-values, which indicates that the larger the size of the unsealed soil, the higher the potential runoff retention, as expected. On the other hand, the SRCCs of the four variables related to sealed soil are all negatively correlated with Dens_Ret and highly significant in terms of *p*-values, as expected as well.

Finally, the variable LST_Cmax, associated with the supply of the HEM ecosystem service, shows a negative and significant correlation with Perc_Tree and a positive and significant correlation with Perc_Lowv, whereas the estimate of the SRCC with respect to Perc_Bush is very low and not significantly different from zero in terms of *p*-value. Such findings entail the following: i., lower LSTs are associated with larger woods and tree canopies, whose shading is generally recognized as an outstanding factor as regards heat waves mitigation; ii., low-height vegetated and sparsely vegetated or bare soils characterize areas with LST comparatively higher than zones featured by shading canopies, which explains a positive LST gradient from such zones towards low-height vegetated or bare soils; iii., since the SRCC concerning LST_Cmax and Perc_Bush is very close to zero, there is no evidence of correlation between the supply of the HEM ecosystem service and land cover characterized by medium-height plants, which implies that such areas show neither a shading effect due to more-or-less extended canopy, nor a positive LST gradient associated with the vegetation height.

3.2 Regressions

The estimates of the coefficients of the Perc_Degr control variable are not significant in terms of *p*-values in two out of three cases. As indicated above, the share of the graduates is identified as a proxy for the income level, and public goods such as the CCS, ROC and HEM ecosystem services are likely to work as luxury goods in urban contexts and eventually as drivers of gentrification phenomena, as stated in section 2.3.2. (Leccis, 2019; Ferreira & Moro, 2013). According to the estimates of the regression models, this only happens in the case of the HEM ecosystem service, represented by the LST_Cmax dependent variable, since the estimated coefficient of Perc_Degr shows a very low and significant *p*-value and a negative sign. This implies that an increase in land surface temperature, which identifies a decrease in the supply of the HEM ecosystem service, is negatively correlated with the share of graduates (a proxy for the income level), consistently with the expectations. On the other hand, changes in Perc_Degr do not show any influence on the supply of the CCS and ROC ecosystem services, which entails that there is no evidence of an income effect as regards the supply of these ecosystem services.

Moreover, the spatially lagged covariates C_Stor_Lag, Dens_Ret_Lag and LST_Cmax_Lag reveal positive and significant estimated coefficients as regards *p*-values, which indicates an adequate control for the spatial autocorrelation associated with the dependent variables.

Since the estimated coefficients of the spatially lagged variables provide evidence of an effective control for the autocorrelation phenomena related to the dependent variables, and the existence of income effects is adequately investigated, the impacts of the explanatory variables associated with permeable and sealed soils can be considered reliable and well-grounded on the basis of the estimates reported in Tab.5.

Variable	**Coefficient**	**t-Statistic**	**p-Value**
Dependent variable: Carbon capture and storage (C_Stor)			
Perc_Tree	-0.04090	-0.86124	0.38929
Perc_Bush	0.21349	2.86994	0.00418
Sup_Nvp	-0.04283	-2.84009	0.00459
Perc_Degr	0.01913	0.87229	0.38324
C_stor_Lag	10.52142	16.87334	0.00000
Mean and Standard deviation of dependent variable: 45.11756, 10.90465			
Adjusted R-squared: 0.21705			
Dependent variable: Runoff retention (Dens_Ret)			
Perc_Tree	-0.02728	-9.93164	0.00000
Perc_Bush	0.04036	9.52346	0.00000
Sup_Nvp	-0.01721	-17.07541	0.00000
Perc_Degr	-0.00049	-0.39350	0.69403
Dens_Ret__Lag	0.77435	26.87518	0.00000
Mean and Standard deviation of dependent variable: 2.36299, 0.99759			
Adjusted R-squared: 0.69620			
Dependent variable: Mitigation of land surface temperature (reference: land surface temperature, LST_Cmax)			
Perc_Tree	-0.03426	-6.87215	0.00000
Perc_Bush	0.04804	43.68462	0.00000
Sup_Nvp	0.00001	7.80715	0.00000
Perc_Degr	-0.03800	-15.12484	0.00000
LST_Cmax_Lag	1.07469	206.51714	0.00000
Mean and Standard deviation of dependent variable: 48.27731, 31.47218			
Adjusted R-squared: 0.93872			

