Spatial Features of a Regional Green Infrastructure and Identification of Ecological Corridors: A Study Related to Sardinia

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Abstract. This study aims at assessing the relationship between the spatial framework of the characteristics of a regional green infrastructure (RGI) and the ecological corridors of a regional network of protected areas. The spatial layout of the regional infrastructure is identified based on the potential supply of seven ecosystem services (intrinsic value of biodiversity, habitat quality, nature-based recreation potential, agricultural and forestry value, regulation of land surface temperature, and carbon storage and sequestration), whereas ecological corridors are detected through a methodological approach which builds on resistance-based models. The maps of the RGI characteristics and of the ecological corridors are overlaid and their correlations are assessed through a regression model. Such methodological approach is applied into the spatial context of the Sardinia Region. Finally, relevant planning implications concerning the implementation of planning policies to improve the effectiveness of the regional network of protected areas through the enhancement of the features related to the RGI are proposed and discussed, as well as the exportability of the methodological approach.

Keywords: Ecological corridors · Green infrastructure · Ecosystem services

1 Introduction

Green Infrastructures (GIs) are broadly defined, both in the literature [1] and in policy documents [2], as multifunctional and interconnected networks of green areas, be they natural, semi-natural, or even artificial, that provide a wide range of benefits to humans. Two main characteristics here stand out, that is, multifunctionality and connectivity [3].

As for the first, GIs are regarded as a means for pursuing environmental, social, and economic goals, especially within urban contexts [4]. Because they pursue such different goals, GIs must implement several functions and deliver various ecosystem services (ESs). Multifunctionality is a distinctive trait of GIs, although at the urban scale GIs are often being designed and implemented with one specific main function in mind [5].

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As for the second characteristic, i.e., connectivity, Ecological corridors (ECs) are the edges of green infrastructures (GIs) identified as networks whose nodes are areas characterized by relevant concentrations of ecosystem services (ESs) and environmental quality. ECs enhance the flows of wild species across the network and facilitate biological exchange processes. Negative impacts manifest as consequences of degradation or destruction of natural ecosystems [6]. Several environmental and landscape features characterize the potential of a GI's ECs to improve genetic exchange and biological flows across the network, such as presence, location and size of natural and anthropic barriers, spatial continuity, and supply of ESs supporting behavioral characteristics of species, such as food catching opportunities, suitable habitats, etc. [6]. Such potential is effectively represented by the concept of connectivity, which associates the movement of species through GI networks to the suitability to such flows of their linear edges, designated as ecological corridors [7].

This study discusses the relationship between the ECs and the capacity of GIs to supply ESs. Methodological approaches to identify GIs as providers of ESs and ECs as linear structures connecting the nodes of a GI are proposed in the second section, and, in the following section, implemented into the case study of a GI, represented by the regional network of protected areas, and related ECs, concerning the regional context of Sardinia. In the fourth section, the spatial taxonomy of the regional GI (RGI) and the ECs map are overlaid, and the correlations between the spatial features of the RGI and of the ECs are detected through a regression model; moreover, planning implications are highlighted.

2 Materials and Methods

2.1 Study Area

The island of Sardinia, among the largest islands of the Mediterranean Sea, is taken as a spatial context particularly suitable to implement the methodological approach of this study since GI features and ESs supply can be analyzed and assessed in a straightforward way, due to the clear-cut identification of the regional borders. In this study, ECs are considered as linear elements connecting the regional natural protected areas (NPAs), which are identified according to the classification defined by Lai *et al.* [8] and include natural regional parks, public woods, permanent oases of faunal protection, Ramsar sites and Natura 2000 Sites (N2Ss) (Fig. 1).

2.2 Data

Because multifunctionality is here considered as the landscape's capacity to supply multiple ESs, seven ESs, chosen across the provisioning, regulating and cultural groups, were modeled and mapped. The seven chosen ES are as follows.

- Intrinsic, non-use value of biodiversity (Conservation value, Consval), cultural ES.
- Ecosystems' capacity to provide habitats for animal and vegetal species (Natural value, Natval), regulating or supporting ES depending on the classification scheme.

