SAGGI

Federica Isola, Sabrina Lai,
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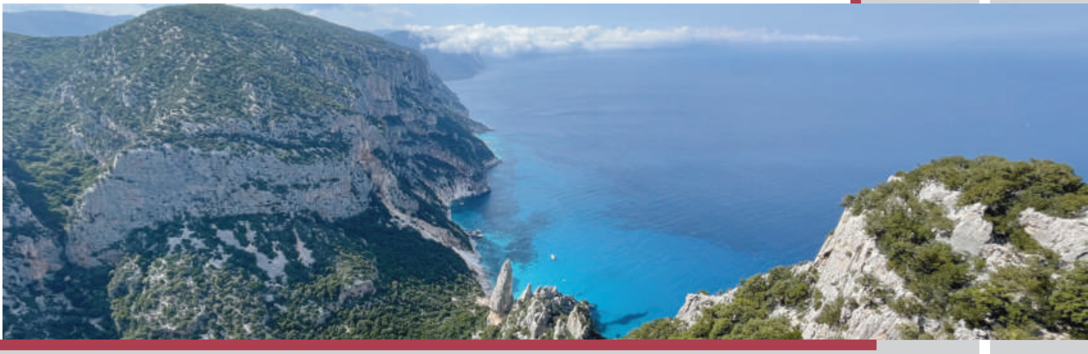
Green Infrastructure and Regional Planning

An Operational Framework

territorio sostenibilità governance



FrancoAngeli

Territorio sostenibilità governance
Collana diretta da Manlio Vendittelli

La collana, suddivisa in tre sezioni (saggi, ricerche, quaderni), analizzando le trasformazioni territoriali, la sostenibilità ambientale e il governo dei processi, vuole contribuire alla costruzione di una nuova concezione del progetto in una cultura multiscalare attraverso tre concetti chiave: complessità sistemica, limite, progetto. Il primo è legato ai risultati strutturali ed estetici che le trasformazioni hanno prodotto e che devono essere governati nella loro complessità; il secondo è definito dalle leggi della sostenibilità; il terzo è frutto della razionalità del fare.
Territorio, sostenibilità e governance diventano pertanto i tre elementi di interazione economica e sociale essenziali nei processi di trasformazione che, nel progetto, devono intrecciarsi per diventare un unicum.
In quest'ottica la riqualificazione dei luoghi dell'organizzazione umana, la ricostruzione di reti ecologiche, la messa a norma del territorio, la valutazione e progettazione strategica e il governo dei conflitti non sono altro che un momento di ricomposizione delle istanze sociali in progetti coerenti di valorizzazione delle risorse locali nella garanzia delle identità, delle diversità, dei valori storico-ambientali.
La sostenibilità diventa il valore attraverso il quale si possono definire le trasformazioni come processo che organizza la cultura del divenire nella cultura del limite, come presupposto della progettazione sistemica, della partecipazione sociale alle decisioni, del governo dei processi.
Aggiungere al concetto di gestione democratica la difesa dei diritti delle generazioni future significa esplorare un terreno di indagine che, seppure agli albori, porta al principio per cui è solo con una nuova cultura sociale che potremo iniziare davvero processi decisionali partecipati e condivisi sulle trasformazioni sociali e sul governo dei conflitti.
Costruire sistemi di conoscenza e strutture sociali di valutazione sul principio della coscienza critica e del controllo sociale dell'informazione è diventato oggi un problema sul quale devono confrontarsi gli stessi principi della democrazia e della scienza.

Tutti i testi pubblicati nella collana sono sottoposti a un processo di blind peer review.

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Cover image: View of Cala Goloritzè from Punta Salinas (Sardinia, Italy).
Photo by Federica Isola

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Foreword

The authors have jointly contributed to the conception, design, execution, and interpretation of the research work reported in this volume.

Individual contributions are as follows.

Sabrina Lai, Federica Isola, Federica Leone and Corrado Zoppi have collaboratively designed the research structure of this volume and have jointly taken care of chapter 1.

Sabrina Lai has taken care of chapter 2, subsections 4.2.1., 4.2.3., 4.3.1. and section 5.1.

Federica Isola, Federica Leone and Corrado Zoppi have collaboratively studied the organization of chapter 3 and have jointly taken care of section 3.1 and subsection 3.2.1.

Federica Isola has taken care of subsection 3.2.2.

Federica Leone has taken care of subsection 3.3.1.

Federica Isola and Federica Leone have jointly taken care of sections 4.1., 5.2. and 5.3.

Corrado Zoppi has taken care of subsections 3.2.3, 3.3.2., 4.2.2. and 4.3.2.

Chapter 1, "Introduction", is partly reproduced from: i) Lai S., Leone F. and Zoppi C. (2018), "Implementing green infrastructures beyond protected areas", *Sustainability*, 10, 10 (3544): 1-16. DOI: 10.3390/su10103544, pp. 1-3, as for the definition of green infrastructure and methodological references; ii) Floris M. and Zoppi C. (2019), *Carbon Sequestration and Land-taking Processes. A Study concerning Sardinia (Italy)*, in: Gargiulo C. and Zoppi C., eds., *Planning, Nature and Ecosystem Services*, FedOAPress, Naples, Italy, pp. 66-79. DOI: 10.6093/978-88-6887-054-6, p. 67, as for carbon sequestration ecosystem service.

Chapter 2, "Defining a spatial taxonomy for a regional infrastructure in Sardinia", partly draws upon: i) *Bridging Biodiversity Conservation Objectives with Landscape Planning through Green Infrastructures: A Case*

Study from Sardinia, Italy, in Gervasi O., Murgante B., Misra S., Borruso G., Torre C., Rocha A.M.A.C., Taniar D., Apduhan B.O., Stankova E. and Cuzzocrea, A., eds., *17th International Conference on Computational Science and Its Applications (ICCSA 2017), Lecture Notes in Computer Sciences Series, Vol. no. 10409, Springer*, Cham, Switzerland, pp. 456-472. DOI: 10.1007/978-3-319-62407-5_39 (as for conservation value, natural value and landscape value) and from ii). Lai S., Leone F. and Zoppi C. (2020), "Spatial distribution of surface temperature and land cover: A study concerning Sardinia, Italy", *Sustainability*, 12, 8 (3186): 1-20. DOI: 10.3390/su12083186 (as for land surface temperature retrieval).

Chapter 3, "Mapping of ecological corridors as connections between protected areas: A study concerning Sardinia, Italy", is reproduced from Isola F., Leone F. and Zoppi C. (2022), "Mapping of ecological corridors as connections between protected areas: A study concerning Sardinia, Italy", *Preprints 2022*, 2022050088: 1-24. DOI: 10.20944/ preprints202205.0088.v1, pp. 1-20. This article was submitted to *Sustainability* and is currently under review.

Chapter 4, "Green infrastructure and environmental risk: A case study concerning landslide and flood hazard mitigation in a coastal area of Sardinia", is partly reproduced from: Lai S., Isola F., Leone F. and Zoppi C. (2021), "Assessing the potential of green infrastructure to mitigate hydro-geological hazard. Evidence-based policy suggestions from a Sardinian study area", *TeMA. Journal of Land Use, Mobility and Environment*, Special Issue 1.2021 "The Emergency Plan for the use and management of the territory": 109-133. DOI: 10.6092/1970-9870/7411.

Chapter 5, "Discussion and planning policy implications", is partly reproduced from: i) Lai S., Leone F. and Zoppi C. (2020), "Land Surface Temperature and land cover dynamics. A study related to Sardinia, Italy", *TeMA. Journal of Land Use, Mobility and Environment*, 13, 3: 329-351. DOI: 10.6092/1970-9870/7143, pp. 344-345, as for afforestation discussion, Section 5.2. "The EC of the regional network of protected areas"; ii) Isola F., Leone F. and Zoppi C. (2022), "Mapping of ecological corridors as connections between protected areas: A study concerning Sardinia, Italy", *Preprints 2022*, 2022050088: 1-24. DOI: 10.20944/ preprints202205.0088.v1, pp. 20-21; this article was submitted to *Sustainability* and is currently under review; iii) Lai S., Isola F., Leone F. and Zoppi C. (2021), "Assessing the potential of green infrastructure to mitigate hydro-geological hazard. Evidence-based policy suggestions from a Sardinian study area", *TeMA. Journal of Land Use, Mobility and Environment*, Special Issue 1.2021 "The Emergency Plan for the use and management of the territory": 109-133. DOI: 10.6092/1970-9870/7411, pp. 125-128, as for Section 5.3 "Natural hazards and GI".

1. Introduction

An important definition of green infrastructure (GI) is proposed by the European Commission in its Communication titled "Green infrastructure: enhancing Europe's natural capital", where GI is regarded as a network having the Natura 2000 sites at its core, capable of delivering numerous ecosystem services (ES), and is "strategically planned", emphasizing the role of GI with regards to the integration of ecological connectivity, and protection of the environment and of ecosystems' multiple functions, drawing on Benedict and McMahon (2006, p. 1), according to whom GI is «an interconnected network of natural areas and other open spaces that (…) provides a wide array of benefits for people and wildlife». As a consequence, identifying and managing GI is a core planning issue (Landscape Institute, 2009) especially under the provisions of the European Landscape Convention (Liquete *et al.*, 2015).

As for connectivity, Lennon (2015) highlights that, notwithstanding differences in defining GI, common conceptualizations of GI relate to networks, hence stressing that rather than protecting individual, isolated parcels of natural or seminatural areas, planning should take care of interconnected networks (Benedict and McMahon, 2002), comprising both core areas that support key ES and corridors that support species movements and dispersal, respectively, "hubs" and "links" in Lafortezza *et al.* (2013).

With reference to multifunctionality, this is commonly understood as the combination of "ecological, social and economic, abiotic, biotic and cultural function of green spaces" (Hansen and Pauleit, 2014) or "the ability to provide several functions and benefits on the same spatial scale" (Millennium Ecosystem Assessment, 2003). As a consequence, GI multifunctionality has been analyzed in the light of the ES framework (Hansen and Pauleit, 2014), where ES are goods and services supplied by nature that sustain life and contribute, both directly and indirectly, to human wellbeing, variously defined, and classified in the literature according to many different frameworks (prominently, the Millennium Ecosystem Assessment (2003); in Europe, the Common International Classification for Ecosystem Services (CICES) by the European Environment Agency[1]; and, in the United States, the Final Ecosystem Goods and Services Classification System (FEGS-CS) by the United States Environmental Protection Agency (Landers and Nahlik, 2013)).

Beneficial functions provided by GI are broadly categorized by Pauleit *et al*. (as cited in Hansen and Pauleit, 2014) into ecological, social and economic categories, while Taylor-Lovell and Taylor (2013) explicitly group those ES and functions that, in their view, should be supplied by GI: production (including provisioning ecosystem services such as food or timber production), ecological (including supporting and regulatory ecosystem services, such as water purification or climate regulation), and cultural (including recreation, landscape quality, cultural heritage); the need to take into account communities' and users' needs and preferences is also underlined. This study emphasizes the second characteristic of GI, that is, the multifunctional use of natural capital that allows for multiple purposes, while connectivity can be easily integrated using the same methodology as in Cannas *et al.* (2018).

According to Hansen and DeFries (2007), protected areas are planned so as to implement virtuous ecological and socio-economic interactive relationships with surrounding areas, and, by doing so, build an integrated ecosystem. Furthermore, the assessment of protected area-related spatial policies could represent a reference point to enhance the efficiency and effectiveness of policy measures aimed at implementing environmental protection and related management measures (Gaston *et al.*, 2006; Ruiz Benito *et al.*, 2010).

Identifying and planning regional GI can be considered as an intentional way of spreading the positive impacts of environmental conservation policies across a spatial context much more complex and larger than the protected areas. Urban and rural settlements can be part of the spatial context of the regional GI as well (Wickham *et al.*, 2010; Spanò *et al.*, 2017).

This study builds upon a methodology applied in previous studies by Arcidiacono *et al.* (2016) and by Lai and Leone (2017), which both map a regional GI taking an Italian region as a case study. In the former, a GI for Lombardy was identified as a multifunctional GI taking into account three values: natural value, recreation value, and landscape value. In the latter, a

[1] CICES Version 5.1 available at the website https://cices.eu/ [Accessed: 22 February 2022].

Sardinian GI was identified based upon four factors, i.e., adding to the three values used in Arcidiacono *et al.* (2016) a fourth layer accounting for conservation value.

Conservation value is based on the presence of areas whose natural characteristics are particularly important because hosting habitats rare, endangered, or representative of European biogeographical regions (i.e., habitats of community interest under the provisions of the Habitats Directive (no. 93/43/EEC)). Such habitats are meant to be maintained or restored in a favorable conservation status, and their presence calls for the designation of Natura 2000 sites, when criteria listed in Annex III of the Habitats Directive (concerning representativity, size, conservation status, and significance of the site) are met. According to a recent study (Salomaa *et al.*, 2017) carried out to explore Finnish experts' perceptions on GI implementation, the importance of GI in relation to biodiversity conservation has been emphasized by the majority of respondents. Moreover, GI can contribute to the reduction of habitat fragmentation which is one of the primary causes of species extinction (Weber *et al.*, 2006).

Natural value is related to biodiversity's capacity of providing ES; hence, it implies ecological integrity and current levels of ecosystem functions, key to supplying human-demanded ES. As such, under the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2003) classification, it would be categorized under the supporting services group. In the literature, trade-offs between ES are often analyzed and assessed through land use/land cover changes (Sharma *et al.*, 2018; Polasky *et al.*, 2011; Yang *et al.*, 2018). For example, Yang *et al.* (2018) studied the impacts of land use changes on ES trade-offs in the case of Yahne watershed in the Loess Plateau, China. In particular, their study investigates land use patterns that mitigate conflicts between food supply and conservation measures in order to be included within future restoration policies.

Recreation value concerns the landscape attractiveness for recreational activities. Landscapes and natural habitats are accounted for when choosing holiday locations or doing outdoor activities (prominently, active tourism), thus they positively affect both local communities' and tourists' quality of life and wellbeing, while also benefitting local economies. Therefore, recreation value accounts for cultural ES, as classified by the Millennium Ecosystem Assessment (2003). In the literature, recreation value is assessed through monetary analyses (Serkan and Rehber, 2008; Martín-López *et al.*, 2009; Lankia *et al.*, 2015; Mayer and Woltering, 2018) or through non-monetary analyses (Kenter, 2016; Kelemen *et al.*, 2014; Eagles *et al.*, 2000). In the last decades, non-monetary methods based on social media approaches have been used to assess recreation value (Wood *et al.*, 2013;

Sonter *et al.*, 2016; Hausmann *et al.*, 2018). For instance, Cunha *et al.* (2018) evaluated recreation services combining social media-based methods (using the InVEST recreation model) and official data sources in the Northwest coast of Portugal. In this study, we implement the ESTIMAP approach to map the spatial potential concerning the recreation ES supply in the regional GI (Zulian *et al.*, 2013).

Landscape value accounts for the interactions between natural and human factors that have shaped European cultures, as per the European Landscape Convention, and it is here assessed based on the endowment of natural and cultural resources, which are identified as landscape-related goods by the Italian Code on cultural goods and landscape (Law enacted by decree no. 2004/42). Various authors have highlighted the importance of landscape value within spatial planning (Zoppi and Lai, 2010; Orantes *et al.*, 2017) and also in relation to the definition of GI (Arcidiacono *et al.*, 2016).

In this study, three factors are added to the set previously used to identify the regional GI, which are related to agriculture and forestry, land surface temperature (LST) and carbon sequestration capacity. Agricultural output and forestry production are classed as provisioning ESs (see, among many: TEEB, 2010; Maes *et al.*, 2013, 2014; Science for Environment Policy, 2015). A close relationship can be identified between forestry, cropland and LST mitigation, as discussed in the following paragraphs. Afforestation is the most relevant reference for planning policies designed to decrease LST and to boost-up the spatial structure of ecological corridors as regards non-urbanized areas, such as rural zones[2].

Finally, carbon sequestration, that is carbon capture and storage, is a phenomenon, based on photosynthesis, which characterizes peat swamps, forests and grasslands, and other similar ecological systems and consists in carbon dioxide removal from the air through its sequestration by soil and plants (Lal, 2008). The interaction involving air composition and soil has a strong influence on climate regulation (Jobbagy and Jackson, 2000) and is strictly correlated to changes in land cover. Moreover, land condition and green areas play an important role in regulating the carbon cycle since they provide carbon capture and storage as an ecosystem service (European Commission, 2012; Millennium Ecosystem Assessment, 2003).

In this volume, a methodological approach, based on the seven factors identified above, is implemented with reference to Sardinia, an Italian insu-

[2] This issue is analytically discussed in the second section of the Conclusions of this volume (Chapter 5).

lar region, both in terms of mapping a spatial taxonomy aimed at scoring the eligibility of patches to be included into the regional GI, and as regards the identification of ecological corridors, as linear connections between the nodes of the regional network of protected areas.

In the next chapter, the methodology to identify the regional GI is presented, the detail of the data-base definition is described, and the outcomes of the assessments are presented through maps that unveil the spatial distribution of areas that are more suitable for the inclusion in the regional GI. The third chapter shows the methodological approach used to detect ecological corridors, which are identified on the basis of the implementation of such methodology. The following chapter focuses on the relations between the regional GI and the spatial structure of landslide and flood hazards in Eastern Sardinia, as a relevant case study. The concluding chapter discusses the findings implications concerning the definition of spatial planning policies aimed at improving the living quality of the local communities on the basis of the implementation of the regional GI and the related ecological corridors.

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2. *Defining a spatial taxonomy for a regional infrastructure in Sardinia*

This chapter focuses on the methodological aspects allowing for the spatial identification of a regional GI through an assessment of the seven factors listed in the introduction, which are as follows: conservation value, natural value, recreation value, landscape value, agricultural and forestry value, land surface temperature, and carbon storage and sequestration capacity. For each of the seven factors, the relevant subsection first provides background information on the chosen value, followed by a description of both the methodology and the input data needs and sources. The closing subsection accounts for the results, graphically accompanied by maps representing the spatial layout of each value; moreover, it provides an example of how such assessments can be used to identify interrelationships between those ES that are reflected within the values, with a view to supporting the definition of appropriate planning strategies aimed at preserving or enhancing current levels of ES provision.

2.1. Conservation value (*Consval*)

Conservation value (*Consval*) is here understood as a proxy for the intrinsic, non-use value of biodiversity, including both existence and bequest value, which are regarded as cultural ES (e.g., Raymond *et al*., 2009). They account for the importance of preserving biodiversity for future generations (bequest value) and of maintaining biodiversity in present times, irrespective of whether it is "used" by humans (existence value) and are a product of social construction: as highlighted by the Millennium Ecosystem Assessment (2005a, p. 34, in Reyers *et al*., 2012), they embed «deeply held historical, national, ethical, religious, and spiritual values people ascribe to ecosystems». Intrinsic, non-use values related to biodiversity conservation for present and future generations have been consistently found out to be prioritized over other ecosystem services in studies assessing communities' perceptions (e.g., Raymond *et al*., 2009; Larson *et al*., 2013; Estruch-Guitart and Vallés-Planells, 2015).

As for evaluation methods, existence and bequest values are often assessed in monetary terms through stated preference models such as contingent valuation methods and willingness to pay exercises (for instance: Pearce, 2007; Yang *et al*., 2008; Gan *et al*., 2011; Huang and Wang, 2015), or through benefit transfer methods when site-specific information is not available (as in Pascal *et al*., 2018). Non-monetary, socio-ecological methods include stakeholders surveys, community mapping (Raymond et al., 2009), participatory geographic information (as in Vieira da Silva *et al*., 2021). Other non-monetary methods use conservation proxies such as bird species indicators (Schröter et *al*., 2020), or indicators related to protected areas, uniqueness/rarity of habitats and species, ecosystem integrity (Schirpke *et al*., 2021), or vulnerability indices for forests and arable species (Dunford *et al*., 2015).

In this study, an indicator for assessing conservation value is proposed based on the European Union (EU)'s key piece of legislation concerning biodiversity protection. Council Directive 92/43/EEC of 21 May 1992 "on the conservation of natural habitats and of wild fauna and flora" aims at ensuring habitats deemed of community interest, i.e., that are endangered or threatened with extinction in their natural range, or have a small natural range, or exhibit typical characteristics of one or more European biogeographical regions. The full list of natural habitats of community interest is provided in Annex I of the Habitats Directive, where a subset of the list is classed as "priority" habitats and marked with an asterisk, which signals a higher importance and calls for stricter conservation measures. Moreover, an interpretation manual of the habitats of community interest, regularly updated following the various EU enlargements, has been produced by the European Commission since 1999 (European Commission, 2013); subsequently, a number of Member States have made available their own interpretation handbooks so as to tailor the EU manual to their national and local specificities, and have produced national or regional maps of natural habitats of community interest.

2.1.1. Assessing conservation value: a novel method based on Natura 2000 standard dataforms and Habitat Directive reporting

Building on a regional report (CRITERIA and TEMI, 2014a, pp. 27-28) that ranks the importance of habitats of community interest in Sardinia with a view to defining a regional monitoring plan, this value was calculated as follows:

- for areas where no habitats of Community interest have been identified:

$$\text{Consval} = 0 \qquad (1);$$

- for areas hosting habitats of Community interest:

$$\text{Consval} = P \cdot (R+T+K) \qquad (2),$$

where:

- *P* indicates whether a given habitat is enlisted as priority habitat (*P*=1.5 in case of priority habitat, *P*=1 in case of non-priority habitat).
- *R* denotes rarity, which, for each habitat of Community interest, can be evaluated based on the number of Natura 2000 sites in which the presence of the habitat was recorded. Since information about sites belonging to Natura 2000 network is provided through standard data forms (European Commission, 2011), the number of sites in which each habitat is present can be easily retrieved in each region, or country, or biogeographical region. We used the 2017 version of the Natura 2000 database[1] as a source, which provides a manageable and handy compilation of all Natura 2000 standard data forms, and chose to categorize the number in the interval (1-5) by normalizing the number of occurrences (which ranges from 1 to 79) in that interval; the lower the number of occurrences, the higher the value of *R*.
- *T* stands for threats, which are recorded in each Natura 2000 standard data form. Hence, the number of threats applies to Natura 2000 sites, which entails that a given habitat of Community interest can have different threat values, one for each site in which the habitat is recorded. We chose to categorize the number of threats recorded in the standard data forms in the (1-5) interval; moreover, the higher the number of threats, the higher the value of *T*.

[1] Available from https://www.eea.europa.eu/data-and-maps/data/natura-8/ [Accessed: 22 February 2022].

- *K* stands for knowledge: since reliable and up-to-date information gathered through on-site surveys is not available for every habitat of community interest and for every Natura 2000 site, we deem the level of knowledge important from a conservationist's standpoint. The level of knowledge in Sardinia was assessed by experts within a regional monitoring project, whose outcomes are available in an unpublished report (CRITERIA and TEMI, 2014b, pp. 42-44). For each habitat, the level of knowledge was therefore classed as "good", "acceptable", "insufficient", "poor". These judgments were converted into values in the 1-4 interval, where the lower the level of knowledge, the higher the value of *K* (hence, poor=4, insufficient=3, acceptable=2, good=1). Since *K* depends on subjective assessments, we chose to assign a maximum score (4) lower than in the case of both *R* and *T*.

With reference to the spatial dimension of this assessment, the following two spatial datasets were used: the first, the so-called "Carta della natura" ("Nature map": Camarda *et al.*, 2015), has a scale of 1:50,000, and makes use of the CORINE[2] biotopes nomenclature, while the second, the so-called "Carta degli habitat" ("Habitat map": CRITERIA and TEMI, 2014b), has a scale of 1:10,000 and maps habitats of community interest by using the Habitats Directive taxonomy within Natura 2000 sites only. The interoperability between the two taxonomies was handled through a conversion tool produced by the Italian Superior Institute for Environmental Protection and Research (ISPRA, 2013), which allowed us to map habitats of community interests also outside Natura 2000 sites by using the "Nature map" after appropriately reclassing the CORINE biotopes code into the Directive codes.

For each habitat listed in at least one standard data form in the Sardinian Natura 2000 network, and whose spatial distribution is retrievable by combining the "Habitat map" with the "Nature map", tab. 1 provides the values of P, K, and R. T is not provided in the table because, for a single habitat, it takes different values depending on the Natura 2000 site in which it is contained.

As a result, where habitats of community interest are present, *Consval* can range from 1 (minimum conservation value) to 21 (max conservation value).

[2] CORINE stands for "COoRdination of INformation on the Environment" and it is a European program initiated in 1985 with the aim of supporting environmental policies through standardization of data collection and classification (https://www. eea.europa. eu/help/ glossary/ eea-glossary/corine). Although prominently known for the land cover taxonomy and datasets, it also offers a standard nomenclature for biodiversity accounts, as well as procedures for data collection and classification (see Moss *et al.*, 1995).

Tab. 1 - Types of habitats protected under the EU Directive 93/42/EEC in Sardinia (listed in 2017 standard data forms and mapped), and three components of Consval

Habitat code and denomination		*P*	*K*	*R*
1110	Sandbanks which are slightly covered by sea water all the time	1	4	2.90
1120	* Posidonia beds (Posidonion oceanicae)	1.5	2	1.62
1130	Estuaries	1	4	4.90
1150	* Coastal lagoons	1.5	3	2.59
1160	Large shallow inlets and bays	1	2	3.21
1170	Reefs	1	4	3.05
1210	Annual vegetation of drift lines	1	3	2.13
1240	Vegetated sea cliffs of the Mediterranean coasts with endemic *Limonium* spp.	1	1	2.33
1310	*Salicornia* and other annuals colonizing mud and sand	1	2	3.67
1410	Mediterranean salt meadows (*Juncetalia maritimi*)	1	2	2.38
1420	Mediterranean and thermo-Atlantic halophilous scrubs (*Sarcocornetea fruticosi*)	1	1	2.33
1430	Halo-nitrophilous scrubs (*Pegano-Salsoletea*)	1	4	4.44
1510	* Mediterranean salt steppes (*Limonietalia*)	1.5	3	3.05
2110	Embryonic shifting dunes	1	3	2.69
2120	Shifting dunes along the shoreline with *Ammophila arenaria* (‘white dunes’)	1	2	2.95
2210	Crucianellion maritimae fixed beach dunes	1	2	2.64
2230	*Malcolmietalia* dune grasslands	1	3	2.95
2240	*Brachypodietalia* dune grasslands with annuals	1	4	3.82
2250	* Coastal dunes with *Juniperus* spp.	1.5	2	2.95
2260	*Cisto-Lavenduletalia* dune sclerophyllous scrubs	1	4	4.59
2270	* Wooded dunes with *Pinus pinea* and/or *Pinus pinaster*	1.5	2	3.82
3120	Oligotrophic waters containing very few minerals generally on sandy soils of the West Mediterranean, with *Isoetes* spp.	1	4	4.74
3130	Oligotrophic to mesotrophic standing waters with vegetation of the *Littorelletea uniflorae* and/or of the *Isoëto-Nanojuncetea*	1	3	4.23
3150	Natural eutrophic lakes with *Magnopotamion* or *Hydrocharition*-type vegetation	1	4	4.74
3170	* Mediterranean temporary ponds	1.5	4	4.13
3280	Constantly flowing Mediterranean rivers with *Paspalo-Agrostidion* species and hanging curtains of *Salix* and *Populus alba*	1	4	4.64
3290	Intermittently flowing Mediterranean rivers of the *Paspalo-Agrostidion*	1	4	4.79
4090	Endemic oro-Mediterranean heaths with gorse	1	2	4.90
5210	Arborescent matorral with *Juniperus* spp.	1	1	2.33
5230	* Arborescent matorral with *Laurus nobilis*	1.5	3	4.54
5320	Low formations of *Euphorbia* close to cliffs	1	3	3.77
5330	Thermo-Mediterranean and pre-desert scrub	1	3	1.00
5410	West Mediterranean clifftop phryganas (*Astragalo-Plantaginetum subulatae*)	1	4	4.64
5430	Endemic phryganas of the *Euphorbio-Verbascion*	1	3	3.15

Habitat code and denomination		*P*	*K*	*R*
6210	Semi-natural dry grasslands and scrubland facies on calcareous substrates (*Festuco-Brometalia*) (* important orchid sites)	1.5	4	4.90
6220	* Pseudo-steppe with grasses and annuals of the *Thero-Brachypodietea*	1.5	3	1.56
6310	Dehesas with evergreen *Quercus* spp.	1	2	4.13
6420	Mediterranean tall humid grasslands of the *Molinio-Holoschoenion*	1	4	4.85
7220	* Petrifying springs with tufa formation (*Cratoneurion*)	1.5	4	5.00
8130	Western Mediterranean and thermophilous scree	1	4	5.00
8210	Calcareous rocky slopes with chasmophytic vegetation	1	3	4.49
8220	Siliceous rocky slopes with chasmophytic vegetation	1	3	4.85
8310	Caves not open to the public	1	2	4.18
8330	Submerged or partially submerged sea caves	1	3	4.28
91E0	* Alluvial forests with Alnus glutinosa and Fraxinus excelsior (Alno-Padion, Alnion incanae, Salicion albae)	1.5	3	4.23
9260	Castanea sativa woods	1	3	5.00
92A0	*Salix alba* and Populus alba galleries	1	2	4.38
92D0	Southern riparian galleries and thickets (*Nerio-Tamaricetea* and *Securinegion tinctoriae*)	1	3	2.44
9320	Olea and Ceratonia forests	1	2	2.95
9330	Quercus suber forests	1	2	3.92
9340	Quercus ilex and Quercus rotundifolia forests	1	3	2.38
9380	Forests of Ilex aquifolium	1	2	4.74
9540	Mediterranean pine forests with endemic Mesogean pines	1	4	4.64
9560	* Endemic forests with *Juniperus* spp.	1.5	4	5.00
9580	Mediterranean *Taxus baccata* woods	1.5	2	4.59

2.2. Natural value (*Natval*)

Natural value (*Natval*) accounts for biodiversity in a broad sense, beyond the intrinsic conservation value implicit in the definition of the Habitats Directive and it is related to ecosystems' capacity of providing home to animal and plant species, which in turn are indispensable for delivering a wide range of ES, since loss of habitats and species impact upon ecosystem functions and processes (Loreau *et al*., 2001; Cardinale *et al*., 2012; Maseyk *et al*., 2017). Numerous studies have demonstrated how biodiversity, in its multiple meanings ranging from genetic variation within a species to differences between species and variety of ecosystems, plays a key role in regulating natural functions and processes (among many: Hooper *et al*., 2005; Balvanera *et al*., 2006; Hector and Bagchi, 2007; Cardinale, 2011; Isbell *et al*., 2011).

For this reason, a long-standing debate on the very essence of this value can be traced in the academic literature, where different denominations appear, each entailing a specific nuance in the meaning and, consequently, a different way to assess the value. Among the most common ones, it is worth citing «ecological integrity» (Burkhard *et al*., 2009), «degree of naturalness» (Paracchini and Capitani, 2011), and «habitat quality» (Nelson *et al*., 2009; Polasky *et al*., 2011).

The debate centers on whether ecosystems' capacity of supporting species should be regarded as an ecosystem service in itself. For the purpose of this research, it should be recalled that the expression "ecosystem services" refers to those goods and services provided by nature that sustain human life and well-being and that various categorizations of ecosystem services have been proposed so far. Among the most widely used, the Common International Classification of Ecosystem Services (CICES) only considers final goods and services, that is those for which a human demand exists (in accordance with Boyd and Banzhaf, 2007), and groups them into three main categories: provisioning, regulating and maintenance, and cultural services. In accordance with Müller (2005) and with Fisher and Turner (2008), other categorizations, such as the Millennium Ecosystem Assessment (2003) and The Economics of Ecosystems and Biodiversity (TEEB) (2011), also include a fourth group (labeled supporting services, or habitat services) that accounts for ecological functions and integrity, not directly "consumed" by people but necessary for ecosystems to produce final goods and services.

Depending on the taxonomy, ecosystems' capacity of hosting species and maintaining their life cycles is included either within the "regulating and maintenance" services or within the "supporting or habitat" services, depending on the taxonomy: the first holds for the CICES classification, and the second for the Millennium Ecosystem Assessment. The issue here is not merely a semantic one; rather, it stems from the conceptualization of ES, and, as pointed out by Liquete *et al.* (2016a), it is affected by scholars' perspectives and it bears consequences on assessments. For instance, economists warn against assessing natural value when evaluating a bundle of ES in monetary terms, because it would lead to double counting (Wallace, 2007; Turner *et al*., 2010; Fu *et al*., 2011), as the value of biodiversity would be counted both in the natural value and in the final ES that is demanded and consumed by humans.

Within this framework, and without addressing the issue of positioning ecosystems' capacity to support biodiversity and in turn other ES within either the supporting and habitat services or the regulating and maintenance ones, in this study natural value is assessed in non-monetary terms, and it is understood as ecosystems' capability to provide suitable conditions for species' persistence at both the individual and the populations levels (Hall *et al*., 1997; Pilogallo and Scorza, 2021). To operationalize to concept, habitat quality is chosen as proxy, by assessing the extent to which terrestrial habitat types are close to their natural condition (Terrado *et al*., 2016), i.e., unaffected by anthropogenic pressures. In other words, natural value in this study accounts for biodiversity's quality, which implies its ecological integrity, current levels of ecosystem functions, and ecosystems' capability to supply final, human-demanded ecosystem services notwithstanding pressures and threats to habitats.

The tool "Habitat quality", part of the InVEST[3] suite, produces habitat quality maps by combining information on land covers and threats to biodiversity, based on the assumption that areas having high values of habitat quality can better support biodiversity, while decreasing levels of quality imply lower biodiversity levels. The tool has been applied extensively for various purposes, as follows.

- To identify priority areas for conservation (Baral *et al*., 2014; Duarte *et al*., 2016; Lin *et al*., 2017; Salata *et al*., 2017) or to ground planning decisions for biodiversity conservation (Nolè *et al*., 2020).
- To prioritize areas for intervention within already established natural protected areas (Sallustio *et al*., 2007) or within polluted sites (Scorza *et al*., 2020a).
- To investigate synergies and tradeoffs between habitat quality and other ES (Bai *et al*., 2011; Yang W. *et al*., 2018).
- To assess impacts on biodiversity generated by land-use changes in general (Polasky *et al*., 2011; Leh *et al*., 2013; Arunyawat and Shrestha, 2016; Yang S. *et al*., 2018), by urban expansion (Sun *et al*., 2018), or by large wind-farm projects (Saganeiti *et al*., 2020; Scorza *et al*., 2020b), by looking at either historical changes or at simulated scenarios.
- To support the spatial identification of ecological networks (Gao *et al*., 2017) and corridors (Cannas *et al*., 2018).

