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Urban Green Infrastructure and Ecosystem Service Supply: A Study Concerning the Functional Urban Area of Cagliari, Italy

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Abstract: Urban green infrastructure (UGI) is a network composed of natural and semi-natural areas, such as greenspaces, open areas, and water bodies, designed to enhance the provision of ecosystem services and to meet the needs and expectations of local communities. UGIs should be accessible and should improve the well-being and health of their users, protect and enhance biodiversity, and allow for the enjoyment of natural resources. The study proposes a methodological approach to defining a UGI, conceived as a network of areas connected by urban ecological corridors and suitable for providing climate regulation, flood risk mitigation, outdoor recreation, and biodiversity and habitat quality enhancement. The methodology is applied to the functional urban area (FUA) of the City of Cagliari, Italy. The analysis results show that areas with high values of climate regulation, carbon storage and sequestration, and habitat quality enhancement are particularly suitable to be part of a UGI. Although values for outdoor recreation appear to be less significant, the provision of this service is particularly relevant within the Cagliari FUA. However, areas characterized by high values of flood risk mitigation show a different behavior, which highlights how the presence of impermeable surface within urban areas is associated with a loss of patch connectivity.

Keywords: urban green infrastructure; urban ecosystem services; functional urban areas; urban planning

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1. Introduction

The European Commission identifies a green infrastructure (GI) as "[A] strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services. It incorporates green spaces (or blue if aquatic ecosystems are concerned) and other physical features in terrestrial (including coastal) and marine areas. On land, GI is present in rural and urban settings" [1] p. 3. "The work done over the last 25 years to establish and consolidate the network means that the backbone of the EU's GI is already in place. It is a reservoir of biodiversity that can be drawn upon to repopulate and revitalize degraded environments and catalyze the development of GI. This will also help reduce the fragmentation of the ecosystems, improving the connectivity between sites in the Natura 2000 network and thus achieving the objectives of Article 10 of the Habitats Directive" [1] p. 7. Spatial planning policies aimed at protecting and increasing the availability of ecosystem services (ESs) should, therefore, focus on GIs as qualitatively and quantitatively relevant production networks of ESs [2–4].

The European Commission identifies GIs as key spatial systems for the conservation and improvement of biodiversity conditions, the effectiveness of spatial linkages of natural ecosystems, and the enhancement of ESs production [5]. Moreover, improving the biodiversity situation and increasing the supply of ESs are two priority purposes concerning spatial planning policies aimed at strengthening the functionality of GIs [2,6].

The concept of urban green infrastructure (UGI) fits within the conceptual and technical horizon outlined by the European Commission and is developed, in a relevant way, through contemporary urban planning practices to characterize urban green area systems as overall relevant references of planning processes [7,8].

UGI is a network composed of natural and semi-natural elements designed with the aim of increasing its ESs supply, in which green spaces, open spaces, and water bodies are recognized and included. These elements are located in built-up areas and, also, in correspondence with non-permeable soils, thus completely artificial. The network of natural structures of a different size, location, and ownership should be maintained and further developed as a joint responsibility of the various political, economic, and civic actors, working in the context of city management.

In terms of contributing to social, ecological, and sustainable urban development, UGIs are characterized as follows [9]:

- Be accessible to all users within the urban context;
- Improve the health and well-being of the same users;
- Conserve and enhance both biological diversity and direct and sustained enjoyment of natural resources;
- Contribute to the aesthetics of the city and improve the quality of life in urban settings and, especially, in densely urbanized ones;
- Preserve and increase the supply of ESs by users of the urban environment, whether they are residents, commuting workers, occasional visitors, tourists, or out-of-town students.

Even fully urbanized and artificialized areas can become part of UGIs through the removal of non-permeable surface cover, greening, and tree planting. The strong inclusiveness of UGIs is emphasized by Tzoulas et al. [8] in relation to natural and semi-natural areal and related ecological systems, both with reference to individual conurbations and in relation to multicenter spatial organizations, including transitional, peri-urban, and rural areas.

UGIs play a particularly important role in urban areas in relation to the continuity of urban green spaces, which are characterized by significant fragmentation due to the widespread presence of sealed areas and physical obstacles of different kinds, such as buildings and their appurtenant areas and transportation infrastructure, a condition that has a strong negative impact on biodiversity. If, therefore, UGIs are not always able to limit the fragmentation of urban greenery, they make available important ESs not directly related to spatial continuity, such as the improvement of air quality, linked to the presence of vegetated surfaces whose positive impact is amplified when these are characterized by the presence, more or less widespread, of trees [10,11].

Green walls and roofs significantly contribute to absorbing the heat generated by sunlight, thus mitigating the negative effects of high temperatures in the established settlement fabrics of cities and, in particular, the urban heat island phenomenon [12].

The protection, management, and development of UGI takes place with the following principles in mind [9]:

- Adapt the usability of available urban ESs according to the needs of users through measures that involve, in a strategic manner, the definition and implementation of urban planning;
- Promote the multipurpose use and multifunctionality of UGIs;
- Make sure that the use of ESs is continuous and effective and make maintenance operations, which limit, often problematically, these uses, as efficient as possible;
- Integrate UGIs into the parts of the urban context where soils are largely sealed through partial permeabilization of the soils, as part of the implementation of nature-based solutions;
- Define and implement urban planning policies aimed at increasing the effectiveness of UGIs, which are characterized by inclusiveness and participation of local societies, with special reference to private entrepreneurship of the for-profit and nonprofit sectors, citizens' committees, voluntary associations, especially those working in the field of

environmental protection, trade union representatives, and all public administrations responsible for the management of the urban environment.

The implementation of a proactive, participatory, and inclusive approach to urban planning geared toward strengthening UGIs is the foundation of a new holistic strategic vision of spatial policymaking that effectively integrates, with reference to local contexts, sustainable economic development and social equity [13–16]. The profile of the compact city within the ecological network is based the overall approach to urban planning in Dresden, aimed at creating a green city [9]. The guiding principle is the planning of compact urban settlements embedded in a network of ecologically functional spaces. The river system (400 waterways and the Elbe River basin) is the basis of the ecological network, which will be gradually expanded together with the provision of freely usable urban green spaces. The following operational functions are assigned to it [9]:

- Improvement of air quality and progressive adaptation to climate change;
- Effective recharge of underground aquifers;
- Flood prevention and runoff control;
- Increasing areas available for outdoor recreation;
- Protection and improvement of habitat quality for flora and fauna, as well as functioning and adequate usability and walkability, of corridors connecting hubs of concentration of urban ESc provision;
- Protection and improvement of the aesthetic quality of the urban built and natural environment.

Dresden's UGI is structured as green connecting hubs and corridors, with respect to which urban policies are, on the one hand, aimed at improving the ecological quality of the network of hubs and connections, and, on the other hand, oriented toward operationalizing a system of regulations to limit or prevent the expansion of the urban built environment. The intentionality of the Dresden municipality's approach is to ensure that the framework of urban ESc provision is perceived by the local community as a complex GI and open spaces as the building blocks of this infrastructure [17,18].

The positions of Sandström, Tzoulas et al., and Breuste [7–9] highlight the importance of the identification of UGI as a conceptual category of spatial analysis and planning where the case of Dresden constitutes a technical and experimental reference of relevant significance. The same positions point out, however, to the lack in the scientific and technical literature of a theoretical and operational definition of UGI, which identifies it in general terms, thus distinct from the conceptual category of GI. According to Breuste, this definition should complement that of GI, cited earlier [1], with references peculiar to the supply of ESs typical of urban contexts, as was operationally the case in Dresden. This study aims, as a general objective, to offer a contribution to filling the research gap reported by Sandström, Tzoulas et al., and Breuste [7–9] in relation to the construction of this general definition using a methodology for recognizing UGIs as an implementation strategy of the conceptual category of GIs in urban contexts, and this study applies it, experimentally, to the spatial context of the functional urban area (FUA) of Cagliari. A methodological approach to identifying a UGI is developed based on three steps, which constitute the contents of the second section. First, the UGI is identified through the spatial taxonomy of the provision of certain ESs that define and characterize the quality of urban settings such as areas for outdoor recreation, flood control, carbon capture and storage, quality of flora and fauna habitats, and urban heat mitigation.

Second, the UGI is structured as a spatial network whose nodes are natural protected terrestrial areas (core areas) and whose edges are identified as the connecting urban ecological corridors (UECs) of the core areas, detected using a methodology based on ecological integrity and degree of naturalness.

Finally, the connecting corridors are superimposed on the spatial taxonomy of ESs to identify whether, and to what extent, the inclusion of areal elements in the corridors is related to the supply of the different types of ESs.

The methodological approach thus defined is applied to the FUA of Cagliari (Sardinia, Italy), synthetically described in the second section as well. The results obtained in relation to the three points of methodology development, mentioned above, are described in the third section and discussed in the next section, with reference to the context of the current literature.

The concluding section proposes some considerations on the peculiarity of UGIs with respect to the general field of GIs and the relevance of the methodological approach, which can be effectively exported to the urban contexts of other FUAs. An important issue for the future development of the research is represented by the profiles and conditions for exporting the methodology implemented in the spatial context of the FUA of Cagliari.

2. Methods and Materials

This section is organized as follows. In the second part, after a preliminary synthetic description of the FUA of Cagliari taken as a case study, the methodology used to define the spatial taxonomy of the UGI is outlined, with reference to the different typologies of ESs that define it and, namely, the areas available for outdoor recreation, the identification of areas with strong potential for flood control and mitigation, and carbon capture and storage (CCS) capacity, the location of habitats particularly significant for the quality of flora and fauna, and the identification of the phenomenon of urban heat mitigation through the spatial definition of land surface temperature (LST). In the third part, the methodology implemented for the identification of UECs is defined, with reference to the integration of the spatial taxonomies of ecological integrity and naturalness conditions. Finally, a linear regression model is presented, which identifies, in comparative terms and in relation to the spatial taxonomy of UGI, the ability of different ESs to contribute to the identification and development of UECs.

2.1. Study Area: The FUA of Cagliari

As per the definition offered by the Organization for Economic Cooperation and Development (OECD), a FUA comprises a city and its commuting zone. By accounting for cities' areas of influence in terms of daily movements of commuters, FUAs represent an effort to identify meaningful "integrated socio-economic units" [19] consistent across countries and integrate core built-up areas having high residential density and at least 50,000 inhabitants within their labor markets [20], usually composed of smaller settlements with lower density and rural areas as well [21].

The FUA of Cagliari, which spans over around 1950 km^2, comprises 32 local authorities, shown in Figure 1. The resident population totaled 476,717 people as of 2022 [22], of which around 30 percent living in the FUA's core area, i.e., the municipality of Cagliari. While the population in the FUA core city has been decreasing for years, its commuting zone shows a steadily increasing trend.

Green spaces, defined after McDonald et al. [23] as the combination of ecological systems having various degrees of naturalness, represent 42.06 percent of the FUA, including green urban areas, which amount to a mere 0.47 percent of the FUA. In addition, blue spaces, mostly coinciding with wetlands and saltpans, make up a further 3.87 percent. Significant differences as to green area endowment emerge between the core urban center (Cagliari) and its commuting zones: the percentage of green and blue spaces amounts to 57.56% in Cagliari and 45.02% in the commuting area; however, because a significant share of the municipality of Cagliari is occupied by wetlands, when blue spaces are removed and only vegetated land covers are considered, the percentage in Cagliari drops to 12.27%, whereas the commuting area shows a negligible decrease to 43.54%.

To implement the methodological steps described in the next sections, a vector fishnet, next referred to as "grid", made up of 100-meter-wide squares and covering all the FUA, was created. Each of the almost 988,000 cells comprised in the grid was used as the reference spatial unit where to map the values of the variables that feed the inferential model described in Section 2.4.

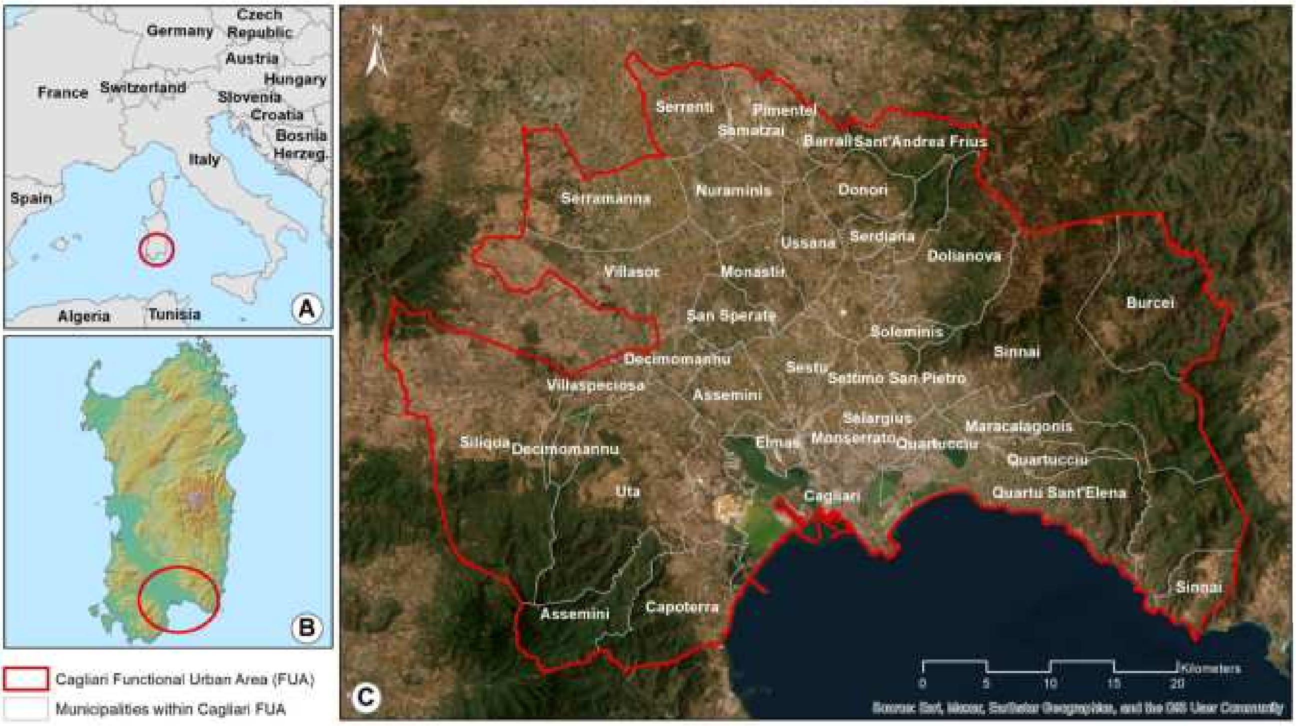

Figure 1. The functional urban area (FUA) of Cagliari in Sardinia, Italy, and its municipalities. Data sources: global administrative boundaries from the Joint Research Centre Data Catalogue for Panel (**A**); digital elevation model and municipal administrative boundaries from the Sardinian geoportal for Panels (**B**) and (**C**), respectively.