Tab.5 Estimates of regression models

As for Perc_Tree, the results show there is no evidence of a significant impact of the covariate associated with the share of wooded and tree areas on the supply of the CCS ecosystem service, which is consistent with the estimate of the SRCC concerning C_Stor and Perc_Tree. As noted above (section 3.1.), this is consistent with the fact that throughout the city of Cagliari wooded and tree areas are featured by the limited size of the small garden beds and planting pits where trees are usually planted, hence allowing for a limited capacity of CCS. Moreover, the limited size of the small garden beds associated with wooded and tree land covers can explain why the ROC ecosystem service, represented by the Dens_Ret dependent variable, is negatively and significantly correlated with the covariate Perc_Tree, since such limited size allows a large part of the runoff waters to flow over the ground and minimizes underground runoff retention. Finally, Perc_Tree shows a negative and significant influence on LST_Cmax, which implies that the impact of the size of the shading tree canopies play a decisive role in mitigating heating waves, which is particularly important in the hottest days of the year (Pace et al., 2021).

With reference to Perc_Bush, the estimated coefficients are positive and significant in terms of *p*-values, which implies that an increase in medium-height shrubby land cover areas is associated with an increase in the supply of the CCS and ROC ecosystem services, which is consistent with expectations, since such land cover entails large room for soil and subsoil carbon storage (He et al., 2020; Maiti et al., 2015), and for drainage capacity, especially in case of relevant meteorological events (Casermeiro et al., 2004). Moreover, the results of the regression concerning the HEM ecosystem service show evidence of a positive impact of Perc_Bush on land surface temperature, which entails that an increase in the share of shrubby medium-height land cover is associated with an increase in LST_Cmax. This indicates that shrubby land cover areas, which do not grant an adequate canopy such as tree and wooded areas, have a negative impact in terms of mitigation of urban heating waves (Shen et al., 2022).

Finally, the impacts of Sup_Nvp on the supply of the CCS, ROC and HEM ecosystem services are always negative, meaning that the higher the share of sealed soil, the lower the provision of CCS, ROC and HEM. This is consistent with the results related to the SRCCs, which show significant negative values as for C_Stor and Dens_Ret, and a positive value with reference to LST_Cmax.

4. Discussion

This section focuses on the discussion of main findings stemming from sections 3.1 and 3.2, therefore looking at the relationships between, on the one hand, CCS, HEM, and ROC, and, on the other hand, trees, bushes, and low-height vegetation and their significance in affecting the provision of the three selected ecosystem services.

Firstly, as for the relationship between the share of a census tract covered by trees and carbon storage, both coefficients in Tab.3 and Tab.5 are negative and, as far as the regression is concerned, not significant. The importance of urban trees in removing carbon from the atmosphere and storing it in their biomass is acknowledged by many authors (e.g., Nowak & Crane, 2002; Johnson & Gerhold, 2003; Roy et al., 2012; Strohbach & Haase, 2012). Urban tree's effectiveness in providing CCS is affected by several factors, first and foremost the size of land covered by trees (Nowak et al., 2013), but also other factors such as tree density, limitation to tree growth due to management such as pruning (Ningal et al., 2010), species type (Soares et al., 2011; Tan et al., 2021; Shen et al., 2023), age, structure, and overall condition (Russo et al., 2014). Most studies focus on urban forests and urban parks, while the role of street trees is under-researched; such role is highly important in our study area because most records concerning trees in the city dataset used in this study refer to street trees. In Cagliari, they usually grow in small planting pits in sidewalks, which can hamper carbon sequestration by affecting the soil substrate and its quality (Schütt et al., 2022), as well as water dynamics and water retention, hence impacting on trees' growth and overall condition (Nielsen et al., 2007). Tang et al. (2016) maintain that the magnitude of carbon density and sequestration by street trees in Beijing is comparable to that of non-urban forests in China, although lower than in European cities; however, Soares *et al.* (2011) report carbon sequestration by street trees to be fairly low in Lisbon, compared to either North-American cities or to urban forests. This might explain the low value of the coefficient linking Perc_Tree to C_stor in both Tab.3 and Tab.5. Moreover, a possibly relevant observation for Cagliari is that by Havu et al. (2022), according to whom street trees in Helsinki can act both as carbon emitters or sinkers depending on their age and on seasonal variations, which might also help explain the lack of significance of the regression coefficient in Tab.5, since no information concerning age is available in the study area.