The tool requires the following input data:

- A current raster land cover map, where the classification of land covers is not predefined and can be chosen by the user; moreover, if scenarios are modeled, the user can optionally also add one baseline and one future land cover map. Land cover maps are used in lieu of habitats type

[3] InVEST, an acronym for "Integrated Valuation of Ecosystem Services and Tradeoffs", is a suite of tools developed by the Natural Capital Project and freely available from https://naturalcapitalproject.stanford.edu/software/invest [Accessed: 22 February 2022]. The suite tools allow for developing spatially explicit assessments of various ecosystem services in biophysical terms; some tools also allow for monetary evaluation.

maps because either they are readily available in many countries or they can be retrieved through remote sensing technique from satellite imagery, also readily available worldwide. Each land cover type is next assessed in terms of its suitability to support biodiversity, through the sensitivity matrix listed in item 5 below.

- A list of current threats to biodiversity, and for each threat a weight (which denotes the threat's relative importance), a decay distance and function.
- A raster map for each current threat source.
- A vector map representing accessibility to sources of degradation, in terms of relative protection to habitats provided by legal institutions.
- A sensitivity matrix, in which each land cover type is assessed in terms of its suitability to being regarded as a habitat type, where habitats represent resources and conditions present in an area that can support the life of given organisms and therefore are not restricted to those of community interest accounted for by *Consval*; moreover, each land cover type is also scored based on its sensitivity to each threat selected as per item 2 above.
- A so-called "half-saturation constant", having default value 0.5.

2.2.1. Natural quality assessment through the InVEST model

In this study, the habitat quality in Sardinia was assessed using the InVEST model. For the raster land cover map, we started from the 2008 Land Cover Map produced by the Regional administration of Sardinia[4]; this is a vector dataset which classes land covers using the standard nomenclature of the European project CORINE, with a finer spatial resolution and a more detailed taxonomy, which is provided at the fifth level for woods and forests, than the one produced at the European level. Since the model requires a raster dataset, this map was first reclassified at the third level of the CORINE taxonomy, and next converted into a raster map having cellsize 25 x 25 meters.

As for the threats, the standard data forms concerning Sardinian Natura 2000 sites were examined; each standard data form lists threats and pressures that generate negative impacts on a given site. Next, from the whole

[4] Available from the regional geoportal: http://www.sardegnageoportale.it/index.php?xsl=2420&s=40&v=9&c=14480&es=6603&na=1&n=100&esp=1&tb=14401 [Accessed: 22 February 2022].

list, those threats and pressures that can be mapped and that impact on terrestrial areas (as opposed to marine areas, which are out of the scope of this study) were selected. As a result, a list of ten pressures and threats was obtained; for the weight and decay distance, a questionnaire was delivered to local experts in the field of biodiversity and environmental impact assessment. In the questionnaire, the weight was to be expressed using a "Likert" scale 1-5, hence grading the relative importance of a given threat, while the decay distance was to be provided in kilometers. For each threat, both the weights and the decay distances provided by the surveyed experts were next averaged; moreover, the weights were normalized in the (0-1) interval as per InVEST's requirements. Tab. 2 provides a list of the ten selected threats, as well as their weights and decay distances, averaged and, as for weights only, also normalized. The decay function was always set as "linear". The ten selected threats were mapped based on vector datasets freely available from the regional geoportal, subsequently converted into raster maps having cellsize 25 x 25 meters. Tab. 2 lists, in detail, the data sources used.

Tab. 2 - Threats to biodiversity in the study area, parameters for the InVEST model (weight, decay distance and function), and spatial data sources

Code	*Threat name*	*Weight*	*Decay distance [km]*	*Decay function*	*Data source (*)*
T01	Cultivation	0.58	1.63	linear	2008 Land Cover Map
T02	Grazing	0.68	0.58	linear	2008 Land Cover Map
T03	Removal of forest undergrowth	0.79	0.65	linear	2008 Land Cover Map
T04	Salt works	0.63	0.83	linear	2008 Land Cover Map
T05	Paths, tracks	0.53	0.55	linear	Regional multi-precision database
T06	Roads, motorways	0.95	3.00	linear	Regional multi-precision database
T07	Airports	0.95	4.75	linear	2008 Land Cover Map
T08	Urbanized areas	0.95	3.25	linear	2008 Land Cover Map
T09	Discharges	1.00	3.50	linear	2008 Land Cover Map
T10	Fire	0.95	2.05	linear	Burnt area maps

(*) All of the spatial datasets can be freely downloaded from the regional geoportal: http://www.sardegnageoportale.it

With regards to accessibility to sources of biodiversity degradation, regional and national parks were considered, as well as areas protected and managed by the public regional forestry agency, as having the highest protection and hence lowest accessibility level (score 0.2); a second level was that of Natura 2000 sites (score 0.5); all the rest of the study area was considered as completely accessible (score 1). To map accessibility, vector maps of parks, areas protected and managed by the public regional forestry agency, and finally Natura 2000 sites, were used, all available from the regional geoportal.

The sensitivity of each habitat to each threat was developed using a two-step expert-based approach: first, each land cover code (at the third level of the CORINE taxonomy) was given a trichotomous value (1 if the land cover could be intrinsically regarded as habitat; 0.5 if it could be considered habitat contingent on external factors; else 0); second, for each land cover code that could be considered as habitat, a score representing that land cover's sensitivity to each threat was assigned. The full matrix is provided in tab. 3.

Tab. 3 - The sensitivity matrix used as input for the InVEST habitat quality model

LC code	*habitat score*	*T01*	*T02*	*T03*	*T04*	*T05*	*T06*	*T07*	*T08*	*T09*	*T10*
111	0	0	0	0	0	0	0	0	0	0	0
112	0	0	0	0	0	0	0	0	0	0	0
121	0	0	0	0	0	0	0	0	0	0	0
122	0	0	0	0	0	0	0	0	0	0	0
123	0	0	0	0	0	0	0	0	0	0	0
124	0	0	0	0	0	0	0	0	0	0	0
131	0	0	0	0	0	0	0	0	0	0	0
132	0	0	0	0	0	0	0	0	0	0	0
133	0	0	0	0	0	0	0	0	0	0	0
141	1	0	0	0	0	0	0.5	0.2	0.5	1	1
142	0	0	0	0	0	0	0	0	0	0	0
143	0	0	0	0	0	0	0	0	0	0	0
211	0.5	0	0.5	0	0	0	0.5	0	0.5	0.5	0.5
212	0.5	0	0.5	0	0	0	0.5	0	0.5	0.5	0.5
221	0.5	0	0.5	0	0	0	0.5	0	0.5	0.5	0.5
222	0.5	0	0.5	0	0	0	0.5	0	0.5	0.5	0.5
223	0.5	0	0.5	0	0	0	0.5	0	0.5	0.5	0.5
224	1	1	1	0.5	0	1	1	0.5	1	1	1
231	1	1	0.5	0	0	0.5	1	0.2	0.5	1	1
241	0.5	0	0.5	0	0	0	0.5	0	0.5	0.5	0.5
242	0.5	0	0.5	0	0	0	0.5	0	0.5	0.5	0.5
243	1	0.5	1	0.5	0	1	1	0.2	1	1	1
244	1	0.5	0.5	1	0	1	1	0.2	1	1	1
311	1	1	0.5	1	0	1	1	0.2	0.5	1	1
312	1	1	0.5	1	0	1	1	0.2	0.5	1	1
313	1	1	0.5	1	0	1	1	0.2	0.5	1	1
321	1	1	1	0	0	1	1	0.5	0.5	1	1
322	1	1	1	0	0	1	1	0.5	1	1	1
323	1	1	1	0.5	0	1	1	0.5	1	1	1
324	1	1	1	0.5	0	1	1	0.5	1	1	1
331	1	0	0	0	0	1	1	0.5	1	1	0

LC code	*habitat score*	*T01*	*T02*	*T03*	*T04*	*T05*	*T06*	*T07*	*T08*	*T09*	*T10*
332	1	0	0	0	0	1	1	0.2	1	1	0
333	1	1	1	0	0	1	1	0.5	1	1	1
411	1	1	0	0	1	0.5	1	0.5	1	1	0
421	1	0.5	0	0	1	0.5	1	0.5	1	1	0
422	1	0.5	0	0	0	0	1	0.2	1	1	0
423	1	0.5	0	0	0	0.5	1	0.2	1	1	0
511	1	0.5	0	0	0	0.5	1	0.2	1	1	0
512	1	0.5	0	0	0	0.5	1	0.2	1	1	0
521	1	0.5	0	0	1	0.5	1	0.2	1	1	0

2.3. Recreation value (*Recrval*)

Recreation value (*Recrval*) is a final ecosystem service part of the cultural ES group. In the MA taxonomy (Millennium Ecosystem Assessment, 2003, p. 58), this group includes different kinds of nonmaterial benefits derived from ecosystems such as “spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences”. Recreation, in particular, accounts for the fact that landscapes and natural habitats are among the factors that people take into account when deciding where they want to spend their holidays or just some leisure time, which not only positively affects residents’ and tourists’ quality of life and wellbeing, but also impacts directly and indirectly on local economies. In contrast to the other cultural ecosystem services, which are hardly ever assessed through quantitative or monetary approaches because of their subjective character, their immaterial and intangible nature (Milcu *et al.*, 2013; Ryfield *et al.*, 2019), as well as their inadequate definition leading to unclear operationalization (Blicharska *et al.*, 2017), recreational services are often measured through economic indicators. The TEEB, for instance, suggests that the recreational value related to biodiversity can be evaluated in monetary terms through travel cost methods (Kumar *et al.*, 2011), which have indeed been used by several scholars (among many, Fleming and Cook, 2008; Serkan and Rehber, 2008; Martín-López *et al.*, 2009; Lankia *et al.*, 2015; Mayer and Woltering, 2018), sometimes in combination with willingness to pay exercises, or with contingent valuation methods (Nielsen *et al.*, 2007; Rosenberger *et al.*, 2012; Jobstvogt *et al.*, 2014; van Berkel and Verburg, 2014).

A different approach is that of non-monetary evaluation, which, according to some scholars, would allow to capture in a broader and multidimensional way people’s understanding and valuing of non-tangible ecosystem services (Kenter, 2014) such as the recreational one. Several qualitative, socio-cultural approaches have therefore been proposed, including document analysis, expert-based approaches, observation approaches, in-depth interviews, focus groups, questionnaires (Scholte *et al.*, 2015); such approaches are advocated as the ones that can provide a clearer picture of the relationship between cultural ecosystem services and their users (Milcu *et al.*, 2013). Other non-monetary approaches rely on quantitative methods, which, in principle, could easily be used to assess recreation values, as they imply collecting data on tourists and visitors from official statistics (as in Eagles *et al.*, 2000), or carrying out ad-hoc surveys (as in Jim and Chen, 2006; Voigt *et al.*, 2014; Kothencz *et al.*, 2017). However, because of the costs and time requirements, such data are often unavailable; as a consequence, social-media based approaches have been proposed that estimate visitor figures and preferences based on the number of pictures uploaded to social media such as Flickr (Wood *et al*., 2013; Richards and Friess, 2015; Sonter *et al*., 2016; Cunha *et al.*, 2018; Arkema *et al*., 2021; Mouttaki *et al*., 2021), Instagram (Hausmann *et al.*, 2017; Vieira *et al.*, 2018; Grzyb *et al*., 2021) or Panoramio (Angradi *et al.*, 2018; Oteros-Rozas *et al.*, 2018), sometimes also combining data from two platforms. Limitations of such models are linked to the digital divide issue, as well as to their reliance on specific platforms, which is often constrained by privacy limitations in accessing and analyzing materials posted by users.

Finally, a different spatially explicit approach is that of ESTIMAP ("Ecosystem Service Mapping Tool"), a suite of conceptual tools developed by a group of researchers from the European Joint Research Centre to assess provision and demand of a set of ES at the EU level (Zulian *et al*., 2014) and comprising a specific model to assess potential provision of nature-based outdoor recreation, as well as the spatial distribution of local populations' met and unmet demand for recreational ES (Paracchini *et al*., 2014). Originally developed to map terrestrial ES, the model was also applied to assess recreation potential in marine and coastal areas (Liquete *et al*., 2016b). Moreover, although conceived for assessing the spatial distribution of ES supply and demand at the continental scale, the model has been and applied at various scales, from the national one in Bulgaria (Ihtimanski *et al*., 2020), to the metropolitan one in Barcelona (Baró *et al*., 2016) and in Oslo (Suarez *et al*., 2020), to the municipal scale in Trento (Cortinovis *et al*., 2018). An overview of adaptations of the original model to tailor it to the local level is provided in Zulian *et al*. (2018) with reference to four urban case studies. A similar conceptual approach, also including aspects that impact negatively on the landscape's attractiveness for recreational users, such as wind turbines, power lines and solar plants, is proposed and applied taking German as a case study by Waltz and Stein (2018).

2.3.1. Recreational ES modeling through ESTIMAP

In this study, the original model as presented in Vallecillo *et al.* (2019) and Barton *et al.* (2019) was applied to Sardinia. This model, which is graphically summarized in fig. 1 and fig. 2, comprises three main steps, as follows:

- Mapping the potential provision of nature-based recreation (fig. 1).
- Identifying areas where the potential ES offer can actually be enjoyed and used (fig. 2).
- Mapping the spatial distribution of population whose demand of nature-based recreation is met or unmet (fig. 2).

The first step, concerning the potential provision of nature-based recreation, in turns comprises various sub-steps that basically serve the purpose of identifying areas that are, in principle, more attractive for recreational users. The original model identifies three groups of characteristics that are of interest to recreational users: i., suitability of land to support recreation; ii., presence of protected areas; iii., water-related elements. Although these characteristics have sometimes been tailored to local specificities and contexts, by either choosing only some (Ihtimanski *et al.*, 2020) or by adding other features (see for instance Cortinovis *et al.*, 2018), we regarded the ones proposed in the original model highly appropriate for analyzing recreational ES at the regional scale and in reference to an island, as Sardinia is.

As for the first characteristic, i.e., the suitability of land to support recreation, the key concept here is that the higher the degree of naturalness, the higher the suitability. The degree of naturalness is assessed based on its opposite, i.e., on an evaluation of the level of disturbance caused by human activities on ecosystems. To this end, the hemeroby index proposed by Paracchini and Capitani (2011) was used, where a score ranging from 1 (no disturbance) to 9 (maximum disturbance, implying that ecosystems are absent because replaced by artificial surfaces) is assigned to land cover classes, by using the third level of the CORINE land cover nomenclature. As shown in tab. 4, such correspondence between hemeroby index and land cover classes is mostly univocal, except for agricultural and forestry areas, where three values can be assigned depending on the intensity of management practices. For agricultural areas, intensity is estimated based on nutrient inputs and livestock density, while for forests it is assumed to depend upon differences between actual and potential vegetation.

To assign a specific value to each agricultural land parcel, data were retrieved from the National Census Institute[5], which provides, among other nutrients, the amount of nitrogen contained in fertilizers distributed in 2019 for agricultural purposes at the province (NUTS3) level (tab. 5).

Tab. 4 - Correspondence between hemeroby values and CORINE land cover (CLC) classes. Adapted after Paracchini and Capitani (2011)

CLC artificial surfaces	*hemeroby index*	*CLC agricultural areas*	*hemeroby index*	*CLC forest and seminatural areas*	*hemeroby index*	*CLC wetlands*	*hemeroby index*
111	9	211	5-6-7	311	2-3-4	411	2
112	9	212	5-6-7	312	2-3-4	421	2
121	9	213	5-6-7	313	2-3-4	422	6
122	9	221	4-5-6	321	2-3-4		
123	9	222	4-5-6	322	2		
124	9	223	4-5-6	323	2		
131	8	231	3-4-5	324	2		
132	8	241	4-5-6	331	2		
133	8	242	4-5-6	332	1		
141	8	243	4-5-6	333	2		
142	8	244	3-4-5	334	6		

Tab. 5 - Total nitrogen contained in fertilizers distributed for agricultural purposes at NUTS3 level in Sardinia, year 2019. Data retrieved from the National Census Institute

Provinces and Metropolitan Cities	*Total nitrogen [kg]*
Cagliari - Città Metropolitana	4411000
Nuoro	678000
Oristano	2301000
Sassari	1569000
Sud Sardegna	8206000

Within each province, the total amount of nitrogen was averaged, by dividing it by the amount of agricultural area in that province, hence each land cover patch belonging to classes starting by "2" could be assigned its nitrogen input (in kilogram per hectare of agricultural area). Moreover, livestock intensity was assessed based on data retrieved from the National Zootechnical Register[6], which provides the number of bovine animals, sheep, goats, equidaes, pigs, and poultry that are reared within each munic-

[5] Available from http://dati.istat.it/#, under Section "Agriculture", subsection "Production means/fertilizers", indicator "nutrients contained, per province" [Accessed: 22 February 2022].

[6] Available from: https://www.vetinfo.it/j6_statistiche/. Data provided by the National Dataset of the Zootechnical Register established by the Ministry of Health at the "G. Caporale" Institute in Teramo. [Accessed: 22 February 2022].

ipality. The number of livestock from such different species was aggregated at the municipal level by making use of the livestock unit (LSU) coefficients available from Eurostat[7], using the simplified categories in tab. 6 and next the total livestock density (Eurostat, 2019) was calculated by dividing, for each municipality, its total livestock unit by its total utilized agricultural area (tab. 7).

Tab. 6 - Livestock unit coefficients (adapted from Eurostat)

Livestock types	*Livestock unit coefficients*
Bovine animals	1
Sheep	0.1
Goats	0.1
Equidae	0.8
Pigs	0.3
Broilers	0.007
Laying hens	0.014
Other poultry	0.03

Tab. 7 - Livestock intensity at the municipal level in Sardinia (LSU: livestock unit; AGRI: agricultural area; LS_D: livestock density), calculated based on the number of livestock retrieved from the National Zootechnical Register

Municipality	*LSU bovine*	*LSU equidae*	*LSU pigs*	*LSU sheep/ goats*	*LSU poultry*	*LSU total*	*AGRI [ha]*	*LS_D [LSU/ha]*
Abbasanta	1503	43.2	48.0	803.2	0	2397.4	3289.32	0.73
Aggius	2825	23.2	91.2	61.3	0	3000.7	3422.30	0.88
Aglientu	1287	17.6	57.3	128.8	0	1490.7	5503.02	0.27
Aidomaggiore	561	17.6	94.5	793.2	0	1466.3	3272.64	0.45
Alà dei Sardi	1423	22.4	130.2	1022.7	0	2598.3	2676.58	0.97
Albagiara	0	3.2	4.5	128.4	161.3	297.4	802.12	0.37
Ales	49	8.0	43.2	345.4	0	445.6	1632.03	0.27
Alghero	665	100.8	353.1	1063.6	0	2182.5	13633.93	0.16
Allai	286	3.2	17.7	135.0	0	441.9	820.33	0.54
Anela	563	15.2	51.6	788.5	0	1418.3	1828.65	0.78
Arborea	32839	36.8	134.7	225.4	0	33235.9	7797.59	4.26
Arbus	657	29.6	300.3	2220.8	0	3207.7	5442.16	0.59
Ardara	740	15.2	86.4	1077.9	0	1919.5	3632.34	0.53
Ardauli	9	6.4	17.7	105.0	0	138.1	933.83	0.15
Aritzo	2297	8.8	48.0	448.3	0	2802.1	169.32	16.55
Armungia	691	1.6	55.8	271.1	0	1019.5	611.15	1.67
Arzachena	2306	81.6	368.7	161.2	5.6	2923.1	8646.36	0.34

[7] Available from: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Livestock_unit_(LSU) [Accessed: 22 February 2022].

Municipality	*LSU bovine*	*LSU equidae*	*LSU pigs*	*LSU sheep/ goats*	*LSU poultry*	*LSU total*	*AGRI [ha]*	*LS_D [LSU/ha]*
Arzana	5299	52.0	303.0	921.4	0	6575.4	1827.41	3.60
Assemini	261	51.2	215.7	1048.8	0	1576.7	4397.95	0.36
Assolo	133	10.4	41.7	231.9	0	417.0	1109.25	0.38
Asuni	189	5.6	33.9	432.9	0	661.4	1188.84	0.56
Atzara	881	11.2	91.5	296.0	0	1279.7	2368.75	0.54
Austis	392	15.2	85.5	711.8	0	1204.5	925.51	1.30
Badesi	365	12.0	24.0	16.3	0	417.3	1499.77	0.28
Ballao	431	3.2	54.3	381.3	0	869.8	965.51	0.90
Banari	211	11.2	5.7	194.1	0	422.0	1008.89	0.42
Baradili	0	0.8	3.3	17.6	0	21.7	545.06	0.04
Baratili San Pietro	0	4.0	20.4	166.0	0	190.4	555.83	0.34
Baressa	0	2.4	15.9	259.9	0	278.2	1041.72	0.27
Bari Sardo	19	52.8	165.6	740	0	977.4	2569.98	0.38
Barrali	32	15.2	36.6	264.1	0	347.9	675.58	0.51
Barumini	133	11.2	25.5	574.8	0	744.5	2521.28	0.30
Bauladu	357	14.4	56.7	331.9	0	760.0	675.24	1.13
Baunei	845	20.8	117.3	485.2	0	1468.3	334.66	4.39
Belvì	106	3.2	27.9	159.7	0	296.8	138.24	2.15
Benetutti	1684	45.6	198.0	2035.8	0	3963.4	6630.41	0.60
Berchidda	1615	33.6	112.2	2059.7	0	3820.5	7673.41	0.50
Bessude	378	17.6	80.7	553.8	0	1030.1	1651.13	0.62
Bidonì	8	0.8	2.4	216.3	0	227.5	412.69	0.55
Birori	778	8.0	32.1	449.2	0	1267.3	1396.17	0.91
Bitti	2005	52.0	129.9	6052.5	0	8239.4	11550.08	0.71
Bolotana	1590	45.6	63.6	2397.3	0	4096.5	7649.75	0.54
Bonarcado	653	36.0	91.8	1040.6	0	1821.4	1868.94	0.97
Bonnanaro	156	32.8	28.2	797.9	0	1014.9	2037.04	0.50
Bono	728	84.8	220.5	2430.3	0	3463.6	4116.07	0.84
Bonorva	2730	112.0	183.6	3720.9	0	6746.5	8427.35	0.80
Boroneddu	26	6.4	8.4	135.7	0	176.5	443.81	0.40
Borore	554	33.6	124.2	1839.3	0	2551.1	3463.79	0.74
Bortigali	4777	36.0	108.0	1598.8	0	6519.8	4995.22	1.31
Bortigiadas	1000	8.8	44.1	133.1	0	1186.0	2271.18	0.52
Borutta	93	3.2	3.3	113.7	0	213.2	401.57	0.53
Bosa	1975	26.4	48.6	1132.3	0	3182.3	2673.26	1.19
Bottidda	1739	17.6	322.5	1107.1	0	3186.2	2094.77	1.52
Buddusò	2450	66.4	204.0	1859.2	0	4579.6	5861.81	0.78
Budoni	887	37.6	196.2	231.4	0	1352.2	2769.69	0.49
Buggerru	46	2.4	12.9	150.9	0	212.2	361.51	0.59
Bultei	2012	34.4	165.9	1620.5	0	3832.8	3765.73	1.02

Municipality	*LSU bovine*	*LSU equidae*	*LSU pigs*	*LSU sheep/ goats*	*LSU poultry*	*LSU total*	*AGRI [ha]*	*LS_D [LSU/ha]*
Bulzi	130	12.0	27.3	536.7	0	706.0	2010.82	0.35
Burcei	1029	12.0	125.7	475.6	0	1642.3	925.27	1.77
Burgos	249	23.2	22.5	590.6	0	885.3	956.82	0.93
Busachi	220	35.2	204.3	1426.3	0	1885.8	2518.12	0.75
Cabras	29	16.0	39.0	671.4	0	755.4	6251.48	0.12
Cagliari	0	53.6	15.9	165.3	0	234.8	534.77	0.44
Calangianus	1188	11.2	43.5	115.8	0	1358.5	2367.61	0.57
Calasetta	42	33.6	9.9	234.5	0	320.0	1867.51	0.17
Capoterra	73	53.6	149.1	349.1	0	624.8	2202.03	0.28
Carbonia	129	68.0	111.6	2334.0	39.2	2681.8	6905.38	0.39
Cardedu	130	21.6	74.4	401.2	0	627.2	1551.27	0.40
Cargeghe	58	8.0	14.7	286.1	0	366.8	730.83	0.50
Carloforte	51	16.8	20.7	13.4	0	101.9	1682.57	0.06
Castelsardo	194	22.4	28.8	457.2	0	702.4	2824.92	0.25
Castiadas	127	32.0	129.6	899.6	0	1188.2	5227.46	0.23
Cheremule	188	11.2	31.8	493.3	0	724.3	1955.17	0.37
Chiaramonti	1963	44.0	412.2	2288.1	0	4707.3	5041.36	0.93
Codrongianos	248	13.6	30.6	983.9	0	1276.1	2768.37	0.46
Collinas	0	5.6	12.6	145.4	0	163.6	1269.29	0.13
Cossoine	389	24.0	73.8	1262.7	0	1749.5	2555.36	0.68
Cuglieri	737	63.2	175.5	1323.9	0	2299.6	5125.80	0.45
Curcuris	3	1.6	9.9	230	0	244.5	517.63	0.47
Decimomannu	0	16.8	77.7	413.8	0	508.3	2113.08	0.24
Decimoputzu	75	35.2	60.3	1469.2	67.2	1706.9	3933.00	0.43
Desulo	1605	10.4	81.6	1283.9	0	2980.9	12.93	230.59
Dolianova	760	57.6	322.5	1163.9	614.3	2918.3	2501.53	1.17
Domus de Maria	181	12.8	71.4	274.7	0	539.9	1395.07	0.39
Domusnovas	163	18.4	93.9	852.4	0	1127.7	1468.79	0.77
Donori	67	12.8	255.9	484.9	0	820.6	2217.73	0.37
Dorgali	798	143.2	416.7	5338.1	112.0	6808.0	9101.89	0.75
Dualchi	214	23.2	55.8	759.7	0	1052.7	1710.83	0.62
Elini	0	4.0	13.5	27.2	0	44.7	337.31	0.13
Elmas	0	13.6	6.0	153.2	0	172.8	685.89	0.25
Erula	518	11.2	60	575.6	0	1164.8	2088.31	0.56
Escalaplano	909	5.6	424.5	1094.4	0	2433.5	2985.13	0.82
Escolca	0	5.6	44.7	221.0	0	271.3	1192.60	0.23
Esporlatu	317	16.0	19.5	839.2	0	1191.7	755.19	1.58
Esterzili	1061	13.6	67.8	425.2	0	1567.6	860.15	1.82
Florinas	37	20.8	43.5	694.5	0	795.8	2603.00	0.31
Fluminimaggiore	139	20	71.1	777.1	68.1	1075.3	1059.41	1.02
Flussio	24	4.8	5.7	255.0	0	289.5	483.06	0.60

Municipality	*LSU bovine*	*LSU equidae*	*LSU pigs*	*LSU sheep/ goats*	*LSU poultry*	*LSU total*	*AGRI [ha]*	*LS_D [LSU/ha]*
Fonni	6575	67.2	289.5	2445.5	268.7	9645.9	4254.34	2.27
Fordongianus	371	8.8	61.5	546.8	0	988.1	1802.74	0.55
Furtei	42	10.4	45.6	177.1	0	275.1	2017.04	0.14
Gadoni	1121	10.4	40.8	266.9	63.0	1502.1	326.94	4.59
Gairo	736	14.4	100.2	362.1	0	1212.7	739.00	1.64
Galtellì	221	16.8	129.3	848.8	0	1215.9	2624.93	0.46
Gavoi	127	48.8	99.9	1166.6	0	1442.3	1717.69	0.84
Genoni	693	26.4	147.6	550.3	0	1417.3	2193.29	0.65
Genuri	0	2.4	5.4	41.4	0	49.2	668.92	0.07
Gergei	47	34.4	112.5	808.6	0	1002.5	3147.03	0.32
Gesico	124	16.0	102.3	780.5	0	1022.8	2490.67	0.41
Gesturi	6	32.8	136.5	722.4	0	897.7	2356.40	0.38
Ghilarza	826	40	124.2	968.8	0	1959.0	4029.36	0.49
Giave	231	32.8	57.9	1341.9	12.6	1676.2	3255.88	0.51
Giba	29	10.4	39.3	340.2	0	418.9	2387.92	0.18
Girasole	0	9.6	136.8	74.4	0	220.8	1055.02	0.21
Golfo Aranci	149	4.0	7.2	28.9	0	189.1	671.22	0.28
Goni	199	7.2	118.8	428.1	0	753.1	384.74	1.96
Gonnesa	14	21.6	33.6	562.6	0	631.8	1759.11	0.36
Gonnoscodina	0	4.8	49.5	5.7	0	60.0	746.92	0.08
Gonnosfanadiga	361	52.8	364.2	2088.6	1512	4378.5	5405.83	0.81
Gonnosnò	0	8.0	51.6	228.7	0	288.3	1227.64	0.23
Gonnostramatza	0	2.4	85.8	486.9	0	575.1	882.90	0.65
Guamaggiore	0	4.8	36.6	184.6	0	226.0	1541.13	0.15
Guasila	829	27.2	66.3	568.3	0	1490.8	4001.73	0.37
Guspini	1924	72.8	420.3	3587.2	75.4	6079.7	10240.26	0.59
Iglesias	594	79.2	402.3	2691.5	0	3767.0	4209.92	0.89
Ilbono	70	16.8	28.8	332.7	36.5	484.8	1889.91	0.26
Illorai	913	16.8	54.3	1338.6	0	2322.7	2992.07	0.78
Irgoli	1082	22.4	669.0	2333.8	0	4107.2	3031.32	1.35
Isili	246	32.8	960	1009.3	0	2248.1	3514.18	0.64
Ittireddu	578	19.2	145.8	1080.4	0	1823.4	1995.31	0.91
Ittiri	192	65.6	149.4	3556.6	0	3963.6	7457.38	0.53
Jerzu	194	19.2	70.8	433.4	0	717.4	2684.71	0.27
La Maddalena	0	4.8	3.3	5.7	0	13.8	0.00	0.00
Laconi	1501	45.6	205.5	933.2	0	2685.3	4699.88	0.57
Laerru	75	8.8	145.8	333.4	0	563.0	1653.85	0.34
Lanusei	18	31.2	504.0	557.0	0	1110.2	2537.26	0.44
Las Plassas	0	8.8	6.3	221.7	0	236.8	1061.40	0.22
Lei	353	10.4	48.3	578.0	0	989.7	981.92	1.01
Loceri	55	12.8	56.1	231.8	5.9	361.6	1279.26	0.28

Municipality	*LSU bovine*	*LSU equidae*	*LSU pigs*	*LSU sheep/ goats*	*LSU poultry*	*LSU total*	*AGRI [ha]*	*LS_D [LSU/ha]*
Loculi	406	8.0	588.9	985.9	0	1988.8	1386.83	1.43
Lodè	395	11.2	65.1	885.2	0	1356.5	3329.96	0.41
Lodine	20	1.6	30	262.0	0	313.6	507.26	0.62
Loiri Porto San Paolo	782	21.6	91.5	575.2	0	1470.3	5375.63	0.27
Lotzorai	175	8.0	143.4	230.7	0	557.1	1325.57	0.42
Lula	1205	29.6	352.5	1425.2	0	3012.3	4094.63	0.74
Lunamatrona	48	6.4	51.3	247.0	0	352.7	1924.03	0.18
Luogosanto	2161	36.0	51.9	165.5	0	2414.4	4725.18	0.51
Luras	1125	20.8	37.2	459.6	0	1642.6	4388.41	0.37
Macomer	3426	62.4	239.7	3162.1	0	6890.2	8700.99	0.79
Magomadas	0	2.4	2.7	62.6	0	67.7	794.86	0.09
Mamoiada	796	36.8	32.1	916.9	503.4	2285.2	3279.12	0.70
Mandas	153	32.0	172.2	671.0	0	1028.2	3419.39	0.30
Mara	214	11.2	31.8	367.6	0	624.6	1147.68	0.54
Maracalagonis	219	32.0	63.3	473.7	0	788.0	2916.58	0.27
Marrubiu	158	41.6	265.2	985.6	154.0	1604.4	4085.51	0.39
Martis	136	6.4	77.7	616.0	0	836.1	2088.10	0.40
Masainas	100	20.8	16.8	159.6	0	297.2	1765.34	0.17
Masullas	60	0.8	68.1	241.7	0	370.6	1140.34	0.32
Meana Sardo	1639	16.0	120.3	752.4	0	2527.7	2113.78	1.20
Milis	176	7.2	53.7	414.5	0	651.4	1454.51	0.45
Modolo	0	0	0.9	14.6	0	15.5	170.67	0.09
Mogorella	305	5.6	51.3	446.5	0	808.4	1342.98	0.60
Mogoro	28	45.6	329.1	785.0	0	1187.7	4194.50	0.28
Monastir	3	16.8	158.4	424.1	42.0	644.3	2481.47	0.26
Monserrato	8	13.6	9.0	42.5	0	73.1	302.94	0.24
Monteleone Rocca Doria	271	4.8	6.0	123.3	0	405.1	440.42	0.92
Monti	622	8.0	69.3	226.8	0	926.1	3867.69	0.24
Montresta	1039	3.2	39.0	340.4	0	1421.6	1009.64	1.41
Mores	3065	69.6	204.0	3121.5	0	6460.1	8653.35	0.75
Morgongiori	52	2.4	48.3	150.3	0	253.0	824.37	0.31
Muravera	167	28.8	134.4	476.0	0	806.2	3704.19	0.22
Muros	0	6.4	13.2	86.3	0	105.9	812.05	0.13
Musei	262	14.4	20.4	1294.1	0	1590.9	1946.06	0.82
Narbolia	433	17.6	59.4	772.4	1.4	1283.8	2350.58	0.55
Narcao	60	8.8	78.0	687.5	0	834.3	2366.44	0.35
Neoneli	60	8.8	75.9	429.3	0	574.0	726.91	0.79
Noragugume	333	15.2	80.1	1331.9	0.8	1761.0	2479.16	0.71
Norbello	491	50.4	72.0	864.8	0	1478.2	2406.26	0.61