2.2. The Spatial Taxonomy of the UGI

As per the Introduction Section, the spatial layout of the UGI is here identified on the basis of the spatial distribution of the supply of five selected ESs, by biophysically assessing and mapping the following: nature-based recreation opportunities; water retainment capacity in case of heavy rainfalls; climate regulation through carbon sequestration and storage; habitat quality as a proxy for habitats' potential to provide niche, food, and shelter for wildlife; and LST as an indicator of green areas' cooling capacity. This section briefly describes the methodological approach used to assess and map the five chosen ESs, listed in Table 1.

Table 1. Selected ecosystem services: input data used to feed the models and their data sources.

Label	Input Data	Data Sources
RECR_OUT	Land cover map	Copernicus land monitoring service
	Population data (census tract level) Census tracts	National census
FLD_CNTR	Land cover map Soil permeability map Curve number values Areas of interest	Regional geoportal
	Precipitation (rainfall depth)	Regional hydrologic annals
CA_CP_ST	Land cover map	Regional geoportal
	Carbon pools (above ground, below ground, dead organic matter, organic carbon)	Regional pilot project on land units and soil capacity in Sardinia National inventory of forests and carbon pools

Table 1. *Cont.*

Label	Input Data	Data Sources
HAB_QUAL	Land cover map	Copernicus land monitoring service
	Protected areas	Regional geoportal
	Threats on habitats	Natura 2000 standard data forms Regional geoportal
	Threats' weights and distance decay Habitats' sensitivity to threats	Expert survey
L_S_TEMP	Landsat Collection 2, level 2 imagery	Landsat Collection 2 surface temperature

RECR_OUT is the indicator accounting for nature-based recreation opportunities; FLD_CNTR for flood control and retention; CA_CP_ST for carbon capture/sequestration and storage; HAB_QUAL for habitat quality as a proxy for biodiversity capacity of supporting wildlife; L_S_TEMP is the indicator representing land surface temperature values.

2.2.1. Nature-Based Recreation Opportunities

Nature-based recreation opportunities were assessed based on two indicators, respectively, concerning areas suitable for outdoor recreational activities and resident population living close to such areas, as potential beneficiaries of the ESc.

As for the first, areas available for nature-based recreation inside the FUA were identified based on the 2018 Urban Atlas land cover dataset issued by the European Land Monitoring Service [24]. Despite having a coarse classification of vegetated areas, the Urban Atlas dataset has a much finer spatial resolution than the 2018 CORINE Land Cover (CLC) dataset [25]: its minimum mapping unit equals 0.25 ha for urban classes (including urban green areas) and one hectare for rural classes compared with the 25-hectare CLC dataset. Land cover types relating to green urban areas (Urban Atlas code 14100), sports and leisure facilities (Urban Atlas code 14200), and vegetated natural areas, i.e., land cover codes beginning with 3, were selected, as well as the edges of inland and marine waters (codes starting with 4 and 5, respectively), because of the significance of the coastline and of riverbanks or wetland or lake shores for nature goers [26–28]. Next, for each 100 $\times$ 100 cell in the grid, the share of green and blue areas offering nature-based recreation opportunities was assessed in percentage terms.

Concerning the second, population data were retrieved from the 2021 national census [29], using census tracts as spatial units of reference. This dataset was chosen because it is the most recent one issued by ISTAT, the national agency in charge of issuing economic, social, and environmental data and information in Italy. A series of GIS operations were performed to estimate the number of residents in each 100 $\times$ 100 cell in the grid, assuming that the resident population is evenly distributed in each census tract once water areas (when present) are removed. Next, for each cell that might potentially attract nature-based outdoor recreation, i.e., for each cell having non-null shares of green and blue areas, the population living within 500 m from the cell was calculated. This is consistent with previous studies (among many [30–33]) where the distance of green areas from home was considered as a factor driving urban outdoor recreation and, therefore, affecting residents' health and environmental (in)justice. For this reason, as pointed out by previous research [32,34,35], some cities have issued regulations whereby every household should have access to urban green areas within a distance that ranges from 300 to 1000 m. In this study and in line with Berlin's regulations [31], a 500 m distance was chosen since it allows slow walkers such as children and the elderly to reach green areas within a 10 min walk, taking into account the climate and hilly topography of the urbanized areas within the FUA of Cagliari.

Finally, the RECR_OUT variable was calculated as the percentage of the green and blue areas in each 100 $\times$ 100 cell times the population living within 500 m from that cell. The process was assessed by RECR_OUT and is graphically summarized in Figure 2.

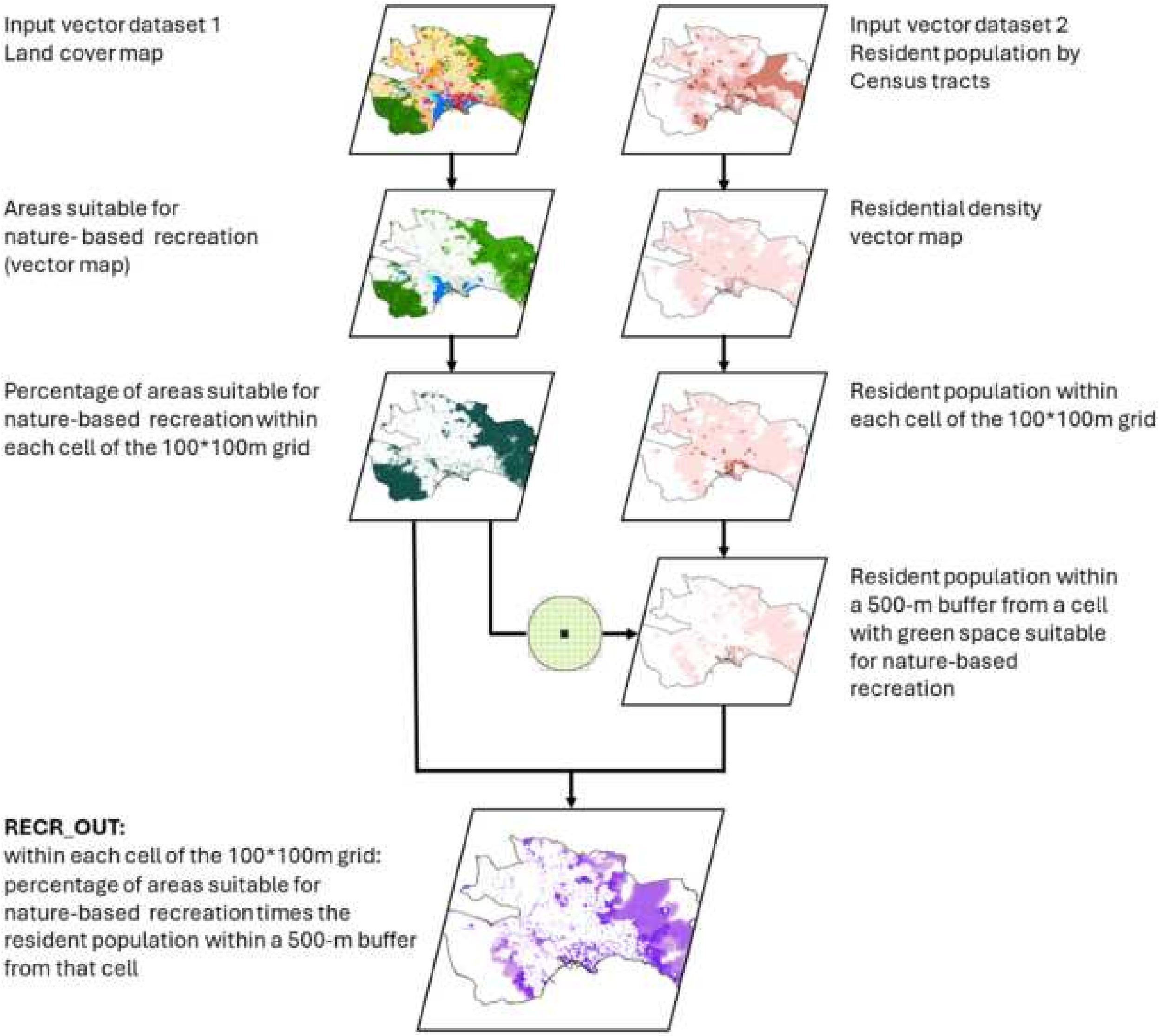

Figure 2. Graphical flow of the assessment of the variable RECR_OUT.

2.2.2. Water Runoff Retention

The "Urban Flood Risk Mitigation" model, part of the InVEST suite [36], was used to map the variable FLD_CNTR. This tool estimates the contribution of ecosystems toward flood regulation by biophysically assessing the water volume intercepted by vegetation and infiltrated by pervious soils in the event of a cloudburst, as well as runoff levels. Input data needed to run the model include the following: two raster datasets, one for land cover types and the other for soil hydrologic groups (SHGs); a vector dataset providing the area of interest; the value of precipitation depth in the area of interest for which runoff and water retention are to be assessed; and a biophysical table assigning the curve number to each possible combination of SHG and land cover type. The runoff retention volume is modeled as dependent on the precipitation depth and on the runoff level, which, in turn, is governed by the curve number; the latter is a dimensionless parameter representing the potential runoff after a cloudburst, and it is empirically estimated based on land cover types and SHGs [37].

The model requires that SHGs be categorized into four groups, labeled with letters from A to D, consistent with the classification used in the United States of America [38], ranging from highly permeable soils that lead to low runoff (A) to low permeable soils, conducive to high runoff (D). To develop the SHG raster map, a regional 1:25,000 vector permeability map [39] was reclassed to match the four required groups and, then, converted into a raster map. To the best of the authors' knowledge, this is the most detailed available dataset allowing for the delineation of SHGs in Sardinia.

As for land cover, the 2008 Sardinian 1:10,000 vector map [40] was used, which details the standard CLC nomenclature [41] up to the fifth level in the hierarchical taxonomy. This data source was selected because a report published by the Sardinian Environmental Agency [42] contains a look-up table that meets the model's requirements concerning the biophysical table, meaning that it provides curve number values for each land cover type in Sardinia, differentiated according to SHG, by making use of the detailed classification of land cover types contained in the regional land cover map, which was, therefore, preferred to the more recent but coarser CLC dataset.

Concerning the precipitation value, it is worth noting that the temporal dynamics of the rainstorm are not accounted for in the model [43] as InVEST only requires a single rainfall value. Therefore, an examination of the 2012–2022 regional hydrological annals, available from the Regional Environmental Agency's website [44], was performed to retrieve the largest precipitation depth documented in the study area in a day, which amounted to 101.8 mm, recorded on 13 November 2021.

Finally, the vector map of the area of interest, containing the polygons where retention volumes are aggregated, was developed from the regional digital terrain model raster map [45] by delineating watershed boundaries. The zonal statistics tool was used to calculate the variable FLD_CNTR as the total volume of water retained in the 100 × 100 cells.

2.2.3. Carbon Sequestration and Storage

The "Carbon Storage and Sequestration" model, part of the InVEST suite [36], was used to map the variable CA_CP_ST. Within this model, the amount of carbon stored on a parcel of land is regarded as the sum of four fractions, each representing the quantity of carbon stored within one of four terrestrial carbon pools, i.e., soil, dead organic matter, belowground biomass, and aboveground biomass. The input data required by the model are a land cover map and a look-up table where carbon density values (i.e., amounts of stored carbon per unit of land) are provided for each land cover type in the map and for each carbon pool. Carbon density values to be provided as input data in the look-up table can be obtained in several ways, including review from the literature, use of inventories and databases, expensive and time-consuming on-site surveys, or allometric equations in case of aboveground biomass.

For this study, the model was applied using only carbon density values concerning dead organic matter, organic soils, and aboveground biomass because no information about carbon stored in the belowground pool in the study area could be retrieved. Carbon density values for the three remaining pools were obtained from two sources: the first is a pilot project carried out jointly by the regional agency for rural development and by AGRIS, the Regional Agency for Scientific Research and Technological Innovation in the Agricultural Sector, which provides data from on-site surveys, and the second is the 2005 National Inventory of Italian Forests [46]. The zonal statistics tool was used to calculate the variable CA_CP_ST as the carbon density in the 100 × 100 cells.

2.2.4. Habitat Quality

A third model contained within the InVEST suite [36], termed "Habitat quality", was used to spatially assess the variable HAB_QUAL. This tool requires as input data a raster land cover map, which was retrieved from the already mentioned 2018 CLC dataset [25] for two reasons: first, the analysis needed to take into account areas outside the FUA for which the Urban Atlas dataset is not available; second, the coarse classification of vegetated areas provided by the Urban Atlas dataset is inappropriate for this model.