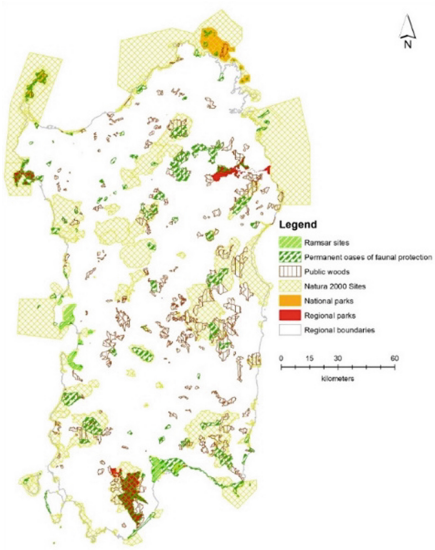

Fig. 1. The regional system of Sardinian NPAs.

- Ecosystems' attractiveness for recreational activities (Recreation value, Recrval), cultural ES.
- Ecosystems' support to sustaining sense of place, cultural identity, and heritage values (Landscape value, Landsval), cultural ES.
- Ecosystems' capacity to provide food, fibers, timber (Agriculture and forestry value, Agrofor), provisioning ES.
- Ecosystems' capacity to regulate local climate (Land Surface Temperature, LST), regulating ES.
- Ecosystems' capacity to regulate global climate (Carbon capture and storage, CO2Stor), regulating ES.

2.3 Methodology

The methodological approach of this study develops as follows. First, the characteristics of the Sardinian RGI are identified; next, ECs are detected on the basis of a resistance-based map. Finally, the maps of the RGI characteristics and of the ecological corridors are overlaid and their correlations are assessed through a regression model.

The Sardinian RGI. Natval and CO2Stor were mapped using two InVEST tools[1], i.e., "Habitat quality" and "Carbon Storage and Sequestration", respectively. As for Recrval, the conceptual model ESTIMAP [9], developed by a group of researchers working at the JRC, was applied; moreover, a plugin developed by Ndossi and Avdan [10] for retrieving the Land Surface Temperature was applied to summer satellite images. As regards the other variables, Consval and Landsval were mapped following Lai and Leone's methods [11]; the first relies on data from a regional monitoring project that assessed the presence of habitats of community interest, protected under the European Directive 92/43/EEC, while the second on data concerning environmental and cultural landscape assets subject to legally binding protection under the provisions of the Regional Landscape Plan (RLP). Furthermore, Agrofor was mapped following the methodology developed by Lai *et al.* [12], where land value is taken as a proxy for agricultural and forestry production. All of the ES were mapped on a regular, squared grid whose cell size equals 300 m; moreover, each ES was normalized in the [0–1] interval, so as to obtain comparable values, where 1 corresponds to the maximum supply of each ES. This entails that, as far as the LST is concerned, temperature values retrieved in Kelvin from the model were not only normalized, but also inverted, so that 1 corresponds to the lowest temperature, and 0 to the highest one. Finally, the elevation was retrieved from a digital terrain model available from the Regional (Sardinian) geoportal.

The identification of the ECs.[2] Spatial connectivity is generally assessed through models that map resistance, which comprise least-cost-path (LCP) models that identify ECs as connections between spatial parcels, detected as habitat locations, featured by the least resistance to movement of species. The map of connectivity is drawn through a four-step methodological approach, originally proposed by Cannas [14, 15] and structured into four steps.

First, a vector map representing the regional spatial taxonomy of the habitat suitability is identified, by means of the 2008 regional land cover map of Sardinia, and of the values of the habitat suitability identified, in species-specific terms, by a study commissioned by the Autonomous Region of Sardinia [16].

Secondly, a vector map representing the regional spatial taxonomy of the ecological integrity is drawn through Burkhard *et al.*'s studies [17], where the capacity of land-cover classes to supply supporting ESs is assessed through an expert-based approach.