Municipality	*LSU bovine*	*LSU equidae*	*LSU pigs*	*LSU sheep/ goats*	*LSU poultry*	*LSU total*	*AGRI [ha]*	*LS_D [LSU/ha]*
Nughedu San Nicolò	905	23.2	146.7	1204.2	3.3	2282.4	3477.09	0.66
Nughedu Santa Vittoria	6	12.8	11.4	238.4	0	268.6	756.10	0.36
Nule	782	34.4	204.6	2399.3	0	3420.3	3752.54	0.91
Nulvi	1100	50.4	229.5	1761.9	0	3141.8	5199.99	0.60
Nuoro	3081	161.6	187.8	2277.4	0	5707.8	9819.73	0.58
Nurachi	0	7.2	5.4	142.0	0	154.6	1505.17	0.10
Nuragus	240	16.8	66.9	800	0	1123.7	1787.65	0.63
Nurallao	195	20.8	69.9	437.5	0	723.2	1419.97	0.51
Nuraminis	0	7.2	24.9	624.7	0	656.8	4287.69	0.15
Nureci	44	3.2	20.4	208.4	0	276.0	852.63	0.32
Nurri	344	26.4	541.2	3132.4	0	4044.0	4829.63	0.84
Nuxis	23	8.8	39.6	179.6	0	251.0	1430.87	0.18
Olbia	3069	128.8	501.9	2591.4	0	6291.1	16529.14	0.38
Oliena	351	102.4	214.8	1882.3	0	2550.5	8294.78	0.31
Ollastra	85	18.4	70.8	742.5	0	916.7	1343.34	0.68
Ollolai	136	38.4	59.4	745.8	57.7	1037.3	835.79	1.24
Olmedo	69	16.8	15.3	311.0	0	412.1	2354.79	0.18
Olzai	770	24.0	65.4	1973.3	0	2832.7	3893.92	0.73
Onanì	362	6.4	13.8	1251.6	0	1633.8	3213.03	0.51
Onifai	430	10.4	88.8	1033.9	0	1563.1	1612.56	0.97
Oniferi	1424	33.6	74.4	1091.8	0	2623.8	2305.06	1.14
Orani	3413	76.0	216.9	3544.7	0	7250.6	5897.01	1.23
Orgosolo	8176	160	632.4	2423.0	0	11391.4	4701.60	2.42
Oristano	426	129.6	120.9	938.3	0	1614.8	6659.70	0.24
Orosei	354	44.0	202.2	720.7	200.2	1521.1	4201.14	0.36
Orotelli	3086	56.0	101.4	2948.4	0	6191.8	2888.28	2.14
Orroli	865	26.4	432.3	1317.8	0	2641.5	3113.58	0.85
Ortacesus	31	10.4	121.8	958.7	0	1121.9	2125.63	0.53
Ortueri	263	26.4	123.3	662.1	0	1074.8	1917.99	0.56
Orune	2718	38.4	90.6	6759.6	0	9606.6	6541.97	1.47
Oschiri	1806	57.6	219.6	3273.6	0	5356.8	10982.28	0.49
Osidda	520	5.6	24.6	719.9	0	1270.1	1890.92	0.67
Osilo	544	115.2	206.7	2189.6	0	3055.5	6744.96	0.45
Osini	241	9.6	39.0	242.5	0	532.1	910.31	0.58
Ossi	49	49.6	29.7	303.7	0	432.0	2273.22	0.19
Ottana	490	48.8	62.7	1799.7	177.3	2578.5	3182.45	0.81
Ovodda	174	25.6	91.5	433.5	0	724.6	855.62	0.85
Ozieri	5164	127.2	784.2	7877.4	300.9	14253.7	22019.29	0.65
Pabillonis	92	12.8	56.1	1066.7	0	1227.6	3642.71	0.34

Municipality	*LSU bovine*	*LSU equidae*	*LSU pigs*	*LSU sheep/ goats*	*LSU poultry*	*LSU total*	*AGRI [ha]*	*LS_D [LSU/ha]*
Padria	513	20.8	54.3	1098.6	0	1686.7	3443.89	0.49
Padru	788	20	238.2	506.3	0	1552.5	4034.90	0.38
Palau	280	12.8	5.7	61.1	0	359.6	1671.46	0.22
Palmas Arborea	210	31.2	127.5	1031.3	0	1400.0	2452.43	0.57
Pattada	2378	97.6	175.2	2305.0	0	4955.8	6803.88	0.73
Pau	19	4.8	28.5	105.7	0	158.0	527.86	0.30
Pauli Arbarei	1	8.8	46.8	604.4	0	661.0	1448.52	0.46
Paulilatino	1289	63.2	145.8	1989.0	0	3487.0	6104.10	0.57
Perdasdefogu	813	12.0	52.5	214.5	0	1092.0	776.45	1.41
Perdaxius	126	8.0	63.0	633.1	0	830.1	1784.67	0.47
Perfugas	1043	28.8	90	1006.0	0	2167.8	4030.29	0.54
Pimentel	39	4.0	198.0	370.3	0	611.3	1323.36	0.46
Piscinas	13	7.2	51.6	295.0	0	366.8	958.19	0.38
Ploaghe	631	79.2	186.9	2441.7	0	3338.8	7600.54	0.44
Pompu	12	1.6	10.5	54.5	0	78.6	465.37	0.17
Porto Torres	53	31.2	43.8	573.9	0	701.9	3355.61	0.21
Portoscuso	31	3.2	2.4	71.7	0	108.3	1088.30	0.10
Posada	274	15.2	109.5	180.1	0	578.8	1940.20	0.30
Pozzomaggiore	1439	68.8	165.0	2249.0	0	3921.8	6917.93	0.57
Pula	15	70.4	75.0	362.0	0	522.4	3023.16	0.17
Putifigari	323	24.0	135.9	1001.0	0	1483.9	2504.97	0.59
Quartu Sant'Elena	40	112.8	65.7	382.7	0	601.2	2638.80	0.23
Quartucciu	3	36.0	3.9	128.0	247.2	418.1	1881.67	0.22
Riola Sardo	3	11.2	108.0	714.4	0	836.6	3855.95	0.22
Romana	39	12.0	39.6	489.9	0	580.5	1163.21	0.50
Ruinas	385	4.8	77.1	786.3	0	1253.2	1495.77	0.84
Sadali	142	32.0	88.5	323.2	346.5	932.2	1163.78	0.80
Sagama	252	6.4	25.5	400	0	683.9	1110.12	0.62
Samassi	14	16.0	29.7	297.0	0	356.7	4046.01	0.09
Samatzai	3	8.0	48.3	305.1	0	364.4	2813.08	0.13
Samugheo	1859	42.4	252.9	1396.8	0	3551.1	4853.09	0.73
San Basilio	96	41.6	551.1	1148.4	0	1837.1	2055.95	0.89
San Gavino Monreale	50	34.4	8481.6	2018.0	0	10584.0	7898.13	1.34
San Giovanni Suergiu	105	69.6	58.5	606.9	0	840.0	5027.90	0.17
San Nicolò d'Arcidano	67	8.8	101.4	793.0	0	970.2	2583.96	0.38
San Nicolò Gerrei	1921	5.6	182.1	755.2	0	2863.9	1088.76	2.63
San Sperate	14	30.4	46.8	201.3	0	292.5	2335.00	0.13

Municipality	*LSU bovine*	*LSU equidae*	*LSU pigs*	*LSU sheep/ goats*	*LSU poultry*	*LSU total*	*AGRI [ha]*	*LS_D [LSU/ha]*
San Teodoro	561	35.2	93.9	160.1	0	850.2	2655.59	0.32
San Vero Milis	1136	27.2	64.8	666.1	0	1894.1	5367.84	0.35
San Vito	713	52.8	212.4	878.2	78.9	1935.3	3458.54	0.56
Sanluri	680	48.8	184.2	1356.0	3.5	2272.5	8036.82	0.28
Santa Giusta	41	31.2	25.2	1180.3	0	1277.7	4164.97	0.31
Santa Maria Coghinas	194	13.6	6.3	195.2	0	409.1	1413.42	0.29
Santa Teresa Gallura	1066	35.2	28.5	64.7	0	1194.4	3579.06	0.33
Santadi	181	16.8	123.3	1452.3	0	1773.4	3759.08	0.47
Sant'Andrea Frius	241	30.4	219.6	607.4	0	1098.4	1217.49	0.90
Sant'Anna Arresi	190	15.2	26.7	493.9	0	725.8	2167.96	0.33
Sant'Antioco	109	48.8	6.9	228.2	42.0	434.9	2677.33	0.16
Sant'Antonio di Gallura	1033	17.6	60.9	56.4	0	1167.9	2637.64	0.44
Santu Lussurgiu	2841	112.0	255.9	2183.4	0	5392.3	6146.66	0.88
Sardara	292	28.8	191.1	802.1	0	1314.0	4596.43	0.29
Sarroch	2	20.8	53.7	188.0	0	264.5	1893.28	0.14
Sarule	2734	42.4	139.2	1565.6	0	4481.2	2854.76	1.57
Sassari	2601	321.6	987.3	9321.2	0	13231.1	41760.73	0.32
Scano di Montiferro	888	32.8	61.2	764.7	140	1886.7	2237.13	0.84
Sedilo	856	116.8	125.7	3018.2	0	4116.7	5604.70	0.73
Sedini	851	24.0	78.9	716.1	0	1670.0	2914.35	0.57
Segariu	60	9.6	75.9	203.3	0	348.8	1330.66	0.26
Selargius	7	59.2	691.5	186.9	0	944.6	2151.19	0.44
Selegas	0	10.4	46.2	461.4	0	518.0	1975.41	0.26
Semestene	576	18.4	56.4	1065.9	0	1716.7	2006.28	0.86
Seneghe	1012	44.0	109.8	598.8	0	1764.6	3085.54	0.57
Senis	133	4.8	151.8	227.8	0	517.4	1412.17	0.37
Sennariolo	31	2.4	20.1	186.2	0	239.7	582.41	0.41
Sennori	11	36.0	15.0	198.6	0	260.6	2190.20	0.12
Senorbì	109	32.0	289.8	631.6	0	1062.4	3216.34	0.33
Serdiana	519	17.6	61.2	792.3	0	1390.1	3736.13	0.37
Serramanna	32	32.0	1042.2	1479.3	0	2585.5	7876.58	0.33
Serrenti	0	26.4	16.8	613.3	0	656.5	3960.87	0.17
Serri	83	13.6	146.1	541.6	0	784.3	1429.01	0.55
Sestu	8	56.8	333.3	672.5	56.4	1127.0	4110.65	0.27
Settimo San Pietro	6	18.4	30.6	99.0	0	154.0	1926.55	0.08
Setzu	0	0.8	1.8	154.3	0	156.9	492.64	0.32

Municipality	*LSU bovine*	*LSU equidae*	*LSU pigs*	*LSU sheep/ goats*	*LSU poultry*	*LSU total*	*AGRI [ha]*	*LS_D [LSU/ha]*
Seui	1753	16.0	32.7	702.4	0	2504.1	677.85	3.69
Seulo	828	26.4	285.0	498.8	0	1638.2	1002.50	1.63
Siamaggiore	96	7.2	49.2	455.8	0	608.2	1255.02	0.48
Siamanna	177	16.8	192.6	847.7	0	1234.1	1579.25	0.78
Siapiccia	37	10.4	62.4	586.9	0	696.7	1037.49	0.67
Siddi	49	3.2	12.0	213.9	0	278.1	726.24	0.38
Silanus	2330	61.6	180.3	2614.0	3.5	5189.4	3699.30	1.40
Siligo	938	22.4	75.0	890.1	0	1925.5	3423.11	0.56
Siliqua	832	46.4	177.3	5375.5	0	6431.2	9351.25	0.69
Silius	625	8.0	163.8	841.9	0	1638.7	810.78	2.02
Simala	87	2.4	23.7	9.0	0	122.1	1164.76	0.10
Simaxis	235	15.2	852.6	693.1	78.4	1874.3	2529.61	0.74
Sindia	2075	64.8	109.2	2512.2	0	4761.2	5129.64	0.93
Sini	32	2.4	24.9	61.1	0	120.4	694.30	0.17
Siniscola	956	59.2	208.5	3228.2	0	4451.9	7815.18	0.57
Sinnai	695	41.6	340.5	1281.1	0	2358.2	3227.88	0.73
Siris	0	0.8	15.3	38.0	0	54.1	426.95	0.13
Siurgus Donigala	935	38.4	1214.4	1459.7	0	3647.5	2906.87	1.25
Soddì	2	4.0	8.1	112.3	0	126.4	398.87	0.32
Solarussa	315	20	48.3	775.9	0	1159.2	2346.96	0.49
Soleminis	16	15.2	27.0	150.7	1459	1668.2	912.98	1.83
Sorgono	542	21.6	48.6	719.3	0	1331.5	2140.09	0.62
Sorradile	21	11.2	39.6	503.6	0	575.4	1190.25	0.48
Sorso	62	40	19.8	91.3	0	213.1	5317.83	0.04
Stintino	913	11.2	27.9	196.8	0	1148.9	3823.54	0.30
Suelli	28	8.0	56.1	429.9	0	522.0	1868.93	0.28
Suni	693	20.8	33.3	1001.4	0	1748.5	3777.22	0.46
Tadasuni	4	0.8	1.8	73.8	0	80.4	332.53	0.24
Talana	4425	7.2	330.3	954.2	0	5716.7	1002.70	5.70
Telti	1372	29.6	108.9	548.0	0	2058.5	5286.54	0.39
Tempio Pausania	3368	64.0	123.0	510.2	0	4065.2	8141.68	0.50
Tergu	455	9.6	36.9	485.0	0	986.5	2065.34	0.48
Terralba	1856	33.6	102.3	298.3	232.4	2522.6	3396.46	0.74
Tertenia	732	23.2	251.1	1622.4	0	2628.7	4060.72	0.65
Teti	225	8.8	62.4	565.9	0	862.1	1056.00	0.82
Teulada	1081	36.0	162.3	1388.3	0	2667.6	3564.24	0.75
Thiesi	2421	57.6	120.9	1388.6	0	3988.1	2949.19	1.35
Tiana	71	3.2	30.9	156.5	0	261.6	280.14	0.93
Tinnura	43	1.6	5.1	62.9	0	112.6	341.89	0.33
Tissi	20	12.0	2.1	28.8	0	62.9	637.41	0.10

Municipality	*LSU bovine*	*LSU equidae*	*LSU pigs*	*LSU sheep/ goats*	*LSU poultry*	*LSU total*	*AGRI [ha]*	*LS_D [LSU/ha]*
Tonara	176	8.8	15.0	135.3	351.4	686.5	72.05	9.53
Torpè	370	15.2	74.4	840.1	0	1299.7	2935.34	0.44
Torralba	390	28.8	60.9	1142.1	0	1621.8	3536.25	0.46
Tortolì	9	30.4	59.1	122.4	0	220.9	1942.81	0.11
Tramatza	27	7.2	39.6	827.8	0	901.6	1656.77	0.54
Tratalias	40	16.8	50.4	808.4	0	915.6	1503.52	0.61
Tresnuraghes	117	14.4	27.9	605.7	0	765.0	1898.02	0.40
Triei	31	11.2	298.8	329.3	0	670.3	1796.59	0.37
Trinità d'Agultu e Vignola	1841	23.2	94.5	218.2	0	2176.9	3539.29	0.62
Tuili	2	18.4	36.6	341.6	7.0	405.6	1838.14	0.22
Tula	1001	24.8	99.9	1115.5	0	2241.2	3416.47	0.66
Turri	366	4.0	4.5	105.6	0	480.1	937.04	0.51
Ula Tirso	0	4.0	44.4	312.5	0	360.9	733.36	0.49
Ulassai	1211	20.8	63.3	447.3	0	1742.4	859.54	2.03
Uras	52	15.2	66.6	1238.4	280.6	1652.8	3308.58	0.50
Uri	342	24.0	78.0	1023.4	0	1467.4	4347.24	0.34
Urzulei	1654	22.4	233.7	592.4	79.8	2582.3	647.60	3.99
Usellus	133	8.8	100.8	846.9	0	1089.5	2453.88	0.44
Usini	30	17.6	10.5	297.2	0	355.3	2629.26	0.14
Ussana	167	21.6	87.0	185.2	86.8	547.6	2947.74	0.19
Ussaramanna	35	7.2	12.9	111.4	0	166.5	906.09	0.18
Ussassai	55	1.6	36.0	108.0	0	200.6	408.52	0.49
Uta	801	84.0	426.6	1183.0	0	2494.6	6874.34	0.36
Valledoria	31	12.8	27.0	79.8	0	150.6	2084.06	0.07
Vallermosa	215	27.2	204.3	1466.7	226.5	2139.7	3557.81	0.60
Viddalba	938	6.4	54.9	121.9	0	1121.2	1114.21	1.01
Villa San Pietro	6	20	47.1	178.6	0	251.7	947.21	0.27
Villa Sant'Antonio	173	6.4	9.6	430	0	619.0	1627.62	0.38
Villa Verde	0	1.6	12.3	167.1	0	181.0	797.38	0.23
Villacidro	335	86.4	2259.6	2268.4	431.8	5381.2	8625.27	0.62
Villagrande Strisaili	6583	52.8	624.6	1753.7	624.9	9639.0	2170.42	4.44
Villamar	25	40	136.5	691.3	0	892.8	3690.98	0.24
Villamassargia	1203	56.8	114.9	2083.8	0	3458.5	4209.11	0.82
Villanova Monteleone	3653	89.6	293.7	2535.3	0	6571.6	7657.26	0.86
Villanova Truschedu	284	4.8	69.9	163.4	0	522.1	603.82	0.86
Villanova Tulo	137	20	228.9	1001.6	0	1387.5	1264.80	1.10
Villanovaforru	28	8.0	13.8	165.2	0	215.0	997.01	0.22

Municipality	*LSU bovine*	*LSU equidae*	*LSU pigs*	*LSU sheep/ goats*	*LSU poultry*	*LSU total*	*AGRI [ha]*	*LS_D [LSU/ha]*
Villanovafranca	1	14.4	37.8	581.0	0	634.2	2589.66	0.24
Villaperuccio	30	5.6	29.7	429.8	0	495.1	1471.63	0.34
Villaputzu	387	16.8	252.9	1002.7	0	1659.4	3709.97	0.45
Villasalto	2210	13.6	164.4	680.6	0	3068.6	1628.59	1.88
Villasimius	9	26.4	53.1	312.9	0	401.4	1563.34	0.26
Villasor	232	21.6	177.3	1299.3	46.5	1776.7	7907.41	0.22
Villaspeciosa	101	19.2	28.8	489.8	0	638.8	2127.05	0.30
Villaurbana	127	18.4	123.9	609.9	0	879.2	2620.55	0.34
Zeddiani	23	6.4	15.3	75.2	0	119.9	1123.95	0.11
Zerfaliu	47	8.8	36.3	335.4	0	427.5	1365.41	0.31

Finally, each land cover patch was assigned the lowest/medium/highest value of the three listed in tab. 8 depending on the levels of both the nitrogen input and the livestock intensity in the municipality to which it belongs. Following Paracchini and Capitani (2011), nutrient and livestock density values can be classed into three categories ("low", "mid", "high"), as per tab. 8, and for each patch the highest value of the two, implying the maximum disturbance, was chosen. Let us take, for instance, a patch whose land cover class is "231" (hence taking 3=lowest, 4=medium, or 5=highest as possible hemeroby index values, as per tab. 8) and that is included within a municipality where, on average, the nitrogen input is low and the livestock density is high; the disturbance in that patch is then regarded as high, which leads to assigning an hemeroby index value equaling 5 to that patch.

Tab. 8 - Management intensity in agricultural areas (after Paracchini and Capitani, 2011)

	Low input	*Mid input*	*High input*
Nitrogen input (kg/ha)	0-30	>30-150	>150
Livestock density (LSU/ha)	0-0.5	>0.5-1.2	>1.2

As for forestry areas, in the absence of detailed data on forestry management practices and presence of alien invasive species, the level of disturbance was only based on a qualitative assessment of the "distance" between actual and potential vegetation. The former is proxied by the land cover in forestry areas, and the latter is the type of vegetation that would be observed if humans had not had any influence, and which only depends on aspects such as climate, geology, geomorphology, and soil types. The potential distribution of vegetation series and geoseries in Sardinia was mapped by Bacchetta *et al*. (2009); after comparing (through a spatial intersection) the actual and potential forest vegetation, each patch classed as "311", "312", "313" or "321" was assigned the lowest, the middle or the highest hemeroby index value in tab. 4 (respectively, 2, 3, or 4) depending on whether the current land cover is compatible, partly compatible, or incompatible with the potential vegetation in that patch.

The degree of naturalness was finally derived from the hemeroby index, by inverting the scale and normalizing it in the 0-1 interval.

The second characteristic in the first step concerns the presence and type of protected areas, which act as catalyzers for outdoor activities: Balmford *et al*. (2009), for instance, reported a global increase in nature-based recreation in natural protected areas, which needs to be appropriately managed so as not to compromise the parks' conservation objectives (Siikamäki *et al*., 2015). Against the previously constantly growing trends, protected areas' attractiveness has recently been affected in opposite ways by the COVID-19 pandemic: on the one hand, globally renowned wildlife sanctuaries have witnessed collapsing numbers (Newsome, 2020) due to travel restrictions and decline in number of international tourists. On the other hand, as far as domestic national parks and other protected areas are concerned, after a dramatic decrease during the initial stay-at home order period (Ugolini *et al*., 2021), also due to park closures enforced in many countries (for instance, Canada: Lesser and Nienhuis, 2020; United States: Landry *et al*., 2020; the United Kingdom: Spencer *et al*., 2020) to prevent people from travelling, visitation numbers have bounced back in the post-lockdown (Venter *et al*., 2021) especially in destinations closer to urban areas (Rice *et al*., 2020). Notwithstanding the challenges they presently face (see Templeton *et al*., 2021), parks and other protected areas' attractiveness for recreational activities in the post-lockdown appears therefore to have been strengthened, as large open spaces allow for social distancing and are perceived as comparatively safe.

Within the ESTIMAP model, protected areas are mapped and scored relative to their potential capacity to attract recreation. Scores are expert-based and can be assigned by local experts either through ad-hoc questionnaires (as in Cortinovis *et al*., 2018), or by having regard to management objectives pertaining to each type of protected area, by using the IUCN categories as a reference framework (as in Zulian *et al*., 2013; La Notte *et al*., 2017). Building on the latter approach, we identified five types of protected areas that are of relevance to Sardinia, which were then scored based on the corresponding IUCN category in terms of management objectives, as per tab. 9.

The third characteristic in the first step concerns water and, in the original ESTIMAP model, it comprises in turns three aspects as follows: distance from the coastline, geomorphology of the coast, and quality of bathing waters. Such focus on marine waters was here retained because it is highly appropriate within an island, but it is worth mentioning that in other contexts, which are non-coastal or whose inland waters have prominent importance, the water component was either skipped (as in Cortinovis *et al*., 2018) or revised to account for both the coastal and inland waters (as in Baró *et al*., 2016, or in Suárez *et al*., 2020).

Tab. 9 - Protected area types in Sardinia, together with their ruling legal framework, IUCN equivalent (having regard to each protected area's conservation objectives), and score

Type	*Legal protection regime*	*IUCN equivalent*	*Score*
National parks	National law on protected areas no. 1991/394	II	0.8
Regional parks	National law on protected areas no. 1991/394 Regional law on protected areas no. 1989/31	II	0.8
Ramsar sites	Decree of the President of the Italian Republic no. 1976/448, enforcing in Italy the International Convention on wetlands signed in Ramsar on February 2, 1971	Ib	1
Natura 2000 sites	Decree of the President of the Italian Republic no. 1997/357, transposing in Italy the EU Habitats Directive no. 1992/43	IV	0.8
Natural monuments	Regional law on protected areas no. 1989/31	III	1
Protected landscapes	Law enacted by decree no. 2004/42 Regional Landscape Plan of Sardinia	V	0.8

As for proximity to the coastline, the assumption here is that areas closer to the coastline are more appealing for daily recreation: therefore, the inverse logistic function in equation (3) was used:

$$f(d)=\frac{1+K}{K+e^{\alpha \cdot d}} \qquad (3),$$

where:

- d is the distance from the coastline [m].
- α and K are two parameters that define the shape of the function, set at $3.5 \cdot 10^{-3}$ and 150, respectively, so that f(d) takes the maximum value (equaling 1) along the coastline and zeroes at about 3 km from the coastline, halving at approximately mid-distance (Paracchini *et al*., 2014).

The second water-related aspect concerns coastal geomorphology, for which data from the European project "EUROSION" were used[8]. The spatial dataset available from the European Environment Agency describes

[8] Available from https://www.eea.europa.eu/data-and-maps/data/geomorphology-geology-erosion-trends-and-coastal-defence-works [Accessed: 22 February 2022].

each homogeneous trait of the coastline, among others, in terms of the coastal morpho-sedimentology. Since the dataset dates back to 2005, it was double-checked against more recent data from the regional geoportal, which led to some local corrections concerning almost exclusively traits classed as «Soft strands of heterogeneous category grain size», which were reclassed as «Coastlines made of soft non cohesive sediments, soft strands with beach-rock», plus few traits that are now artificial (e.g., enlargement of harbor areas). Following Liquete *et al.* (2016b), each morphological class was scored as per tab. 10, where the higher the score, the higher the attractiveness of a given trait of coastline.

Tab. 10 - Ranking (in terms of potential attractiveness for recreation) of coastal traits. After Liquete et al. (2016b)

Coastal morpho-sedimentology	*Score*
Developed beaches, small beaches, small beaches separated by rocky capes, artificial beaches	1
Coastlines made of soft non-cohesive sediments, soft strands with beach-rock	0.8
Rocks, hard cliffs, pond or lake shore type, soft strands with rocky intertidal flat	0.6
Conglomerates, eroded cliffs	0.5
Soft strands of heterogeneous category or of unknown category grain size	0.3
Strands made of muddy sediments, estuaries, harbor areas, coastal embankments for construction, polders, mine-waste sediments, artificial shoreline, dikes, unclassified	0

The third, and final, water-related aspect concerns the quality of bathing water, for which data from the European Environment Agency were retrieved. Under Directive 2006/7/EC of the European Parliament and of the Council of 15 February 2006, "concerning the management of bathing water quality" (which replaced an older version in force since the '70s), Member States in the bathing season must monitor indicators of microbiological pollution in fresh and coastal waters used as bathing places. The 2020 update[9], containing data points corresponding to sites monitored in 2019, was used. As for Sardinia, the dataset contains 663 monitoring points, of which 653 were classed as "excellent", 5 as "good", 3 as "poor", and 2 as "not classified" in summer 2019. A 1-km buffer was next drawn around each point, and scores were assigned as follows: 1 if the quality was either excellent or good, 0.5 if it was "sufficient" (but this value could not be found for Sardinian data points), 0 if it was poor; not classified points and their buffer zones were excluded.

[9] Available from https://www.eea.europa.eu/data-and-maps/data/bathing-water-directive-status-of-bathing-water-12 [Accessed: 22 February 2022].

Finally, the total water-related value was obtained by summing the scores assigned to the three aspects; since each aspect could reach a maximum of 1, water-related value could range in the (0-3) interval and was next rescaled in the (0-1) interval to make it comparable with the first two components of the potential provision of nature-based recreation, i.e., suitability of land to support recreation and presence of protected areas, which both range in this interval. The potential provision of nature-based recreation was then obtained by summing the value of its three components.

Once completed ESTIMAP's first step, the recreational value (*Recrval*) is therefore assessed and mapped, as it accounts for the benefits that ecosystem can provide. Fig. 3 provides the spatial layout of the three components and of the total potential provision of nature-based recreation. The following two steps in the model can be implemented if, beside the potential supply, the demand and potential use of this ES are of interest.

In the second step, areas where the potential provision of the ES can actually be enjoyed and used by humans on a daily basis are identified. In this regard, a key assumption in the ESTIMAP model is that the recreational use of interest is limited to outdoor walks or cycling, without the use of any motorized means of transportation. Consequently, in the model the ES that can flow from ecosystem to humans is only a share of the total potential provision, and it is the share produced by high-quality ecosystems that are located close to human settlements and infrastructure. The Sardinian road layout was retrieved from the regional geoportal[10], while for human settlements the 2018 CORINE land cover map (classes 1.1.1 «Continuous urban fabric», and 1.1.2, «Discontinuous urban fabric» only) was used in combination with 2011 data from the national census[11], which has a finer resolution, although it is a bit older.

The distances from roads and residential areas are therefore cross-tabulated (after Vallecillo *et al*., 2018) as per tab. 11.

[10] From the comprehensive 1:10,000 geodatabase available from https://www.sardegnageoportale.it/index.php?xsl=2425&s=330839&v=2&c=14414&t=1&tb=14401, layer 01 "roads, mobility, and transport" was used [Accessed: 22 February 2022].

[11] From the so-called "Spatial baseline data" made available by the national census (https://www.istat.it/it/archivio/104317), the 2011 layer "Inhabited places of Italy" was uses, from which the types 1 (cities, towns and villages), 2 (hamlets), as type 3 comprises industrial and commercial areas, while type 4 comprises the rest of the national territory not covered under the first three types, as explained in the metadata available from https://www.istat.it/it/files//2013/11/Descrizione-dati-Pubblicazione-2016.03.09.pdf [Accessed: 22 February 2022].

Tab. 11 - Cross tabulations used to produce the Human input map. Source: Vallecillo et al. (2018)

		Distance from roads [km]					*Input map classes: legend*	
		<0.5	*0.5-1*	*1-5*	*5-10*	*>10*		
Distance from urban areas [km]	<0.5	1	1	2	3	4	near	1
	0.5-1	1	1	2	3	4		2
	1-5	2	2	2	4	5	proximal	3
	5-10	3	3	4	5	5	far	4
	>10	3	4	4	5	5		5

A second cross-tabulation is next performed between the potential ecosystem-based provision of the recreation ES (i.e., *Recrval*) and the Human input map. This preliminarily requires reclassing *Recrval*, which is a continuous variable in the (0-1) interval, into four classes, which, again after Vallecillo *et al*. (2018) are labelled as "very low", "low", "high", and "very high". For this reclassification, the quantile values were used in this study.

Tab. 12 provides the cross-tabulation matrix that allows classing each part of the study areas in terms of the combination of its levels of potential supply of the recreational ES and of proximity to urban settlements and infrastructures within the so-called "Recreation Opportunity Spectrum map". Fig. 4 provides the maps of the distances from the roads and from the urban areas, as well as the maps of the Human input and of the Recreation Opportunity Spectrum. It is worth noticing that the distance from roads is always lower than ten kilometers, and therefore the seventh column in tab. 11 was not used in this analysis.

The third and final step of the ESTIMAP model allows to map the spatial distribution of met and unmet demand for daily based nature-based recreation in terms of number of trips per year to areas supplying high levels of *Recrval*; the trips are only those taken by resident population within a 4-km distance from where they live.

The model makes therefore a few assumptions, that can be summarized as follows:

- Only trips within walking distance or within light cycling trips (i.e., round trip shorter than 8 km) are considered.
- Only trips made by resident population in the study area are accounted for, hence leaving away tourists, who in certain areas can make up a large share of nature-goers.
- Only trips made without any motorized means of transportation are included, which means that activities in remote areas, which are often very attractive for hikers, climbers, bikers, are not taken into account.
- Only areas providing high levels of *Recrval* are considered; this assumption, coupled with the first item in this list, entails that only areas

scoring 9 in tab. 12 (High provision - near) as considered as effective suppliers of the recreational ES.

- The number of trips decreases when distance increase.

Under these assumptions, the number of visits to high-provision areas can be calculated through equation 4 (after Vallecillo *et al.*, 2019a):

$$N = \sum_{i=1}^{4} \frac{(1+k_i)}{(k_i + \exp(-\alpha_i \cdot Pop_i))} \quad (4),$$

where:

- N is the total number of trips per week expected from population living within 4 km from high-provision areas.
- i takes four values representing four buffer distances (1 km, …, 4 km) from high-provision areas.
- α_i and k_i are two parameters that depend on the distance, and that have been estimated based on the outcomes of a survey in the UK (Vallecillo *et al.*, 2018).

Tab. 12 - Cross tabulations used to produce the Recreation Opportunity Spectrum (ROS) map. Source: Vallecillo et al. (2018)

		Recrval classes						
		Very low	*Low*	*High*	*Very high*	*ROS map classes: legend*		
		1	2	3	4			
Human input classes	5	1	1	4	7	Low provision	far	1
	4	1	4	4	7		proximal	2
	3	2	2	8	8		near	3
	2	3	5	5	9	Medium provision	far	4
	1	3	6	6	9		proximal	5
							near	6
						High provision	far	7
							proximal	8
							near	9

By using a raster dataset providing population data in the year 2015, having resolution of 250 m (Schiavina *et al.*, 2019), available from the repository of the Joint Research Centre of the European Commission and by using the function in equation (4), the spatial distribution of met and unmet demand for nature-based recreation can be mapped (fig. 5).

2.4. Landscape value (*Landsval*)

Similarly to recreation value discussed in Section 2.3, landscape value is a final ecosystem service comprised within the cultural ES group. As argued by the Millennium Ecosystem Assessment (2005b, p. 457), cultural ES are deeply interwoven and difficult to assess in isolation because they are often provided simultaneously. This is especially the case of a subset of intangible, and socially constructed, services provided by the landscape. In the Millennium Ecosystem Assessment taxonomy, this set comprises cultural identity, heritage value, and aesthetic appreciation of both natural and managed landscapes, and within the CICES nomenclature[12] their partially overlapping correspondents «things in nature that help people identify with the history or culture of where they live or come from", "using nature as a national or local emblem », and «the beauty of nature». Such ES are highly dependent on contexts and culture, because shaped through individual and collective (at the community level) system values, in turn related to individual and collective relationship with, and experience of, their environments. In Schaich *et al.*'s (2010) words, such ES «create strong ties between humans and their natural surroundings and play a crucial role in feeling at home in a landscape» (p. 270), place attachment, identification and memories being the most prominent ties (Lewica, 2008; Tengberg *et al.*, 2012). Further complexity is added when considering that this relationship is dual: humans' relationship with their natural environment both shapes and is shaped by culture, collective history, and memories (Fish *et al.*, 2016), which entails that the value that a person or a community attributes to a landscape is a complex combination of factors that characterize the environment and factors that characterize the person or the community (Gee and Burkhard, 2010). In addition, pristine and undisturbed natural environments are almost absent in European countries, where for millennia land uses have been managed, and consequently landscapes have been shaped, with the ultimate goal of sustaining human life by improving some services deemed more valuable than others (Schaich *et al.*, 2010; Tengberg *et al.*, 2012).