Moreover, two mandatory tables are required by the model. The first concerns the threats that affect the quality of habitats in the study area. To build the list of such pressures, the standard data forms of Natura 2000 sites [47] were scrutinized as they provide official and reliable information on land uses and human activities that affect species and habitats.

Out of the many threats that are listed in the standard data forms, the ones that concern marine areas were dismissed, as well as those for which no spatial information was available, such as illegal hunting or undefined noise disturbance, which led to identifying ten threats as follows: urban areas, roads and motorways, airports, paths and tracks, agriculture, grazing, removal of forest undergrowth, saltpans, landfills, and fire and burnt areas. Next, local experts in environmental assessments were surveyed to score the significance of each threat using a zero-to-five Likert scale and their decay distance and function as both pieces of information are required by the model. Significance scores provided by local experts were averaged and normalized in the zero-to-one range, whereas decay distances, provided in kilometers, were only averaged.

The second table required by the model was a look-up table that scored the sensitivity of each habitat to each threat, for each land cover that can be classed as a habitat. Sensitivity scores were assigned in this study through expert-based judgments ranging from zero to one, with higher scores corresponding to higher sensitivity.

Finally, accessibility to threats that might degrade the quality of habitats can be accounted for in the model as optional input data. The assumption of the model is that legal and institutional restrictions to accessibility and movement, as the ones associated with natural protected areas, may reduce the negative effects on habitats that would otherwise stem from threats. Therefore, in this study, the spatial layout of natural protected areas was considered. In Sardinia, on land, these include national and regional parks, the Natura 2000 network, and public forests managed by the regional forestry agency—for each type, the spatial dataset was retrieved from the regional geoportal [48]. Each type of protected area was given a score in the (0–1) range where higher scores corresponded to higher accessibility, hence lower barriers against threats. The zonal statistics tool was used to calculate the variable HAB_QUAL as the mean habitat quality value modeled by InVEST in the 100 $\times$ 100 cells.

2.2.5. Land Surface Temperature

The spatial distribution of LST is globally available through various sources, such as the United States Geological Survey (USGS), provided through the Earth Explorer interface [49] or the European program "Copernicus—Europe's Eye on Earth". The latter provides hourly values as well as statistical overviews; however, its 5 km spatial resolution makes it less appropriate than the former (30 m) considering the size of our study area. Several remotely sensed datasets can be searched through the Earth Explorer interface by setting the user's parameters such as area of interest, cloud cover, and data range; among the datasets, Landsat Collection 2 Level-2 products, which comprise 30 m LST raster maps, are included.

In this study, the area of interest corresponds to the FUA of Cagliari, whereas for the time range, a five-month interval, ranging from May to October 2023, hence fully including the summer season, was selected. Additionally, only images having cloud cover smaller than 10 percent were considered. Thirteen LST maps were retrieved, from which we chose the one with the highest average LST across the terrestrial study area whose unique identifier is LC08_L2SP_192033_20230730_20230805. The zonal statistics tool was then used to calculate the variable L_S_TEMP as the mean LST in the 100 $\times$ 100 cells.

2.3. The Identification of the Urban Ecological Corridors

Various methodologies have been used in the literature to identify UECs. According to a study by Peng et al. [50], the methodologies can be grouped into four classes: empirical assessment, suitability/sensitivity analysis, network analysis, and minimum cumulative resistance analysis/least-cost path analysis. The first group is included within qualitative methods and relies on expert judgments related to the natural and landscape context of the study area to identify the most suitable areas for the identification of UECs. The second group represents a quantitative method that evaluates the ecological and natural characteristics of the study area to understand which areas are most suitable for hosting UECs.

For example, Ferretti and Pomarico [51] propose an integrated approach that uses spatial analysis in a GIS environment and multicriteria analysis to create maps based on sensitivity analysis that may address planning choices and strategies. Network analysis is based on graph theory, which conceptualizes the landscape as a network structure consisting of points, lines and polygons. For example, Li et al. [52] propose a methodological approach that integrates graph theory and land-use simulation models to assess the landscape connectivity of the ecological network in the Chaoyang District, in Beijing, in order to support planning choices and strategies in terms of biodiversity conservation in urban areas. The fourth group concerns the analysis of minimum cumulative resistance or least-cost path analysis (LCP), conceived as the resistance wildlife experiences to move along a given pathway. For instance, Li et al. [53] developed a methodological approach for defining an ecological network within Shenzhen City, China, by integrating a morphological spatial pattern analysis and a minimum cumulative resistance model. Methodologies based on graph theory and LCP models are widely used in the literature to measure connectivity [54]. In this study we propose an approach that combines graph theory with LCP model through the Linkage Mapper (LM) tool 3.1.0., an extension of ArcGIS software 10.8.2 [55].

The methodology developed in this study is based on the research by Cannas et al. [56–59] and Isola et al. [60–62] for the identification of ecological corridors (ECs). In these studies, ecological corridors are conceived as linear elements that connect the natural protected areas of the Sardinia Region. Specifically, the methodological approach based on the LCP model consists of four steps, each of which results in the definition of a spatial map, as follows.

1. Step 1: land naturalness mosaic map.
2. Step 2: ecological integrity map.
3. Step 3: resistance map.
4. Step 4: map of cost-weighted distance (CWD) and map of ecological corridors.

The methodology developed in this study differs from Cannas et al.'s methodology [56–59] in relation to Phase 1. Indeed, this study focuses on UECs, which must not only meet ecological needs but also integrate recreational, cultural, aesthetic, and social functions [50]. Therefore, the study considers the naturalness degree rather than the suitability according to which a habitat is likely to be used by species. The habitat suitability map, identified in several studies [56–62], exclusively takes into account the ecological functions performed by corridors. The identification of the degree of naturalness is based on the landscape mosaic methodology (LMM) developed by the Joint Research Centre (JRC) and the European Commission's science and knowledge service [63,64]. A detailed breakdown of the methodology is provided in Appendix A.

The second phase focuses on elaborating a map of ecological integrity, building on Burkhard et al.'s research [65,66]. This phase involves assessing the capacity of various land cover classes to provide ESs based on expert judgments. The basic concept is that the greater the ecological integrity, the greater the capacity for "species" to migrate and move. Ecological integrity is essential for maintaining ecosystem services (ESs), which contribute to the preservation and enhancement of other types of ESs, including provisioning, regulating, and cultural services. The ecological integrity index is determined by adding up the scores from seven ESs supply indicators (abiotic heterogeneity, biodiversity, biotic water flows, metabolic efficiency, exergy capture, nutrient loss reduction, and storage capacity). These indicators reflect supporting ESs in relation to each of the 44 third-level land cover classes of the CLC nomenclature. Therefore, mapping the ecological integrity index values results in an ecological integrity vector map for the FUA of Cagliari.

The third phase of defining the resistance map involves some key steps that utilize land naturalness mosaic map and ecological integrity map, drawing on methodologies from LaRue and Nielsen [67]. A detailed breakdown of the process is provided below.

1. Conversion of the two vector maps (land naturalness mosaic and ecological integrity) into raster maps;

2. Elaboration of two new raster maps by computing the inverse of the naturalness degree index and the ecological integrity index;
3. Scaling the newly-identified raster maps on an ordinal scale from 1 to 100 based on guidelines from the European Environment Agency [6] where 1 is the lowest resistance and 100 is the highest level of resistance;
4. Summing the values of the two rescaled raster maps on a patch-by-patch basis. The resulting map represents the resistance map. The resistance map provides a spatial taxonomy that identifies varying levels of resistance across the landscape, which can be crucial for ecological planning and management.

The fourth phase concerns the spatial identification of UECs that connect natural protected areas included within the FUA boundaries using the Linkage Pathways Tool (LPT) from the GIS LM Toolbox. The terrestrial natural protected areas (NPAs) included in the study as core areas to be connected through UECs are regional natural parks, Natura 2000 sites, and Ramsar sites. This phase employs the LCP approach by calculating the cost-weighted distance (CWD). The results of this process are linear mapping of UECs and raster mapping of CWD values. A detailed description of the process is provided in Appendix B.

Table 2 shows the input and output data for each phase.

Table 2. Identification of ecological corridors: input and output data, and operationalized tools and models.

Phase	Input Data	Source	Output Data	Tool/Model
Step 1: land naturalness mosaic map.	Land cover map	Copernicus land monitoring service	Land naturalness mosaic map	Guido Toolbox [68]
Step 2: ecological integrity map.	Land cover map	Copernicus land monitoring service	Ecological integrity map	Burkhard et al.'s matrix [65]
Step 3: resistance map.	Land naturalness mosaic map.	Step 1	Resistance map	Analysis in the GIS environment
	Ecological integrity map.	Step 2		
Step 4: map of cost-weighted distance (CWD) and ecological corridors.	Resistance map	Step 3	CWD map Spatial identification of UCS	Linkage Pathways Tool from the GIS Linkage Mapper Toolbox.
	Map of core areas	Regional geoportal [69,70]		
		European Environmental Agency dataset [71]		

2.4. The Spatial Relations between Ecosystem Service Supply and Ecological Corridors

The relationships between the supply of ESs and the identification of UECs are assessed using a multiple linear regression model. In this model, the UECs are identified linearly by applying the least-cost path (LCP) algorithm to the spatial distribution of CWD. Hence, UECs are the edges that identify the minimum CWD between nodes in the UGI. These edges, therefore, make the resistance to spatial flows between nodes minimal. In other words, it is the nodal connections that offer the highest values of the combination of urban naturalness and ecological integrity. Once the linear lay of UECs is found, through the implementation of the LCP algorithm into the spatial taxonomy of CWD, their areal morphology is identified with the system of patches with CWD values falling within the 20th percentile of the CWD statistical distribution.

This threshold uniquely determines the boundaries of the linear UEC elements, connecting the patches in a way that minimizes CWD between the nodes of the UGI network. The model operationalizes in the following form:

$$\text{CO\_W\_DIS} = \beta_0 + \beta_1\text{RECR\_OUT} + \beta_2\text{FLD\_CNTR} + \beta_3\text{CA\_CP\_ST} + \beta_4\text{HAB\_QUAL} + \beta_5\text{L\_S\_TEMP} + \\ + \beta_6\text{ALT\_ELEV}. \quad (1)$$

In this model, the dependent and explanatory variables link the spatial structure of the UECs to the provision of various ESs that define the UGI. All observations of these variables pertain to the spatial units formed by the patches that are part of the UECs.

The dependent variable and covariates are defined as follows:

- CO_W_DIS is cost-weighted distance (CWD);
- RECR_OUT is the percentage share of the area available for outdoor recreational activities times the resident population in a buffer of 500 m;
- FLD_CNTR is the volume of water runoff, which is prevented to flow away;
- CA_CP_ST is the amount of organic carbon that can be sequestered and stored;
- HAB_QUAL is habitat quality;
- L_S_TEMP is land surface temperature (LST) as the urban heat measure and reference for its mitigation;
- ALT_ELEV is a control variable related to average elevation.

The values of the regression coefficients quantitatively describe the relationships between the core wilderness areas (CWDs) of the spatial units within the UECs and the supply of various ecosystem services (ESs). In this context, regarding the spatial taxonomy of CWDs for patches within the UECs, a multiple linear regression model is employed. This approach is common in studies examining interactions between spatial variables, especially when there are no predefined hypotheses about the correlations between the variables [72–75].

The multiple linear regression model, in this context, represents a hyperplane in an n-dimensional space that is tangent to a surface with an unknown equation. This surface represents the phenomenon being studied—in this case, the spatial taxonomy of core wilderness areas (CWD) within the UEC patches and its seven covariates. The model provides a linear approximation of the unknown surface equation in the infinitesimal vicinity of the tangency point. Consequently, the linear equation (1) serves as the projection or trace of a hyperplane on a surface with an unknown equation in an eight-dimensional space [76,77].

The variable ALT_ELEV serves as a control covariate to assess the impact of elevation on core wilderness areas (CWD). If the estimated β6 coefficient is significant, it would indicate that elevation has either a positive or negative effect on CWD, depending on the coefficient's sign, with the magnitude of the impact determined by the coefficient's value.

Finally, to evaluate the significance of the estimated β coefficients in the model (1), a series of *p*-value tests is conducted.

3. Results

This section presents the results of the implementation of the methodological approach described in the previous section related to the FUA of Cagliari. In the first part, these refer to the UGI taxonomy based on the spatial organization of ESs concerning outdoor recreation, flood control and mitigation, CCS, habitat quality, and urban heat mitigation. The second part proposes the outcomes concerning the identification of UECs based on the taxonomy of CWD and the LCP algorithm. Finally, the coefficient estimates of multiple linear regression offer a picture of the contribution of different ESs to defining the spatial organization of UECs.

3.1. The Spatial Taxonomy of the UGI

As for nature-based recreation opportunities (Figure 3, Panel "A"), almost two-thirds of the cells in the grid show null RECR_OUT values; these include both cells without any green areas suitable for nature-based recreation, for instance, cells located in the agricultural plain or in the densest parts of the FUA built-up areas and cells with vegetated land cover in whose proximity no resident population is recorded in the national census, such as the woods on the eastern and western borders of the FUA. Cells showing the highest values coincide either with urban green areas in the inner parts of the settlements (an example is provided in Figure 4, Panels "A1" to "A3") or with green peri-urban areas on their outskirts (an example is provided in Figure 4, Panels "B1" to "B3"), whereas notable clusters of low-to-intermediate values characterize the eastern part of the FUA where low-density developments have taken place in otherwise natural areas (an example is also visible in Figure 4, Panels "B1" to "B3").