Thirdly, the resistance regional spatial taxonomy is defined based on an article by LaRue and Nielsen [18] through the following steps. First, two raster maps are derived

[1] InVEST is a suite of tools that allows for developing spatially explicit assessments of various ecosystem services. Developed by the Natural Capital Project, it is freely available from https://naturalcapitalproject.stanford.edu/software/invest, last accessed 2022/03/21.

[2] A detailed description of the procedure for the identification of ECs can be retrieved from Chapter 3 by Lai *et al.* [13].

from the vector maps of the habitat-suitability and of the ecological-integrity indexes; secondly, two raster maps are generated from such raster maps, by mapping the inverse of the habitat-suitability and of the ecological-integrity indexes; thirdly, an ordinal scale, which identifies the resistance scores ranging between 1 and 100, is used to order the two raster maps, building on a report by the European Environment Agency [19]; finally, a (total) resistance map is defined by summing up the resistance scores of the two raster spatial taxonomies identified in the third phase.

The ECs connecting the regional NPAs are identified by means of the Tool "Linkage Pathways" (LPT) of the GIS Toolbox "Linkage Mapper". LPT adopts the Cost-Weighted Distance (CWD) as the reference variable to detect ECs through an LCP-related model [20]. Data used by LPT are the raster resistance map defined in the third step and the vector map of the regional NPAs. The linear path of the ECs and the CWD raster map are the outputs made available by LPT.

The regression model to detect the correlations between the RGI and the ECs. The spatial taxonomy of the RGI based on the supply of the seven types of ESs above described is overlaid on the ECs connecting the regional NPAs. Patches are included in ECs if their CWD is included in the first two deciles of the CWD distribution. The CWD of a patch i which belongs to the EC connecting two elements, A and B, of the NPAs vector map is detected as follows:

$$\mathrm{CWD_i} = \mathrm{CWD_{iA}} + \mathrm{CWD_{iB}}, \tag{1}$$

where $\mathrm{CWD_{iA}}$ $\mathrm{CWD_{iB}}$ are the CWDs between patch i and the core areas A and B.

A multiple linear regression is used to assess the correlations between the CWD of patches included in ECs and the normalized supply of ESs, which characterize the Sardinian RGI. The regression operationalizes as follows:

$$\begin{aligned}\mathrm{ECWD} = {} & \beta_0 + \beta_1 \mathrm{Consval} + \beta_2 \mathrm{Natval} + \beta_3 \mathrm{Recrval} + \beta_4 \mathrm{Landsval} \\ & + \beta_5 \mathrm{Agrofor} + \beta_6 \mathrm{LST} + \beta_7 \mathrm{CO2Stor} + \beta_8 \mathrm{Altd} + \beta_9 \mathrm{Aut},\end{aligned} \tag{2}$$

where dependent and explanatory variables are identified by the overlays of ECs and patches providing ESs:

- ECWD is the CWD of a patch included in an EC.
- Consval, Natval, Recrval, Landsval, Agrofor, LST, CO2Stor are seven values representing the potential supply of as many ecosystem services, as per Sect. 2.2.
- Altd is a control variable related to the altitude of a patch included in an EC.
- Aut is a control variable which controls for spatial autocorrelation.

The regression estimates account for the marginal effects of the covariates on the CWD of patches included in ECs. A multiple regression model is used since no priors are recognized as regards the influence of the variables which identify the ESs which characterize the Sardinian RGI on ECWD [21], and, as a consequence, a local linear approximation of the unknown surface which generally represents the n-dimensional relational phenomenon related to the dependent variable and covariates of model (2) is the most suitable way to detect information on such influence [22].

The altitude-related variable controls for systematic differentials in the impacts of different ecosystem services on CWD due to elevation. A spatially lagged variable, Aut, calculated using GeoDa[3], is used to control for spatial autocorrelation. Lastly, the p-values of the coefficients of the covariates are references to implement hypothesis tests to assess their estimates' significance, e.g., at 5%. As per the regression results reported in Table 1, the estimates of the two control variables' coefficients are significant and they highlight negative effects on the patches' performance.