Contrary to Perc_Tree, both Perc_Bush and Perc_Lowv show positive and significant correlation with C_Stor (Tab.3) and the impact of Perc_Bush on C_Stor is positive and significant as far as the regression model is concerned (Tab.5). As with trees, factors such as species type, size, and structure are important in CCS provided by urban shrubs (Khan et al., 2020). Although it is well known that shrubs store less carbon than trees (see for instance, Curry et al., 2016 for an assessment in Michigan, United States), a study by Edmondson et al. (2014) on gardens in Leicester (UK) shows that carbon storage in the topsoil is higher under trees, followed by topsoil beneath urban shrubs and herbaceous vegetation, which both perform better than non-urban agricultural fields, hence highlighting the importance of mid- and low-height vegetation in fostering carbon storage in soils. Furthermore, a relevant study on CCS by shrubs is that by Baraldi et al. (2019), who, despite estimating their CCS capacity lower than that by trees because of their smaller structure and leaf coverage, report that evergreen shrubs can perform better than deciduous trees because their removal activity through photosynthesis spans across the year. This is most likely of importance in Cagliari, where large areas are covered by evergreen shrubby vegetation, such as Mediterranean maquis with Euphorbia in south-eastern hills along the coastline, halophyte mid-height plants closer to the two larger wetlands, woody bushes and low, immature coniferous trees in the most important urban parks.

Secondly, as far as ROC is concerned, Tab.3 highlights the positive significant correlation between Dens_Ret and Perc_Bush and Perc_Lowv, as well as the positive, but far less significant, correlation between Dens_Ret and Perc_Tree. This signals that, in general, ROC is positively correlated with whichever type of vegetated land cover, not only because of the soil's higher porosity, but also because vegetation, even when herbaceous, channels water fluxes through the roots (Técher & Berthier, 2023), although trees have been found to deliver the higher levels of runoff mitigation in urban forests in a study by Rahman et al. (2023), possibly because of their deeper roots which slow down water saturation in superficial soil layers. Moreover, Tab.5 singles out Perc_Bush as the most important factor in positively driving Dens_Ret, while, and counterintuitively, the coefficient of Perc_Tree is negative, although quantitatively modest.

Trees recorded in the city dataset are mostly street trees in planting pits surrounded by paved surfaces; therefore, this highlights the significance of permeable, vegetated areas in retaining rainwater, therefore also shedding light on the quantitatively relevant, negative, and significant Pearson coefficient reported in Tab.3 as for the relationship between Dens_Ret and Sup_Nvp. This is in line with Armson et al. (2013), who found grassy areas to contrast stormwater runoff much better than trees in planting pits in Manchester because of the reduced infiltration within tree pits, while also showing that even small tree pits help reducing surface runoff if compared with fully paved sidewalks and roads.

The negative impact of impervious areas is fully acknowledged in several other studies, some of which propose mitigating solutions that result in increased vegetated areas, such as planting bushes and trees in paved areas to improve infiltration in Turin (Salata et al., 2021) or unsealing paved areas and planting native shrubs to improve water retention in Izmir (Turkey) (Salata et al., 2022).