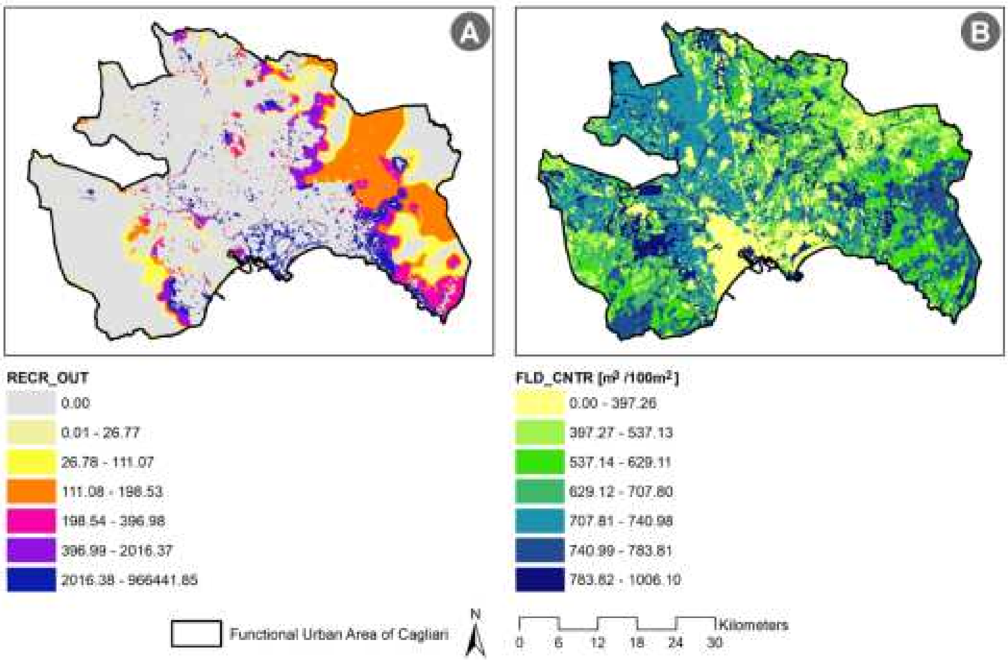

Figure 3. The spatial layout of the first and second selected ESs in the study area: RECR_OUT (Panel (**A**)) and FLD_CNTR (Panel (**B**)).

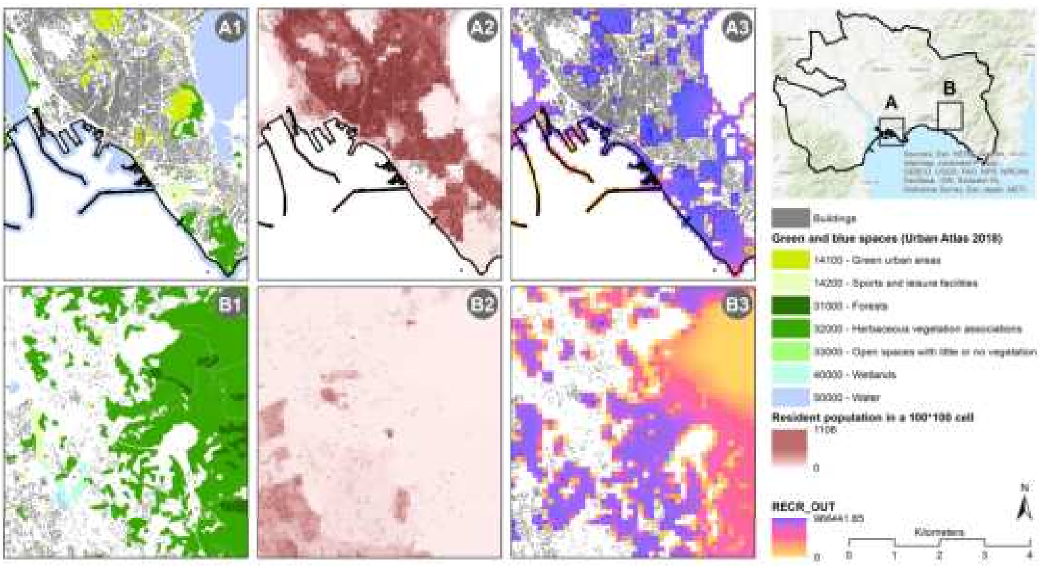

Figure 4. Two snapshots concerning recreational nature-based opportunities in a dense urban area (Panel (**A**)) and in a peri-urban area (Panel (**B**)): availability of green and blue spaces (**A1**,**B1**); distribution of the resident population (**A2**,**B2**); RECR_OUT (**A3**,**B3**).

Second, the variable FLD_CNTR, associated with water runoff retention, takes null or extremely low values in built-up areas, while high values (dark blue in Figure 3, Panel "B") tend to correspond to agricultural and natural land cover types associated with highly permeable soils located in low-elevation areas. However, high values are also featured in two small promontories along the coastline, which split the bay into two parts and whose rocks are characterized by karstification and fracturing.

Third, extremely low values of CA_CP_ST (yellow in Figure 5, Panel "A"), the indicator representing carbon sequestration and storage, aggregate in the south-central part of the FUA, corresponding to the urban fabric of Cagliari and to the wetlands; moreover, two yellowish linear clusters departing from Cagliari to the north, coinciding with the main road arteries, are also clearly visible. The highest values can be found in the woods to the east and to the west, the former managed by the Regional Forestry Agency and the latter included in a Regional Natural Park. Agricultural plains and hilly areas with low or sparse vegetation tend to show intermediate values.

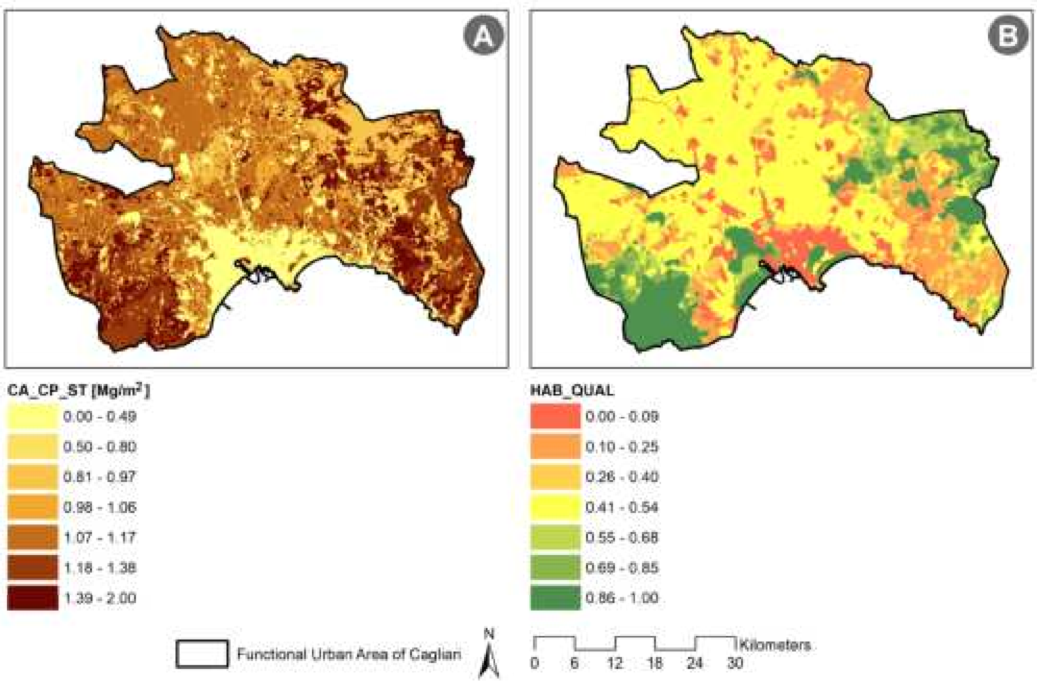

Figure 5. The spatial layout of the third and fourth selected ESs in the study area: CA_CP_ST (Panel (**A**)) and HAB_QUAL (Panel (**B**)).

Fourth, null values of the variable HAB_QUAL (yellow in Figure 5, Panel "B"), taken as a proxy for the quality of biodiversity and its capacity to maintain or regulate either refuge habitats or nursery populations and habitats, characterize 6.8 percent of the cells, largely coinciding with artificial land cover types. The highest values (green in Figure 5, Panel "B") can mostly be found in wooded areas distant from degradation sources and the inner areas of the wetlands, whereas agricultural areas always show intermediate values.

With reference to the fifth selected ES, i.e., biodiversity capacity to regulate and mitigate temperature, assessed through the variable L_S_TEMP during the summer 2023, the map in Figure 6, Panel "A", clearly shows that the highest temperatures cluster not only in built-up areas but also along the Campidano agricultural plain, while the lowest temperatures, corresponding to higher values of the ES, characterize wetlands, reservoirs, and the peaks of the hills and of the mountains to the east and to the west of the FUA.

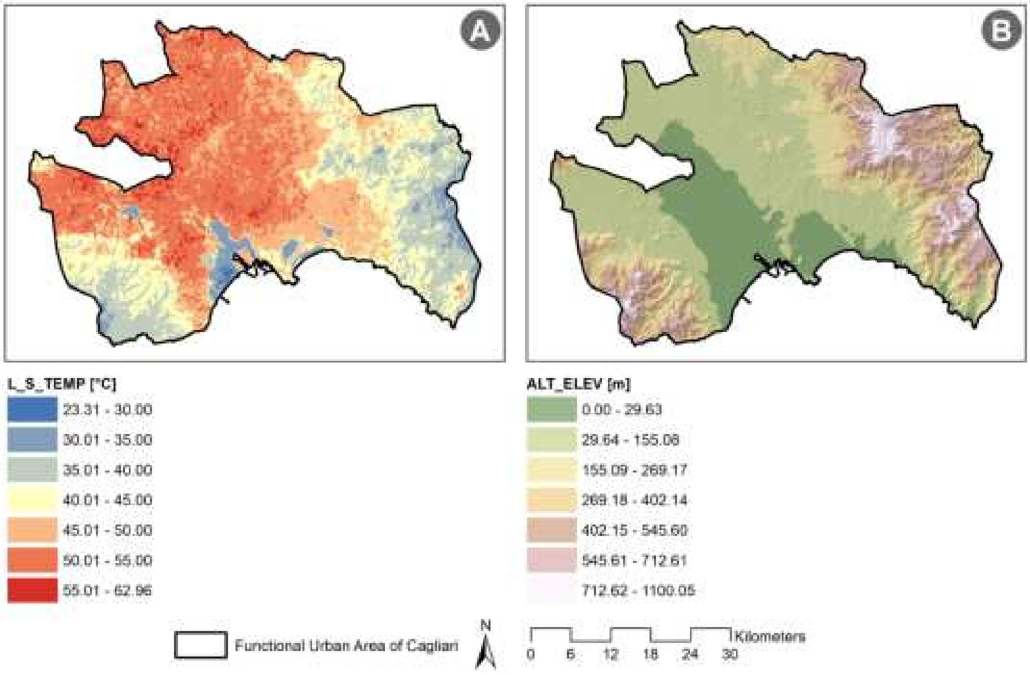

Figure 6. The spatial layout of the fifth selected ES (L_S_TEMP, Panel (**A**)) and of the elevation (ALT_ELEV, Panel (**B**)) in the study area.

Finally, Figure 6, Panel "B", depicts the spatial distribution of the only control variable used in the inferential model, i.e., elevation. The most prominent landscape feature in this map is the Campidano agricultural plain (green), which stretches diagonally from northeast to southwest separating the two mountain chains on the eastern and western edges of the FUA, which transitions into the coastal area with two wetlands surrounding the core built-up area of the municipality of Cagliari.

3.2. The Identification of the Urban Ecological Corridors

The methodological approach based on the LCP model consists of four steps. Each step provides an output. Figure 7 shows the land naturalness mosaic map (Panel A) and the ecological integrity values map (Panel B), the output of Step 1 and Step 2, respectively. Figure 8 shows the map of resistance values (Panel A), the output of Step 3, and the map of core areas, which shows the spatial identification of natural protected areas (Panel B).

Two are the results of the application of the methodological approach developed in this study and detailed in Section 2.2: a raster map of the CWD values and the linear identification of the UECs that connect natural protected areas within the FUA of Cagliari. Figure 9 shows the CWD values (Panel A) and the spatial identification of UECs (Panel B). Specifically, LM identifies 11 UECs, and the CWD values range from 0 to 108,760 km. CWD values are zero in the vicinity of the protected areas, while they take on maximum values in the northwest of the FUA, characterized by the presence of agricultural uses, and in the urbanized areas that correspond to the countries that are part of the study area.

Moreover, LM provides two indicators, which are CWD/ED and CWD/LCP [78,79]. The first indicator, calculated as the ratio of CWD to Euclidean distance, demonstrates the quality of the connection between two adjacent core areas. Low values of this indicator show high connection quality. The second indicator, calculated as the ratio of CWD to EC length, points to the average resistance of species movement along a given pathway. In this case, low values of the CWD/LCP indicator correspond to low resistance to species movement. Corridors nos. 8 and 4, which connect core areas nos. 3 and 8, and 2 and 3, respectively, show the lowest values of the CWD/ED indicator and, therefore, the highest quality of connection. Corridors nos. 9 and 10, which connect core areas nos. 4 and 5, and 5 and 6, respectively, show the highest values and, consequently, the lowest quality of connection. With reference to the CWD/LCP indicator, corridors nos. 8 and 4 show the lowest values and, therefore, the least resistance to movement; while corridors nos. 9 and 10 show the highest values and, consequently, the greatest resistance to movement. Figure 10 shows the core areas, categorized by type, with the UECs connecting them. For each identified UEC, Table 3 defines the protected areas it connects, identified by their name and area type, and shows the values for the two indicators, CWD/ED and CWD/LCP, for all identified corridors.