3 Results

The outcomes of the implementation of the methodology described in the previous section are shown in the following three subsections.

3.1 The Spatial Taxonomies of the Supply of Ecosystem Services

The spatial layout of the supply of the seven chosen ESs is provided in Fig. 2, together with an eightieth map that provides the sum of the seven normalized ESs.

Consval is null in approximately 66% of the island's land mass, where no habitats of community interest have been identified and monitored; areas taking non-null values are mostly, but not exclusively, located within Natura 2000 sites and highly spatially clustered in their immediate surroundings.

As for Natval, a mere 3.44% of the island takes null values. High values mostly concern the island's largest forests, and regional and national natural protected areas.

Recrval is null in a negligible part of the island. The spatial patterns of Recrval are similar to Natval's ones, except for the coastal area, where Recrval takes high values.

Landsval equals 0 in 61.18% of the region. Among non-null values, the maximum value spatially dominates, mainly because of the presence of the main environmental assets protected under the under the RLP.

Agrofor is null in around 34.1% of the island; approximately 47.3% takes low values (Agrofor ≤ 0.33), while only 14.1% takes mid values ($0.33 <$ Agrofor ≤ 0.66), and a mere 4.5, clustered along the two main plains, takes high values ($0.66 <$ Agrofor ≤ 1).

LST in summer mostly (59.9%) takes mid normalized values ($0.33 <$ LST ≤ 0.66), whereas 38.7% of the island is characterized by low normalized values ($0 <$ LST ≤ 0.33), meaning that the surface temperature is hot, and a mere 1.4% takes high nor-malized values ($0.66 <$ LST ≤ 1), hence it is cooler than the rest of the island.

CO2Stor is null in around 2.2% of the island. No clear spatial pattern emerges, except for low and very low values, coinciding with urban areas and inland waters.

Finally, the total value map provides a simple overview of the level of multifunctionality through the multiple ecosystem services landscape index (MESLI) [23], i.e., the sum of the seven normalized ESs values.

[3] GeoDa is an open-source software program developed by L. Anselin and his team; it is freely available from https://geodacenter.github.io/ [last accessed: 2022/03/21].

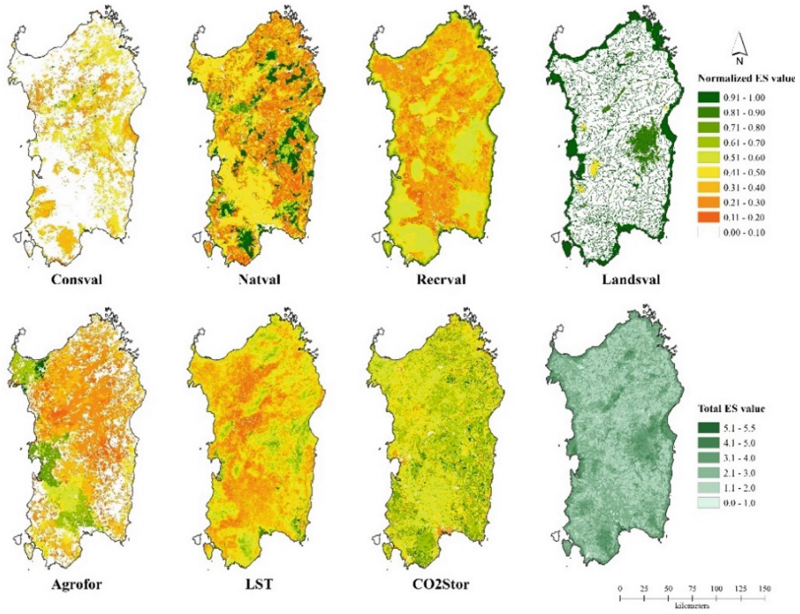

Fig. 2. Spatial distribution of the seven components of the Sardinian RGI, and of the sum of their normalized values.