As a consequence, the value that people assign to a landscape is affected by their familiarity, experiences and traditions (Scholte *et al.*, 2015), which makes cultural ES in general difficult to assess: as noted in Section 2.3, ex-

[12] Common International Classification of Ecosystem Services (CICES) for Integrated Environmental and Economic Accounting, version 1.5, available from https://cices.eu/content/uploads/sites/8/2018/03/Finalised-V5.1_18032018.xlsx [Accessed: 22 February 2022].

cept for nature-based recreation, all the other services pertaining to this group are seldom assessed through monetary approaches because, as with culture, they are intrinsically non-economic (Fish *et al*., 2016) and non-marketable (Milcu *et al*. 2013), which makes it hard "to find meaningful ways of comparing the intangibles to the economic values generated from ecosystems" (Gee and Burkhard, 2010, p. 357).

Some monetary approaches, such as hedonic pricing (as in Sander and Haight, 2012), travel cost methods, and deliberative democratic monetary valuation to elicit social (as opposed to individual) willingness to pay (Orchard-Webb *et al*., 2016) have been used to assess landscape quality (de Groot *et al*., 2010) and cultural heritage (Daniel *et al*., 2012). Monetary approaches to visual appreciation of landscapes can also be used in combination with mapping techniques to make the evaluation spatially explicit (as in van Berkel and Verburg, 2014).

However, the most common approaches to assessing landscape values related to cultural heritage, identity, and quality are non-economic and rely on techniques proper to the realms of sociology and human geography, to engage stakeholders and elicit their perceptions, interpretations, and values. These include questionnaires (as in Gee and Burkhard, 2010), in-depth interviews (Plieninger *et al*., 2013; Csurgó and Smith, 2021) or focus groups, meetings and workshops (as in Walter and Hamilton, 2014), sometimes complemented with visual aids and materials (as in Stewart *et al*., 2004; Tengberg *et al*., 2012; Frank *et al*., 2013; Zoderer *et al*., 2016) or with on-site surveys (as in Bieling and Plieninger, 2013), and participatory mapping (as in Brown *et al*., 2012; Sherrouse *et al*., 2011; Garcia-Martin *et al*., 2017; for a comprehensive discussion on the use of participatory mapping to appraise place values see Brown *et al*., 2020). The assessment of landscape-related values by using GIS-based desk analysis, in the absence of any stakeholder involvement, is usually limited to studies that only appraise visual aspects (as, for instance, in Swetnam *et al*., 2017), which are referred to as landscape aesthetics, natural sceneries, scenic beauty depending on the study. Additionally, social media data in this kind of works can be used to elicit stakeholders' values (as in Langemeyer *et al*., 2018).

In this study, landscape value accounts for the interactions between natural and human factors as understood in the European Landscape Convention, which allows for integrating historic artifacts, archaeological sites and cultural heritage in general within managed ecosystems and makes it possible to incorporate their value within the ES framework (Hølleland *et al*., 2017; Eliasson *et al*., 2018). Within the European Landscape Convention, landscape is a complex system that includes not only its traditional factors from the natural sciences (including, for instance, landforms, habitats composition and configuration), but also individual historic monuments and landmarks, minor spots of land (De Montis, 2016), and even everyday or degraded landscapes that have contributed to shaping the identity of European cultures. Landscape value, in this sense, is not restricted to areas of outstanding natural beauty, archaeological remains, historic monuments, or listed buildings, but it is grounded on people's perception of their territories, and on the recognition that different places show different characters. In compliance with the Convention, whose implementation varies across countries (De Montis, 2014), landscapes are to be protected, managed, and planned. Consequently, landscape plans are the tools whereby landscapes are interpreted, landscape quality and related values are identified, and protection devices taking various forms that span from strict regulations to soft guidelines to orient future scenarios are devised.

2.4.1. Assessing landscape value based on the provisions of the Regional Landscape Plan

Following Arcidiacono *et al.* (2016), in this study Landscape value (*Landsval*) is assessed based on the endowment of natural and cultural resources, which are identified as landscape-related goods by the Italian Code on cultural heritage and landscape (Law enacted by decree no. 2004/42), and it accounts for the landscape assets protected under the Regional Landscape Plan, in force in Sardinia since 2006.

The plan provides descriptive, prescriptive and indicative contents to which local land-use plans must conform (Zoppi and Lai, 2010), and moreover some prescriptive contents aimed at preserving current landscape quality values and setting restrictions on possible transformations of land uses are legally binding for the general public. The plan focuses especially on the coastal zone, but protection on certain categories of landscape features extends to the whole island, inland areas included. Landscape values to be preserved were identified within the plan-making process in the absence of adequate public participation, only limited to meetings with local authorities (Colavitti *et al.*, 2021), in stark contrast to common value-based approaches that rely on stakeholder consultation to elicit the importance attributed to cultural resources in general, and landscape features in particular (Tengberg *et al.*, 2012).We therefore identified protection levels defined in the plan, and a score was assigned to each protected landscape asset in the (0-1) interval depending on the level of restriction stemming from the plan implementation code, having also regard to other restrictions originating from national and regional legislation, under the assumption that the level of restriction reflects the significance of the landscape value identified within the plan-making process. The full list of protection levels is provided in tab. 13, together with reference to the articles of the implementation code that provide rules and directions for each protection level, and finally the score we assigned, expressing the landscape value. As for the spatial layout, the full spatial dataset of the protection levels established by the Regional Landscape Plan was used, which is retrievable from the regional geoportal[13]. It is worth noting that parcels subject to multiple protection levels were assigned the score corresponding to the strictest protection level in force in that parcel.

Tab. 13 - Landscape value: types of protected landscapes established in Sardinia by the Regional Landscape Plan, and value assigned on the basis of the restrictions in force

	Protected landscape type	*Plan implementation code: ruling articles*	*Value*
Environmental assets	Coastal strip	8, 17, 18, 19, 20	1
	Coves, cliffs and small islands	8, 17, 18	0.8
	Sand dunes and beaches	8, 17, 18	0.8
	Coastal wetlands	8, 17, 18	0.8
	Areas above 900 m	8, 17, 18	0.8
	Lakes, reservoirs, wetlands and their 300-m buffers	8, 17, 18	1
	Rivers, creeks and their 150-m buffers	8, 17, 18	1
	Areas of significant importance for wild animals	17, 18, 38, 39, 40	0.2
	Areas of significant importance for plant species	17, 18, 38, 39, 40	0.2
	Grottos and caves	8, 17, 18	0.8
	Monumental trees	8, 17, 18	0.2
	Natural monuments (as per regional law 1989/31)	8, 17, 18	0.5
	National parks and marine protected areas	8, 17, 18	0.5
	Volcanoes	8, 17, 18	0.5
Historic and cultural assets	Listed buildings and areas (art.146 Decree 2004/42)	8	0.8
	Listed archaeological heritage	8, 47	1
	Archaeological areas subject to building restrictions	8, 47	0.5
	Areas with prehistoric, historic, cultural remnants	8, 47, 48, 49, 50	1
	Historic districts	8, 47, 51, 52, 53	0.8
	Traditional Sardinian farmer's building complexes	8, 47, 51, 52, 54	0.8

[13] The full spatial dataset can be retrieved from https://www. sardegnageoportale.it/index.php?xsl=2420&s=40&v=9&c=14482&na=1&n=10&esp=1&tb=14401 [Accessed: 22 February 2022].

2.5. Agricultural and forestry value (*Agrofor*)

Agricultural crops and forestry production are a conspicuous part of the provisioning group of ES (among many: Millennium Ecosystem Assessment, 2003; Kumar *et al.*, 2011; Maes *et al.*, 2013). They are both influenced by the socio-economic context and heavily dependent on human management, including choice of crops, use of plant protection products, additional inputs (e.g., water, energy, and nutrients) to increase productivity (Zhang et al. 2007). All of these factors shape, either positively or negatively, interactions between agricultural and forestry production and other ES (Balbi *et al.*, 2015), which often results in trade-offs and/or clashes (Power, 2010; Raudsepp-Hearne *et al.*, 2010).

Provisioning ES have been assessed, so far, in a number of ways. A very common one is that of monetary evaluation based on market prices, which has been implemented, for instance, by Schirpke *et al.* (2015; 2017) for mushrooms, fodder production, and timber production in Natura 2000 sites in Italy, or by Adekola e*t al.* (2012) at a very local scale, that of a wetland in South Africa. The absence of comprehensive and detailed spatial data on agricultural and forestry plots and yields, together with the volatility of market prices, which are extremely variable across time and space, makes monetary evaluations at the regional/national/supernational scales quite challenging. Thus, when the number of crops of interest is large or the scale goes beyond local, other methods are preferred.

Bio-physical assessments rely on quantitative models that estimate the amount of biomass that can be yielded by agricultural or forestry plots. Franzese *et al*. (2009) have compared two such methods (based on gross energy requirement and on emergy synthesis, respectively) to estimate annual corn production and willow production in Italy, while Vallecillo *et al.* (2019b) have spatially assessed the amount of 13 agricultural crop types produced in the EU by using a so-called "fast-track" approach that allows to disentangle the ecosystem contribution, which entails that human inputs in agricultural production are not accounted for. The latter approach was also applied to estimate biomass timber production from Italian forests (Comitato Capitale Naturale, 2021). Another bio-physical, spatially explicit, approach, links land covers with crops' yields based on national statistics on observed yields; this model can be further enriched with data on fertilizers and has been applied, for instance, by Cao *et al.* (2017) and by Li *et al*. (2020).

Finally, another monetary approach posits that the economic value of agricultural and forestry ES is embedded into land prices (Ma and Swinton, 2011). Under this assumption, the monetary value of rural land can be taken as a proxy for the potential provision of agricultural and forestry ES (Munafò *et al.*, 2014).

2.5.1. Estimating agricultural and forestry value using land value as a proxy

Building on the latter approach, in this study the agricultural and forestry value (*Agrofor*) was estimated based on two national datasets for agriculture and forestry areas, both providing monetary values of the land per unit of area; moreover, the 2018 CORINE land cover map[14] was used to make the assessment spatially explicit.

As for agricultural areas, a spreadsheet[15] produced by the National Research Council of Agriculture and Agricultural Economics (Italian acronym: CREA) was used, which provides the value of land plots in the year 2017 based on the type of crop, on elevation zone, and on location (by taking provinces[16], i.e., Italian NUTS3 statistical regions, as the basic spatial units). Therefore, in order to map such values, two preliminary operations were required as summarized below.

First, a correspondence was established between CREA's taxonomy of crop types and CORINE land cover agricultural classes, as per tab. 14; as for land cover class "242 - Complex cultivation patterns", in the absence of any correspondence, for each province and elevation zone the land value was set as the mean agricultural land value in that province and elevation zone.

[14] Available from https://land.copernicus.eu/pan-european/corine-land-cover/clc2018 [Accessed: 22 February 2022].

[15] Available from https://crea-qa.cube.extrasys.it/-/banca-dati-valori-fondiari-bdvf [Accessed: 22 February 2022].

[16] A province in Italy is an intermediate tier of government between that of a region and that of a municipality and is composed of several adjacent municipalities. In Sardinia, provinces have varied several times as regards both number (ranging from a minimum of 3 to a maximum of 8) and boundaries (which depend on the set of included municipalities). Therefore, whenever provinces are involved for the assessment of agricultural and forestry values, the aggregations of the included municipalities at the relevant dates were considered, rather than the boundaries of the provinces, which are available only for some points in time.

Tab. 14 - Correspondence between agricultural areas in the CREA taxonomy and in the CORINE Land Cover one

CREA taxonomy: crop types		*CORINE Land Cover classes: agricultural areas*	
Code	*Nomenclature*	*Code*	*Nomenclature*
14	Arable land, vegetable gardens, garden center	211	Non-irrigated arable land
		212	Permanently irrigated land
		213	Rice fields
		241	Annual crops associated with permanent crops
15	Pastures	231	Pastures
16	Orchards and citrus groves	222	Fruit trees and berry plantations
17	Vineyards	221	Vineyards
18	Other utilized agricultural areas (UAA)	243	Land principally occupied by agriculture, with significant areas of natural vegetation
		244	Agro-forestry areas
8	Olive groves	223	Olive groves
---	---	242	Complex cultivation patterns

Second, because in the CREA's dataset the land value associated with a specific crop type varies depending on provinces and on the so-called "elevation zones" (original Italian: *zone altimetriche*), and because the spatial layout of elevation areas was not available off the shelf, an investigation on what these elevation zones are and how they can be mapped was carried out. Types of elevation zones are defined, for rural statistic purposes only, in a document produced by the National Census Institute (ISTAT, 1958, pp. 8-9), and in Sardinia they are as follows:

- Mountains: areas characterized by diffuse mountains above 700 m a.s.l., together with valleys or plateaus included between such mountains; the altitude can vary depending on the upper limit of olive orchards.
- Hills: areas characterized by diffuse hills below 700 m a.s.l.; as with mountains, the altitude can vary depending on the upper limit of olive orchards. A further differentiation is made, in Sardinia, between inner hills and coastal hills to account for the influence of the sea on climate and, in turns, on yielding potentials.
- Plains: low and flat areas characterized by the absence of diffuse elevated land.

Therefore, four "elevation zone" types are present in Sardinia. As far as their spatial layout is concerned, the above-mentioned document produced by the National Census Institute (ISTAT, 1958, pp. 84-86) provides a list of so-called "rural regions" (original Italian: *regioni agrarie*) included within each elevation zone type. Since agrarian regions are basically groups of contiguous municipalities (each listed in the document), this made it possible to derive the spatial layout of agrarian regions first and elevation zones next from that of Sardinian municipalities through a series of reclassification and dissolve operations.

As for forestry areas, data were retrieved from the National Revenue Agency[17] and the values are here differentiated according to type of production, provinces, and, again, rural regions as above defined. As with agricultural areas, a preliminary correspondence was established between the taxonomy of the National Revenue Agency (which includes, for instance, the following wood types of relevance to Sardinia: carob, chestnut, hazelnut, walnut, cork tree, as well as shrubby pastures, wood pastures, coppice) and that of the CORINE land cover sub-classes belonging to the 3.1 and part of the 3.2 second-level classes ("forests" and "shrubs", respectively) of significance for forestry uses.

Moreover, since the land value dataset of the National Revenue Agency refers to 2007 (for the provinces of Cagliari, Oristano, and Sassari) and to 2011 (for the province of Nuoro only), all of the values were discounted[18] to 2017 to make them comparable with the values obtained for agricultural areas. The value ranges from zero (non-agricultural and non-forestry land) to a maximum of approximately 22,500 euros per hectare.

2.6. Land surface temperature (*LST*)

Land surface temperature (*LST*) is defined as «a fundamental aspect of climate and biology, affecting organisms and ecosystems from local to global scales» (Hulley *et al*., 2019), as «the radiative skin temperature of the ground» (Hofierka *et al*., 2020), which is affected by solar reflectance, thermal emissivity, and heat capacity. This entails that *LST* combines interactions between land surface and atmosphere with ground-atmosphere energy fluxes. *LST* represents therefore a key climate variable and its study allows researchers to analyze the behavior of the Earth's environmental system (Neinavaz *et al*., 2020)

Moreover, numerous studies have shown that *LST* is heavily affected by the presence, type, and abundance of vegetation and by the properties of

[17] Available from https://www.agenziaentrate.gov.it/portale/web/guest/ schede/ fabbricatiterreni/ omi/banche-dati/ valori-agricoli-medi/valori-agricoli-medi-sardegna [Accessed: 22 February 2022].

[18] Discount rates were retrieved from http://rivaluta.istat.it:8080/Rivaluta/ [Accessed: 22 February 2022].

bare soil (Weng *et al.*, 2004), hence ultimately by land covers (Ayanlade, 2017; Lai *et al.*, 2020a; 2020b) and their changes (Feizizadeh *et al.*, 2013; Pal and Ziaul, 2017; Li *et al.*, 2020, Abir and Saha, 2021). Therefore, ecosystems affect local climate and exert a regulatory and mitigation function that can contribute to human wellbeing and quality of life, especially in urban areas, where the urban heath island effect is of concern and has become a significant field of research (Yuan and Bauer, 2007; Li *et al.*, 2016; Estoque *et al.*, 2017; Zhang *et al.*, 2017; Wang *et al.*, 2019) as regards urban ES.

LST is usually retrieved through remotely sensed thermal infrared data (Quattrocchi and Luvall, 1999; Weng, 2009; Lv and Zhou, 2011). A thorough theoretical background, also comprising an overview of the physics equations that allow to derive *LST* from the sensed spectral radiance, is provided by Li *et al.* (2013a; 2013b), who also discuss some algorithms and methods that have been implemented to handle radiometric calibration and cloud detection, as well as emissivity and atmospheric effects.

2.6.1. LST retrieval from Landsat imagery

A QGIS plugin implemented by Ndossi and Avdan (2016) implements a five-step procedure where various algorithms for *LST* retrieval are embedded. The plugin has been employed to extract *LST* from Landsat images in various studies, mainly at the city level, to assess the significance of urban trees in mitigating temperatures (Barbierato *et al.*, 2019), to investigate the urban heat island effect (Alves, 2016), or to estimate the impact of urban land-use change on *LST* (Dhar *et al.*, 2019; Sayão *et al.*, 2020; Ebrahimi *et al.*, 2022).

In the first step, the top-of-atmosphere spectral radiance is calculated for each pixel using thermal Landsat 8's band 10 pixel values as input, using equation (5) (USGS, 2021):

$$\mathrm{TOA} = (\mathrm{M_L} \cdot \mathrm{Q_{cal}}) + \mathrm{AL} \qquad (5),$$

where:

- *TOA* is the top-of-atmosphere spectral radiance [W/(m^2 · sr · μm)].
- M_L is the band-specific multiplicative rescaling factor (retrievable from the image's metadata, provided by USGS as a plain text file together with the image, as "RADIANCE_MULT_BAND_10").
- Q_{cal} is the band 10 image pixel values (i.e., digital numbers), quantized and calibrated.

- *AL* is the band-specific additive rescaling factor (retrievable from the image's metadata, provided by USGS as plain text file together with the image, as "RADIANCE_ADD_BAND_10").

In the second step, the top-of-atmosphere spectral radiance is converted into the top-of-atmosphere brightness temperature as per equation (6) (USGS, 2021):

$$T=\frac{K_2}{\ln\left(\frac{K_1}{TOA}+1\right)} \quad (6),$$

where:

- BT is the top-of-atmosphere brightness temperature [K].
- TOA is the top-of-atmosphere spectral radiance.
- K_1 and K_2 are two specific thermal conversion constants (retrievable from the image's metadata, provided by USGS as a plain text file together with the image, as "K1_CONSTANT_BAND_10"and "K2_CONSTANT_BAND_10", respectively).

In the third step, the normalized difference vegetation index is calculated using Landsat 8's bands 4 and 5 images as inputs, through equation (7) (Townshend *et al.*, 1985):

$$NDVI = \frac{NIR\text{-}RED}{NIR+RED} \quad (7),$$

where:

- NDVI is the normalized difference vegetation index.
- NIR is the near-infrared band. For Landsat 8 images, this is band 5.
- RED is the visible red band. For Landsat 8 images, this is band 4.

Once the NDVI is known, in the fourth step, the Land Surface Emissivity (LSE) can be calculated using various algorithms. Among those implemented in the plugin, the algorithm by Zhang *et al.* (2006) has been reported to yield the best results (Ndossi and Avdan, 2016) as per *LST* retrieval. This algorithm, which builds upon van de Griend and Owe's (1993) findings concerning the correlation between LSE and NDVI, is summarized in tab. 15.

Tab. 15 - Relation between Land Surface Emissivity (LSE) and the normalized difference vegetation index (NDVI). Source: Ndossi and Avdan, 2016

NDVI	*LSE*
NDVI < −0.185	0.995
−0.185 ≤ NDVI < 0.157	0.985
0.157 ≤ NDVI ≤ 0.727	1.009 + 0.047 · ln(NDVI)
NDVI > 0.727	0.990

Finally, in the fifth step, *LST* can be calculated using four algorithms, of which the so-called "Planck function" is reported to be "easier to use in comparison to the other algorithms as it does not require atmospheric variables" (Ndossi and Avdan, 2016, p. 28), and makes use of equation (8) (Artis and Carnahan, 1982):

$$\mathrm{LST} = \frac{\mathrm{BST}}{1+(\lambda \cdot \frac{\mathrm{BT}}{\alpha}) \cdot \ln(\mathrm{LSE})} \quad (8),$$

where:

- LST is land surface temperature [K].
- BT is top-of-atmosphere brightness temperature [K].
- LSE is land surface emissivity.
- λ is wavelength of the emitted radiance [m] = $1.0895 \cdot 10^{-5}$ m for Landsat 8 TIRS (Zhao *et al*., 2018).
- $\alpha = h \cdot c/\sigma$ (where *h* is Planck's constant, *c* is the velocity of light, and *σ* is Boltzmann's constant) = $1.438 \cdot 10^{-2}$ mK (Avdan and Jovanovska, 2016).

The above-listed five steps were implemented by using two sets of Landsat 8 satellite images concerning Sardinia, acquired in Spring and Summer 2019. Landsat 8 OLI (Operational Land Imager) and TIRS (Thermal Infrared Sensor) images are freely available from the US Geological Survey Earth Resources Observation and Science website[19], where data can be searched and retrieved based on spatial and temporal criteria. Two searches were performed; the first concerns the mid-summer season (15 July - 30 August 2019), in which temperature peak in Sardinia, while the second concerns the mid-spring season (15 April - 31 May 2019), in which vegetation growth is at its highest, before the dry season and the annual crop harvesting. For each time period, five images were retrieved, two belonging to Landsat scene 192 (on May 16 for the spring search and August 20 for the summer search) and three to Landsat scene 193 (on May 23 for

[19] Available from: https://earthexplorer.usgs.gov/ [Accessed: 22 February 2022].

the spring search and August 11 for the summer search). No single-date images covering the whole island can be retrieved because of the configuration of the satellite acquisition paths.

Details for each image are provided in tab. 16, while fig. 6 provides the spatial layout of scenes 192 and 193, shown as dotted rectangles, and the images' footprints, shown as colorful squares inside the scenes.

Tab. 16 - Selected Landsat 8 images

Image code	*Scene*	*Cell size*	*Date*	*Season*
LC08_L1TP_192032_20190516_20190521_01_T2	192	30 m	May 16, 2019	Spring
LC08_L1TP_192033_20190516_20190521_01_T1	192	30 m	May 16, 2019	
LC08_L1TP_193031_20190523_20190604_01_T2	193	30 m	May 23, 2019	
LC08_L1TP_193032_20190523_20190604_01_T1	193	30 m	May 23, 2019	
LC08_L1TP_193033_20190523_20190604_01_T1	193	30 m	May 23, 2019	
LC08_L1TP_193031_20190811_20190820_01_T1	193	30 m	August 11, 2019	Summer
LC08_L1TP_193032_20190811_20190820_01_T1	193	30 m	August 11, 2019	
LC08_L1TP_193033_20190811_20190820_01_T1	193	30 m	August 11, 2019	
LC08_L1TP_192032_20190820_20190903_01_T1	192	30 m	August 20, 2019	
LC08_L1TP_192033_20190820_20190903_01_T1	192	30 m	August 20, 2019	

By implementing the steps in Ndossi and Avdan's plugin, ten *LST* raster maps (one for each satellite image in tab. 16) were retrieved, each having cell size 30 meters. The five spring images were next merged, as well as the five summer images; a full overview of the process is provided in fig. 7. In this way, two *LST* regional maps were obtained, one for the time period 16-23 May, 2019 and one for the time period 11-20 August, 2019 (fig. 8).

Since in both cases images from scene 192 overlap those from scene 193 (as shown in fig. 6), and since in both cases the maximum values always correspond to pixels belonging to scene 193, for overlapping pixels the value associated to images in scene 193 was consistently retained. Moreover, it is worth mentioning that that some parts of the island were covered by clouds when the spring images where produced; as this locally affected both NDVI and *LST* values, such parts were filtered and excluded from the process.

2.7. Carbon storage and sequestration capacity (*CO_2Stor*)

Carbon sequestration is the process whereby carbon dioxide (CO_2), the most important greenhouse gas generated by human activities (EPA, 2021), is removed from the atmosphere and transferred to either water or terrestrial carbon pools. By doing so, carbon sequestration and storage prevents or mitigates the impacts that would be caused by increased carbon concentrations in the atmosphere, such as higher global temperatures, sea-level rise, wildfires, and other phenomena associated with climate change (Lal, 2008).

Carbon (C) can be removed from the atmosphere through two broad processes, i.e., abiotic and biotic. Abiotic processes comprise various engineered trapping mechanisms through which carbon dioxide is stored in geological sinks (Kambale and Tripathi, 2010); although carbon sequestration can be driven by humans and various technologies to capture, transport, and store carbon within appropriate reservoirs have been available for decades now (Lackner, 2003), anthropogenic sequestration is only a modest fraction of the total carbon uptake compared to the natural one (Ghommem *et al*., 2012). The biotic process occurs naturally through photosynthesis, that is, the process through which vegetation captures carbon dioxide and converts it into oxygen, which is next released again into the atmosphere, and carbon, which is stocked either into the ocean and other minor water basins, or into one of the available terrestrial pools. While the ocean is by far the most important carbon pool on Earth (Lal, 2008), on land the greatest storage capacity is that of soil, followed by vegetation (Smith, 2012); however, the pools are interconnected with each other and to the atmosphere via flux exchanges (Dixon *et al*., 1994), which entails variability in the amount of carbon stored in each sink. Indeed, there is more than just one type of terrestrial sink because, once removed from the atmosphere by vegetation, carbon is first stocked into living plant matter (both above-ground biomass, such as leaves, branches, trunks, and below-ground biomass, i.e., living roots); next, as vegetation dies, carbon is stored into dead organic matter (such as dead leaves and deadwood) which finally decomposes, hence stabilizing carbon in the soil through mineralization or through leaching processes (Błońska *et al*., 2019).

Therefore, on land, the beneficial process of removing carbon dioxide is undertaken by ecosystems, and it is deeply affected by land cover change (Jobbagy and Jackson, 2000), to the extent that, according to IPCC (2013), land cover change is the second most important driver of CO_2 emissions after fossil fuel burning. The relationship between land cover changes and CO_2 emissions is actually ambivalent, since land conversion can result either in increased or in decreased atmospheric carbon (Gries *et al*., 2019) depending on the type of change, as well as on agricultural management practices, some of which can in principle increase the amount of organic carbon in soils (Smith, 2012). Moreover, other factors add further layers of complexity to the relationship between land cover changes and global temperature, making it not straightforward and even counterintuitive. Bala *et al*. (2007), for instance, argued that while large-scale deforestation produces a warming effect due to increased quantities of atmospheric carbon, nonetheless it results in an overall cooling effect because of increased land surface albedo and decreased evapotranspiration, which in turns, depending on the latitude (Bonan, 2008), triggers changes in rainfall patterns and wind speed (Malhi *et al*., 2008).

Soil organic carbon can be easily quantified through appropriate sampling and direct measurement; however, the costs to carry out large-scale measurements can make direct assessment cost-ineffective (Smith *et al*., 2020), which favors modeling simulations and remote sensing techniques. As for carbon stored in both below- and above-ground biomass, it is often estimated by multiplying the total biomass by a conversion factor (Ponce-Hernandez, 2004); prior estimation of the amount of biomass is therefore req*uired, which can be based on field surveys, on inventories, or on spectral analysis of satellite imagery. For a thorough list of methods, the reader can refer to Petrokofsky *et al*. (2012, Appendix B).

2.7.1. Modeling carbon storage and sequestration through the InVEST suite

The InVEST "Carbon Storage and Sequestration" model, part of the InVEST suite,[20] only considers terrestrial carbon sinks[21] and assumes that carbon can be stored in four pools as follows: above-ground biomass, below-ground biomass, dead organic matter, and soil (by considering the top 30-cm deep layer). The total amount of carbon currently stored in the area of interest is estimated in biophysical terms based on a land cover map coupled with a table that provides, for each land cover type, the carbon density (i.e., the amount of carbon per unit of land) that each land cover stores in each carbon pool that the user wants to consider, or for which data are available. The output is a carbon density map, whose unit of measurement is Mg of carbon per pixel, where the amounts of carbon stored in each pool are aggregated as per equation 9:

[20] InVEST is freely available from https://naturalcapitalproject.stanford.edu/software/invest [Accessed: 22 February 2022].

[21] Another tool in the suite, named "Marine Blue Carbon", models carbon removed by, and stored in, vegetal biomass such as mangroves and seagrasses; it can therefore be regarded as an adaptation of the Carbon Storage and Sequestration" model developed for coastal and marine areas (Guerry *et al*., 2012).

$$CT_{LCk,i,j} = CA_{LCk,i,j} + CB_{LCk,i,j} + CD_{LCk,i,j} + CS_{LCk,i,j} \quad (9),$$

Where *i,j* denotes a cell in the raster map whose land cover type is LCk, CA, CB, CD, CS are the carbon densities in above-ground biomass, below-ground biomass, dead organic matter, and soil respectively, while CT is the total carbon density.

The model was used in several studies at various scales and with different purposes as follows.

- To quantify the amount of carbon stored in terrestrial pools at various scales (Grafius *et al*., 2016 for three English towns; Chacko *et al*., 2019 for a natural protected area in India; Piyathilake *et al*., 2021 for a province in Sri Lanka).
- To assess impacts on the amount of stored carbon generated by historical land-use changes at the district level in Seoul (Han *et al*., 2018), or at the state level in Minnesota, US (Polasky *et al*., 2011) and in Ghana and Cote d'lvoire (Leh *et al*., 2013).
- To estimate the potential loss of carbon stored in the above-ground pool as a consequence of a natural disaster, by looking at hurricanes in Florida (Delphin *et al*., 2013)
- To predict changes in carbon storage resulting from urban expansion (He *et al.*, 2016; Lahiji *et al*., 2020), from agricultural expansion (Chaplin-Kramer *et al.*, 2015) or, in more general terms, from land-use changes associated with alternative future scenarios at the local scale (Nelson *et al*., 2009; Kovacs *et al*., 2013; Babbar *et al*., 2021) or at the global scale (Nelson *et al*., 2010), in the latter case by looking only at carbon stored in biomass.

A challenging task is that of assigning to each land cover its appropriate carbon density value, which can be done based on sample collection (as in Rajbanshi and Das, 2021), on available literature (as in Leh *et al*., 2013; Grafius *et al*., 2016; Han *et al*., 2018; Babbar *et al*., 2021; Piyathilake *et al*., 2021) or datasets (as in Nelson *et al*., 2010 and in Chaplin-Kramer *et al*., 2015), on national inventories (as in He *et al.*, 2016; Pilogallo *et al.*, 2019; Scorza *et al*., 2020b), on plot-level inventories (as in Delphin *et al*., 2013). Due to the lack of data on below-ground biomass, in the InVEST model only the remaining three carbon pools (i. above-ground biomass, ii. soil organic content, iii. dead organic matter) were considered; for each pool the corresponding carbon density values were assigned based on the

2005 National Inventory of Italian Forests[22] and on a regional pilot project concerning land units and soil capacity in Sardinia[23]. The model was run by Maddalena Floris as part of her doctoral thesis (Floris, 2020), to which the reader can refer for further details.

2.8. Mapping the components of a regional GI and identifying relevant areas for ES provision

This section is organized as follows. In the first subsection, the spatial distribution of each single value presented in the previous sections is mapped and the values are discussed individually; in the second subsection, building on the assessment of the seven values, their interaction is assessed in terms of synergies and trade-offs, and a method for identifying areas that provide similar bundles of ecosystem services is presented.

2.8.1. Spatial distribution of the seven components of a regional GI

Fig. 9 provides the spatial layout of the seven ecosystem services assessed as per the previous sections in this chapter. All of the values are normalized in the [0-1] interval; as for *LST*, the summer map in fig. 8 was chosen over the spring one due to the absence of clouds, and the values were inversely normalized, so lower scores correspond to higher temperatures and vice versa.

Firstly, as for Conservation value (*Consval*), areas taking non-null values are mostly, but not exclusively, located within Natura 2000 sites and highly spatially clustered in their immediate surroundings. A large part of the island (approximately 66%) takes null conservation values, which means that it does not host any habitats of community interest.

Out of the rest of the island (34%), in which such habitats can be found ($Consval \neq 0$), the most part takes low values: only 0.90% of the island's surface takes values higher than 0.75; 4.95% takes values between 0.50 and 0.75, and finally 27.80% shows values below 0.50.

Secondly, concerning Natural value (*Natval*), only a small part of the is-

[22] Available from: https://www.sian.it/inventarioforestale/ [Accessed: 22 February 2022].

[23] Available from: http://www.sardegnageoportale.it/index.php?xsl=2420&s=40&v=9&c=14481&es=6603&na=1&n=100&esp=1&tb=14401 [Accessed: 22 February 2022].

land (3.44%) takes null values (*Natval* = 0); 35.51% of the region hosts low-quality habitats taking (*Natval* ≤ 0.33), while 62.45% of the region hosts middle-quality habitats (0.33 < *Natval* ≤ 0.66), and, finally, the remaining 13.8% hosts high-quality habitats (0.66 < *Natval* ≤ 1). The mean value across the region equals 0.43. High values mostly concern the island's largest forests (to the south-west, Gutturu Mannu and Linas; to the south-east, Sette Fratelli, to the mid-east the Gennargentu and Supramonte chains) and, especially, the regional and national protected areas: although very small in size, the Asinara and La Maddalena National Parks as well as the Capo Caccia and Tepilora Regional Parks are clearly identifiable to the north, as well as the Gutturu Mannu and Molentargius Regional Parks to the south.

Thirdly, Recreation value (*Recrval*) equals 0 in a negligible part of the island. Approximately 49.5% of the island takes low values (*Recrval* ≤ 0.33), and around 44.75% takes mid values (0.33 < *Recrval* ≤ 0.66), while only the remaining 5.75% takes very high values (0.66 < *Recrval* ≤ 1). The spatial patterns of *Recrval* are somewhat similar to those of *Natval*, meaning that areas having high and low values correspond, to some extent, although *Recrval* is less fragmented than *Recrval*; moreover, they tend to differ along the coastline, where *Recrval* always takes high values, contrary to *Recrval*, which ranges freely in the [0-1] interval.