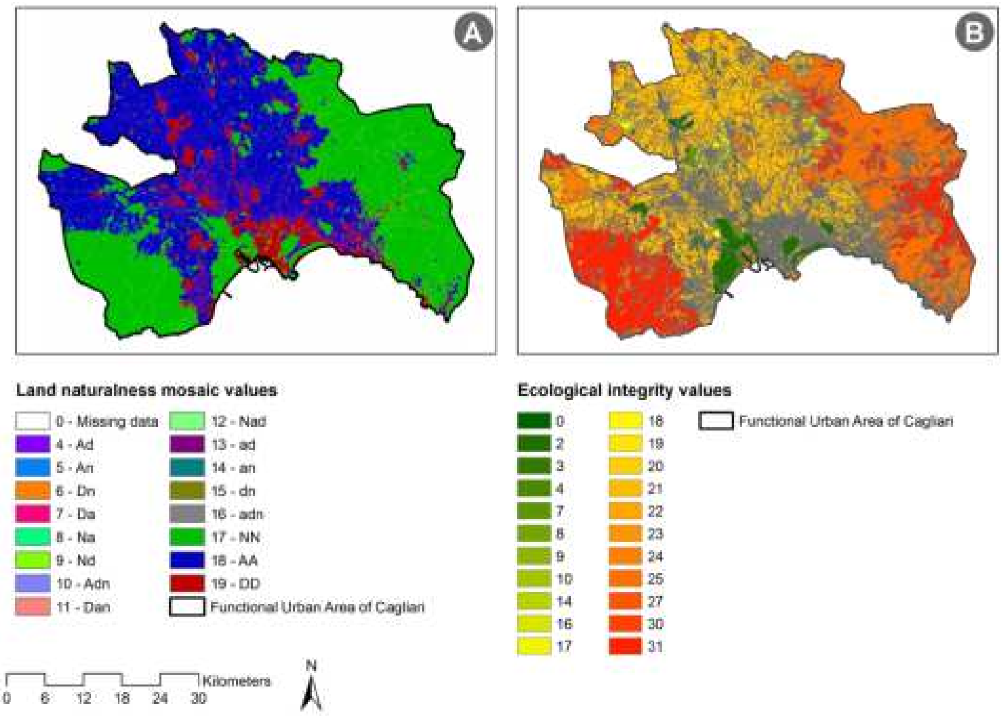

Figure 7. Land naturalness mosaic map (Panel (**A**)) and map of ecological integrity values (Panel (**B**)).

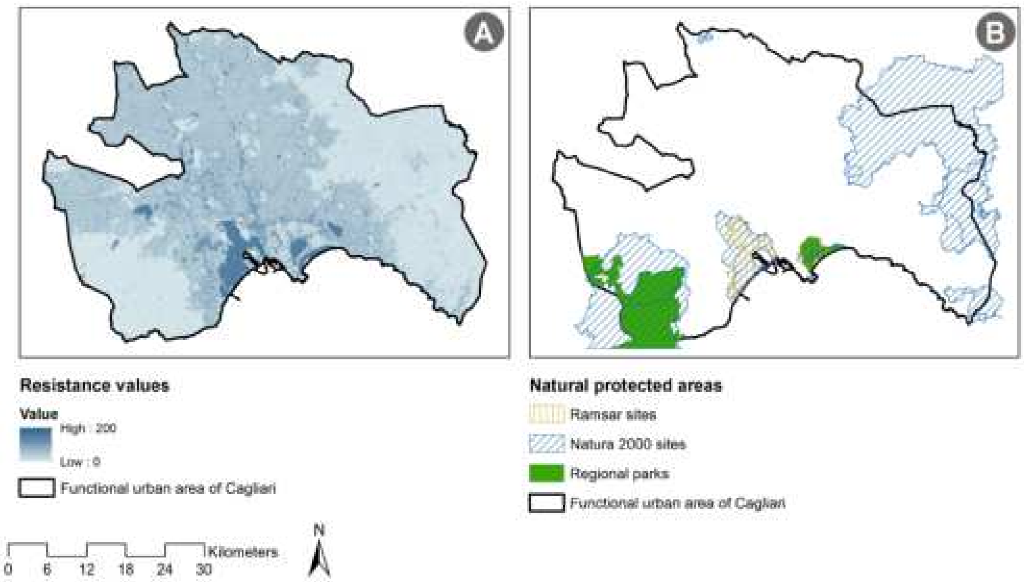

Figure 8. Map of resistance values (Panel (**A**)) and spatial identification of natural protected areas (Panel (**B**)).

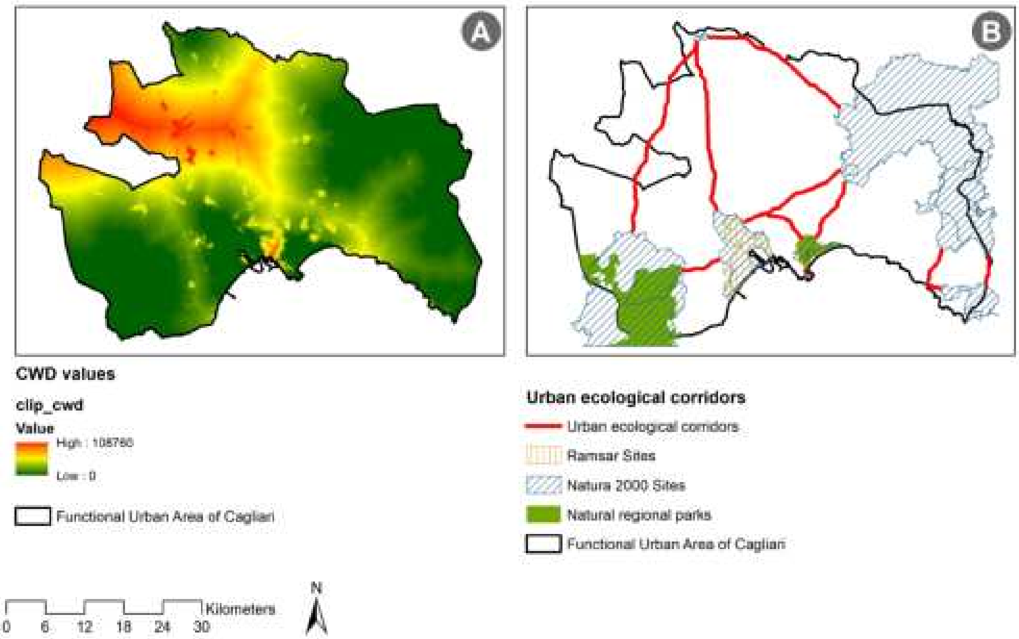

Figure 9. Map of CWD values (Panel (**A**)) and spatial identification of UECs within the FUA of Cagliari (Panel (**B**)).

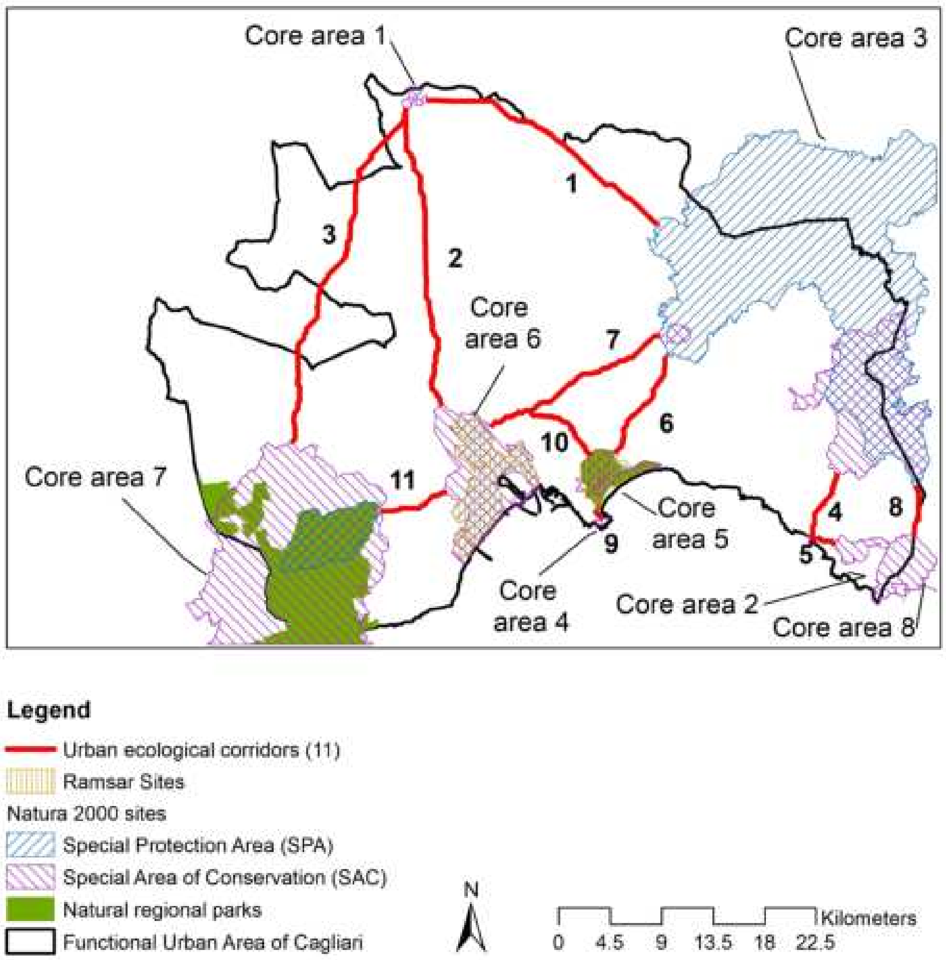

Figure 10. Spatial identification of UECs and core areas, classified in relation to their typology.

Table 3. Urban ecological corridors, name and typology of natural protected areas, and values of indexes CWD/ED and CWD/LCP.

UEC Code	Core Area Code	Name of Connected NPA	Typology of NPA	CWD/ED	CWD/LCP
1	1	Monte Mannu—Monte Ladu (colline di Monte Mannu e Monte Ladu)	SAC	4.15	3.83
	3	Monte Sette Fratelli	SPA		
		Monte dei Sette Fratelli e Sarrabus	SAC		
		Riu S. Barzolu	SAC		
2	1	Monte Mannu—Monte Ladu (colline di Monte Mannu e Monte Ladu)	SAC	5.40	5.06
	6	Stagno di Cagliari	Ramsar Site		
		Stagno di Cagliari	SPA		
		Stagno di Cagliari, Saline di Macchiareddu, Laguna di Santa Gilla	SAC		
3	1	Monte Mannu—Monte Ladu (colline di Monte Mannu e Monte Ladu)	SAC	4.93	4.45
	7	Foresta di Monte Arcosu	SAC		
		Foresta di Monte Arcosu	SPA		
		Parco naturale regionale di Gutturu Mannu	Natural regional park		
4	2	Bruncu de Su Monte Moru—Geremeas (Mari Pintau)	SAC	3.87	3.56
	3	Monte Sette Fratelli	SPA		
		Monte dei Sette Fratelli e Sarrabus	SAC		
		Riu S. Barzolu	SAC		
5	2	Bruncu de Su Monte Moru—Geremeas (Mari Pintau)	SAC	4.43	3.87
	8	Costa di Cagliari	SAC		
		Isola dei Cavoli, Serpentara, Punta Molentis e Campolongu	SAC		
6	3	Monte Sette Fratelli	SPA	5.49	4.83
		Monte dei Sette Fratelli e Sarrabus	SAC		
		Riu S. Barzolu	SAC		
	5	Saline di Molentargius	SAC		
		Stagno di Molentargius e territori limitrofi	SAC		
		Stagno di Molentargius	Ramsar site		
		Parco naturale regionale di Molentargius-Saline di Cagliari	Natural regional park		
7	3	Monte Sette Fratelli	SPA	5.63	4.52
		Monte dei Sette Fratelli e Sarrabus	SAC		
		Riu S. Barzolu	SAC		
	6	Stagno di Cagliari	Ramsar Site		
		Stagno di Cagliari	SPA		
		Stagno di Cagliari, Saline di Macchiareddu, Laguna di Santa Gilla	SAC		

Table 3. *Cont.*

UEC Code	Core Area Code	Name of Connected NPA	Typology of NPA	CWD/ED	CWD/LCP
8	3	Monte Sette Fratelli	SPA	3.51	3.26
		Monte dei Sette Fratelli e Sarrabus	SAC		
		Riu S. Barzolu	SAC		
	8	Costa di Cagliari	SAC		
		Isola dei Cavoli, Serpentara, Punta Molentis e Campolongu	SAC		
9	4	Torre del Poetto	SAC	13.85	10.02
		Monte Sant'Elia, Cala Mosca e Cala Fighera	SAC		
	5	Saline di Molentargius	SPA		
		Stagno di Molentargius e territori limitrofi	SAC		
		Stagno di Molentargius	Ramsar site		
		Parco naturale regionale di Molentargius-Saline di Cagliari	Natural regional park		
10	5	Saline di Molentargius	SPA	20.79	5.51
		Stagno di Molentargius e territori limitrofi	SAC		
		Stagno di Molentargius	Ramsar site		
		Parco naturale regionale di Molentargius-Saline di Cagliari	Natural regional park		
	6	Stagno di Cagliari	Ramsar Site		
		Stagno di Cagliari	SPA		
		Stagno di Cagliari, Saline di Macchiareddu, Laguna di Santa Gilla	SAC		
11	6	Stagno di Cagliari	Ramsar Site	5.18	4.23
		Stagno di Cagliari	SPA		
		Stagno di Cagliari, Saline di Macchiareddu, Laguna di Santa Gilla	SAC		
	7	Foresta di Monte Arcosu	SAC		
		Foresta di Monte Arcosu	SPA		
		Parco naturale regionale di Gutturu Mannu	Natural regional park		

Although the methodological approach used for the spatial identification of UECs does not take into account existing physical connections, the map of UECs is overlaid with vector maps of the water network and the road and pedestrian network to see if there is any correspondence. From the analysis conducted, it appears that in some cases, the UECs correspond to sections of the water networks and pedestrian areas. For example, Figure 11 shows two stretches of two identified ecological corridors that overlap the Riu Saliu (Panel B) and a large pedestrian area (Panel A) in one case, and a stretch Riu Is Cungiaus (Panel C) that starts from the part of the Molentargius Wetland called Bellarosa Minore.