3.2 The Ecological Corridors Connecting the Sardinian Natural Protected Areas

The raster map of the CWD values and the spatial identification of the ECs connecting the regional network of the Sardinian NPAs are the two outputs obtained through the implementation of the methodological approach described in Sect. 2.3. The ECs are identified by patches with CWD values lower than the second decile of the CWD distribution. Figure 3 shows the identification of ECs by patches with CWD values lower than the second decile.

3.3 Regression Results

The regression outcomes (Table 1) show the marginal effects of the supply of the seven ecosystem services on CWD of patches, and, by doing so, they identify a hierarchy of ESs in contributing to their inclusion in the spatial system of ECs.

Consequently, the assessment of the estimates of the other explanatory variables can be easily implemented, and, in so doing, the hierarchy of the supply of the seven ecosystem services can be straightforwardly identified, in terms of their contribution to the inclusion of patches in the ECs' spatial system.

The estimates of the coefficients of the seven explanatory variables are significant with respect to the p-value test described above and entails the following.

First, three out of the seven ESs have a negative impact on CWD, or, they increase the eligibility of a patch to be included in an EC, everything else being equal. These covariates are LST, Agrofor and Landsval. The largest impact is related to LST, which,

on average, shows a 1% decrease in CWD associated to a 10% decrease in LST, whereas the marginal effects of Agrofor correspond to a 3.9‰. The estimated coefficient of the dichotomous variable Landsval indicates that a relevant increase in the supply of landscape assets is associated to a 1.6‰ decrease in CWD.

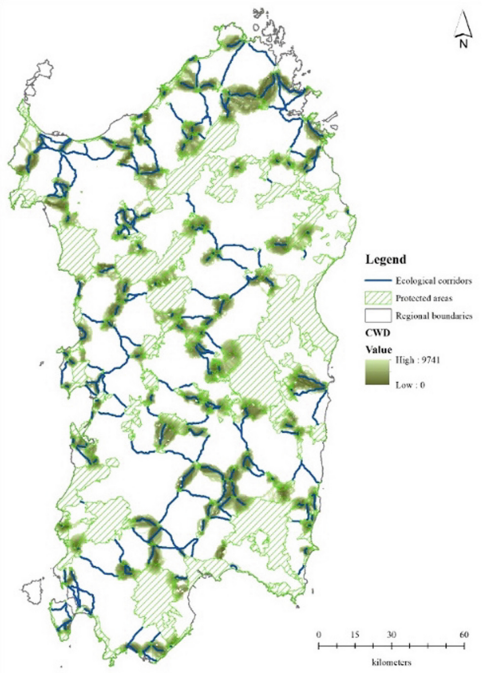

Fig. 3. The spatial identification of ECs and patches with CWD values lower than the second decile

Secondly, the variable Consval shows a positive impact on CWD which can be considered almost irrelevant, since even a 100% increase in conservation value would be associated to a very low increase in CWD (lower than 1‰).

Finally, Natval, Recrval and CO2Stor show positive marginal effects on CWD: on average, a 10% increase in the variables is associated to 3.08‰, 8.54‰ and 2.90‰ increases in CWD, respectively.

Therefore, the estimates of the model put in evidence that the supply of ESs related to ecosystems' capacity of providing home to animal and plant species (Natval), leisure-related and recreational opportunities (Recrval) and capture and storage capacity of carbon dioxide are the most problematic in order to identify ECs throughout the Sardinian RGI. On the other hand, mitigation of LST, agricultural and forestry production, and landscape assets are the most effective ESs to implement connections between NPAs through ECs.

Table 1. Regression results.

Explanatory variable	Coefficient	Standard deviation	t-statistic	*p*-value	Mean of the explanatory variable
Consval	8.918	44.2792	6.777	0.000	0.118
Natval	300.073	35.4105	23.516	0.000	0.395
Recrval	832.710	64.1078	2.159	0.031	0.403
Landsval	−151.722	22.1392	−6.853	0.000	0.290
Agrofor	−377.346	37.8409	−9.972	0.000	0.195
LST	−1,023.733	65.4963	−15.621	0.000	0.431
CO2Stor	282.343	50.3026	5.613	0.000	0.543
Altd	0.930	0.0355	26.213	0.000	356.766
Aut	0.541	0.0022	245.322	0.000	5595.630

Dependent variable: ECWD: Mean: 4,925,323 km; Standard deviation: 2,866.858 km; Adjusted R-squared: 0.530.