Fourthly, Landscape value (*Landsval*) equals 0 in 61.18% of the region. Furthermore, this variable is categorical and only takes the following values: 0.20 (0.26% of the regional land mass); 0.5 (4.21%); 0.8 (4.17%) and 1 (30.18%). Therefore, among non-null values, the maximum value spatially dominates, mainly because of three main environmental assets: "Coastal strip", "Lakes, reservoirs, wetlands and their 300-m buffers" and "(listed) Rivers, creeks and their 150-m buffers"; the first is protected under the Regional Landscape Plan (article 20 of the plan implementation code), which forbids any kind of new development while allowing restoration or renewal of existent buildings, while the second and the third are protected under the national law on cultural goods and landscape, whereas the Regional Landscape Plan only maps areas that are preserved and protected as belonging to this type. A fourth type of landscape asset, belonging to the cultural group, and comprising both "Listed archaeological heritage" and "Areas with prehistoric, historic, cultural remnants", also brings about the maximum value, but is less significant in terms of size.

Fifthly, Agricultural and forestry value (*Agrofor*) is null in around 34.1% of the island; around 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 takes high values (0.11 < *Agrofor* ≤ 1). The latter are remarkably clustered along the two main plains: Nurra to the north, and, especially, Campidano, stretching from the mid-west to the south.

Sixthly, Land surface temperature (*LST*) in summer mostly (59.9%) takes mid normalized values ($0.33 < LST \leq 0.66$), whereas 38.7% of the island is characterized by low normalized values ($0 < LST \leq 0.33$), meaning that the surface temperature is hot, and a mere 1.4% takes high normalized values ($0.66 < LST \leq 1$), hence it is cooler than the rest of the island. No real clusters emerge, here: the small, darker spots in the map generally correspond to lakes and wetlands, while the medium-to-dark shades of green in general correspond to mountain chains and peaks. The medium-to-dark shade to the south-east of the island is to be attributed to the fact that satellite images in this part of the island were retrieved in a different date than the rest of the region.

Finally, Carbon storage and sequestration capacity (*CO2Stor*) is null ($CO2Stor = 0$) in around 2.2% of the island, and only 4.8% takes low values ($0 < CO2Stor \leq 0.33$), while the large majority, corresponding to approximately 74.4%, takes mid values ($0.33 < CO2Stor \leq 0.66$), and around 18.6% takes high values ($0.66 < CO2Stor \leq 1$). As with *LST*, and even more so, no clear spatial pattern emerges, except for low and very low values, which generally correspond to urban areas, artificial areas, and inland waters.

2.8.2. Identifying priority areas through an assessment of synergies and trade-offs between ecosystem services

The availability of spatially explicit assessment of multiple ES makes it possible to identify priority areas for the inclusion in a regional that can be used to ground planning policies aiming at preserving or enhancing current levels of ES supply. Such identification can be done, basically, in two ways. One simply relies on assessing which areas have the highest potential to deliver several ES by calculating the sum of the bio-physical values, normalized for the sake of comparability. The second relies on spatial statistics methods, which allow for more nuanced results because the mere total value does not let the analyst, and the decision maker, understand which values contribute to the total and which do not, hence it does not make it possible to understand the strengths and weaknesses, in delivering ES, of a given area. Methods based on spatial statistics that assess interrelationships between ES, in terms of both synergies and trade-offs, do not lead to oversimplifying the assessment through a single value, and therefore the results need to be carefully interpreted and communicated; rather, they provide a multifaceted representation of the combinations of ES supplied.

For such analyses, the municipal level is the optimal territorial unit, in Italy, because municipalities represent the lowest administrative tier of government in charge of land-use planning, whose provisions can greatly affect the provision of ES. Therefore, ES data presented in the previous subsection need to be preliminarily preprocessed so as to retrieve the mean normalized value for each municipality. In the Sardinian case, the number of municipalities is 377, which entails building a matrix having 377 rows and seven columns, each representing a single ES, where cells contain the average municipal value of an ES in a municipality. Fig. 10 provides an overview of the average normalized values of each ES at the municipal level.

Following Raudsepp-Hearne *et al.* (2010), Turner *et al.* (2014), Queiroz *et al.* (2015), the analysis comprises three steps, as follows.

- For each ES, spatial patterns are analyzed by assessing spatial autocorrelation through Moran's *I* index; hot spots and cold spots of municipalities having statistically significant higher or lower values than their surrounding municipalities are identified through the Getis-Ord Gi* statistics.
- Statistically significant (linear) correlations between each pair of ES are assessed through Pearson's correlation coefficient.
- Clusters comprising municipalities having a level of in-group similarity higher than their dissimilarities with respect to municipality not belonging to the group are spatially identified by applying first a principal component analysis (PCA), aimed at reducing redundancies due to the presence of correlations, and next a cluster analysis through the k-means algorithm.

The analysis of spatial autocorrelation carried out using the queen contiguity conceptualization[24], shows evidence of spatial agglomeration ($I>0$) statistically significant and decreasing up to the fifth level of (cumulative) contiguity for all the ES, as shown in fig. 11, but for *Natval*, for which *I* is significant only at the first two levels.

The results of the hot spot and cold spot analysis are shown in fig. 12, which puts in evidence that some parts of the island can be either hot spots or cold spots, depending on the ES at stake.

The Campidano plain, for instance, which spans from the eastern coast to the southern one, is a hot spot for *Agrofor*, and a cold spot for *Consval*,

[24] This means that two polygons, i.e., two municipalities, are regarded as contiguous if their boundaries share at least a point, as opposed to rook contiguity, whereby two polygons are regarded as contiguous if a trait of their boundaries is shared.

Recrval, and partially also for *Landsval*, while large part of the inner island is a hot spot for *Consval* and a cold spot for *Agrofor;* southern Ogliastra, a subregion laying to the west of the island, is a hot spot for *CO2Stor*, *Recrval* and *LST* and a cold spot for *Agrofor*. From this assessment, spatial patterns of agglomerations concerning single ES emerge.

The Pearson coefficients (tab. 17) show that 16 out of the 21 pairs of ES are significantly and linearly correlated; negative correlations always concern *Agrofor* and *CO2Stor*, which therefore compete with other ES and, furthermore, with each other. Positive significant correlations (synergies) characterize *Recrval* and *LST*; the correlations between *Recrval* and *Landsval* and between *Recrval* and *LST* are strong (ρ=0.725 and ρ=0.542, respectively), while the others are generally moderate.

*Tab. 17 - Analysis of the mutual correlations between the seven ES. Above the diagonal: Pearson coefficients (ρ); the shades of grey signal the strength of the correlation. Below the diagonal: significance of the correlations (***: p <0.001; **: p <0.01; *: p <0.05)*

Consval	0.158	0.359	0.138	-0.541	0.147	0.407
**	Natval	0.320	0.173	0.080	-0.036	0.033
***	***	Recrval	0.725	-0.407	-0.011	0.542
**	***	***	Landsval	-0.095	-0.314	0.486
***		***		Agrofor	-0.308	-0.372
**			***	***	CO2Stor	0.155
***		***	***	***	**	LST

Due to the presence of mutual correlation, the territory can be conceived of as a provider of bundles of ES, rather than of single, independent, ES, hence the PCA is helpful to reduce redundancies. When applying the PCA, several methods exist to identify the new principal components, which are linear combinations of the original components, which, in this case, are the seven ES. Such methods, however, lead to different results[25]; therefore, the choice of the method is to a certain extent, a matter of subjectivity. As the last column in tab. 18 shows, approximately 93% of the variance can be explained through four new axes, or around 97% through five axes, which represent as many combinations of the seven ES. When applying Cattell's scree test (Cattell, 1966), this would be not the first, but the second elbow in the graph shown in fig. 13.

The number of new principal components can be used to run the k-means algorithm to perform the cluster analysis, hence retrieving five

[25] Reviews and comparisons of methods for reducing dimensionality, the so-called "stopping rules", are provided, for instance, by Jackson (1993), Peres-Neto *et al.* (2005), Cangelosi and Gorieli (2007), Abdi and Williams (2010).

groups, whose spatial layout is shown in fig. 14, together with the spider diagrams that provide the mean value of each ES in each group.

Tab. 18 - PCA results: percent and accumulative eigenvalues

Principal component	*Eigenvalue*	*Percent of eigenvalues*	*Accumulative of eigenvalues*
1	0.03999	51.6942	51.6942
2	0.01822	23.5484	75.2426
3	0.00749	9.6777	84.9203
4	0.00687	8.8793	93.7996
5	0.00241	3.1201	96.9198
6	0.00163	2.1055	99.0252
7	0.00075	0.9748	100.0000

The outcomes of the cluster analysis, run through the k-means algorithm in ArcGIS®ESRI, version 10.7, are shown in fig. 14, which provides the spatial layout of the five municipal clusters here identified; municipalities in each cluster share common features in terms of bundles of ES provided, and they also share some distinctive environmental and socio-economic characteristics. Group 3, where *Landsval* and *Recrval* dominate, comprises almost exclusively coastal municipalities, whose economies rely on tourism, and whose urbanization levels are generally higher than those within the rest of the island, while *Agrofor* and, especially, *Consval* levels are quite low.

Group 2, having high values of both *Agrofor* and *CO2Stor*, corresponds to the island's main plains, hosting intensive agriculture and farming that yield comparatively high incomes with respect to Sardinian standards; *Natval* takes intermediate values, in this group, owing to the fact that non-intensive agricultural areas can act as habitats especially for birds, as well as forestry areas, which can host numerous types of both animal and plant species; *Recrval* takes, on average, mid-to-low values, while *Landsval* and, especially, *Consval* are very low.

Groups 1 and 4, both showing high values of *CO2Stor*, mainly differ as regards *LST* (high in 1 and in low 4); *Natval* in both groups takes intermediate values, as well as *Recrval*, while *Landsval* and, especially, *Consval* are very low; both groups comprise inner and sparsely populated municipalities, and they differ as for the morphology, which is gentler in group 4, and the vegetation, which in group 4 is richer in steppe and other herbaceous vegetation and pastures. Finally, group 5 comprises municipalities having high values of all ES except *Agrofor*; it includes the island's main mountain areas, whose landscapes are marked by maquis and forests, the greatest providers of ES in Sardinia.

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3. *Mapping of ecological corridors as connections between protected areas: a study concerning Sardinia, Italy*

An important set of ES provided by GI consists of habitats and species protection and improvement, which coincides with biodiversity conservation and enhancement. The EU Biodiversity Strategy for 2030 recommends that Member States «[E]nsure no deterioration in conservation trends and status of all protected habitats and species by 2030. In addition, Member States will have to ensure that at least 30% of species and habitats not currently in favourable status are in that category or show a strong positive trend» (European Commission, 2020, pp. 6-7). From this perspective, one of the most outstanding features of GI is its attitude towards addressing the negative impacts of habitat fragmentation on the supply of ES related to biodiversity by strengthening the effectiveness of connections between protected areas.

Building on a methodological approach defined in previous studies by Cannas, published in a set of articles between 2017 and 2018 (Cannas and Zoppi, 2017a; 2017b; Cannas *et al.*, 2018a; 2018b), this chapter identifies ecological corridors (EC) with reference to the spatial layout of a set of protected areas. Moreover, such methodological approach is implemented into the context of the Sardinian region to map EC, which form, together with protected areas, a network representing the spatial framework of a regional GI. Finally, the relation between the EC and the spatial taxonomy of the landscape components featured by environmental relevance (LCFER), identified by the Regional Landscape Plan (RLP) is analyzed, in order to assess if, and to what extent, the present regional spatial zoning code can be used as a basis to implement regulations aimed at protecting EC.

3.1. Introduction

The EC are important spatial structures aimed at improving the effectiveness of ecological networks by supporting their connection capacity as for migration of wild species, their spatial layout and their potential in terms of genetic exchange. EC connection capacity can manifest through minimizing impacts on wild species and genetic flows coming from pressures generated by human activities, such as agriculture and forestry, air and water pollution, gray infrastructure and urban expansion. These threats could cause negative environmental effects as a consequence of the break-up of ecosystem matrices (D'Ambrogi *et al.*, 2015).

The conceptual category of connectivity expresses more precisely than that of connection the capacity of connecting ES, since it includes environmental and landscape aspects, such as the spatial position, the physical continuity, and the presence, type and dimension of natural and anthropic structures, and functional and ecological features, such as the functional perception of species, their ecological and behavioral needs, and their specialization characteristics as well (Battisti, 2004; D'Ambrogi *et al.*, 2013; 2015). This is in line with Baudry and Merriam (1988) who claim that flows of species across ecological networks are often correlated to the connectivity of spatial, mostly linear, elements, which can be defined as EC.

As per the operational definition of GI given by the European Commission, spatial connectivity concerning the provision of ES is strictly related to the conceptual category of ecological network, since a GI can be considered as «[A] strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ESs. 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» (European Commission, 2013, p. 3), and, «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» (European Commission, 2013, p. 7). This implies that GI and ES are strictly related to each other, and that public policies should prioritize ecological networks in terms of environmental protection and enhancement (Liquete *et al.*, 2015). As a consequence, regional and urban planning processes should adequately manage, improve and monitor the effectiveness of GI as ecological network which provides ES and the spatial connectivity of such systems.

This also entails that GI are particularly important as regards restoration of biodiversity, decrease of ecosystem fragmentation and increase of their capacity of providing ES (Directorate-General Environment, European Commission, 2012). That being so, an operational management goal concerning GI can be identified as its role in promoting and improving ES provision and habitat restoration (EEA, 2014; Liquete *et al.*, 2015).

In the second section, the study area is described with reference to the protected areas which are assumed as the nodes of the spatial layout of the Sardinian ecological network, and the methodology adopted to identify EC is presented. Moreover, the methodological approach used to analyze the spatial relationship between EC and the LCFER, identified by the RLP, is described as well.

Section 3 shows the results concerning the identification of Sardinian EC and the assessment of the relation between EC and the LCFER. whereas the implications of the chapter in terms of planning policy recommendations, its limitations and future research perspectives are presented in the fifth chapter of this volume.

3.2. Materials and methods

This section is organized as follows. The first subsection describes the study area and the set of protected areas which are identified as the nodes of the Sardinian regional ecological network. This subsection was written by Lai and reproduced from a previous article by Lai *et al.* (2017). The following subsection presents the methodological approach implemented to identify the EC, which is based on studies by Cannas published in a set of articles between 2017 and 2018 (Cannas and Zoppi, 2017a; 2017b; Cannas *et al.*, 2018a; 2018b). Finally, the third subsection discusses the regression model used to assess the relation between EC and the LCFER, identified by the RLP.

3.2.1. Spatial identification of the ecological corridors

The concept of landscape connectivity was introduced by Taylor *et al.* (1993) as a relevant measure of the landscape structure in line with the theory developed by Dunning *et al.* (1992). According to Taylor *et al.* (1993), landscape connectivity is defined as the «degree to which the landscape facilitates or impedes movement among resource patches» (p. 571). According to With *et al.* (1997), landscape connectivity concerns «the functional relationship among habitat patches, owing to the spatial contagion of habitat and the movement responses of organisms to landscape structure» (p. 151).

In particular, the second definition reflects the dual nature of connectivity, which entails a structural and a functional dimension (structural connectivity, functional connectivity). Structural connectivity is environmentally oriented, while functional connectivity is species-oriented (Issii *et al.*, 2020). In this chapter, the second dimension of connectivity is considered and used. In a nutshell, functional connectivity concerns the movement capacity of species as a function of their intrinsic mobility and of spatial patches suitability to facilitate species movement (Tischendorf and Fahrig, 2000; Taylor *et al.*, 1993).

The concept of landscape connectivity as a means to counter landscape fragmentation has been increasingly embedded into environmental policies, e.g., through technical categories such as greenways, GI and EC, in order to address the problem of biodiversity loss (Balbi *et al.*, 2019; Simberloff *et al.*, 1992). The concept of EC is treated in the literature with reference to different scientific and technical profiles (among many, Saunders and Hobbs, 1991; Rosenberg *et al.*, 1995; Hess and Fischer, 2001). According to Hess and Fisher (2001), the use of the term "corridor" is associated to two important theories of conservation biology, i.e., island biogeography (MacArthur and Wilson, 1967) and metapopulations (Levins, 1969), which focus on functional connectivity.

Functional connectivity is often analyzed through resistance-based models, where resistance «represents the willingness of an organism to cross a particular environment, the physiological cost of moving through a particular environment, the reduction in survival for the organism moving through a particular environment, or an integration of all these factors» (Zeller *et al.*, 2012, p. 778). Resistance-based models are widely described and discussed in the literature. The most complex models, such as the circuit theory-based (McRae *et al.*, 2008) and the individual-based models (Palmer *et al.*, 2011), are difficult to implement due to the overwhelming quantity of input data, and to the needed accuracy in data collection and computational power (Balbi *et al.*, 2019). On the other hand, least-cost path (LCP) models are increasingly used to identify EC (Wu *et al.*, 2021; Guo *et al.*, 2020).

LCP models detect spatially identified pathways, which connect habitat patches, characterized by the minimum resistance to species movement, or by the highest probability of movement to take place. LCP models postulate that organisms have an in-depth knowledge of the landscape that leads them to follow the optimal route (Balbi *et al.*, 2019).

According to Sawyer *et al.* (2011), the attractiveness of this typology of models reflects three important points. First, LCP models make it possible to quantitatively compare potential movement paths within large areas. Secondly, complex effects of habitats on species movement can be integrated into these models. Finally, LCP models go beyond the limits of analyses based exclusively on structural connectivity by incorporating the species' perception of the surrounding environment. LCP models are particularly effective as regards computational efficiency, model implementation ease, and flexibility related to the inclusion of different environmental profiles and aspects in the model structure (Adriaensen *et al.*, 2003; Coulon *et al.*, 2015; Wu *et al.*, 2021). LCP models often integrate experts' judgments into spatial datasets in order to identify resistance values of areal units (Sawyer *et al.*, 2011; Osborn and Parker, 2003; Kong *et al.*, 2010; Larkin *et al.*, 2004).

Building on a methodology developed by Cannas (Cannas and Zoppi, 2017a; 2017b; Cannas *et al.*, 2018a; 2018b), the spatial taxonomy of connectivity is identified on the basis of an LCP model, through four phases, as follows:

- definition of a habitat-suitability map;
- definition of an ecological-integrity map;
- definition of a resistance map;
- spatial identification of EC.

The first phase aims at defining a habitat-suitability map, where habitat suitability is defined as the probability of habitat use by species. The elaboration of this map is based on the Sardinian land cover vector map and on a study concerning species-specific values of habitat suitability. Land covers are classed according to the Sardinian land cover vector map produced by the Regional Administration of Sardinia in 2008, at the third level of the CORINE[1] Land Cover (CLC) nomenclature[2]. Moreover, species-specific values of habitat suitability are identified on the basis of a study by AGRISTUDIO *et al.* (2011), commissioned by the Regional Administration of Sardinia, concerning the conservation status of species and habitats of community interest within the Sardinian N2S. The study provides habi-

[1] CORINE is the acronym of COoRdination de l'INformation sur l'Environnement [Coordination of the information concerning the environment].

[2] A complete description of the CORINE Programme is available at the website https://www.eea.europa.eu/publications/COR0-landcover [Accessed: 22 February 2022].

tat-suitability species-specific values, on an ordinal scale between 0 and 3 (0: non-suitable; 3: extremely suitable), for each CLC class of the Sardinian land cover map in relation to each Sardinian N2S. The evaluation is based on experts' judgments. A habitat-suitability map is elaborated on the basis of two assumptions. First, the habitat suitability species-specific values, associated to land cover classes located in the N2S by the AGRISTUDIO *et al.'s* (2011) study, are associated to the same land cover classes of areas outside the N2S as well. Secondly, the total value of the species-specific habitat suitability associated to each land cover class is equal to the average value of the single species-specific values associated to the land cover class. Finally, a habitat-suitability vector map is defined, which identifies a taxonomy concerning the entire regional area.

The second phase aims at defining an ecological-integrity map, which builds on studies developed by Burkhard *et al.* (2009; 2012), where an assessment of land cover classes' capacities to provide ES is implemented through experts' judgments, on the basis of the founding concept that the higher the ecological integrity, the higher the suitability to species' transition and movement. Ecological integrity concerns supporting ES defined as ES which help to maintain and enhance the supply of the other types of ES, namely provisioning, regulating and cultural ES. The ecological-integrity index is equal to the sum of the scores associated to seven ES supply indicators (abiotic heterogeneity, biodiversity, biotic waterflows, metabolic efficiency, exergy capture, reduction of nutrient loss and storage capacity) that represent supporting ES in relation to each of the 44 third-level land cover classes of the CLC taxonomy. As a result, by mapping the values of the ecological-integrity index, an ecological-integrity vector map is obtained for the entire regional area.

The third phase aims at defining the resistance map by means of the habitat-suitability and ecological-integrity maps, building on a study by LaRue and Nielsen (2008). First, the two vector maps are converted into raster maps; secondly, two maps are defined by mapping the inverse of the sum of the habitat suitability and of the ecological-integrity index; thirdly the new raster maps are scaled, on an ordinal scale between 1 and 100 (1: the lowest resistance; 100: the highest resistance), according to a study by the European Environment Agency (2014). Finally, the values of the two re-scaled raster maps are summed-up and mapped on a patch-by-patch basis. The resulting spatial taxonomy is the resistance map.

The fourth phase aims at spatially identifying EC that connect the Sardinian NPA through the use of the Linkage Pathways Tool (LPT) of the GIS Linkage Mapper (LM) Toolbox. LPT implements the LCP approach by identifying the Cost-Weighted Distance (CWD) (McRae and Kavanagh, 2017). The LCP laying between two core areas is identified by the path which shows the minimum CWD. Input data required by the LPT are a vector map of core areas and a raster resistance map. In this study, each core area is identified either by a single NPA, in case the overlapping of multiple NPA does not occur, or by the spatial envelope of overlapping NPA, whereas phases 1 thru 3 identify the resistance map.

The CWD of a path between two core areas is obtained by: i. averaging the resistance values of pairs of adjacent patches; ii. multiplying such average values times the geometric distance of the patches' centers (Shirabe, 2018); and, iii. summing-up the results of item ii. along the path.

The relevant outputs offered by LPT are the linear developments of the EC and the raster map of the CWD values. Fig. 2 shows the implementation of the LPT processing process.

LPT proceeds as follows, in order to identify the LCP between two core areas A and B.

First, the normalized distance related to each patch i connecting A and B, ND_{iAB}, is calculated, as follows:

$$ND_{iAB} = CWD_{iA} + CWD_{iB} - LCWD_{AB} \quad (1),$$

where: ND_{iAB} is the normalized distance between A and B measured along a path which includes patch i; CWD_{iA} and CWD_{iB} are the cost-weighted distances from patch i to core areas A and B; and, $LCWD_{AB}$ is the least CWD, i.e. the CWD measured along the LCP connecting A and B (McRae and Kavanagh, 2017).

Secondly, the LCP, i.e., the EC, connecting A and B, is identified by the spatial sequence of patches j's which show $ND_{jAB} = 0$.

3.2.2. Study area[3]

Our case study is related to the Sardinian regional context. Sardinia is the second largest Italian island, located in Western Mediterranenan, with an area of around 24,000 km^2. Sardinia is part of the European Mediterra-

[3] This subsection builds on Lai S., Leone F. and Zoppi C. (2017), "Anthropization processes and protection of the environment: An assessment of land cover changes in Sardinia, Italy", Sustainability, 9, 12 (2174): 1-19. DOI: 10.3390/su9122174, Subsection 3.1. Study Area and Protection Levels, pp. 3-4 (written by Sabrina Lai).

nean biogeographical region (European Commission, 2016; Council of Europe - Directorate of Culture and Cultural and Natural Heritage, 2010).

Two regimes of environmental protection are identified by the Italian legislation, that is, natural protected areas (NPAs) and Natura 2000 Sites (N2Ss). Sardinian NPAs and N2Ss are shown in Figure 1.

N2Ss are managed by the national government, whereas the regional governments rule over the regional NPAs.

Four regional natural parks are established under the provisions of Regional Laws nos. 1999/4, 1999/5, 2014/20 and 2014/21 respectively, that is, Porto Conte, Molentargius-Saline, Gutturu Mannu and Tepilora.

Moreover, our study includes, among the regional NPAs, public woods, permanent oases of faunal protection and Ramsar sites. Public woods, managed by the Regional Agency of Forests, are characterized by significant environmental and landscape values, whose conservation and enhancement is important in order to address and mitigate negative impacts caused by natural disasters, such as fires, floods and landslides. Regional Law no. 1998/23 identifies the permanent oases of faunal protection. Nine Sardinian sites are protected under the provisions of the Ramsar Convention, signed in 1971.

As regards the N2Ss, the Natura 2000 Network includes areas designated under the provisions of Directive no. 92/43/EEC (the Habitats Directive) and of Directive no. 2009/147/EC (the Birds Directive), and encompasses more than 27,000 sites, representing the backbone of the European Union's policies on protection of nature and biodiversity (Directorate-General Environment, European Commission, 2016). N2Ss include the following: sites of community interest (SCIs) and special areas of conservation (SACs), established under the Habitats Directive, and special protection areas (SPAs), established under the Birds Directive. SPAs are designated by the European Union member states in relation to a number of scientific criteria, in order to provide bird protection. As regards SCIs and SACs, the designation process develops from Member States' proposals addressed to the European Commission who is responsible for their establishment. SCIs can become SACs within six years since their establishment, provided that conservation measures are identified. Sardinian N2Ss are classified as follows: 31 SPAs, 87 SACs and 10 SCIs[4].

[4] Data available at the website https://www.eea.europa.eu/data-and-maps/data/natura-13/natura-2000-spatial-data/natura-2000-shapefile-1 [Accessed: 22 February 2022].

3.2.3. Relation between EC and landscape components

The LCFER represent a spatial taxonomy of the regional land aimed at defining differentiated levels of protection depending on the value of nature and natural resources. This taxonomy was defined in the RLP approved by the Deliberation of the Sardinian Regional Government no. 36/7 of September 5, 2006, and implemented a protection regime which did not take account of ecological corridors, whereas their importance was recognized by art. 10 of the Habitats and Birds Directives, according to which EC make the Natura 2000 Network internally connected from the functional and ecological points of view. As a consequence, EC can be considered areal structures connecting habitats to enhance and support biodiversity, and, in so doing, increasing the ES provision (Cannas *et al.*, 2018a; 2018b).

Thus, the implementation of EC protection into the Sardinian spatial planning framework, established under the provisions of the RLP code, has to be developed by identifying EC as areas with the highest protection level among the LCFER.

The spatial layout of EC connecting core areas is defined by the raster map of CWD values clustered into ten deciles, whose second's upper limit is assumed as the threshold for the inclusion of a patch in an EC (Cannas and Zoppi, 2017a). The CWD of a patch j, included in an EC connecting the core areas A and B, is calculated as follows:

$$CWD_j = CWD_{jA} + CWD_{jB} \qquad (2),$$

where CWD_{jA} and CWD_{jB} are the cost-weighted distances from patch j to core areas A and B.

The assessment of the relations between EC and LCFER is implemented through a linear regression model which relates the eligibility of a patch to be included in an EC and the areas of the LCFER overlaid by the corridors.

The LCFER classed by the RLP implementation code (IC)[5] are the following[6]:

- natural and subnatural areas, which include: scrub vegetation in dry areas and wetlands (areas covered with sparse vegetation, between 5% and 40%; riparian areas covered with non-arboreal vegetation; Mediterrane-

[5] The text of the RLP IC is available at the website http:// www. regione.sardegna.it/documenti/ 1_22_20060911101100.pdf [Accessed: 22 February 2022].

[6] Information drawn from the "Legenda Piano Paesaggistico Regionale" [Caption Regional Landscape Plan], available at the website http://www. sardegnaterritorio.it/documenti/6_83_20061006113400.pdf [Accessed: 22 February 2022].

an scrub; river beds larger than 25 meters; inland marshes; salt marshes; rock faces); and, woodlands (mixed coniferous and broadleaf woods; broadleaf woods);
- seminatural areas, which include: grasslands (steady meadows; natural pastures; thickets and shrublands; garrigues; natural recolonization areas); and, cork and chestnut woods;
- areas dedicated to agriculture and forestry, which include: specialized and tree crops (vineyards; orchards; temporary olive- and vineyard-related crops; temporary crops related to other permanent crops); artificial woods (coniferous woods; poplar, willow and eucalypt woods; other trees for timber; arboriculture with coniferous forest trees; artificial recolonization areas); and, specialized herbaceous crops, agricultural and forest areas, and uncultivated areas (non-irrigated arable land; artificial meadows; simple arable land and full-field horticultural crops; paddies; breeding grounds; greenhouse crops; complex parcel cropping systems; areas characterized by prevailing agricultural crops and residual important natural land; uncultivated areas).

According to the RLP IC, the protection regime concerning natural and subnatural areas forbids whichever spatial transformation, including new buildings or land use modifications, which is likely to undermine the ecosystem structure, steadiness and functionality, or the landscape enjoyment potential. As for dunal and retrodunal habitats featured by non-arboreal vegetation or Mediterranean scrub, vehicle and pedestrian access and temporary installations are not allowed if they may put at risk natural resources conservation. Moreover, the RLP IC forbids the implementation of spatial transformations which may cause water pollution or landfill as regards wetlands. Finally, afforestation is not allowed if potentially harmful to priority habitats designed by the Habitats and Birds Directives, with the exception of conservation operations.

As for seminatural areas, the RLP IC states that whichever spatial transformation, including new buildings or land use modifications, which is likely to undermine the ecosystem structure, steadiness and functionality, or the landscape enjoyment potential, is not allowed, with the exception of operations aimed at improving the ecosystems structure and functioning, the conservation status of biotic and abiotic natural resources, and at mitigating environmental hazard and degradation of natural resources. In woodlands, land use modifications are forbidden except land use changes related to the development of new faunistic or floristic populations and to the enhancement of the habitats of protected wildlife. Moreover, new facilities are not permitted, whereas restoration of existing buildings is allowed provided that they will be used to improve the conditions of nature and natural resources, and that the operations do not entail an increase in building volume, floor area and covered surface.

New infrastructure, such as roads, power lines, hydraulic pipelines, etc., which may alter the forest land cover or increase fire or pollution hazards are not allowed in seminatural areas, with the exception of operations aimed at forest management and soil protection. Furthermore, the RLP IC forbids new roads, power lines and wind turbines close to wetlands and to areas characterized by the presence of species of community interest, especially with reference to birdlife, or which may generate negative impacts on the landscape perception. River systems and riparian areas have to be protected from soil-sealing operations, afforestation implemented by using alien species and removal of sand and sediments from the river beds.

As for dunal systems and sandy seashores, vehicle traffic is strictly forbidden, and sand and sediment removal is not allowed as well. Finally, a general rule concerning seminatural areas concerns a ban on the use of alien species for afforestation, reforestation, and renaturation.

With reference to areas dedicated to agriculture and forestry, and uncultivated areas, the RLP IC forbids transitions from agriculture and forestry to other land uses, with the exception of changes motivated by reasons related to the implementation of relevant public utilities for which it is demonstrated that no other location is presently available. Limited land use transitions are allowed to make more effective infrastructure, facilities and machinery exclusively devoted to agriculture or forestry. Moreover, the biodiversity improvement as regards native species of agrarian interest, the conservation of local traditional agricultural systems and the protection of typical rural scenery are indicated as important addresses, stated as planning rules as per art. 29 of the RLP IC, in particular with reference to periurban zones and historic terrace farming areas.

All in all, the RLP IC identifies rules concerning natural, subnatural and seminatural areas which are almost entirely consistent with a nature protection regime aimed at strengthening the effectiveness of EC. The main regulatory feature of the RLP IC with respect to these areas is the general objective of protecting the structure and functionality of ecosystems, biodiversity, nature and natural resources, with particular attention to habitats and species identified by the Habitats and the Birds Directives, dunal and coastal environments, and wetlands as main sources of biodiversity, especially as regards birdlife. In woodlands, modifications of land use are not allowed, except for improvement of wildlife habitats and increase in faunistic and floristic populations. Rules concerning agriculture and forestry are less restrictive, since land use transitions are allowed if they aim at improving farm and forest productivity, even though protection of traditional practices, scenery and biodiversity protection with reference to rural landscapes and environments are targeted as important planning policy goals.

The relation between EC and the LCFER described so far is analyzed through a multiple linear regression model which assesses the correlations between CWD and the areas of the LCFER which overlay EC. The model takes the following form:

$$ECWD = \beta_0 + \beta_1 SCRB + \beta_2 WOOD + \beta_3 GRAS + \beta_4 CCHW + \beta_5 SPTC + \beta_6 ARWO + \beta_7 HAFU + \beta_8 ALTD, \quad (3)$$

where dependent and explanatory variables identify the areal dimensions of EC and of the overlays of EC and the LCFER:

- ECWD is the CWD of a patch included in an EC;
- SCRB is for scrub vegetation in dry areas and wetlands;
- WOOD is for woodlands;
- GRAS is for grasslands;
- CCHW is for cork and chestnut woods;
- SPTC is for specialized and tree crops;
- ARWO is for artificial woods;
- HAFU is for specialized herbaceous crops, agricultural and forest areas, and uncultivated areas;
- ALTD is a control variable which represents the average altitude in an EC.

The outcomes of the regression model identify the quantitative correlations between the linear dimension of EC, ECWD, and the presence of LCFER.

As per many studies related to correlations between spatial variables, a regression model is used since no prior hypothesis seems to be plausible as regards the effect of covariates on the dependent variable (among many: Cheshire and Sheppard, 1995; Stewart and Libby, 1998; Sklenicka *et al.*, 2013; Zoppi *et al.*, 2015).

Thus, a surface, characterized by an unknown equation, representing a spatial phenomenon featured by n factors, is approximated, in an infinitesimal neighborhood of one of its points, by its tangential hyperplane. The infinitesimal area shared by the hyperplane and the surface, is identified by the known equation of the tangential hyperplane, that is, by the linear relation between the covariates. Such linear relation locally approximates the unknown surface. That being so, multiple regression model (3) estimates the trace of an eight-dimensional hyperplane on an eight-dimensional surface whose equation is unknown (Bera and Byron, 1983; Wolman and

Couper, 2003), which shows the linear correlations between ECWD and the eight dependent variables defined above.

The variable ALTD is utilized as a control variable to check the effect of the altitude of an EC on its areal dimension; so, if the estimate of the coefficient β_8 were significant, this would imply that the altitude is likely to cause a relevant impact on ECWD. The sign of the estimated coefficient indicates if the impact is positive or negative, i.e., if the greater the altitude, the lower ECWD, or the other way around.