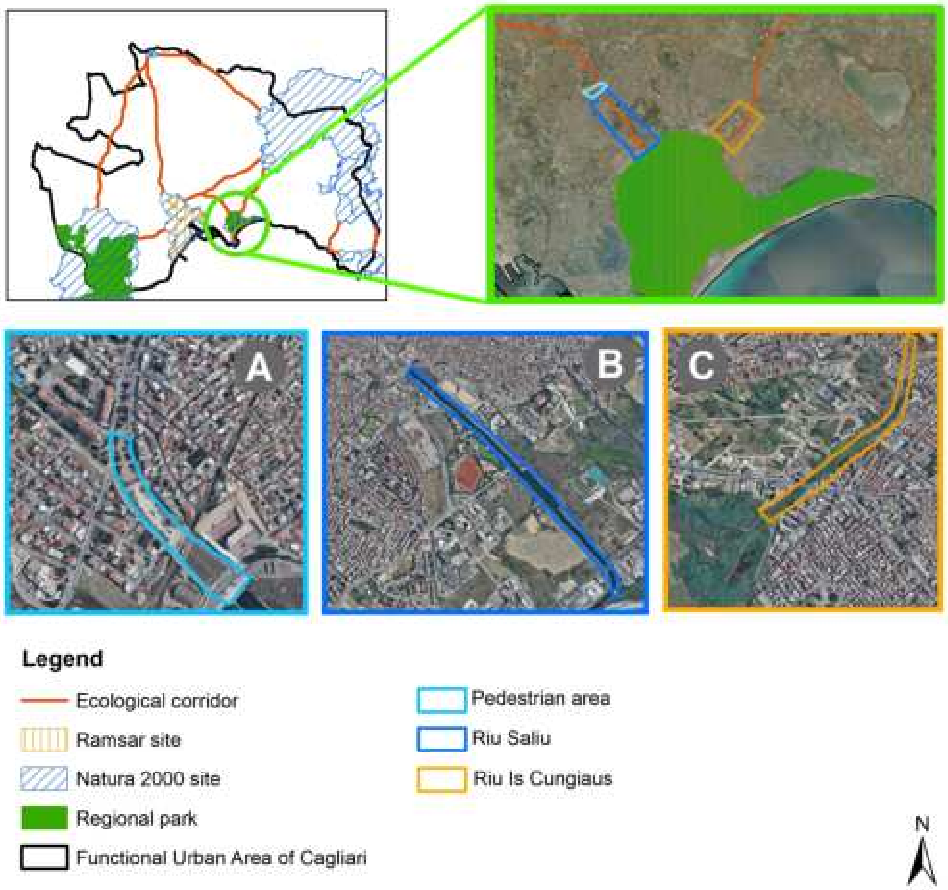

Figure 11. Examples where urban ecological corridors identified by the proposed methodological approach coincide with existing pedestrian areas (Panel (**A**)) and water networks (Panel (**B**,**C**)).

3.3. The Spatial Relations between Ecosystem Service Supply and Ecological Corridors

The results of the multiple linear regression (1) estimation are described in Table 4, which reports the marginal effects, in value and sign, of the variables expressing the supply of different ESs on CWD and the related *p*-values, key references for assessing the reliability of the estimates.

Table 4. Regression estimates.

Explanatory Variable	Coefficient	t-Statistic	*p*-Value	Mean of the Explanatory Variable	Elasticity at the Mean Values of CWD and Expl. Var's, Related to a 10% Increase in Expl. Var's [(Δy/y)/(Δx/x), %]
RECR_OUT	−0.019	−11.183	0.000	2059.537	−0.199%
FLD_CNTR	1.574	7.189	0.000	614.434	4.797%
CA_CP_ST	−2569.171	−19.302	0.000	1.044	−13.308%
HAB_QUAL	−4254.389	−28.333	0.000	0.466	−9.835%
L_S_TEMP	1728.278	237.612	0.000	46.143	395.542%
ALT_ELEV	−17.013	−78.048	0.000	205.219	−17.317%

Dependent variable: CWD: Mean: 20,161.61 km; Standard deviation: 21,180.06 km; Adjusted R-squared: 0.436.

For the reading and description of the results, it is important to recall how the suitability of a patch to be part of a UEC located in the FUA of Cagliari increases as CWD decreases and how, therefore, the negative sign of the estimated coefficient in the regression implies a positive impact on this suitability by the variable to which the ES refers and vice versa.

The outcomes of the multiple linear regression (1) show significant *p*-values. Thus, the estimated coefficients are to be considered reliable references of the relationships between CWD and the supply of ESs that the associated variables represent. An effective representation of the CWD behavior concerning the supply of different ESs is given by the elasticities of the CWD (with respect to the supply of different ESs). These elasticities are given in the last column of Table 4 and are calculated at the mean values of the CWD and of the supply of different ESs, for a 10 percent increase in the supply, that is, of each explanatory variable.

While all of the estimated coefficients are significant in terms of *p*-values, the impact of an increase in the supply of the ESs associated with them on CWD is definitely quite diverse. It can be seen that a 10 percent increase in the average L_S_TEMP would generate a fourfold increase in CWD, meaning that ESs that decrease L_S_TEMP are particularly effective in making a patch eligible to be recognized as part of a UEC. Equally effective in this direction are the carbon capture and storage service (variable CA_CP_ST) and habitat quality (variable HAB_QUAL), where a 10 percent increase in supply is associated with a decrease of about 13 percent and 10 percent in CWD, respectively, which shows that they go, essentially, in the same direction, in terms of proportion, the strengthening of UECs in the FUA of Cagliari, and the availability of ESs for carbon capture and storage and habitat quality.

Regarding the relationship between CWD and ES related to the supply of recreational services, we show that the negative impact of RECR_OUT on CWD is positive in relation to the eligibility of a patch to be included in the UGI, with an elasticity of about 2‰. Since variable RECR_OUT comes from the percentage share of the area available for outdoor recreational activities times the resident population in a buffer of 500 m, it must be noted that an average 10 percent increase in recreational area at the average value of resident population (2057 residents) in a 500 m buffer of census tracts (2057 residents) is associated with a decrease of 11,151 m in CWD, which identifies a 52.69 percent decrease in CWD at its mean value. The provision of recreational services within the FUA of Cagliari is, thus, configured as significantly relevant.

With regard to flood control, i.e., the ES associated with water retention capacity, the estimated coefficient reports an increasing trend in CWD in relation to supply (variable FLD_CNTR), with an elasticity of just under 5 percent. It shows how the suitability of a patch to be included in a UEC of the FUA of Cagliari is associated with low values of water retention, or, in other words, how the greater presence of permeable surfaces in urban areas is associated with a loss of connectivity of patches.

Finally, the coefficient of altitude, taken as a control variable, indicates how land elevation is negatively correlated with CWD; therefore, how increasing altitude is associated with an increase in the suitability of patches to be part of UECs, everything else being equal. This result is related to the fact that, at altitude, connectivity between patches in the FUA of Cagliari is facilitated by the lower presence of road infrastructure, which makes the coefficient estimate of ALT_ELEV consistent with expectations. In addition, at higher altitudes, connectivity is likely to be enhanced by the more structured presence of scrub or woodland vegetation.

4. Discussion

The outcomes presented in the previous section are discussed here in light of significant experiences offered in the current literature, highlighting their similarities and differences. The section maintains the layout of the previous two and is, therefore, divided into three parts: the first referring to the characteristics of UGI, the second concerning UECs, and the third focusing on the contributions of the different ESs, which structure the taxonomy of UGI, to the construction of UECs.

4.1. The Spatial Taxonomy of the UGI

The findings from this study contribute to the literature on the significance of green spaces in urban and peri-urban areas in supplying multiple benefits, particularly when it comes to recreational and regulating services.

As for the recreational ES and in line with the outcomes of a study by Larondelle and Haase [80], neither an urban-rural gradient [81] nor a U-shaped distribution, where outdoor recreation decreases from the urban to the peri-urban area and then increases from the latter to more natural spaces [82], has been observed here. In the FUA of Cagliari, built-up areas are critical in this regard as blocks having extremely high values are interspersed within blocks whose resident population does not have access to green areas in their proximity; this highlights issues of distributional justice as to uneven and unequitable access to natural resources [83,84]. On the other hand, in the peri-urban and rural parts of the FUA, the key factor is the presence of potential beneficiaries in the proximity of service-providing areas because the indicator here used to assess daily outdoor recreation accounts for both supply and demand, hence the potential flow of this ES. As a result, in this study, the nature-based recreation indicator increases along with the number of beneficiaries, which also entails that it is driven by population growth in both urban and rural areas, consistent with previous studies [85]. Moreover, the spread of agricultural areas leads to decreasing provisions of this ES, whereas higher potential supplies are associated with urban expansion and the intrusion of urbanization into natural spaces. Additionally, in some rural parts of the FUA, the indicator paradoxically increases as a consequence of land-taking processes; these spur higher accessibility to green and blue areas [86] and might be associated with the ever-increasing demand for living closer to nature and for daily outdoor recreation [87]. Therefore, integrated planning policies and tools in the FUA of Cagliari could play a crucial role in balancing the impacts of urbanization in peri-urban and rural areas provided that they take a holistic perspective that bridges, and goes beyond, the sectoral approaches of urban and rural development plans [88]. Such policies should also foster appropriate management of rural and peri-urban areas, for instance, by ensuring that amenities and facilities that foster nature-based activities and attract walkers and cyclists are in place [23,89].

As for regulating ESs, the spatial pattern of carbon storage and sequestration and of habitat quality shows, consistent with expectations [90], a clear gradient from artificial to agricultural to natural land cover types. In the former case, this results in a smooth transition of the ES provision from urban to peri-urban to rural and forestry areas; in the latter case, the adjacency of the core built-up area of Cagliari to the two main wetlands in the FUA, both having high HAB_QUAL values, leads to a U-shaped urban-rural-natural gradient.

A deviation from the expected monotone urban-rural gradient is apparent in the LST regulation map where the rural part coinciding with the agricultural plain shows values similar to, and even higher than, the urban built-up core area of Cagliari and its hinterland. Counterintuitive as it might appear and challenging the general assumption that the provision of ESs correlates with the degree of imperviousness [90], this finding is consistent with previous studies concerning arid or Mediterranean regions [91–94]: in summer in Sardinia, once herbaceous crops are yielded, the loss in biomass leaves the soil bare and akin to impervious surfaces, hence with high LST values. Additionally, other mitigating factors in urban areas that might contribute to this counterintuitive pattern in the FUA of Cagliari are the shadows of the buildings [95–97] and ventilation corridors along streets enclosed between high-rise buildings [98], as well as the adjacency of the seaside and of two large wetlands to the core built-up area of Cagliari and its hinterland, due to the role of blue infrastructure in mitigating local temperature [99,100].

With reference to the spatial distribution of flood retention, it is important to underline that this ES is driven by two key factors: on the one hand, land cover as an indicator of the properties of vegetation and ecosystems, which affect water interception; on the other hand, soil properties such as texture and porosity, which control water infiltration [101]. Moreover, also some characteristics of the surface runoff [101], such as the topography of the area, which governs the watershed layout, or the geo-lithology, play a role. These factors affect the urban-rural gradient observed in the FUA of Cagliari where the flood regulation performed by agricultural fields on permeable soils is comparable with that of forests on rocky hills and mountains. The significance of farmland on water retention has been highlighted in some previous studies (for instance [102]), whereas, everything else being equal, forests are usually found to perform better than agricultural areas (as, for example, in [103]). Therefore, because forests tend to regulate floods better than farmlands, afforestation of grasslands and agricultural spaces, especially in peri-urban areas, has often been advocated as a nature-based solution to counter floods in a climate adaptation perspective. The findings from this study entail that the afforestation policy should not be understood as a one-size-fits-all solution with regard to flood management, in line with [104]. Moreover, pluvial flood retention in built-up areas in the FUA of Cagliari takes extremely low values: if urban development and the spread of artificial land are substantial drivers of flood magnitude and frequency worldwide [105], then planning policies should be oriented toward increasing interception through green interventions in urban areas, as well as enhancing infiltration through de-sealing practices and maintenance of permeable soils.

Finally, the spatial patterns of the five selected ESs shown in Section 2.2 offer evidence that the co-occurrence of high values in all the ESs cannot be found in any area of the FUA, meaning that no part of the FUA can be regarded as an optimal providing area [80], which highlights a sort of spatial specialization of the various types of green and blue spaces [23] and calls for a careful planning and management and a “creative use” [106] of the UGI to ensure the maintenance of its multifunctionality.

4.2. The Identification of the Urban Ecological Corridors

The methodological approach used in this study to identify UECs provides two results: the map of the spatial configuration of UECs and the map of CWD values. In relation to the ecological corridor concept, this study focuses on UECs, which have slightly different characteristics than the classical ECs assessed and studied at the regional or national scale. First, UECs play a key role in providing connectivity between isolated patches by easing species flows in urban environments [107]. In addition, within cities, UECs also provide cultural services, such as outdoor recreational activities, by increasing awareness about the value of place and enhancing the aesthetic value of places [108,109]. The cultural and social aspects are less investigated than ecological values. Xu et al. [110] analyzed the existing literature about the cultural and recreational functions performed by UECs. Their study focused on the analysis of 92 corridors, which exert both an ecological and a cultural function, in relation to several aspects such as the approaches and tools used for their identification. The spatial definition of UECs exerts an impact on both ecological processes [107] by reducing spatial conflicts between biodiversity conservation and protection and urban development instances [111], as well as on social and recreational aspects [110].