Finally, in regard to HEM, Tab.3 and Tab.5 highlight the positive impact of Perc_Tree on HEM, since both coefficients are significant and negative, hence an increase in the size of treed areas within a census tract is associated with lower maximum values of the surface temperature, although the magnitude of the impact is small, as signaled by the low regression coefficient. Zardo et al. (2017) assess the effects of tree canopy coverage, soil cover, and unsealed land size on the cooling capacity of three climatic regions; one of the most important, and straightforward, finding, is that size matters: in the Mediterranean area, unsealed soils smaller than two hectares have limited cooling capacity even when having a good canopy coverage. This helps explain the counterintuitive positive coefficient that relates LST_max and Perc_Lowv in Table 3, which, in the built-up and dense part of the city, include all of the small green areas within building blocks retrieved through the NDVI map, as explained in section 2.2.

In agreement with the above finding by Zardo et al., Marando et al. (2019) confirm that the HEM capacity of urban trees in the Mediterranean context is affected by the size of the area they stand on: by taking Rome as a case study, they show that the mitigating capacity of tree canopies in road tree lines is approximately half that of urban and periurban forests; according to the authors, and in line with evidence from Cagliari, this happens because street trees' roots are mostly constrained within planting pits surrounded by sealed soils which hamper evapotranspiration, and ultimately the cooling effect. The limited cooling capacity of tree lines can be improved through appropriate design, which includes not only choosing the most appropriate species (Ballinas & Barradas, 2016) to increase both evapotranspiration and the size of the shadow, but also selecting the appropriate interval between individual trees depending on their height and width (Park et al., 2019). What is more important, notwithstanding their lower cooling capacity compared to urban forests, tree lines or even isolated trees within built-up areas are significant in reducing heat-related illnesses in the elderly, thus improving human well-being, as discussed by Venter et al. (2020), who simulate tree removals and apply a counterfactual model to the city of Oslo.

Similar positive effects of scattered trees in densely urbanized areas on the health of vulnerable populations have also been reported in the case of Boston (Tiesken et al., 2022), to the extent that the authors assert that the HEM capacity of urban trees is underestimated.

In this vein, the city of Los Angeles has launched its "Million Trees LA initiative", whose benefits in terms of reducing mortality rates have been assessed by McPherson et al. (2011) through scenario simulation. Finally, with reference to the low-height vegetation land-cover type, which includes grassland, lawns and gardens, contrary to the findings from this study its HEM service has been found to be observable, although much lower than that of trees, in previous literature (for instance Park et al., 2021 as regards Yongin-si, in South Korea, or Zhang et al., 2017 as for Nanchang City, China).

5. Conclusions

This study focuses on the impacts of intensive urbanization on the supply of ecosystem services. The city of Cagliari, a medium-sized Italian regional capital city, is targeted as the urban environment to analyze such impacts, on the basis of the assessment of the relationships between the provision of ecosystem services and the spatial framework of the urban fabric, characterized by land covers identified by unsealed and sealed soils. Unsealed soils are classed as wooded and tree areas, medium-height shrubby land cover, and ground cover featured by low-height vegetation and sparsely vegetated or bare soils. Moreover, four characteristics of sealed soils are targeted, which are highly correlated with each other, such as population density, built volume density, density of housing units, and unsealed area. The supply of three ecosystem services is assessed, identified with CCS, ROC, and HEM, with reference to spatial distributions which target census tracts as reference areal units.

Two complementary methodological approaches are implemented in order to assess the relationships between the supply of urban ecosystem services and the size of unsealed and sealed soils. First, the SRCCs concerning the variables associated with the supply of the three ecosystem services and with the characteristics of sealed and unsealed soils, are computed and assessed in terms of p-values. Second, regression models are estimated to control for the impacts on the provision of the three ecosystem services generated by a set of covariates associated with urban land cover features. The results related to the SRCCs are significant and in line with expectations in terms of the signs of the coefficients, and consistent with the estimates of the regression models.