Finally, a 5% p-value significance test is used with reference to the estimated coefficients of model (3) to see if their estimates are significantly different than zero.

3.3. Results

This section is organized as follows. The first subsection presents the spatial layout of the EC identified through the implementation of the methodology described in subsection 3.2.2. The following subsection operationalizes the regression model defined in subsection 3.2.3.

3.3.1. The spatial layout of ecological corridors

The implementation of the methodological approach developed by Cannas (Cannas and Zoppi, 2017a; 2017b; Cannas *et al.*, 2018a; 2018b), and described in section 3.2.2., generates two outputs: i. the raster map of the CWD values; ii. the spatial identification of the EC that connect the NPA of the Sardinian protected area network. Fig. 2 shows the EC identified in the study area and fig. 3 reports the CWD values, included in a range between 0 to 225,201 km. As described in section 3.2.3., the CWD values are clustered into ten deciles, whose second's upper limit is assumed as the threshold for the inclusion of a patch in an EC. The CWD values included in the first two deciles range from 0 to 9,741 km. In fig. 2 and 3, the EC are shown as linear elements.

Through LPT, 240 EC are identified, with length values ranging between 0.07 km and 27.34 km. Moreover, two important qualitative attributes of the EC connecting two core areas have to be emphasized: the ratio of the CWD to the Euclidean distance (CWD/ED) and the ratio of CWD to the length of the EC (CWD/LCP) (Feng *et al.*, 2021; Dutta *et al.*, 2016). The former measures the resistance to species movement between two core areas in relation to their proximity, i.e., the connectivity quality of the connecting EC, as long as the latter identifies the average resistance to species movement along the EC which connects two core areas.

Tab. 1 - Name and typology of NPA included within core areas connected by EC which shows the highest and lowest values of CWD/ED index and CWD/LCP index

EC code	*Core area code*	*Name of connected NPA*	*Typology of NPA*
22	7	Monte dei Sette Fratelli	SPA
		Monte dei Sette Fratelli e Sarrabus	SAC
		Monte Genis	Permanent oases of faunal protection
		Castiadas-Sette Fratelli	Permanent oases of faunal protection
		Campidano	Permanent oases of faunal protection
		Campidano	Public woods
		Campidano Santo Barzolu	Public woods
		Castiadas	Public woods
		San Vito	Public woods
		Sa Scova	Public woods
		Sette Fratelli	Public woods
		Villasalto	Public woods
122	24	Baccu Arrodas - Rio Molas	Public woods
	47	Olzai	Public woods
	148	Monte Gonare	SAC
112	49	Ussai	Permanent oases of faunal protection
		Barigadu	Public woods
	40	Foresta di Uatzo	Public woods
12	4	Parco Naturale Regionale di Molentargius saline	Natural regional park
		Monte Sant'Elia, Cala Mosca e Cala Fighera	SAC
		Stagno di Cagliari, Saline di Macchiareddu, Laguna di Santa Gilla	SAC
		Stagno di Molentargius e territori limitrofi	SAC
		Torre del Poetto	SAC
		Stagno di Cagliari	SPA
		Saline di Molenatrgius	SPA
		Santa Gilla	Permanent oases of faunal protection
		Stagni di Quartu Molentargius	Permanent oases of faunal protection
		Stagno di Molentargius	Ramsar Site
		Stagno di Cagliari	Ramsar Site
	10	Bruncu de Su Monte Moru - Geremean (Mari Pintau)	SAC
		Costa di Cagliari	SAC

EC code	Core area code	Name of connected NPA	Typology of NPA
		Capo Carbonara e stagno di Notteri – Punta Molentis	SPA
		Fascia litoranea sud orientale	Permanent oases of faunal protection
	140	Stagno di Santa Caterina	SAC
		Stagno di Porto Botte	SAC
228	152	Isola Rossa e Capo Teulada	SCI
		Promontorio, dune e zona umida di Porto Pino	SCI
		Sassu - Cirras	SAC
		Stagno di S'Ena Arrubia e territori limitrofi	SAC
	3	Stagno di S'Ena Arrubia	SPA
		S'Ena Arrubia	Permanent oases of faunal protection
9		S'Ena Arrubia	Ramsar Site
		Stagno di Pauli Maiori di Oristano	SAC
		Stagno di Santa Giusta	SAC
	5	Stagno di Pauli Maiori	SPA
		Pauli Maiori	Permanent oases of faunal protection
		Stagno di Pauli Maiori	Ramsar Site
		Altopiano di Campeda	SAC
		Catena del Marghine e del Goceano	SAC
		Piana di Semestene, Bonorva, Macomer e Bortigali	SPA
		Monte Pisanu	Permanent oases of faunal protection
	80	Foresta Anela	Permanent oases of faunal protection
192		Anela	Public woods
		Bono	Public woods
		Monte Artu	Public woods
		Monte Bassu	Public woods
		Monte Burghesu	Public woods
		Monte Pisanu	Public woods
		Foresta Fiorentini	Permanent oases of faunal protection
	81	Fiorentini	Public woods
		Monte Pirastru	Public woods
119	43	Pabarile	Public woods
	142	Riu Sos Mulinos - Sos Lavros - M. Urtigu	SAC
		Parco Naturale Regionale di Molentargius saline	Natural regional park
14	4	Monte Sant'Elia, Cala Mosca e Cala Fighera	SAC
		Stagno di Cagliari, Saline di Macchiareddu, Laguna di Santa Gilla	SAC

EC code	Core area code	Name of connected NPA	Typology of NPA
		Stagno di Molentargius e territori limitrofi	SAC
		Torre del Poetto	SAC
		Stagno di Cagliari	SPA
		Saline di Molenatrgius	SPA
		Santa Gilla	Permanent oases of faunal protection
		Stagni di Quartu Molentargius	Permanent oases of faunal protection
		Stagno di Molentargius	Ramsar Site
		Stagno di Cagliari	Ramsar Site
	15	Ovile Sardo	Permanent oases of faunal pro-tection

With reference to the CWD/ED index, EC nos. 22, 112, and 122 show the lowest values and, as a consequence, the highest connectivity quality (see tab. 1 and fig. 5), whereas EC nos. 12, 228, and 9 show the highest values and, that being so, the lowest connectivity quality (see tab. 1 and fig. 6).

As regards the CWD/LCP index, EC nos. 192, 119, and 112 show the lowest values and, as a result (see tab. 1 and fig. 7), the lowest average resistance to species movement along the path, while EC nos. 12, 228, and 14 show the highest values and, for that reason, the highest average resistance to species movement (see tab. 1 and fig. 8).

3.3.2. Discussion on the overlay of ecological corridors and landscape components

The estimated coefficients of the explanatory variables of model (3) show the correlations between the ECWD of a parcel included in an EC and the covariates of the multiple linear regression, identified by the LCFER and by the control variable ALTD.

The descriptive statistics related to dependent and explanatory variables of model (3) are shown in tab. 2, whereas tab. 3 reports the estimates of the multiple linear regression.

The estimated coefficient of the altitude-related variable shows significant p-values and a positive sign. This implies that a decrease in ECWD is associated with lower altitudes, everything else being equal, which is entirely consistent with expectations, since higher connectivity, or lower ECWD, is expected to take place in flat areas, generally characterized by comparative lower altitudes. Our findings entail that a decrease of 100 meters in altitude will be correlated to a decrease of about 145 m in ECWD.

Since the estimate of the coefficient of the control variable is statistically significant and consistent with expectations, the estimated effects on ECWD generated by the covariates related to the LCFER can be considered reliable as regards the implementation of model (3).

Tab. 2 - Definition of variables and descriptive statistics related to model (3)

Variable	*Definition*	*Mean*	*St.dev.*
ECWD	Cost-weighted distance of a patch included in an EC (km)	4,947.08	2,865.14
SCRB	Scrub vegetation in dry areas and wetlands in a patch included in an EC (ha)	16,962.44	26,775.40
WOOD	Woodlands in a patch included in an EC (ha)	18,038.76	29,513.47
GRAS	Grasslands in a patch included in an EC (ha)	18,879.67	27,314.39
CCHW	Cork and chestnut woods in a patch included in an EC (ha)	3,190.58	12,865.24
SPTC	Specialized and tree crops in a patch included in an EC (ha)	3,107.70	11,326.36
ARWO	Artificial woods in a patch included in an EC (ha)	4,721.13	16,500.74
HAFU	Specialized herbaceous crops, agricultural and forest areas, and uncultivated areas, in a patch included in an EC (ha)	23,207.82	31,984.68
ALTD	Control variable which represents the average altitude in a patch included in an EC (m)	365.36	275.76

Tab. 3 - Estimate of multiple linear regression model (3)

Variable	*Coefficient*	*t-statistic*	*p-value*
SCRB	-2.77172	-1.60534	0.108428
WOOD	-7.20867	-4.16805	0.000031
GRAS	-5.80510	-3.35834	0.000785
CCHW	-6.91227	-3.49271	0.000479
SPTC	7.70003	3.69729	0.000218
ARWO	-5.33205	-2.85482	0.004309
HAFU	-3.16692	-1.84476	0.065081
ALTD	1.45191	22.37541	0.000000

The results of the coefficient estimates of model (3), reported in tab. 3, are related to the explanatory variables expressed by the percentage share of the area of a landscape component in the total area of a patch. Such estimates show the marginal effects of the explanatory variables on ECWD. The estimates exhibit p-values lower than 6.6%, with the exception of scrub vegetation in dry areas and wetlands (SCRB), which, at any rate, shows a weakly significant p-value (10.8%).

Moreover, the regression results put in evidence that all the LCFER are correlated to increases in the eligibility of a patch to be included in an EC, i.e., an increase in the percentage area of an LCFER is correlated to a decrease in ECWD everything else being equal, except for specialized and tree crops (SPTC), whose coefficient is positive and indicates that an average increase of 1% in SPTC is associated to an average increase of 7.7 meters in the CWD of EC.

As for the other LCFER, the outcomes show that woodlands (WOOD) and cork and chestnut woods (CCHW) are the most suitable to enhance the effectiveness of EC, since their marginal effects on ECWD imply that a 1% increase is correlated to 7.2- and 6.9-meter decrease in average CWD, respectively. Less relevant positive effects on the eligibility of a patch to be included in an EC are exhibited by grasslands (GRASS) and artificial woods (ARWO), whose marginal effects on ECWD are 5.81 and 5.33 meters. The impacts of the covariates associated to scrub vegetation in dry areas and wetlands (SCRB), and to specialized herbaceous crops, agricultural and forest areas and uncultivated areas (HAFU), are definitely less important, since their coefficients entail that an average increase of 1% is correlated to a 2.77- and 3.16- meter decrease in ECWD, respectively.

These outcomes make it easy to identify relevant planning policy implications related to the enhancement of the regional network of protected areas through the protection and the improvement of its EC. Such implications are discussed in the concluding chapter of this volume.

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4. Assessing the potential of green infrastructure to mitigate hydro-geological hazard: evidence-based policy suggestions from a Sardinian study area

This chapter focuses on the relations between the definition and implementation of a GI and hydro-geological hazard. GI are spatial structures supplying a wide range of ecosystem services, here related to the following: nature, natural resources and biodiversity conservation; landscape and recreation; agricultural and forestry production; local climate regulation; climate change impact mitigation through capture and storage of carbon dioxide. A methodological framework is defined to assess the relations between GI and hydro-geological hazard through inferential analysis based on dichotomous-choice Logit models, under the assumption that the implementation of GI within planning policies could enhance environmental protection and people's wellbeing. By applying the methodology to a coastal study area in Sardinia (Italy), this chapter shows that landslides are more likely to occur in areas showing high natural values and high carbon dioxide capture and storage capacity, whereas productive agro-forestry areas are comparatively more likely to feature severe floods, and areas with significant landscape assets and recreation potential are associated with low flood and landslide hazard. On these bases, a better understanding of the role that could be played by GI as regards hydro-geological hazard is gained, and policy recommendations aimed at mitigating the associated risks are identified.

4.1. Introduction

Climate change negatively impacts on the hydrological cycle of the Earth and on phenomena connected with water management. Hydrogeological instability is conceptualized as a change of the natural flow of water on, above and below the surface of the Earth due to its interaction with the anthropized spatial system (Margottini, 2015). Therefore, hydrogeological instability represents a hazard to local population, infrastructures, and economic and productive systems (Trigila *et al.*, 2018). For example, in 2018 in Italy 7,275 municipalities (91% of the Italian ones) were found to be exposed to landslide and/or flooding hazards. Moreover, 16% of the national territory is classified as high-hazard area, and 1.28 million people live in areas featured by landslide hazard and more than 6 million in flooding hazard areas (Trigila *et al.*, 2018; Di Giovanni, 2016).

Typical consequences of hydrological phenomena are landslides, flooding, coastal erosion, subsidence, and avalanche.

According to Cruden and Varnes (1996), «The term 'landslide' describes a wide variety of processes that result in the downward and outward movement of slope-forming materials including rock, soil, artificial fill, or a combination of these. The materials may move by falling, toppling, sliding, spreading, or flowing» (p. 36). The increase in rapid development, deforestation and urbanization results in higher probabilities of landslide events (Tiranti and Cremonini, 2019). Moreover, although several authors studied the impacts of climate change on landslide occurrence and magnitude through the use of model projections (Seneviratne *et al*., 2012; Stoffel *et al*., 2014), the influence of climate change on stability of slopes is still a matter of debate (Gariano & Guzzetti, 2016).

According to the European Union Directive 2007/60/EC on the management of flood risk, flood means «the temporary covering by water of land not normally covered by water. This shall include floods from rivers, mountain torrents, Mediterranean ephemeral water courses, and floods from the sea in coastal areas, and may exclude floods from sewerage systems» (art. 2, paragraph 1). Flood events are affected by sea level rise, heavy rainfalls, impervious surfaces, and ageing drainage infrastructures (Chen *et al.*, 2019).

Although for a long time gray infrastructure has represented the only operational tool to address landslide and flooding hazard and related environmental damages (Badiu *et al.*, 2019), more recently the implementation of nature-based solutions has revealed very effective in mitigating the impacts of such disasters (Caparrós-Martínez *et al.*, 2020). Therefore, the use of GI has gained increasing importance within the international debate. Caparrós-Martínez *et al.* (2020) argue that, even though the technical functions of GI are connected to the management of the integrated water cycle, GI should be mainly identified in relation to three issues: smart growth, climate change adaptation, and social health and wellbeing. According to the US-EPA (United States Environmental Protection Agency, 2017), «Green infrastructure is a cost-effective, resilient approach to managing wet weather impacts that provides many community benefits. While single-purpose gray stormwater infrastructure - conventional piped drainage and water treatment systems - is designed to move urban stormwater away from the built environment, green infrastructure reduces and treats stormwater at its source while delivering environmental, social, and economic benefits». In other words, the US-EPA identifies GI as a provider of mitigation of landslide and flooding impacts, since GI is engineered to intercept rainfalls, increase the availability of permeable surfaces and soil water storage, and delay and decrease the intensity of peak flows (Bartens and Mersey Forest Team, 2009). For instance, large trees may potentially absorb 80% of precipitation, whereas little trees absorption is around 16% (Xiao and McPherson, 2002).

Caparrós-Martínez *et al.* (2020) identify three types of benefits, i.e., economic cost savings, multifunctional character and lower environmental cost, and ability to adapt to different territorial scales. In their view, GI includes healthy ecosystems that help to restore and reestablish spatial connections between damaged habitats and, in general, between natural and semi-natural areas, in contrast to gray infrastructure that requires continuous adaptations to social and economic factors, such as population growth (European Commission, 2013a). Furthermore, GI entails benefits such as water purification generated by natural wetlands, conservation and enhancement of biodiversity, and carbon capture and storage, while gray infrastructure, such as a treatment plants, are single-purposed, in that they only aim at purifying wastewater (European Commission, 2013a; 2013c). Finally, GI may be adapted to different scales, ranging from the regional to the urban level (Caparrós-Martínez *et al.*, 2020).

Moreover, several studies (Lai and Zoppi, 2017; Lai *et al.*, 2017a; 2018; Liquete *et al.*, 2015; Ronchi *et al.*, 2020) highlight that GI may represent a tool to mitigate land-taking processes. In particular, Lai and Zoppi (2017) analyze how the provision of Natura 2000 sites, regarded by the EU as core areas within GI, affect land-taking processes. The results of this chapter put in evidence that the presence of natural and semi-natural areas, such as Natura 2000 sites, is negatively correlated to land-taking processes. Land cover transitions from natural and semi-natural areas to artificial areas due to urbanization, agricultural expansion and abandonment, and deforestation, entail habitat fragmentation and degradation and, as a consequence, biodiversity loss (Calvache et al., 2016). GI as a network of natural and semi-natural areas reduces habitat fragmentation, and, that being so, policies aimed at increasing natural and semi-natural areas are strategically relevant to mitigate land-taking processes (Lai *et al.*, 2017b).

The relation between GI and hydrological instability is a matter of study in recent literature (Zucaro and Morosini, 2018). Mei *et al.* (2018) investigate the role of GI in mitigating flood events through the stormwater management model (SWMM) and life cycle cost analysis (LCCA), in order to support planning and decision-making processes. Chen *et al.* (2019) assess the effectiveness of the implementation of practices based on GI on water supply and quality. Papathoma-Koehle and Glade (2013) analyze how changes in vegetation and land cover influence landslide events in terms of occurrences, consequences, and implications.

Although the implementation of GI based on natural and semi-natural areas is quite effective to mitigate the negative impacts of landslides and floods, its use is still limited due to the difficulty to project and forecast economic impacts and feasibility (Caparrós-Martínez *et al.*, 2020; European Commission, 2013b). Indeed, the assessment of GI-related planning policies is generally based on counterfactual methodologies which imply the availability of huge databases and complex economic approaches that are often too expensive in terms of financial resources and time needed to obtain reliable outcomes (Palmer *et al.*, 2015).

The assessment of the effectiveness of GI practices on hydrological events is therefore an important issue in the current literature; however, available studies mainly focus on specific GI practices, such as green roofs, permeable pavements, bioretention cells, rain barrels, and vegetated swales (Palla and Gnecco, 2015; Liu *et al.*, 2014). This chapter aims at defining a methodological approach to investigate the relations between a regional GI (RGI) and hydrogeological hazards, identified by landslides and floods, by combining GIS-based analysis with regression models in order to define strategies and policies to mitigate the potential negative environmental impacts generated by such hazards. The methodological approach is implemented into a coastal area of Eastern Sardinia, Italy.

This chapter is structured into four sections as follows. The Introduction is followed by the second section, which describes the study area, shows how the dataset is built, and discusses the methodological approach, which combines a GIS-based spatial analysis with a regression model. The third section presents the results derived from the implementation of the methodological approach in relation to the study area. The results are discussed in the fourth section, while the implications of the chapter in terms of planning policy recommendations, its limitations and future research perspectives are presented in the fifth chapter of this volume.

4.2. Materials and methods

This section is organized as follows. In the first subsection the study area is described within the regional spatial context of Sardinia. Next, the discrete-choice Logit model estimated to detect the relations between RGI and environmental hazard is defined and discussed. In the last subsection, the data which operationalize the model are presented.

4.2.1. Study area

The area chosen for this chapter lies on the eastern side of Sardinia, one of the main islands in the Mediterranean Sea (fig. 1). With a size of approximately 24,000 km^2 and a population of 1,611,621 inhabitants[1], Sardinia has a very low residential density of around 67 inhabitants/km^2, mostly concentrated in coastal zones and peaking in the main urban areas. To the contrary, inner areas are sparsely populated and present worrying trends of steady depopulation, to which the persistent low levels of infrastructure and services greatly contribute. The climate of the island is typically Mediterranean, and the landscape is mostly hilly and rugged, with only a few plains that are significant for agriculture. Close to the coastline, several small valleys can be found in correspondence with rivers' estuaries and coastal wetlands, and in these valleys recent coastal urbanization, often connected to the tourism sector, has replaced traditional agricultural and grazing uses.

Bordering the Tyrrhenian Sea to the East, the study area chosen for this chapter stretches over 1306.12 km^2, roughly amounting to one twentieth of the whole island. As shown in fig. 1 (panel "C"), fourteen coastal municipalities are fully comprised within the study area, with a fifteenth one (Gairo) only included as far as its coastal area is concerned; the latter is an enclave completely separated from the rest of the inland municipal territory to which it belongs and enclosed between the sea and the two municipalities of Cardedu and Tertenia. The morphology is quite hilly and rugged in the central part of the study area (i.e. the Gulf of Orosei), characterized by limestones and dolomites, and hosting canyons, steep cliffs and pocket beaches (Arisci *et al.*, 2000; Cossu *et al.*, 2007). The northern and southern parts, still hilly but with gentler slopes, host large sandy beaches (such as, for instance, Orrì in Tortolì to the south, or La Cinta in San Teodoro to the

[1] Data from the National Census as of January 1st, 2020, available at the website http://dati.istat.it/ [Accessed: 22 February 2022].

north: Batzella *et al.*, 2011), as well as rivers of significance in the regional context and their alluvial plains (for instance, Rio Quirra in Tertenia, Rio Cedrino in Orosei, and Rio Posada in the namesake municipality), lagoons and wetlands (for instance, in Tortolì, Orosei, and San Teodoro).

As in all of Sardinia, the climate in the study area is Mediterranean: winters are mild and moderately rainy, while summers are hot and dry. Concerning physiography, approximately 60% of the study area belongs to the thermo-Mediterranean zone and the remainder to the meso-Mediterranean zone, as per the map developed by Canu *et al.* (2015). Vegetation series are closely linked to physiography, and the study by Bacchetta *et al.* (2009) shows that nearly all the study area hosts species belonging to either the Sardinian thermo-meso-Mediterranean series or the Sardinian thermo-Mediterranean series, as follows: approximately 53% is taken by the holm oak tree series, 20% by the cork tree series, 12% by the wild olive tree series, and 6% by the *Juniperus turbinata* series; finally, negligible percentages of several other vegetation series concern the rest of the study area.

Hydrogeological hazard has historically been significant in the study area, hence its significance for this chapter. As for floods, extreme events in recent history took place in this part of the island in 1951, 2004, 2013 (Bodini and Cossu, 2010; Cossu *et al.*, 2007; De Waele *et al.*, 2008; Righini *et al.*, 2017). As far as landslides are concerned, approximately 175 events occurred up to 2007 have been recorded by the Italian landslide inventory (IFFI) project[2] in the study area. Such events are mainly clustered in the central and south-most parts of the study area; the former includes the municipalities of Baunei, Dorgali and Orosei, where fall and topple types prevail (Cinus *et al.*, 2007), while in the latter, only concerning the municipality of Tertenia, topples prevail[3], although some translational slides have also occurred (Cinus *et al.*, 2007).

Finally, as for urbanization, tab. 1 provides data on population and land take in the study area. As per the definition by the European Environment Agency (2019), land take is here understood as the «change in the area of

[2] IFFI is the acronym of "Inventario dei Fenomeni Franosi in Italia", which can literally be translated as "Inventory of Landslide Events in Italy". For the Sardinian region, the full IFFI 2007 dataset can be retrieved from https://idrogeo.isprambiente.it/app/page/open-data. Moreover, a larger spatial dataset, which includes also more recent observations and provides additional information such as event date and pictures, can be visualized at the website https://idrogeo.isprambiente.it/app/iffi/r/20 [Accessed: 22 February 2022].

[3] For the full taxonomy of landslide types the reader can refer to Varnes (1978) and to Crudern and Varnes (1996).

agricultural, forest and other semi-natural land taken for urban and other artificial land development», which, in Italy, is monitored on an annual basis by the National Institute for the Protection of the Environment (original Italian: ISPRA - Istituto Superiore per la Protezione e la Ricerca Ambientale). Data from the latest available report (Munafò, 2020) show that, if all of the 15 municipalities in the study area are taken into account, then land take is higher than that of the whole island, both in terms of quantity of land taken per unit of area, and in terms of land taken per capita (tab. 1, penultimate and last column respectively).

Tab. 1 - Municipalities in the study area: size, population, population density, and land take

Municipality	*Area [km^2]*	*Population (*)*	*Population density [residents/km^2]*	*Land take [%] (**)*	*Land take [m^2/inhab.]*
Bari Sardo	37.43	3,908	104.40	5.97	572.20
Baunei	212.08	3,549	16.73	0.78	465.49
Budoni	56.17	5,191	92.40	8.74	945.69
Cardedu	32.35	1,953	60.36	4.32	715.93
Dorgali	224.82	8,502	37.82	2.51	662.83
Gairo (***)	78.32	1,365	17.43	1.79	1027.63
Girasole	13.23	1,320	99.77	6.73	674.59
Loiri Porto San Paolo	118.43	3,604	30.43	3.32	1090.79
Lotzorai	16.51	2,115	127.59	7.23	566.29
Orosei	90.55	6,928	76.51	6.33	826.93
Posada	33.07	3,041	91.97	6.56	713.18
San Teodoro	104.76	4,978	47.48	5.34	1124.93
Siniscola	199.87	11,509	57.57	3.86	670.20
Tertenia	117.76	3,883	32.97	2.12	642.77
Tortolì	40.47	10,769	266.11	13.09	492.01
Total 15 municipalities	1375.82	72,615	52.77	3.79	718.94
Sardinia	24,090	1,611,621	66.90	3.28	490.28

(*) As of January 1st, 2020. Source: National Census (available at the website http://dati.istat.it/ [Accessed: 22 February 2022]).
(**) As of 2019. Source: Munafò, 2020. Defined as “Consumed soil” in the supplementary materials (available at the website http://groupware.sinanet.isprambiente.it/uso-copertura-e-consumo-di-suolo/library/consumo-di-suolo/indicatori/ [Accessed: 22 February 2022]).
(***) Data in this table refer to the whole municipality, but in this chapter only the coastal area (8.62 km^2) is included; data on population and land take are not available for Gairo’s coastal enclave only.

However, a closer look at tab. 1 unveils a very uneven situation across municipalities in the study area, as land take as percentage of the “consumed soil” per unit of area ranges between 0.78% (Baunei) and 13.08% (Tortolì). However, such figures are highly dependent on the size of the municipal area. Hence, the unbalanced distribution of land take across the

15 municipalities is more significant if the share of "consumed soil" per capita is considered.

What is quite evident, here, is that in well-renowned coastal tourist destinations, such as Budoni, San Teodoro, or Loiri Porto San Paolo, land take per unit of resident population is approximately (or even higher than) twice as much as the regional figure, which exposes the impact of tourism and related infrastructure on urbanization in coastal areas.

4.2.2. Methodological framework

Multiple or dichotomous choice models (DCMs) analyze phenomena characterized by multiple or dichotomous nominal alternatives. These models were originally formalized and applied by McFadden (1978; 1980) in order to characterize behavioral choices of consumers. McFadden (1978; 1980; 2000) built on William's work (1977) through the implementation of choice models related to agents' behavior on the basis of standard microeconomic theory. These models integrate sets of agents' features as covariates, whose alphanumerical values may or may not be part of the available information; were they not available, they would be integrated into the model as random characteristics. A number of studies are points of reference to formalize multiple or DCMs (Ben-Akiva and Lerman 1985; Ortúzar and Willumsen 2001; Train 2009), which assume imperfection of agents' rationality and information incompleteness (Tversky 1972).

In this chapter, DCMs are used because the variables which identify flood and landslide hazards are dichotomous, since both flood hazard and landslide hazard can be classified into the "relevant" and "weak" categories, by grouping the hazard classes of the Sardinian region as follows: in case of flood hazard, "presence of flood hazard" into the former and "no hazard" into the latter; in case of landslide hazard, "very high," "high" or "medium" hazard into the former, and moderate or no hazard into the latter.

Building on Nerlove & Press' (1973), Greene's (1993), and Zoppi and Lai's (2013), this chapter implements a Logit DCM. Logit models (LMs) associate a logistic probability distribution to the two events that characterize the phenomenon at stake.

The model considers a set of two events {0,1}, with probability of event "1" and "0" given by, respectively:

$$\text{Prob}\ (1) = \frac{e^{\beta'_1 x_1}}{1+\sum_{k=0}^{1} e^{\beta'_k x_k}} \qquad (1),$$

$$\text{Prob}(0) = \frac{1}{1+\sum_{k=0}^{1} e^{\beta'_k x_k}} \quad (2),[4]$$

where β is a vector of coefficients and x is a vector of characteristics related to the event k, $k \in \{0,1\}$. As per Greene (1993, p. 666, see footnote 3), a unique non-zero vector β_1 can be identified, and, as a consequence, a unique vector of coefficients β, i.e. vector β_1 of formula (1), is estimated by solving the maximization problem of the following log-likelihood function, ln L, in the vector of coefficients β:

$$\ln L = \sum_{i=1}^{M} \sum_{k=0}^{1} d_{ik} \ln Prob\ (k) \quad (3),$$

where M is the total number of observations, and d_{ik}=1 if in the i-th observations the event k occurs, and d_{ik}=0 otherwise. The vector of coefficients β is implemented into (3) through formulas (1) and (2), where the Prob(k)'s are expressed as functions of vector β through formulas (1) and (2).

The maximization of the likelihood function ln L is identified by a system of N+1 equations in the N+1 coefficients of vector β. Each equation takes the following form:

$$\frac{\partial \ln L}{\partial \beta_j} = \sum_{i=1}^{M} [d_{ik} - \ Prob\ (k_i)] x_{ij} = 0 \quad (4),$$

where β_j is the j-th coefficients of vector β, x_{ij} is the i-th observation concerning characteristic j of vector x, k_i is the event associated to the i-th observation, such that $k_i \in \{0,1\}$, and $j \in \{0,N\}$ is the number of components of vectors β and x.

The values of the vector of coefficients β which solve the maximization problem (4) make it possible to calculate the marginal effects of a change of the value of a characteristic x_i of vector x on the probability that the event k occurs, $\frac{\partial Prob\ (k)}{\partial x_i}$, as follows:

$$\frac{\partial Prob\ (k)}{\partial x_i} = [Prob\ (k)]\{\beta_i - \sum_{j=0}^{N} [Prob\ (k)]\, \beta_j\} \quad (5)$$

[4] If $\beta_j^* = \beta_j + q$ for any nonzero vector q, the identical set of probabilities result, as the terms involving q all drop out. A convenient normalization that solves the problem is to assume vector $\beta_0 = 0$. The probability for Y = 0 is therefore given by (2) (Greene, 1993, p. 666).

The model's estimates make it possible to derive the marginal effects of formula (5), for instance as regards the x_i's mean values, and the probabilities of the events k's. Furthermore, the model makes it possible to derive the standard errors of the components of vector β and of the marginal effects of formula (5).

A further assumption is that the random distribution of the event k, $k \in \{0,1\}$, is such that observations are independent from each other, which entails that the observations concerning the explanatory variables are unrelated to each other, and deterministically identified by the available data. As a consequence, the random element of the distribution of event k, ε, is featured as follows (Cherchi, 2012; Cannas and Zoppi, 2017):

$E(\varepsilon|x) = 0$, i.e., the expected value of the random term conditional on the values of vector x equals zero; x is the set of explanatory variables;

$Var(\varepsilon) = \sigma^2$, i.e., the variance of the random term is constant;

$E[\varepsilon_i\varepsilon_j|X] = 0$, there is no correlation between the random terms of the observations, which entails that the covariance equals zero; X is the set of observations concerning vector x.

Model (1) through (5) operationalizes as follows.

Two models are estimated, where the dependent dichotomous variables are, respectively, flood hazard and landslide hazard. These variables correspond to the k's events in model (1) through (5), $k \in \{0,1\}$.

Tab. 2 - Definition of variables and descriptive statistics

Variable	*Definition*	*Mean*	*St.dev.*
FH	Flood hazard - dichotomous variable: 1 if any level of flood hazard but no hazard is detected; 0 if no hazard is detected	0.090	0.286
LH	Landslide hazard - dichotomous variable: 1 if the level of flood hazard is "very high," "high" or "medium"; 0 if eitherthe level of landslide hazard is moderate or no hazard is detected	0.448	0.497
Natval	Natural value. Continuous variable in the interval [0,1]. Potential capability of biodiversity to supply final ecosystem services in face of threats and pressures it is subject to. The value was calculated using the software "InVEST"[5],	0.844	0.269

[5] InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) is a free software program developed by the Natural Capital Project and available at the website http://data.naturalcapitalproject.org/nightly-build/invest-users-guide/html/index.html [Accessed: 22 February 2022].

Variable	*Definition*	*Mean*	*St.dev.*
	tool "Habitat quality", as per chapter 2 in this volume. Data inputs for the model were: land cover types as per the 2008 Regional land cover map (rasterized); raster maps of ten spatial threats listed in the standard data forms for Natura 2000 sites. The ten selected threats are as follows: cultivation; grazing; removal of forest undergrowth; salt works; paths, tracks, and cycling tracks; roads and motorways; airports; urbanized areas; discharges; fire and fire suppression; weights and decay distance for each threat from expert judgments; sensitivity of each land cover type to each threat from expert judgments; accessibility to sources of degradation, in terms of relative protection to habitats provided by legal institutions. The three categories we used are as follows: natural parks, areas protected and managed by the regional Forestry Agency, Natura 2000 sites		
Consval	Conservation value. Continuous variable in the interval [0,1]. Presence of natural habitat types of Community interest (as listed in Annex I of the Habitats Directive) and conservation importance thereof. As per chapter 2 in this volume, Consval=0 for areas where no habitats of Community interest have been identified; else Consval=P*(R+T+K) [normalized in the interval [0,1] where: priority habitats P = 1.5 in case of priority habitat, P = 1 in case of non-priority habitat; rarity R = [1,5] depending on the number of Natura 2000 standard data forms in which the habitat is listed within the regional Natura 2000 network; the higher the number of occurrences, the lower the value of R; threats T = [1,5] depending on the number of threats recorded in the standard data forms for the Natura 2000 sites in our study area; the higher the number of threats, the higher the value of T; knowledge K = [1,4] depending on the level of current knowledge (e.g. number of onsite surveys, existence of up-to-date and reliable monitoring data) of a given habitat within the regional Natura 2000 network; the lower the knowledge, the higher the value of K	0.148	0.195
Landsval	Landscape value. As per chapter 2 in this volume, discrete variable in the interval [0,1] accounting for whether, and to what extent, a given parcel of land is protected under the 2006 Regional Landscape Plan either as "Environmental landscape asset" or as "Cultural-historic landscape asset". For each protection level defined in the Regional Landscape Plan, a score was assigned in the [0,1]	0.521	0.497

Variable	*Definition*	*Mean*	*St.dev.*
	interval depending on the level of restriction. In case of overlapping protection levels, the maximum score was assigned to the parcel		
Recrval	Recreation value. Continuous variable in the interval [0,2.83]. Potential provision of daily, non-motorized, ecosystem-based recreation, assessed trough the conceptual ESTIMAP model, as per chapter 2 in this volume, as the sum of three components; suitability landscapes and natural habitats to support recreation; nature-related elements; water-related elements	1.44	0.576
Agrofor	Agroforestry value. In the absence of comprehensive spatial data on agricultural and forestry productivity, estimated value of rural plots (k€/ha) as of 2017 was used as a proxy, as per chapter 2 in this volume	3.601	4.029
LST	Land surface temperature detected in August 2019 (K), retrieved as per chapter 2 in this volume	311.174	3.554
CO2Stor	Carbon dioxide storage per unit of area ($Mg/(100\ m^2)$), retrieved as per chapter 2 in this volume	1.098	0.350
Altitud	Elevation (m)	234.084	226.531
Slope	Slope. The inclination of slope is provided as percent rise, also referred to as percent slope. The values range from 0 to essentially infinity. A flat surface is 0% and a 45-degree surface is 100%, and as the surface becomes more vertical, the percent rise becomes increasingly larger.[6]	23.009	21.501

The characteristics which are the components of vector $x = (1, x_1, \ldots, x_N)$ and their descriptive statistics are reported in tab. 2. The occurrences of the k's events are conditional upon the X_i's characteristics, according to a logistic distribution estimated through the identification of the coefficients which are the components of vector β, by implementing model (1) through (5). The characteristics are the following: natural value, conservation value, landscape value, recreation value, agroforestry value, land surface temperature and carbon dioxide capture and storage capacity. Moreover, altitude and slope are used as control variables. These characteristics are described and discussed in the following subsection.