In the current literature, several methods are used to define UECs. Peng et al. [50] compared different methods used to assess connectivity and identify UECs in urban settings. According to their study, suitability/sensitivity analysis uses computational indices to evaluate suitability and sensitivity that go beyond the subjectivity and arbitrariness that characterize empirical assessment methods. On the other hand, the lack of standardized evaluation indices does not allow for the identification of suitability thresholds. Network analysis allows us to assess connectivity and identify UECs taking into account the characteristics of landscape matrices. However, network analysis fails to assess different functions that characterize individual patches. The LCP model is widely used in the literature to identify potential UECs by identifying the paths that show the least resistance to movement between two adjacent areas characterized by high ecological values [112,113]. The main advantage of this method concerns the capacity to combine landscape components with ecological functions and processes [50]. However, the LCP model provides linear identifications and potential directions of UECs [114,115] without giving any indication of the width of the corridors [116]. In relation to the study's goal of analyzing the relationship between UECs and the supply of different types of ESs in them, the LCP model has been evaluated as the most suitable as it takes into consideration the functions of individual patches.

In terms of results, CWD values are lower in areas characterized by the presence of natural protected areas. This result is not surprising since these areas are characterized by a high degree of naturalness and by a high value of ecological integrity. In a study developed by Isola et al. [61], the relationship between ecological corridors and landscape components classified as environmentally relevant by the Sardinian Regional Landscape Plan is assessed through a multiple linear regression analysis. The study highlights that landscape components characterized by the presence of forests, corks, and chestnut groves are the most likely to improve the effectiveness of ECs. Natural protected areas, in which zero or very low values of CWD are recorded, represent zones characterized by the forest land cover. In addition, the study conducted by Zhang et al. [116] on the relationships between the spatial structure and the functional connectivity of UECs shows that CWD is a useful indicator for assessing the length of UECs. In fact, UECs are identified by taking into account both the length of the pathway and the resistance per unit distance along that pathway. Consequently, high CWD values in an urban area may be determined by two factors: the length of the distance between pairs of patches with high ecological values and the presence of impediments and/or obstacles along the path. Protected natural areas definitely have fewer impediments such as roads or sealed surfaces than urbanized areas.

The system of connectivity defined through the application of the methodology is characterized by a substantial endowment of equipped urban green spaces considered by a link of continuity and the presence of quality vegetation they generate. The approach made it possible to model landscape connectivity according to the degree of naturalness [117]. As several studies show, actions to protect and restore high-nature areas that maximize the co-benefits of carbon storage and connectivity have the capacity to significantly contribute to the achievement of greenhouse gas emission reduction targets and biodiversity conservation [118]. Consequently, it is necessary to implement planning processes that ensure the preservation and continuity of connectivity of UGIs as an essential element in the management of healthy ecosystems that can conserve biodiversity, sustain key ecological functions [119], and ensure the maintenance of multifunctionality.

In this sense, the spatial distribution of UGIs serves as an important element, considering that the LCP model provides the linear identification and potential direction of ecological corridors. From the perspective of possible future research developments, the identified spatial connectivity systems can represent the elements on which to base the zoning and location of areas designated for standards in urban planning processes. With reference to the territory of the Cagliari FUA, the effects due to the rapid anthropogenic expansion of the metropolitan area in recent years have led to consequent phenomena of habitat fragmentation [120]; an approach based on the development of ecological corridors through a structured system of green spaces [121] can represent a concrete example of green infrastructure. Consistent with the principle of connectivity, UGIs' effectiveness in providing services and benefits when they are embedded in a physically connected system through the landscape represents a concrete example—not only ecological connectivity as an element to be protected but a system of connections on which to base the future spatial transformation of the territory, i.e., a transformation based on elements that direct urban development from the perspective of functional habitat protection to the maintenance of ecological security and non-fragmentation of the territory.

4.3. The Spatial Relations between Ecosystem Service Supply and Urban Ecological Corridors

The significant link between CWD and L_S_TEMP, highlighted by the outcomes of this study with regard to the FUA of Cagliari, is in line with the results that Gao et al. [122] obtained from the analysis of the correlation between spatial connectivity and L_S_TEMP in the urban context of Wuhan, China. This characteristic of patches is evidenced by an index of connectivity between urban heat island generating sources and areas characterized by the absence, or very low levels, of ES provision. This is, also, an index of spatial connectivity between areas characterized by significant ES provision. In the Wuhan-related study, an increase in the SCSS Index (spatial connectivity between patches of the heat source and sink) of 10 percent is estimated to be associated with a decrease in LST of about 1 °C. This is consistent with what is implied by the coefficient estimate of L_S_TEMP in (1). This outcome of the regression analysis is as follows: at the mean temperature, there is a decrease of 1 °C, or about 2.2 percent, with an increase in CWD of about 9 percent. The recent study by He et al. [123] concerning the relationship between the spatial taxonomy of LST and the shape and extent of blue and green urban infrastructures in the Shanghai metropolitan context also identified a close correlation between the decrease in temperature and the extent and relative shape index, which is related, in decreasing terms, to the level of fragmentation of these infrastructures, spatial hotspots of ES provision in the urban context. These outcomes are in line with studies by Zhang et al. [124] and Zhao et al. [125] related to the Chinese cities of Xuzhou and, again, Wuhan. Carbon capture and storage is an ES closely related to the continuity of green spaces in urban settings and, thus, to the effectiveness and robustness of the urban structure of UECs. This result is presented and discussed with regard to the spatial distribution of green spaces and urban ecological networks by Valente et al. [126], with reference to the landscape service index spatial taxonomy implemented for the city of Lecce, in South Italy. There is a profile of relevance in relation to the functional link between carbon capture and storage supply by UECs, represented by the fact that the main feature of these corridors is the supply of equipped urban green spaces, characterized by the presence of quality vegetation, which generates significant availability of carbon dioxide sequestration. This aspect is discussed in detail in several studies available in the literature, including, for example, those by Lv et al. [127] and Zhang et al. [128], related to ecological restoration in Southwest China, with particular references to karst zones. In line with these observations are some findings from a study by Floris and Zoppi [46], according to which, first, there is evidence of a negative correlation between temporal variation in the land-taking process and the carbon capture and storage capacity, and, therefore, a close connection between urban sprawl and increased land take (Stachura et al. [129]). Second, it is noted that the reduction in the carbon capture and storage capacity, as a consequence of the process of land consumption, is significant in quantitative terms. From this point of view, the study by Floris and Zoppi [46] offers evidence of how the presence and size of protected areas (which, in this study, represent the heads of UECs) limit urban sprawl and, therefore, land take—these are important factors in preserving and, possibly, improving the carbon sequestration capacity [130,131]. Regarding the link between the spatial taxonomy of habitat quality (variable HAB_QUAL) and the suitability of spatial parcels to be recognized as being part of UECs, Lai et al. [132] highlight the importance of two key factors. First, there is a reduction in environmental threats associated with activities such as the renaturalization of impervious land due to urban expansion, the land use change for both legal and illegal landfill areas, the enhancement of city woodlands, the control of fallow zones, and the displacement of industrial settlements. Second, the processes of soil degradation and land cover change that lead to lower habitat quality are of minor importance [133,134] as habitat quality largely depends on soil quality. These findings are corroborated by other articles. He et al. [135] suggest a model to estimate the effect of land cover transitions on habitat quality by combining cellular automata with simulations concerning future scenarios and the InVEST habitat quality tool. Their findings recommend two policy strategies to enhance habitat quality: reducing urban sprawling phenomena by controlling the growth of urbanized areas and implementing balanced agricultural policies to curb the spread of scattered rural residential villages, which diminish habitat quality in neighboring spatial contexts. Sallustio et al. [136] developed a methodological approach to assisting policy-makers in selecting environmental protection areas and addressing habitat quality and soil decay with regard to the current Italian normative framework concerning environmental conservation. Their research indicates that habitat quality declines as proximity to densely populated areas increases, and it also diminishes close to intensive croplands where conservation rules are less stringent.

The outcomes, presented and discussed here with regard to the correlation between CWD and spaces for recreational activities (RECR_OUT), are in line with a recent study by Song and Liu [137] whose findings, related to the reticular pattern of movements for the performance of leisure activities, show that these are related to the availability of urban equipped green spaces accessible, preferably, without transportation. The article highlights how this association of public equipped green spaces with UECs as neighborhood connection spaces has also become more pronounced as a result of the inertia of habits associated with the pandemic emergency period, characterized by the fact that the feeling of safety with respect to the danger of contagion is accentuated in open green spaces that, at the same time, allow for multiple recreational activities and the maintenance of reassuring distances between users. The perceived relevance of outdoor recreation spaces, identified as networks of nodal areas and UECs in relation to the quality of urban life, and the strengthening of their structure as an effective approach to its improvement, are emphasized by Park [138], with reference to the Phoenix metropolitan area. Park highlights how much the perception of the local communities is influenced by the greater or lesser sensitivity of public opinion to the issues of protection and proper enjoyment of urban open spaces, a sensitivity that is boosted, within the most sensitive communities, with regard to recreational activities of hiking and contact with wildlife. Based on a virtual landscape experiment, Richards et al. [139] recognized the importance of building or restoring ecological connections to increase the attractiveness of outdoor recreational activities, especially sports and relaxation-related activities, concerning areal units characterized by land cover types that are particularly valuable in terms of providing ESs, such as forests, woodlands, and native vegetation, especially when located near waterways or wetlands.

Finally, in relation to the variable of runoff control (FLD_CNTR), it has already been noted that the estimated coefficient, shown in (1), reports an increasing trend in CWD. This result is related to the fact that SHGs that characterize patches with higher eligibility for inclusion in UECs—patches that have comparatively lower values of CWD—are associated with higher values of runoff (SHGs labeled "C" and "D," see Section 2.2). In other words, patches characterized by comparatively higher values of land cover with the presence of forests, woodlands, and native vegetation, associated with higher values of the supply of ESs related to outdoor recreation, carbon capture and storage, habitat quality, and LST control, are characterized by comparatively lower values of flood control when the soil types associated with these covers have a comparatively lower capacity for water infiltration (slow or very slow rates of water infiltration). This result is not generalizable and is related, in specific terms, to the characteristics of the FUA of Cagliari. A rigorous analysis of runoff recognition based on so-called curve numbers and on the spatial taxonomy of SHGs in the Little Eagle Creek Watershed (Nevada) is described and discussed by Lim et al. [140] whose findings confirm how runoff patterns are site-specific. The considerable complexity of the relationships between soil cover, SHGs, and runoff size is discussed by Jordán et al. [141] who point out the significant heterogeneity of runoff size, in relation to soils and soil covers, with reference to the environmental context of the Sierra de Ojén, in Los Alcornocales Natural Park (Southern Spain). The same features of heterogeneity are found in the results of the study by Stewart et al. [142] concerning 30 watersheds in Arizona and New Mexico. In this case, the results are characterized by significant uncertainty related to the incomplete knowledge of SHGs and the consequent uncertainty in identifying the spatial taxonomy of curve numbers.

The effectiveness of the methodology implemented in this study is highlighted by comparison with these results. Indeed, in the case of the relationship between spatial connectivity and LST, it should be emphasized that while the outcomes referring to the spatial contexts of the Wuhan and Shanghai metropolitan areas are based on the axiomatic assumption that SCSS and shape indexes constitute effective measures of connectivity, the methodological approach used here is not based on a priori assumption, but, exclusively, on relationships between CWD and representative variables of ESs supply, surveyed locally through coefficient estimates of a multiple linear regression [76,77]. The outcome of this study, which does not derive from a priori assumptions, is consistent with Gao et al.'s [122] and He et al.'s [123], thus pointing out a character of greater generality than the Wuhan and Shanghai cases.

As in the case of the relationship between connectivity and ES concerning LST mitigation, the substantial convergence of the results obtained in this article with those of other studies, applied to urban and metropolitan contexts, implemented through different methodological approaches [135,136], is also evident with respect to carbon capture and storage and habitat quality improvement.

Finally, with regard to RECR_OUT, the results of the cited studies [137–139] are consistent with the implementation of the methodology proposed here, concerning the relationship between the connectivity between nodes and edges of the UGI of the Cagliari FUA and the supply of the ESs referred to the endowment of spaces for outdoor recreational activities related to the pedestrian accessibility of the urban green areas. The outcomes of this implementation show how UECs play a role of particular relevance in the FUA of Cagliari, with regard to the connectivity of spaces for outdoor recreation in relation to the mitigation of landscape fragmentation to be attributed to the conspicuous presence of sealed areas, as well as to increasing resilience against multiple physical impediments, such as buildings and their appurtenant lots, roads and infrastructure of various kinds. If, however, UECs do not generate a complete continuity of spaces for outdoor recreation, they, nevertheless, make available a significant supply of ESs, such as the improvement of air quality associated with the presence of surfaces rich in vegetation and trees, whose positive impact is amplified in the FUA of Cagliari if not by continuity, then, at least, by the close contiguity of patches. This observation is consistent with the studies by Lee et al. [143] concerning the urban context of Gwacheon, South Korea, and by Samways et al. [144] related to South Forestry production.