Policy implications can be straightforwardly identified, which entail that increases in the supply of the CCS, ROC, and HEM ecosystem services target the expansion of shrubby and low-height ground covers, and of wooded and tree areas grounded on large garden beds, or, even better, on continuous vegetated areas. The increased size of vegetated areas, be they characterized by forests or woodlands, or medium- or low-height vegetation, would be associated with increases in CCS and in the effectiveness of ROC, whereas the presence of trees and wooded areas would be correlated with heating mitigation. That being so, the integrated increases in the size of vegetated areas and of tree-covered areas would generate a comprehensive significant improvement in the city quality of life (Lai et al., 2020; Gómez-Baggethun & Barton, 2013), in terms of the three targeted ecosystem services. Policies aimed at pursuing such integrated increases should be associated with virtuous behaviors on behalf of the local communities, organized citizen groups, building companies, and public administrations (Mazzeo et al., 2019; Zoppi & Lai, 2013).

An important issue concerns the narrow relationship between the value of land and the maximum permitted volume, in terms of either residential or service buildings. In this perspective, the plantation of new vegetated areas, be they covered by trees, shrubs, or low vegetation, or the expansion of areas characterized by such land covers, would imply the implementation of appropriate planning measures. Said measures should carefully integrate the landowners' demands and the public interest which would entail a plea for a robust increase in the size of urban green areas, in face of a significant decrease in the value of a share of the urban land.

In view of this, rigorous rules should be operationalized to control over building permits related to new and existing urban settlements, which should be associated with an adequate provision of wooded and tree areas or vegetated areas, such as green roofs, walls and facades, rain gardens, swales, and related collection tanks (Berland et al., 2017; UNaLab, 2019), as much as green and blue urban grids, as it occurred in East London (Jenning et al., 2016; Mathey et al., 2011).

Moreover, a structured system of public financial incentives should be planned to make the implementation of urban greening policies attractive for landowners and investors (De Noia et al., 2022; Bramley & Watkins, 2014; Webster, 2005). Such operational framework can be based on the integration of several instruments, such as grants made available to building firms on condition that new developments are endowed with an agreed-upon amount of wooded, tree or green areas, impact fee reductions, and VAT and property tax allowances (Slätmo et al., 2019; Buijs et al., 2019). Lastly, the commitment of local governments towards increasing the supply of the CCS, ROC, and HEM ecosystem services should be made visible and recognizable to the local societies through flagship financial operations such as public purchasing of areas where to implement urban greening policies (Pérez-Urrestarazu et al., 2015; Fors et al., 2015).

The methodological approach defined in this study, and the outcomes provided by its implementation with reference to the city of Cagliari, effectively address the research question highlighted in the Introduction, namely, how and to what extent is the endowment of sealed and unsealed areas related to ecosystem supply in intensively urbanized urban areas? As discussed across the article, the findings indicate that an adequate endowment of vegetated areas and of tree-covered areas would be associated with a comprehensive and relevant urban living quality, which builds on suitable levels of the CCS, ROC, and HEM ecosystem services.

The value added of the methodology here implemented is identified by the fact that it is readily exportable to other urban contexts of different demographic sizes, and physical and social conditions, since it develops through databases whose structure is easy to build and whose data are straightforward to retrieve and collect, across cities located in different regions and countries. Moreover, not only is the methodological approach easy to export, but also the results of its implementation as regards cities located in different national and international urban contexts can be readily and effectively compared.

Finally, this study leaves plenty of room for future research concerning other ecosystem services supplied in and by urban environments, such as food production, recreational services, natural and cultural heritage, and so on, whose analysis can build on the identification and assessment of their relations with urban land covers and uses, whose specification can be different and possibly more detailed than the characteristics considered in this article.

Authors' contributions

Sabrina Lai (S.L) and Corrado Zoppi (C.Z.) collaboratively designed this study. Individual contributions are as follows: C.Z. wrote Sections 1; 2.3, 3, and 5. S.L. wrote Sections 2.1, 2.2, and 4.

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Image Sources

Fig.1 to 3: Author's elaboration.

Table Sources

Tab.1, 2: Different sources mentioned in the tables;

Tab.3 to 5: Author's elaboration.

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