4 Discussion and Conclusions

The regression outcomes show that three out of the seven ESs, that is LST, Agrofor and Landsval, contribute to increase the eligibility of a patch to be part of an EC.

In relation to LST, a decrease in CWD values is associated to a decrease in LST. The reason of this behavior can be related to the presence of agricultural areas, which are likely to negatively impact connectivity [24] since they may possibly reduce the flow of species within ECs. In particular, the main sources of negative impacts generated by agricultural land uses are physical barriers such as fences and hedges, cultivation techniques and methods, and the use of herbicides, pesticides, and fertilizers. Moreover, both intensive and extensive agriculture can exert relevant impacts on LST due to low and dense vegetation that prevents evapotranspiration and reduces air circulation and downwind cooling [25].

Agrofor, as well as LST, is influenced by the presence of agricultural areas that represent a potential obstacle to the flow of species. The higher the productive potential, which is related to crop type, site elevation, and geographical location, the higher the decrease in connectivity. On the other hand, the presence of forest areas shows positive effects on connectivity, since it is associated to a decrease in CWD values. One of the main causes of habitat loss are changes in forest covers [26], which reduce the habitat areal size and increase habitat fragmentation.

As regards Landsval, regression results show that an increase in the supply of landscape assets entails a decrease in CWD values. In this study, patches characterized by the presence of landscape assets associated to more restrictive rules under the provisions of the Sardinian RLP show the highest values of Landsval. Among such landscape assets, the RLP includes the coastal strip, lakes, reservoirs, wetlands, rivers, and creeks. Rivers are especially effective in enabling connectivity by protecting wildlife through riparian

formations and floodplain woods and by providing water resources and food. Riparian formations and floodplain woods represent preferential corridors for several terrestrial and semiaquatic species, such as reptiles and amphibians, and birds [27].

In conclusion, a number of recommendations concerning policies aimed at strengthening the spatial frame of ECs are implied by the outcomes of this study; such policies focus on lowering land surface temperature, boosting forestry coverage and increasing the quantity and spatial dimension of the landscape assets protected under the provisions of the Sardinian RLP.

Policies that promote afforestation are the most effective in lowering the land surface temperature [28], and hence increasing the LST variable used in this study, in non-urbanized zones, such as rural areas. Consequently, combining the regression outcomes related to the marginal effects expressed by the coefficients of Agrofor and LST, afforestation is the leading policy recommendation concerning the strengthening of ECs, which effectively addresses both lowering land surface temperature and boosting forestry coverage, even if transitions to forestry are frequently hindered by the strong cultural bond which characterize the relation between farmers and agriculture and by the high-rents of arable land [29, 30].

The presence of landscape assets is also relevant to improve the ECs that enable linkages between protected areas. Protected landscape assets can be either man-made or natural, and the stricter the conservation policy is, the higher Landsval. Therefore, policy makers could act in two directions: first, raising the levels of statutory provisions in case of already protected landscape features; second, amplifying the types of landscape features that are subject to such protection regime. This is especially important in case of linear goods and assets, such as tree lines, hedgerows and drywalls that have been proven to be key to support connectivity within landscapes [31], higher levels of biodiversity [32], and species' movement. New landscape features such as line trees and hedgerows, which incidentally are also recognized as integral parts of local identities in many cultures (among many: [33]), should therefore be treated as protected landscape assets in a future, updated, version of the RLP.

The methodology here applied, which combines assessment of multifunctionality in terms of ES provision and identification of ECs based on LCP approaches, can be applied in other contexts and re-adjusted as needed. For instance, the selection of ESs to be assessed, as well as the choice of models used to assess the spatial distribution of their provisioning areas, can be appropriately re-considered and tailored to local distinctive aspects, data availability, and modelers' expertise.

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