[6] Available at the website https://desktop.arcgis.com/en/arcmap/10.7/tools/spatial-analyst-toolbox/slope.htm [Accessed: 22 February 2022].

4.3. Data

Flood hazard and landslide hazard in Italy are mapped at the subnational level, within a sectoral planning tool termed PAI (an acronym for "Piano di Assetto Idrogeologico", verbatim "Hydrogeological Setting Plan"), with which municipal land use plans and their zoning schemes must conform. Notwithstanding several disasters occurred in the XX century, such as Polesine in 1951, Vajont in 1963, or Florence in 1966, it was only in 1989 that the first law (no. 183/1989) making provisions for basin management was passed. Such law made it compulsory to approve watershed management plans that were conceived of as knowledge-providing tools, as well as planning tools that ought to identify technical interventions to reduce hydrogeological risks and impacts on human activities and set up a financial program to be revised every three years. Because of the comprehensive character of such plans, the implementation process was extremely slow (Scolobig *et al.*, 2014). Therefore, when the Sarno debris flow disaster occurred in 1998, a new law (no. 267/1998) was quickly passed to speed up these planning processes and ensure that each River Basin Authority approved at least a "smaller" plan, the PAI. Albeit still part of the comprehensive watershed management plan, PAI's focus only on hydrogeological risk and include assessment and mapping of flood and landslide risks, hence also assessment and mapping of flood and landslide hazards, as well as of vulnerable areas, buildings, and infrastructure[7].

Because the island of Sardinia is identified as a macro-basin, a single watershed management plan and its PAI concern the whole region. The Sardinian PAI, first approved in 2004, in its initial version mapped hydrogeological risk and hazard only within specific parts of the island, such as, for instance, those in which severe landslides were known to have taken place in history, or those in which so-called "critic river segments" were identified through hydraulic models (RAS, 2000). Hazard classes within the PAI range in the 0-4 interval, as per tab. 3.

Since 2004, both flood and landslide hazard and risk maps in the Sardinian PAI have continuously been updated through two main mechanisms: first, studies commissioned by the regional administration; second, studies commissioned by municipal administrations, usually as part of their land-use plan-making processes, because updated flood and landslide assessments concerning the whole municipal territory are prerequisite for the ap-

[7] Within the Sardinian PAI, the traditional disaster risk equation is used: R=H*V, where R=risk, H=hazard, V=vulnerability.

proval of land-use plans. Municipal assessments make use of the same hazard levels as the PAI, i.e., those listed in tab. 3, and of the same methodologies as the River Basin Authority, which means that the outcomes of the regional and municipal assessments are comparable.

Tab. 3 - Flood and landslide hazard classes as per the Sardinian PAI (RAS, 2004, pp. 23-25

Hazard level	*FH level definition*	*LH level definition*
0	Absent (not even mapped)	Absent
1	Low (return period: 500 years)	Moderate
2	Moderate (return period: 200 years)	Medium
3	High (return period: 100 years)	High
4	Very high (return period: 50 years)	Very high

Despite being thoroughly examined and approved by the River Basin Authority, not all the assessments and maps commissioned by the municipalities call for a revision of the PAI; in other words, it is up to the River Basin Authority to decide when the maps commissioned and produced at the municipal level are to be integrated within a new version of the regional PAI. Therefore, when looking for data on landslide and flood hazard in Sardinia, one must necessarily take account of four datasets, two for each type of hazard, freely available from the Regional geoportal[8] and enlisted in tab. 4: first, the most updated versions of the PAI maps; second, the maps commissioned by the municipalities and approved by the River Basin Authority.

In the study area, for each hazard type the two spatial datasets partly overlap in twelve of the fifteen municipalities, while for three of them (Bari Sardo, Dorgali, and Baunei) a study at the municipal level has not been produced and approved so far.

However, the area of interest for this research was analyzed within a study commissioned by the regional administration and approved in 2011[9] that led to an early revision of the Sardinian PAI, which means that both landslide and flood hazard data for the three aforementioned municipalities can be retrieved from the regional PAI, although in some parts of Dorgali's territory the landslide hazard map is void.

[8] Available at the website http://www. sardegnageoportale.it/webgis2/ sardegnamappe/?map=pai [Accessed: 22 February 2022].

[9] Available at the website http://www.regione.sardegna.it/index.php?xsl=509&s=1&v=9&c=9305&tb=8374&st=13 [Accessed: 22 February 2022].

Tab. 4 - Landslide and flood hazard datasets used within this chapter

Title of the spatial dataset (original)	*Content of the spatial dataset*	*Latest update*	*Metadata and download URL [Accessed: 22 February 2022]*
Pericolo Geomorfologico Rev. 42 (Pericolo Frana PAI)	*LH*, PAI (revision 42)	31/01/2018	http://webgis2.regione.sardegna.it/catalogodati/card.jsp?uuid=R_SARDEG:eb38d6c0-b51f-4df1-acdc-f7a752e7664c
Art.8 Hg V.09 (Pericolo Frana Art.8)	*LH* assessment commissioned by the municipalities and approved by the River Basin Authority	31/01/2018	http://webgis2.regione.sardegna.it/catalogodati/card.jsp?uuid=R_SARDEG:127d7692-14c0-4d85-a364-62476a0a3cc9
Pericolo Idraulico Rev. 41 (Pericolo Alluvioni PAI)	*FH*, PAI (revision 41)	31/01/2018	http://webgis2.regione.sardegna.it/catalogodati/card.jsp?uuid=R_SARDEG:9b3a1b64-2a59-4658-98ed-7f6cec366128
Art. 8 Hi V.09 (Pericolo Alluvioni Art.8)	*FH* assessment commissioned by the municipalities and approved by the River Basin Authority	31/01/2018	http://webgis2.regione.sardegna.it/catalogodati/card.jsp?uuid=R_SARDEG:34d2c0f6-a8c3-4bcb-8a64-abbec8723574

As for the other twelve municipalities, in case of overlapping patches where the PAI and the municipal maps identify two different hazard levels[10], within this chapter we consider the latter, for the following three reasons: first, the municipal assessments and maps are more recent than the corresponding PAI ones; second, the municipal assessments and maps have already been approved by the River Basin Authority, which serves as a certification of their quality; third, the municipal assessments can in principle reply the PAI ones any time soon, whenever the River Basin Authority decides that they are to be integrated within a new revision of the PAI.

For each municipality in the study area, tab. 5 provides details on the most updated landside and flood hazard maps (bearing in mind that the PAI *LH* and *FH* maps concern all of the 15 municipal territories).

The methodology through which *Natval*, *Consval*, *Landsval*, *Recrval, Agrofor*, *LST, CO2Stor* were assessed and mapped has been presented in the second chapter of this volume, and their spatial distribution has been

[10] This is possible because the regional and the municipal assessment have different spatial and temporal resolution, and the hazard level can vary over time: for instance, it can be lowered through appropriate mitigation interventions.

provided in subsection 2.8.1. As for elevation (*Altitud*) and slope (*Slope*), their values were retrieved from the 10-m resolution digital terrain model available from the Regional geoportal[11].

Tab. 5 - Municipalities included in the study area: approval date of the most recent hazard maps

Municipality	*Approval of the LH & FH maps [year]*	*Study commissioned by*
Bari Sardo	2011	Sardinian regional administration
Baunei	2011	Sardinian regional administration
Budoni	2012	Municipal administration
Cardedu	2013	Municipal administration
Dorgali	2011	Sardinian regional administration
Gairo	2014	Municipal administration
Girasole	2012	Municipal administration
Loiri Porto San Paolo	2012	Municipal administration
Lotzorai	2015	Municipal administration
Orosei	2013	Municipal administration
Posada	2010	Municipal administration
San Teodoro	2015	Municipal administration
Siniscola	2013	Municipal administration
Tertenia	2015	Municipal administration
Tortolì	2011	Municipal administration

For each variable, tab. 6 summarizes data inputs and their sources, tool employed (when available; otherwise, ordinary GIS tools were used), and references.

Tab. 6 - Spatial datasets developed for this chapter: input data, sources, tools, and references

Variable	*Input data*	*Input data source(s)*	*Tool*	*References*
FH	PAI *FH* maps Municipal *FH* maps	Regional geoportal		---
LH	PAI *LH* maps Municipal *LH* maps	Regional geoportal		---
Natval	Regional land cover raster map Protected areas map Threats to biodiversity (spatial data only)	Regional geoportal	InVEST - Habitat quality model	Lai and Leone, 2017 Cannas *et al.*, 2018
	Expert judgments	Questionnaires		
Consval	Habitats of Com-	Regional administra-		

[11] Available at the website http://www. sardegnageoportale.it/ areetematiche / modelli-digitalidielevazione/ [Accessed: 22 February 2022].

Variable	Input data	Input data source(s)	Tool	References
	munity interest	tion		
	Regional monitoring report			
	Natura 2000 standard data forms	Environmental ministry's website		
Landsval	Regional landscape plan dataset	Regional geoportal		
Recrval	Study area	Regional geoportal	ESTIMAP model for assessing ecosystem based-recreation potential	
Agrofor	2018 Corine land cover map	Copernicus Land monitoring service		---
	Land value (Agricultural areas)	National Research Council of Agriculture and Agricultural Economics' website		
	Land value (Forestry areas)	National Revenue Agency's website		
LST	Landsat 8 TIRS and OLI satellite imagery	USGS's Earth Resources Observation and Science's website	LST QGIS plugin by Ndossi and Avdan (2016)	Lai *et al.*, 2020a Lai *et al.*, 2020b
CO2Stor	Regional land cover raster map	Regional geoportal	InVEST - Carbon storage and sequestration model	Floris, 2020
	Carbon pool data	2005 National Inventory of Italian Forests Regional pilot project on land units and soil capacity in Sardinia		
Altitud	10-m resolution Digital terrain model	Regional geoportal		---
Slope	10-m resolution Digital terrain model	Regional geoportal		---

Finally, through rasterization of vector maps and resampling of raster maps, a 30-m resolution raster map was developed for each variable; by overlaying such maps, an attribute table providing for each cell the corresponding value of each variable was produced to feed the regression model presented in Subsection 4.2.2.

Fig. 2 provides a complete overview of the methodology presented in Subsections 4.2.2 and 4.2.3.

4.4. Findings

This section contains two subsections. In the first, the spatial features of the hazard-related dichotomous variables and of the covariates of the Logit models are presented. In the following subsection, the estimates of the models are described and discussed.

4.4.1. Flood and landslide hazards and their drivers

Fig. 3 provides the spatial distribution of both dependent (left hand side panel) and independent (right hand side panel) variables.

Very high landslide hazard values concern less than the 5% of the study area; as the map shows, they form elongated clusters along the southwest-northeast direction due to geological and geomorphological reasons, along deep canyons in the Baunei, Dorgali, and coincident with the northern side of the Monte Albo karst mountain chain in Siniscola. Nearly 15% of the study area is classed as high hazard, while most of the study area is classed as either medium (about 25.5%) or moderate hazard (circa 40%). Only about 6% of the study area is classed as having no landslide hazard, while in the remaining part (approximately 8.5%), included in the municipality of Dorgali, landslide hazard was not assessed and mapped.

As for flood hazard, 90.5% of the study area shows null values; in the remaining parts, its level is mostly (6%) very high. The remaining 3.5% concerns high, moderate and low values. This is because flood hazard usually takes the maximum value in correspondence to riverbeds, river estuaries, coastal wetlands and their closest surroundings, while its level decreases (more or less quickly depending on factor such as morphology or soil type) as the distance increases. As shown in fig. 3, flood hazard is mostly found to the south and the north of the study area, and almost absent in the central part.

Concerning the independent variables, *Natval* takes extremely high values in most of the study area (around 72.8%) and medium values in around 23.5%, while the null value only concern the remaining 3.7% circa of the study area, corresponding to artificial surfaces such as villages and towns' footprints.

Consval, which in principle can range in the 0-1 interval, in the study area takes 0.76 as maximum value and it is null in around 61% of the territory. This is because habitats of Community interest are identified and mapped mostly within Natura 2000 site, while comprehensive assessments outside the network are missing. It is therefore not surprising that non-zero values are mostly found in the central part of the study area, hosting one of the largest Sardinian Special Conservation Area (ITB020014 “Golfo di Orosei”).

Landsval is null in approximately 47.5% of the study area and, as clearly visible in fig. 3, takes the highest values along the coastline, because the Regional Landscape Plan strictly protects coastal landscapes, and along some the main rivers and creeks, also protected under the national landscape law.

Recrval takes the null value in a very negligible part of the study area (around 0.015%), while areas taking the maximum values are to be found mostly along the coastline, and, especially, along sandy beaches. This is not surprising, since, in compliance with the standard ESTIMAP methodology, a third of the total score is assigned based on the water-related elements, that account for proximity to the coast areas, type of geomorphology, and quality of bathing water, always excellent in the study area.

Agrofor is null in nearly a half (49.4%) of the study area. The highest values are observed in the southern and northern parts of the study area, especially in river valleys and coastal plains, as far as agricultural activities are concerned.

LST hot and cold values are quite clustered, and the clusters mostly correspond to those having high elevation or high slope values, as the maps in fig. 3 show.

Finally, *CO2Stor* ranges between zero and two Mg per hectare, with more than 61% of the study area above 1 Mg/ha, while low values are clustered mainly along the coastline to the north and along rivers and wetlands to the south.

4.4.2. Estimates of the Logit models

Tab. 7 and 8 show the results of the estimates of the Logit models related to the dichotomous variables *FH* and *LH*, and its correlations with the seven environmental features which characterize the RGI. The outcomes partly differ for the two variables, and the differences can be explained through the environmental profiles of the two types of hazards.

In the case of *FH*, *Natval* and *Consval* reveal opposite impacts on the probability of a parcel to be associated either to a relevant or to a weak hazard condition. *Natval* shows a positive correlation to hazard decrease, i.e., a negative marginal effect, whereas *Consval* reveals a negative correlation, or a positive marginal effect.

The estimates of the Logit model concerning *LH* show the opposite correlations.

Secondly, *Recrval* and *Landsval* reveal impacts on the probability of weak flood and landslide hazards consistent with each other and positive in case of *Recrval* and negative as regards *Landsval*, which indicates that these two features of the RGI should be targeted in the opposite way with reference to prevention and control of flood and landslide hazards. This also implies that environmental and cultural attractiveness, and identification and protection of landscape and cultural resources, should be considered as points of reference to fight environmental hazard.

Thirdly, the impacts of *Agrofor* on *FH* and *LH* are opposite as well. Agricultural and forestry productive land shows a positive impact on decrease of landslide hazard and likewise a negative effect on flood hazard. As a consequence, effective control on environmental hazard implies that the most productive agricultural and forestry activities should not be located close to floodplains and their surroundings, where agricultural and forestry land should be used just to counter flooding. Productive agriculture and forestry should be implemented elsewhere, and in particular near areas characterized by a relevant landslide hazard.

Tab. 7 - Marginal effects on the probabilities of FH=1 of variables described in subsection 4.2.3, whose definitions and descriptive statistics are reported in Tab. 2

Variable	*Marginal effect*	*z-statistic*	*p-value*
Marginal impact on *FH*=1 probability, ∂Prob (*FH*=1)/dx_i, Prob (*FH*=1) = 9.00%			
Natval	-0.0014	-5.555	0.0000
Consval	0.0120	24.578	0.0000
Landsval	0.0158	34.685	0.0000
Recrval	-0.0071	-31.487	0.0000
Agrofor	0.0011	32.863	0.0000
LST	-0.0018	-34.632	0.0000
CO2Stor	-0.0037	-18.252	0.0000
Altitud	-0.0001	-62.400	0.0000
Slope	-0.0002	-20.796	0.0000
Log-likelihood goodness-of-fit test			
Log-likelihood ratio = 74241.04 - Prob. > chi-square = 0.00000 (9 degrees of freedom)			

The sixth characteristic of the RGI is *LST*, which is an indicator of how, and to what extent, land covers help to mitigate negative phenomena such as heat islands and waves, and to improve the quality of the rural and urban environments (Lai *et al.*, 2020a). As in the cases of *Recrval*, the estimates of the two Logit models reveal impacts on the probability of weak flood and landslide hazards consistent with each other and positive, which indicates that this feature of the RGI does not need particular attention in terms of landslide and flood hazard control. Indeed, the estimates of the Logit models imply that the higher the *LST*, the lower the two hazards. Since the question related to *LST* as regards climate regulation focuses on policies to decrease *LST*, it can be concluded that the issue of *LST* is not connected to control landslide and flood hazards.

Tab. 8 − Marginal effects on the probabilities of LH=1 of variables described in subsection 4.2.3, whose definitions and descriptive statistics are reported in tab. 2

Variable	*Marginal effect*	*z-statistic*	*p-value*
Marginal impact on *LH*=1 probability, ∂Prob (LH=1)/dx_i, Prob (LH=1) = 44.80%			
Natval	0.3628	70.253	0.0000
Consval	-0.2474	-40.901	0.0000
Landsval	0.0901	27.937	0.0000
Recrval	-0.0948	-32.049	0.0000
Agrofor	-0.0186	-60.698	0.0000
LST	-0.0292	-76.328	0.0000
CO2Stor	0.0600	20.265	0.0000
Altitud	0.0002	40.777	0.0000
Slope	0.0089	130.201	0.0000
Log-likelihood goodness-of-fit test			
Log-likelihood ratio = 123488.80 - Prob. > chi-square = 0.00000 (9 degrees of freedom)			

Furthermore, *CO2Stor* shows opposite impacts on the probability of a parcel to be associated either to a relevant or to a weak hazard condition. This is entirely consistent with expectations, since, in the case of flood hazard, areas vegetated and rich in soil are likely to increase the probability of weak hazard, since they work as drainage areas to absorb excess flooding and filter sediment, whereas, in the case of landslide hazard, the positive impact on the probability of hazard increase is likely to be connected to the fact that areas rich in soil are comparatively more suitable to debris flow, especially in zones characterized by steep slopes. That being so, adequate monitoring of environmental hazard implies that the RGI should encourage the conservation of vegetated and rich-in-soil areas in the surroundings of floodplains, even though not used as croplands, as it is put in evidence above as regards the impacts on flood hazard by *Agrofor*, while the most productive agricultural and forestry activities should be located not close to floodplains and their surroundings, and likewise not close to zones featured by steep slopes.

Finally, the estimated marginal effects of the two control variables, *Altitud* and *Slope*, reveal the expected signs in both cases, since, on the one hand, it is expected that the lower the altitude and the lower the slope, the higher the probability of severe flooding to take place, whereas the higher the altitude and the higher the slope, the higher the probability of serious landslide events. Moreover, all the estimated marginal effects are significant in terms of p-values, and, in general, the marginal effects on the probability of relevant flood hazard are much lower than the impacts on the probability of relevant landslide hazard since the cumulative probability of relevant flood hazard (lower than 10%) is much lower than the cumulative probability of relevant landslide hazard (about 50%). The goodness of fit of the estimates of the two models is excellent, as shown by the two log-likelihood ratios measures.

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5. *Conclusions*

The concluding chapter discusses the outcomes of the studies presented in the volume and the related planning policy implications. It develops through three sections. The first highlights the relations and the advancements entailed by the spatial taxonomy which identifies the RGI. The next section focuses on the planning measures concerning the implementation of the Sardinian regional network of protected areas, with particular reference to its EC. The third section addresses the issue of the relations between the spatial framework of landslide and flood hazards, and the effectiveness of GI in decreasing the size of such hazards.

5.1. The spatial taxonomy to identify the RGI

The availability of spatially explicit assessment of multiple ES makes it possible to identify priority areas for the inclusion in a regional GI. One possible approach is that of identifying those areas that have the highest potential to deliver several ES by calculating the sum of normalized biophysical values (as, for instance, in Arcidiacono *et al*., 2016; Lai and Leone, 2017; Cannas *et al*., 2018) or by calculating the total economic value of the supplied ES. Although helpful in providing a quick, and easy to communicate, assessment of potential ES supply, such approaches oversimplify the multifaced characters of landscapes. Indeed, as stated in the introductory chapter of this volume, in the words of the European Commission (2013), a GI is «a strategically planned network of natural and semi-natural areas […] designed and managed to deliver a wide range of ecosystem services» (p. 3). By using the phrase "a wide range", this definition problematically implies that several ES can be delivered simultaneously. While research has consistently shown that some ES are often jointly provided and intertwined (Bennett *et al*., 2009; Marsboom *et al*., 2018), several studies highlight that some interrelationships are negative and result in trade-offs (among many, Madureira and Andresen, 2014), especially as regards provisioning ES (Balbi *et al.*, 2015, Power, 2010; Raudsepp-Hearne *et al.*, 2010). Therefore, multifunctionality, that is, an area's capacity to provide simultaneously multiple ES, can be effectively investigated in terms of synergies and tradeoffs.

The analysis of bundles of ES provision at the municipal levels, carried out by integrating various types of spatial statistics, unveils, as expected, that agricultural and forestry productivity competes with the other ES; moreover, and this was less expected, it also reveals trade-offs between carbon capture and storage and the other ES. For this reason, areas that are relevant for the delivery of a certain ES might be not so important when another ES is considered. However, the key take-away message from the analysis carried out concerning multifunctionality, and therefore the identification of a potential spatial layout of a regional GI, is that such identification should be based on a thorough analysis of bundles of ES, rather than on single ES. Indeed, the presence of mutual interactions between ES, be they positive or negative, makes it possible to identify homogeneous subregions that supply different composite baskets of ES. By analyzing such interactions, spatial patterns emerge, which reflect both ecological and socioeconomic patterns. Land-use planning and landscape planning should, on the one hand, use the assessment of potential ES delivery as a reference point to develop their strategies; on the other hand, when envisaging planning actions, planners and decision makers should have clear what the consequences of such actions would be on current and future levels of ES supply.

In the case of Sardinia, for instance, planning actions concerning group 3 should aim at preserving current levels of *Landsval* and *Recrval*, which are already very high, while there is scope for increasing *Natval*, *CO2Stor*, and *LST*, for instance through afforestation measures to be carried out in urban and peri-urban areas, as well as by developing green corridors along the coastal wetlands that characterize these municipalities, together with the pertaining traits of rivers and canals. Within group 3, actions to strengthen agricultural and forestry production, hence *Agrofor*, are to be carefully pondered, both because the morphology is not appropriate for forestry, and because intensive agriculture would risk being detrimental for *Recrval* and *Natval*.

As for group 2, maintaining current levels of agricultural productivity should be the main goal here, both because it contributes to local food security and because it generates revenues and jobs, hence strengthening social stability. While it is very difficult to envisage actions that might increase

Consval, as this depends on the presence of habitats of community interest, which would displace agricultural crops, actions to increase *LST* and *Recrval* might be put in place. As for the first, afforestation measures in this group should target not only urban areas, whose surface is negligible except for the municipality of Sassari, which stands out, to the north, for its size; rather, afforestation should target unused lots and land subject to the so-called *usi civici.* These represent the Italian way to the commons (Ostrom, 1990) in that, due to laws and customs that date back to the Middle Ages, they are at the disposal of the local community of the municipality in which the plots of land are located, for either grazing, or collecting firewood, or picking non-wood produce. As these areas cannot be privately owned and can be neither sold nor rented out by the public institution because they belong to the local community, afforesting these areas would pose no harm to economic activities, as it would do in private and farmed plots. As for the second, because the water-related component cannot be increased, to raise *Recrval* one would need to enhance either the suitability for nature-based recreation, or the nature-related elements, or both. To achieve this aim, afforestation of the commons could be complemented with the establishment of small natural parks in the same areas, which could attract visitors from the nearby settlements, especially if properly equipped with recreation facilities. Incidentally, this would also help dramatically reduce the unmet demand for ecosystem-based recreation mapped in fig. 5 of the second chapter in this volume, as unmet demand mostly concerns municipalities comprised in group 2.

Concerning groups 1 and 4, the main goal in both cases is maintaining the good levels of *CO2Stor*, by preventing new land take and, especially, new soil sealing. This would also contribute to preserving the good levels of *LST* observed in group 1, while, for group 4, policies similar to those identified as regards group 2 (i.e., afforestation of the commons and establishment of small natural parks) would be beneficial to increase *LST* and *Recrval*.

Finally, within group 5 the key objective should be that of preserving the levels of ES provided, which are all comparatively high except for *Agrofor*. Municipalities included in group 5 tend to have very limited agricultural areas, both due to morphological characters, as they include the island's main mountain areas, and due to the prevailing vegetation, which comprises maquis and forests. Hence, if *Agrofor* is to be enhanced, then a possible way would be that of raising the forestry value, rather than the agricultural one. This, however, is problematic for several reasons: first, forests are mostly publicly owned; second, the wood mass-market, such as that of paper and furniture, for instance, requires types of woods that grow faster and higher than the Sardinian ones; third, Sardinian forestry was quite important in the past: during the XVIII and the XIX centuries, for instance, large forests were fell to export the wood for the naval industry (Costa, 2008), but in more recent times forestry was linked to local consumption only, for the construction of the railroad (Sistu and Perelli, 2011), for the paper industry, or for burning and producing coal (Beccu, 2000). Hence, it is quite unlikely that any efforts to position the island's forestry in the wood market would be successful.

To sum up, based on the analysis of spatial patters of bundles of ES, a case can be made for the existence of a territorial specialization (Queiroz *et al.*, 2015) that should be accounted for within land-use plans, whose actions can either enhance or degrade the supply of some ES. Awareness should be raised on the fact that planning provisions aimed at fostering some ES (first and foremost, agricultural productivity) are often detrimental to the maintenance of other ES, as, for instance, regulation and cultural ES (Martín-López *et al.*, 2012), while, in case of synergies, actions aiming at increasing a single ES end up with enhancing other synergic ES. Thus, such synergies and trade-offs call for careful ex-ante assessments in plan-making processes.

5.2. The EC of the regional network of protected areas

The results of model (1), shown in the third chapter, make it possible to assess if, and to what extent, the current zoning code of the RLP can represent a solid basis for effectively protecting EC, and highlight important implications for spatial planning practice.

The transition from agricultural to forest land uses, which should be supported by financial grants aimed at compensating differential yields, is associated to a decrease in CWD, and, as a consequence, to a strengthening in the EC's spatial structure.

Planning measures focused on agroforestry transition are more straightforward and easier to implement as regards the areas classed as HAFU (as for specialized herbaceous crops, agricultural and forest areas, and uncultivated areas), and, even more, with reference to zones classed as SPTC (as for temporary crops related to other permanent crops). On the other hand, land cover transitions from intensive agricultural production areas, characterized by high crop yields, to less profitable woodlands (WOOD) or cork and chestnut woods (CCHW), can hardly be compensated by means of public grants, due to the size of the needed financial effort (Hyytiainen *et al.*, 2008). As regards intensive agricultural production zones, agroforestry transition should be implemented through a cooperative and integration-oriented policy by the involved public administrations at different spatial scales, in terms of technical expertise and financial feasibility assessment (Sagebiel *et al.*, 2017; Hou *et al.*, 2018; Zavalloni *et al.*, 2021). For instance, in case of goat and sheep farming, land cover change from grazing land to wooded areas can be effectively financed through public grants, so as to mitigate or even fully compensate the yield decrease implied by such transition. Different is the case of cattle grazing areas, characterized by very high yields, whose transition would possibly generate relevant, and even dramatic and destabilizing, impacts on the regional livestock economy, since wooded pasture, such as the Spanish *dehesa*, is not economically suitable to cattle farming.

Furthermore, afforestation intensity should be carefully assessed. As per Li *et al.* (2021), an increasing trend in wooded areas may possibly be associated to a progressive rise in the ratio of costs to benefits of afforestation processes. Feng *et al.* (2005) show that unbalanced development of woodlands is likely to put at risk food safety. This implies that trade-offs between the provision of different ecosystem services and their economic and social benefits should be analyzed in detail.

A specific assessment of the question of afforestation, based on land cover transition from farming to forestry, is proposed in a study related to social and economic factors driving from croplands to afforestation, which are particularly focused on the identification of the determinants concerning policy-making decisions (Ryan and O'Donoghue, 2016). From this standpoint, the perception of benefits coming from farming are important obstacles as regards afforestation (Howley *et al.*, 2015). This is basically due to the farmers' strong perception of the positive effects related to the non-market value generated by flexible farming-related practices, and to their unwillingness to lose their durable expertise, which in their view is likely to be more important than the expected increase in income coming from afforestation (Ryan and O'Donoghue, 2016). Transition from intensive farming to forest land cover differs significantly from afforestation which originates from extensive croplands (Duesberg *et al.*, 2014) In the former case, a transition is quite unlikely, whereas it is much more probable in the latter, since the expected income from forestry is likely to exceed the income coming from extensive farming, while intensive farming, which develops from permanent agriculture through high-yielding crops, is expected to have the highest rent (Kumm and Hessle, 2020). Extensive and intensive farming should be targeted in terms of planning measures to decrease LST, based on incentive schemes. Agricultural farmers may possibly engage in afforestation, and, by doing so, disengage from low-income farming. The incentive effectiveness is likely to be identified in afforestation coming from transitions from mosaic farmlands and grazing lands, whereas it is quite unlikely that this is case as regards intensive agriculture (Hyytiainen *et al.*, 2008). Moreover, the expansion of forest areas throughout rural zones featured by high-income farming should be carefully assessed by planning agencies in terms of financial feasibility as much as they should carefully consider the negative impact of afforestation on the traditional rural framework in terms of economic, social and landscape degradation (Behan *et al.*, 2006).

All in all, planning policies and measures to strengthen operational capacity and effectiveness of the regional network of protected areas through the protection and the improvement of the spatial framework of its EC have to be studied, structured and implemented by focusing on the ruling concept that habitat quality, ecological integrity and ecosystem conditions have to be enhanced and boosted-up (Samways *et al.*, 2010).

From this standpoint, it has to be highlighted that the methodological approach defined and implemented in the third chapter of this volume can be easily exported to the EU local, regional and national scales, since spatial databases consistent with each other are available for Sardinia and Italy as for the other regions and countries.

5.3. Natural hazards and GI

The methodological approach proposed in this volume and implemented in the previous chapter analyzes the relations between RGI and environmental hazards, represented by landslides and floods. In particular, the chapter focuses on nine variables that are here regarded as proxies for the RGI functions. The results imply the definition of planning policies based on ecosystem service conservation and enhancement (Baskent, 2020). The estimates of the Logit models highlight some issues worth discussing.

Landslides are more likely to occur in areas characterized by high natural values (Zhang *et al.*, 2018) and their negative impacts as regards these areas entail relevant systemic effects with respect to the complex environmental matrices which characterize such areas (Yousefi *et al.*, 2020), particularly sensitive to landslides and floods (Dragicevic *et al.*, 2011).

Areas characterized by high values of *Consval*, such as Natura 2000 sites, show a higher probability of flood hazard occurrences. Natural and semi-natural zones located within protected areas mitigate flood hazard and its potential negative impacts by providing permeable surfaces characterized by the presence of vegetation that absorbs floodwaters. Conservation planning theory focuses on the concept of vulnerability and deems the establishment of a widespread network of protected areas, such as Natura 2000, as a key planning tool to protect natural ecosystem services and mitigate natural hazards (Turner *et al.*, 2007). Recent natural disasters caused by floods have demonstrated how past planning choices have drained, dammed and diverted watercourses not paying any attention to the involved delicate environmental matrices (Stolton *et al.*, 2008; Isola and Leone, 2019). Moreover, protected areas are characterized by natural vegetation, such as forests, which prevent or mitigate landslides, snowslides and avalanches (Stolton *et al.*, 2008). According to Guareschi *et al.* (2020), natural and conservation values represent the potential capability of biodiversity to provide ecosystem services despite threats and pressures. Therefore, analyzing the probability of an area to be associated to specific hazard conditions is essential to the spatial and sustainable development of the area and to define appropriate planning choices aimed at protecting the environment (Dragicevic *et al.*, 2011).

High values of *Recrval* and *Landsval* are mainly concentrated in coastal areas characterized by significant environmental, social, and cultural qualities. As a result, in these areas planning policies and strategies are fundamental in order to mitigate the effects of flood and landslide hazard, especially in relation to problems concerning coastal erosion that affects the entire Sardinian regional coastal zones. Damages caused by floods and landslides threaten the integrity of coastal areas, whose protection requires a great effort to balance development pressures, and economic and environmental sustainability. According to the UNESCO's final report on the "Results of the second cycle of the periodic reporting exercise for the Europe Region and Action Plan" (UNESCO, 2015), landscape and cultural resources are extremely exposed to the adverse effects of natural hazards. This problem is also highlighted in the "Sendai Framework for disaster risk reduction 2015-2030" (United Nations, 2015), whose vision aims at supporting the implementation of the 2030 Agenda for Sustainable Development, one of which objectives is to «strengthen efforts to protect and safeguard the world's cultural and natural heritage» (Goal n. 11, target 11.4). In this regard, the study proposed by Ravankhah *et al.* (2019) is worth mentioning, because it defines a «taxonomy of natural hazards in relation to cultural heritage based on a theoretical and conceptual framework» (p. 1). By taking historic center of Réthymno, in Crete, as a case study, the authors identify and analyze those hazards that are likely to generate damages to the historic elements of the towns in order to support decision-making processes in designing and implementing mitigation interventions.