5. Conclusions

As pointed out in the Introduction, the general objective of this study is to offer a contribution to filling the research gap reported by Sandström, Tzoulas et al., and Breuste [7–9] in relation to the lack, in scientific and technical literature, of a theoretical and operational definition of UGI, which identifies it in general terms, thus, in a manner distinct from the conceptual category of GI. In the wake of this general objective, the methodological approach for the identification of UGI, implemented with reference to the Cagliari FUA, is developed in three steps. Of these, the first consists of the identification of the spatial taxonomy of the supply of a set of ESs, the outcome of which is proposed as a kind of dashboard of urban quality of life understood as a complex system of benefits for local society based on the production of multiple services generated by nature. These ESs are identified in the provision of space for outdoor recreation, runoff control, carbon capture and storage, quality of flora and fauna habitats, and urban heat mitigation. Next, the spatial structure of the UGI is interpreted as a network of nodes and edges, in which the former is represented by areas that, due to their naturalistic value, are subject to an environmental protection regime. The edges, which are made up of linear elements, the UECs, are marked by a high degree of urban connectivity related to the supply capacity of ESs. Finally, in the third stage, the UECs are characterized in relation to the supply of the different types of ESs in order to identify their impact in terms of spatial connectivity in the urban environment.

So, in relation to the construction of a theoretical and operational definition of UGIs, in terms of the general objective of this study, the results obtained for Cagliari's FUA allow, in an effective way, for recognizing the relevance of the quantitative profile related to urban public green spaces, which constitutes a very significant instance in relation to the definition and implementation of urban planning policies. The function of the endowment of green spaces, whether tree-lined or forested, linked by UECs, should, therefore, be taken as a structural reference for urban policies. These policies should plan for a significant and widespread increase in urban green spaces, including the identification and enhancement of UECs as key connective elements of UGIs.

The methodology developed here is configured as exportable to other urban contexts, particularly those identified as FUAs. The supply of ESs and the consequent identification of UGIs can be replicated with reference to other FUAs, especially taking into account that the ES supply framework, on which the identification of the FUA of the Cagliari UGI is based, constitutes an effective matrix in general terms, although not exhaustive. The spatial database on which the UGI of the Cagliari FUA is based also consists of data generally available in the urban contexts of the FUAs, such as the urban contexts of the OCDE countries.

With reference to the identification of UECs, in the case of the UGI of the Cagliari FUA, there is evidence of a substantial endowment of connecting spaces between the nodes of the UGI, suitable for constituting a robust plot of UECs. When applying the methodology to identify UGIs of other FUAs, this aspect should be carefully considered in problematic and assertive terms as UECs are fundamental structural elements for the ontology of UGIs, and the lack of adequate connections between UGI nodes could compromise their identification and functioning.

The limitations of the proposed methodological approach are tentatively represented by the following profiles. First, the set of ESs used to identify the UGI and its related UECs, which deterministically defines its spatial structure in terms of the supply of ESs, is limited to five types in the experiment proposed in this study. There is no doubt that an expansion to new types of ESs in the spatial database would make it possible to structure UGIs in an increasingly broad and comprehensive manner, in terms of a knowledge base for effectively reading the determinants of urban quality of life. For example, in the case of this study, we highlight the lack of ESs related to agricultural production and livestock farming and the availability of cultural, historical, and archaeological assets.

A second profile concerns the quality of the data. It is evident how information on the supply of ESs for outdoor recreation, carbon capture and storage, and runoff control is not based on primary survey data, the availability of which is not given, but on estimates based on secondary data. According to this second profile, it should be pointed out, that in the case of carbon capture and storage, an important piece of information, which would help to complete the picture of the effectiveness of this ES and which, at the moment, is not available for the Cagliari FUA, is the spatial identification and quantitative size of carbon dioxide emissions.

Finally, it should be emphasized that the results of this study indicate, in terms of spatial policies, how it is highly desirable to overcome the approach, unfortunately still widespread in the planning offices of local public administrations, which considers, in the city's analysis and planning processes, the arrangement of ESs as subordinate to that of built-up areas. In other words, it would be desirable that the maximization of land rent be progressively replaced as the fundamental lever for planning the city's possible and desirable futures by maximizing the effectiveness of UGIs, recognized and analyzed in detail, in terms of the urban spatial system. The maximization of this effectiveness is identified with the maximization of the supply of ESs provided by UGIs. The latter profile also signals how the availability of direct observations, largely unavailable, would certainly improve the reliability of assessments and the potential for translating the results of spatial analyses into operational spatial policy terms, with reference to the awareness building of local communities.

Two promising avenues for future research development can, therefore, be recognized. First, a refinement of the methodology for identifying UECs would be desirable, including a comparative analysis of the results of this study with those derived from the methodologies mentioned in Section 2.3. Second, it would be very important for the methodology for identifying UECs to be refined as reported in terms of limitations. In particular, it would be very important to critically reconsider the set of ESs assumed in this study for the identification of UGIs in the Cagliari FUA, refining the methodological approaches used to assess the supply of Ess, and possibly including new types of ESs.

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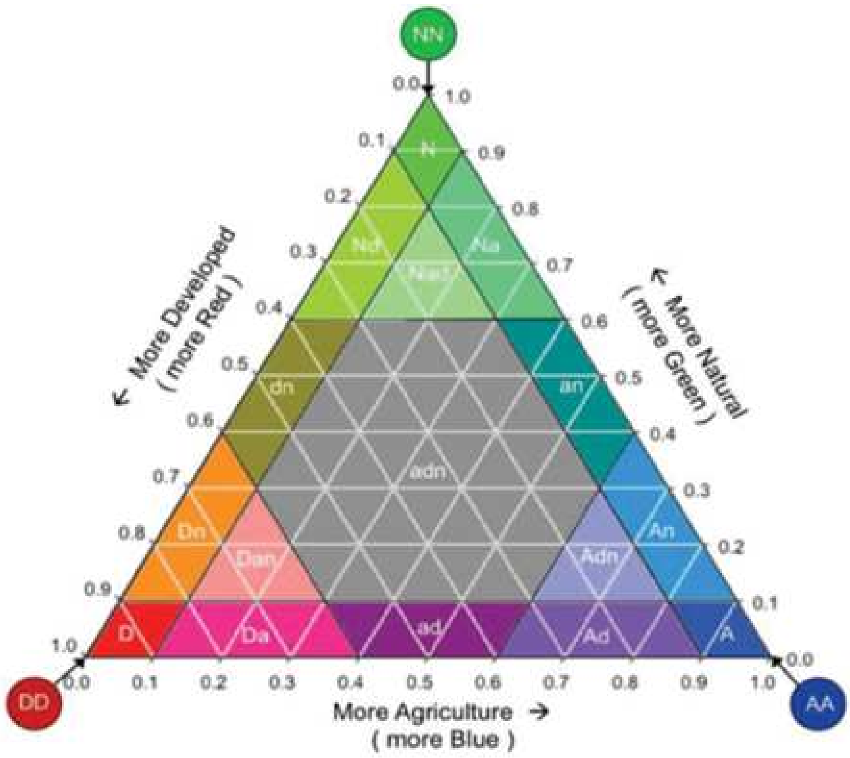
Appendix A

LMM is based on a tripolar classification scheme where a given patch is classified by taking into account the influence exerted by patches placed within a window surrounding that patch. All patches are classified in relation to three land covers, that is, agricultural, natural, and artificial. This methodology has been used in several studies [145–148] and is implemented through the Guido Toolbox (Graphical User Interface for the Description of image Objects and their shapes—GTB) 3.3. [149], a free and open-source software, developed by Vogt, that offers a comprehensive range of general raster image processing functions [150]. LMM classifies the land surface into 19 classes defined in relation to three threshold values, 10%, 60%, and 100%, which indicate the presence, the dominance or the uniqueness of a land cover class, namely, agricultural, natural, and artificial. Figure A1 shows the tripolar classification scheme where each axis represents one of the three land covers, and the three vertices correspond to the uniqueness of a land cover type. Each class is identified by the initial letters of each land cover. The letter "A" or "a" identifies agricultural cover, the letter "N" or "n" natural cover, and the letter "D" or "d" artificial cover. The capital letters indicate that the corresponding land covers contribute a value equal to, or greater than, 60% but lower than 100%. The lowercase letters indicate that corresponding land covers contribute a value equal to, or greater than, 10% but lower than 60%. The non-presence of letters indicates that the corresponding land covers contribute less than 10%. In the map obtained by applying the LMM, each pixel shows three values indicating the contribution of the corresponding land covers (agricultural, natural, and artificial) [68]. The final map was developed by assigning each of the 19 classes a value ranging from 0 to 1, where 0 represents maximum artificialization, while 1 represents maximum naturalness.



Value [byte] - Class Name	Color	RGB
0 - Missing		255/255/255
1 - A		000/000/255
2 - D		255/000/000
3 - N		000/255/000
4 - Ad		128/000/255
5 - An		000/128/255
6 - Dn		255/128/000
7 - Da		255/000/128
8 - Na		000/255/128
9 - Nd		128/255/000
10 - Adn		128/128/255
11 - Dan		255/128/128
12 - Nad		128/255/128
13 - ad		128/000/128
14 - an		000/128/128
15 - dn		128/128/000
16 - adn		128/128/128
17 - NN		000/191/000
18 - AA		000/000/191
19 - DD		191/000/000

Figure A1. Tripolar classification scheme of LMM displaying 19 classes and their proportions of the three land covers. Source [68] p. 33.

Appendix B

CWD along a path between two areas is obtained through a three-step process: (i) average of the values of the resistances between pairs of adjacent cells; (ii) product between the average of the resistance values and the geometric distance between pixels [151]; and the sum of all products along the path. Once CWD is calculated, LPT identifies the LCP between two core areas, A and B, through the following formula:

$$ND_{iAB} = CWD_{iA} + CWD_{iB} - LCWD_{AB}$$

where:

- ND_{iAB} represents the normalized distance between core areas A and B measured along a path that passes through patch *i*;
- CWD_{iA} e CWD_{iB} are the CWDs between patch *i* and core areas A and B, respectively;
- $LCWD_{AB}$ is the minimum CWD that is the CWD calculated along the LCP that connects A and B [152].

UECs are identified as the pathways in which ND is equal to zero.
Figure A2 provides a visual explanation of the process.

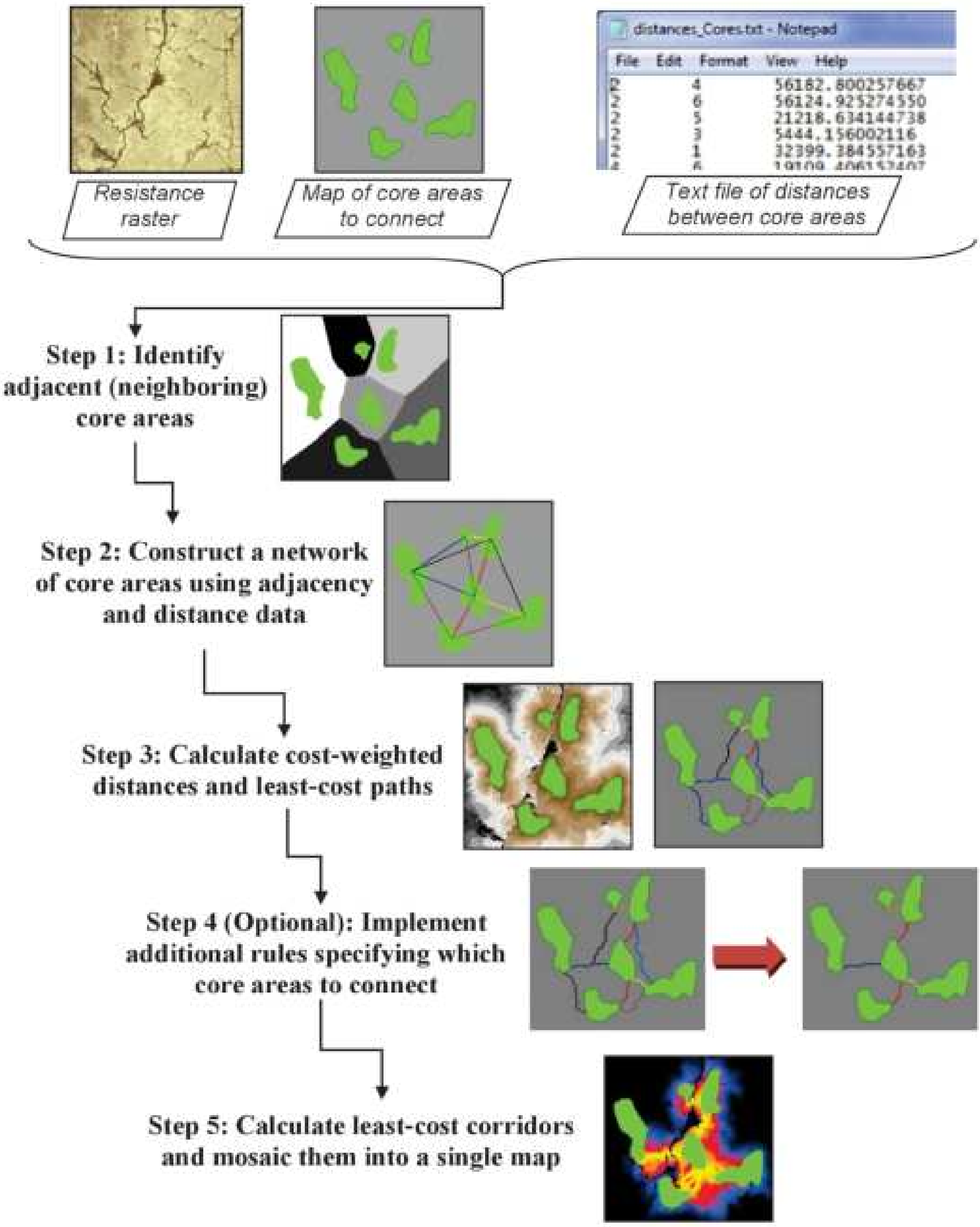


Figure A2. LPT process. Source: McRae and Kavanagh. Source [152] p. 11.

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