As regards *Agrofor*, the findings suggest that agricultural and forestry land should be used only to face flooding (O'Connell *et al.*, 2007), while the productive use of agricultural and forestry areas should be implemented elsewhere. However, riparian areas are particularly productive and, therefore, profitable for farmers due to their proximity to water resources. The study by Fedele *et al.* (2018), by looking at the provinces of West Kalimantan and Central Java in Indonesia, suggests that natural hazards ought to orient adaptation strategies in local contexts so as to reduce risks to which affected people are exposed; among such strategies, the authors propose to implement land use changes that entail trade-offs in the provision of different types of ecosystem services. Such aspects have to be carefully analyzed when designing policies to enhance the quality of RGI.

In relation to *CO2Stor*, the chapter's outcomes are entirely consistent with the findings of several studies which put in evidence direct positive correlations between carbon capture and storage, and mitigation of the impacts of climate change through abatement of greenhouse gases (among many, Aminu *et al.*, 2017; Floris and Zoppi, 2020).

According to the European Environment Agency (2015), the role of RGI in mitigating the impacts of natural hazards is crucial (Salata *et al.*, 2016). Indeed, the role that RGI plays in mitigating flood hazard in relation to Natval is straightforward; however, in the case of floodplains flood hazard the RGI should encourage the negative sign of *Natval* puts in evidence that encouraging conservation of vegetated and rich-in-soil riparian areas may possibly be associated to a decrease in the potential capability of biodiversity to supply final ecosystem services.

Furthermore, the issue of the potential damage generated by the interaction of different types of hazard should be carefully taken into consideration (Yousefi *et al.*, 2020) when designing and implementing risk-reduction projects at the regional and local scales (Pourghasemi *et al.*, 2020).

A number of policy implications and recommendations can be derived from the outcomes of the previous chapter.

The results concerning the influence of *Natval* and *Consval* on the probability of comparatively higher flood and landslide hazards imply that, in case of landslide hazard, prevention and control should target areas with a relevant natural value, that is, areas endowed with a significant potential supply of ecosystem services, while, in case of flood hazard, they should focus on areas featured by the presence of natural habitats types of Community interest, as identified under the Habitats Directive. Since areas showing high values of *FH* are mostly concentrated in the floodplains and their surroundings, while areas having high values of *LH* are widespread over the study area, and, in more general terms, over the whole Sardinian island, these findings entail different implications concerning prevention and control hazards when defining spatial planning policies to implement the RGI. That being so, the definition and implementation of the RGI should carefully study and develop spatial policies related to waterways and their surroundings, which should entail strict regulations related to anthropic access and visits in floodplains areas characterized by significant values of *Consval*, i.e., by a relevant concentration of habitats of Community interest. Moreover, the RGI-related spatial policies should carefully balance the relationship between *Natval* and landslide hazard, that is, they should address the issue of the exploitation of natural ecosystem services located in areas endowed with high supply potentials, and likewise characterized by a relevant landslide hazard. This is entirely consistent with the position of the Commission of the European Communities, which recommends that «working with nature's capacity to absorb or control impacts in urban and rural areas can be a more efficient way of adapting than simply focusing on physical infrastructure» (Commission of the European Communities, 2009, p. 5). Since Natura 2000 sites within Sardinia include most coastal wetlands, estuaries, waterways, and large stretches of coastal areas, it is pretty straightforward that parcels located in these areas should show a relevant impact on flood hazard. Spatial planning policies should therefore include strict regulations related to new settlement development in floodplains, oriented to protect nature and natural resources belonging to riparian areas and their surroundings, which are characterized by high figures of Consval. Consistently with these observations, the Lower Danube Green Corridor Agreement focuses on the restoration of around 2,000 square kilometers of floodplains, side channels and associated habitats along the Danube as a control measure to mitigate the destructive impacts of floods in the region. The estimated cost (about 50 million euros) is lower than the cost related to the environmental damages caused by floods in 2010 (European Commission, 2010).

The impact of *Natval* on the probability of high landslide hazard entails that spatial policies should protect forests, which exert a relevant action to mitigate soil erosion, surface water runoff and slope instability, and, in so doing, to reduce landslide hazard (Trigila *et al.*, 2018). Moreover, silvicultural activities generate outstanding negative impacts on forests if they neglect best available practices related to forest management (Siry *et al.*, 2005). In terms of ecological stability, high forests should be preferred, with the exception of areas characterized by high values of *LH*, high slopes and low soil power, where shrub species are expected to be more suitable. Furthermore, forest road systems require appropriate planning, implementation, and maintenance in order to avoid concentration of surface water runoff and erosion, and triggering of landslides along the slopes (Sapač *et al.*, 2017).

The outcomes of the regression model imply that forestry activities should be favored in riparian areas and their surroundings to mitigate flood hazard, while agricultural uses should be moved to more distant locations. Agriculture displacement may possibly be implemented by means of incentives, assigned to low rent farmers in order to become forest farmers (Lai *et al.*, 2020). Moreover, maintenance interventions in agriculture and forestry contribute to mitigating flood hazard. In areas characterized by arable land-pasture, terraces or permanent non-terraced crops, agro-forestry-pastoral interventions may entail benefits in terms of soil conservation, such as applications of specific innovative agricultural practices, crop diversification or buffer strip systems between agricultural areas and waterways (Regione Piemonte, 2018).

Spatial planning policies are potentially powerful in terms of mitigation of flood and landslide hazards (Hartmann and Spit, 2015); however, the normative frameworks of water resource management and soil protection are quite inconsistent with each other. At the European level, the EU Water Framework Directive (Directive 2000/60/EC) and the European Directive on the Assessment and Management of Flood Risk (Directive 2007/60/EC) represent the statutory policies concerning water resource planning and management at the European level. As for landslide hazard, a European normative framework is still missing. At the Italian national level, notwithstanding the approval of some specific laws, such as the already mentioned no. 183/1989 and no. 267/1998, a comprehensive and integrated normative system related to protection from landslide and flood hazards is missing as well, and the Italian legislation mainly focuses on water catchment management. Sardinia is characterized by high landslide and flood hazards (Trigila *et al.*, 2018), and its hydrogeological structure is quite unstable due to natural phenomena and anthropic actions. The Sardinian government has designed three regional plans concerning landslide and flood hazards: the already mentioned PAI in 2006, focusing on protection and conservation of soils and on prevention and management of landslide and flood hazards; a management plan for riversides and their surrounding areas in 2015; and finally a flood risk management plan consistent with the Directive 2007/60/EC in 2016, aimed at mitigating negative consequences of floods on life quality, environment, cultural heritage, and social and economic activities.

Moreover, the methodological approach implemented in this volume shows two innovative aspects. Firstly, the relationship between flood hazard and the implementation of GI is assessed at the regional level, whereas the current literature mainly uses municipal and sub-municipal frameworks to analyze their interdependence, for instance, by making reference to green roofs and permeable pavements. The regional scale is much more suitable to deal with the integration of environmental hazards management and GI implementation, in terms of planning policy, awareness-building and decision-making processes. Secondly, the methodological approach uses data that are easily accessible to researchers, policy makers, and practitioners, and comparatively cheaper than complicated microeconomic estimates, in terms of both costs and time.

In conclusion, the methodological approach proposed in this volume may represent a tool in support of spatial decision-making processes that can be exported to other European contexts, due to its adaptability to the national planning and normative framework, on the basis of the European legislation concerning protection and improvement of nature and natural resources. The implemented methodology is effective in supporting civil officers, practitioners, and local public authorities to deal with the impacts of land cover and land use changes. From this perspective, the integration of GI-related and environmental planning policies may represent a basis to drive local decision-making processes towards prevention or, at least, mitigation of damages generated by landslides and floods, and towards the establishment of appropriate regulations.

Promising directions for future research can be identified as follows. A particular focus should be given to building a new normative framework to implement the RGI conceptual and technical category, conceived as a provider of ecosystem services, into the theoretical and technical approaches of the European and national spatial planning practices. Moreover, a relevant profile to be explored is represented by the role of local communities as regards the definition and implementation of planning processes aimed at managing environmental hazard through policies related to ecosystem service protection and enhancement. These processes should be based on the progressive improvement of the scientific, technical, and cultural expertise of the local societies concerning the provision of goods and services generated by the ecosystems, and are identified by the category of urban bioregion (Magnaghi, 2019). In this conceptual framework, the communities' incremental awareness can be identified as a main driver of the qualitative improvement of the spatial, environmental and landscape heritage at the local level. Under this perspective, mitigation and control of landslide and flooding hazards can be included in the planning practices implemented by the local governments representing societies fully aware of the importance of nature and natural resources as regards their potential in terms of life quality improvement (Magnaghi, 2020).

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6. Figures

6.1. Figures Chapter 2

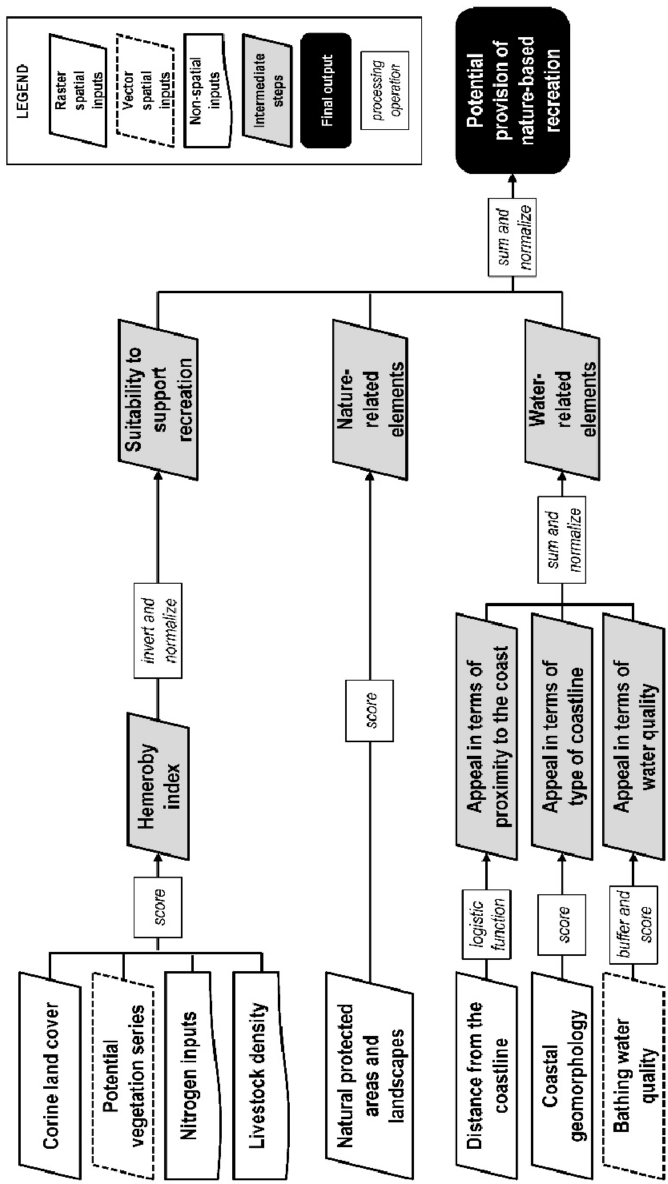


Fig. 1 - Flow chart of the process whereby the potential provision of nature-based recreation is mapped (adapted from Vallecillo et al., 2019a; Barton et al., 2019)

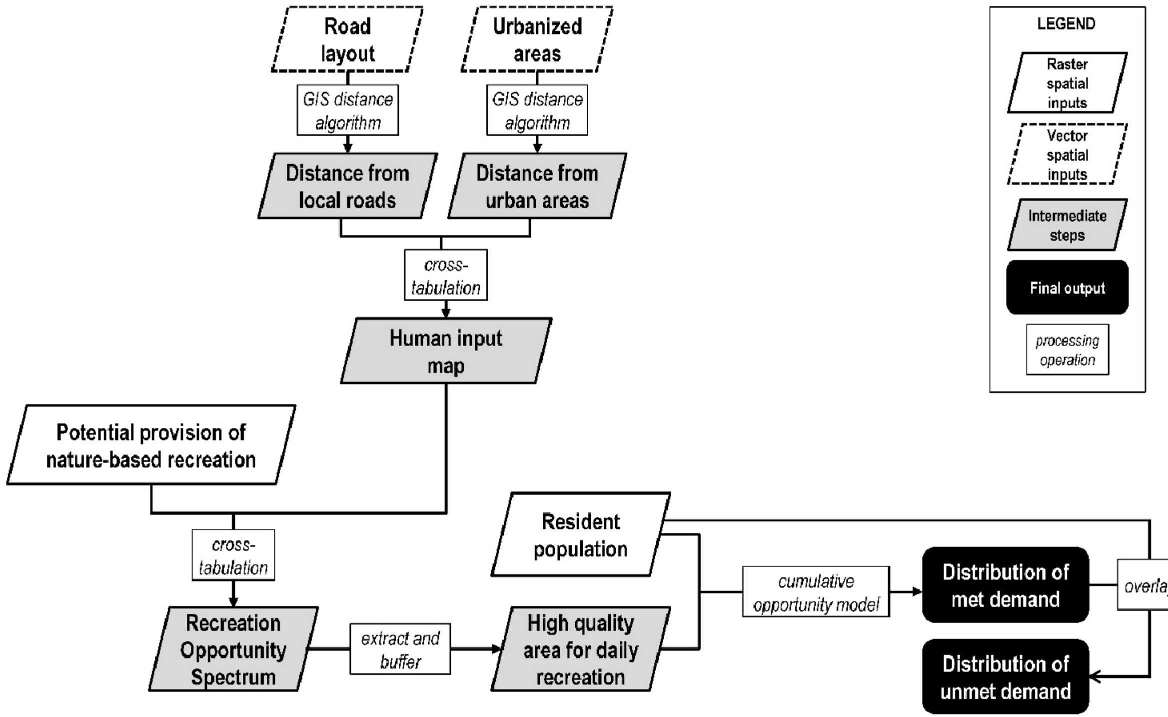


Fig. 2 - Global flow chart of the ESTIMAP model (after Vallecillo et al., 2019a; Barton et al., 2019)

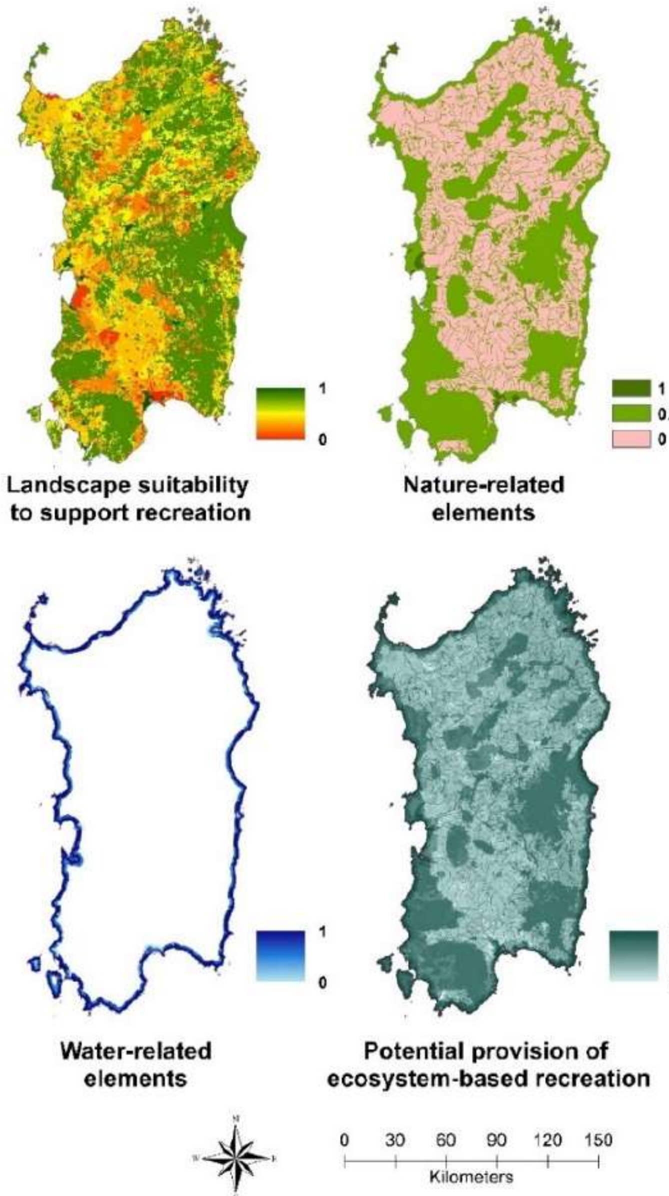


Fig. 3 - Spatial layout of the total potential provision of nature-based recreation (bottom right) and of its three components

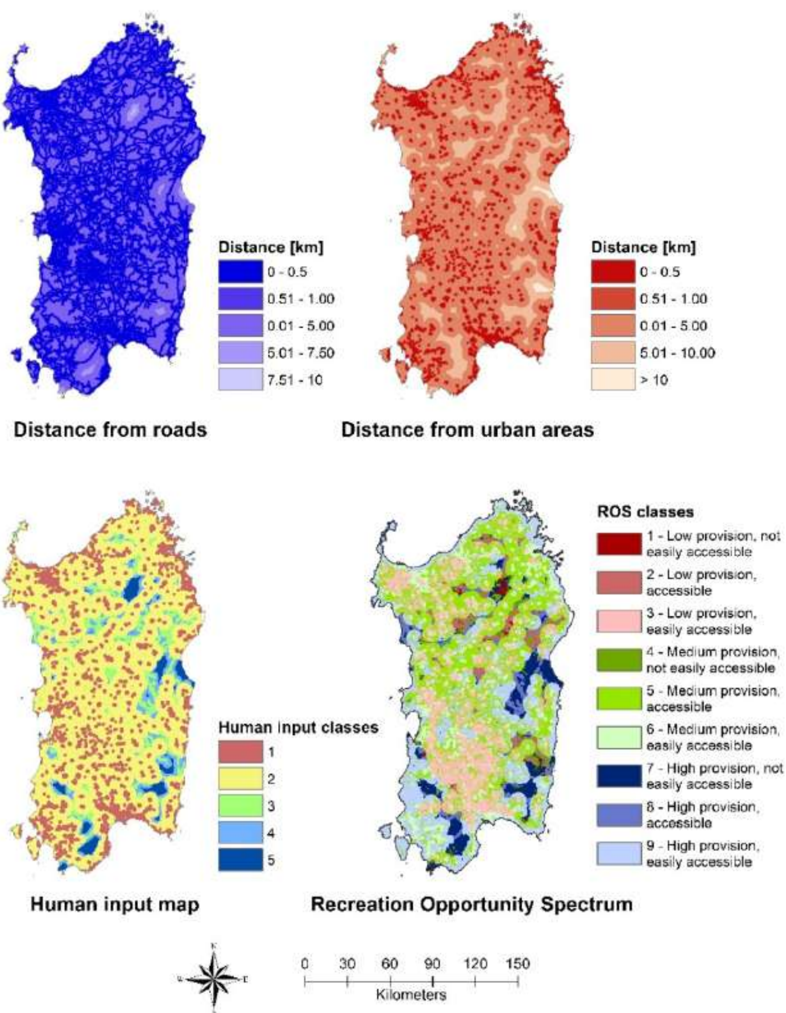


Fig. 4 - Spatial layout of the distance from roads and urban areas; Human input map, retrieved by cross-tabulating the two; Recreation Opportunity Spectrum (ROS), retrieved by cross-tabulating the Human input map and the Potential provision of nature-based recreation map

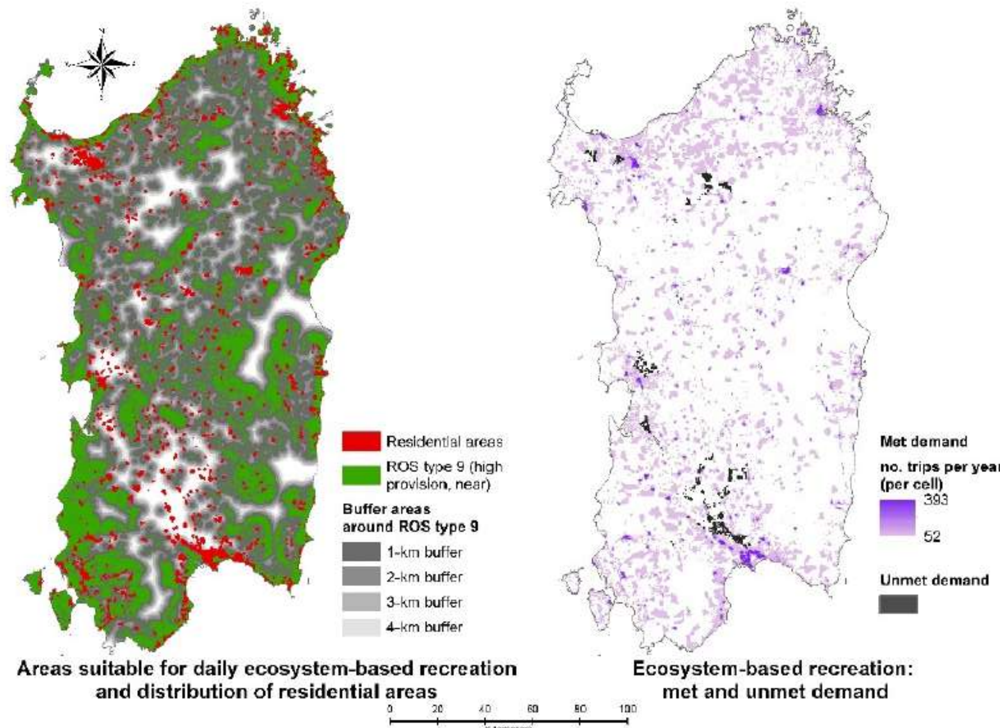


Fig. 5 - Spatial layout of the met and unmet demand for ecosystem-based recreation (right- hand side), mapped by considering only round trips shorter than eight kilometers from the nearest high-providing area (left-hand side)

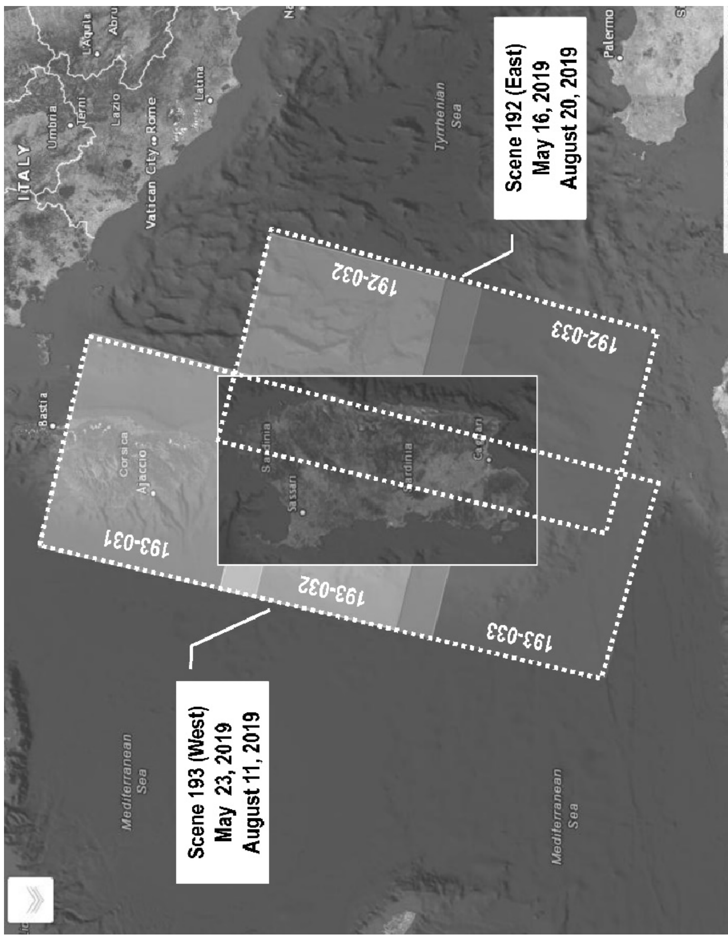


Fig. 6 – Spatial layout of the ten Landsat 8 OLI-TIRS images selected for this study (https://earthexplorer.usgs.gov/)

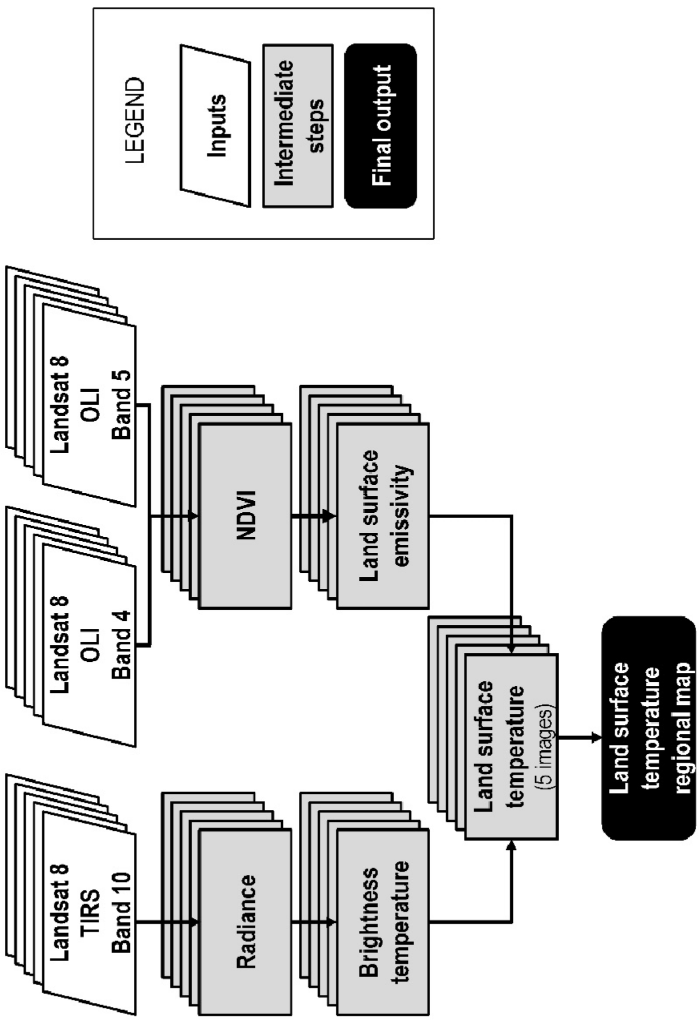


Fig. 7 - LST retrieval from Landsat images: an overview of the process

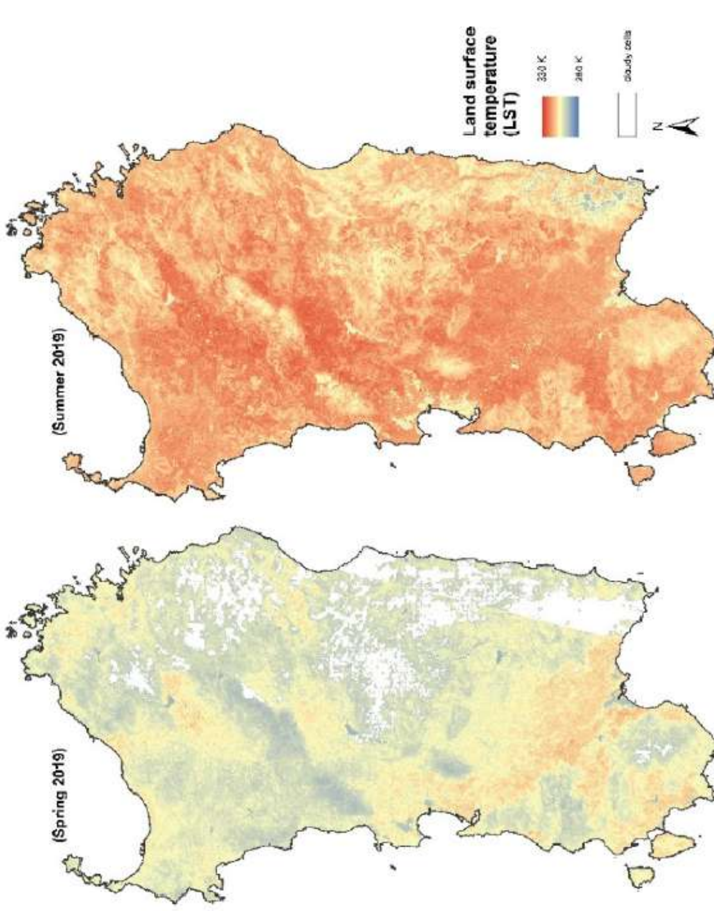


Fig. 8 - LST spring and summer maps

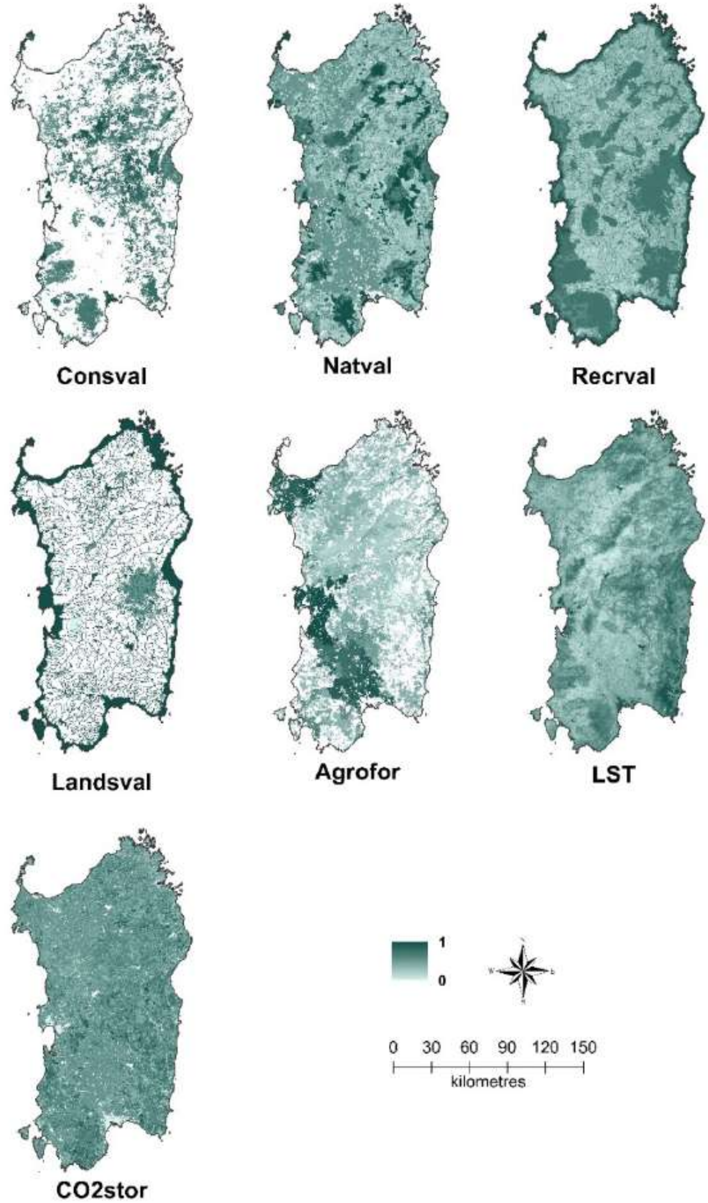


Fig. 9 - Spatial distribution of the seven ES. Values are normalized in the 0-1 range.

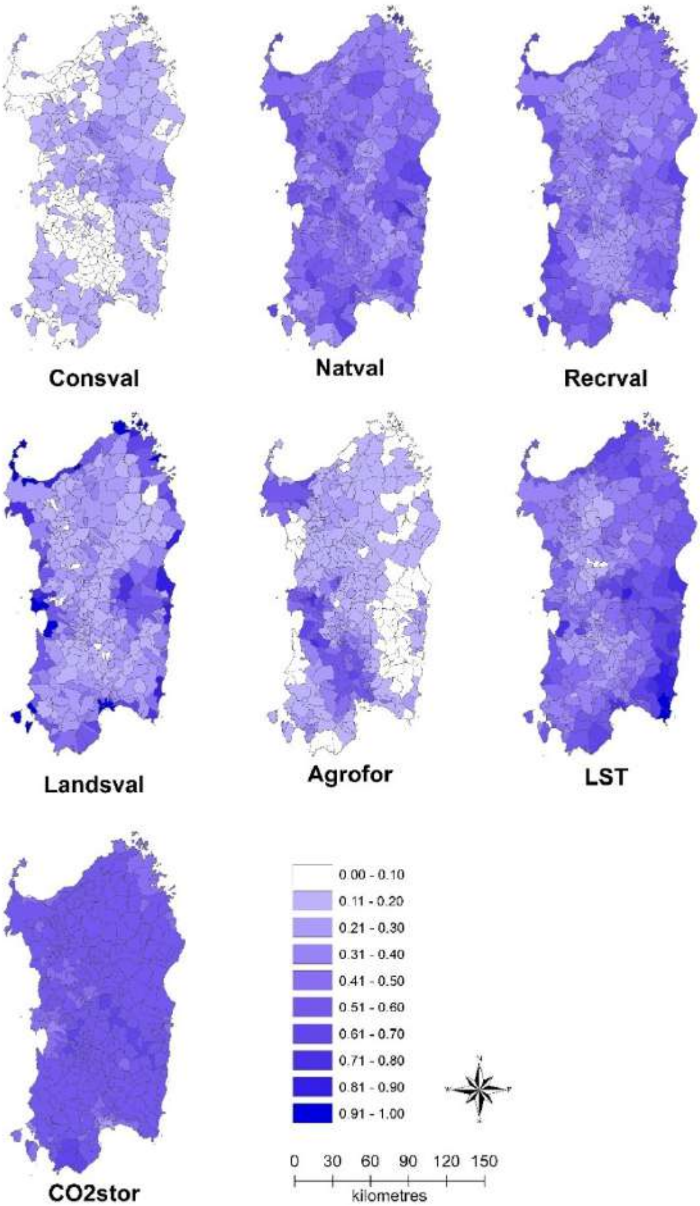


Fig. 10 - Spatial layout of the mean average values of the seven ES at the municipal level.

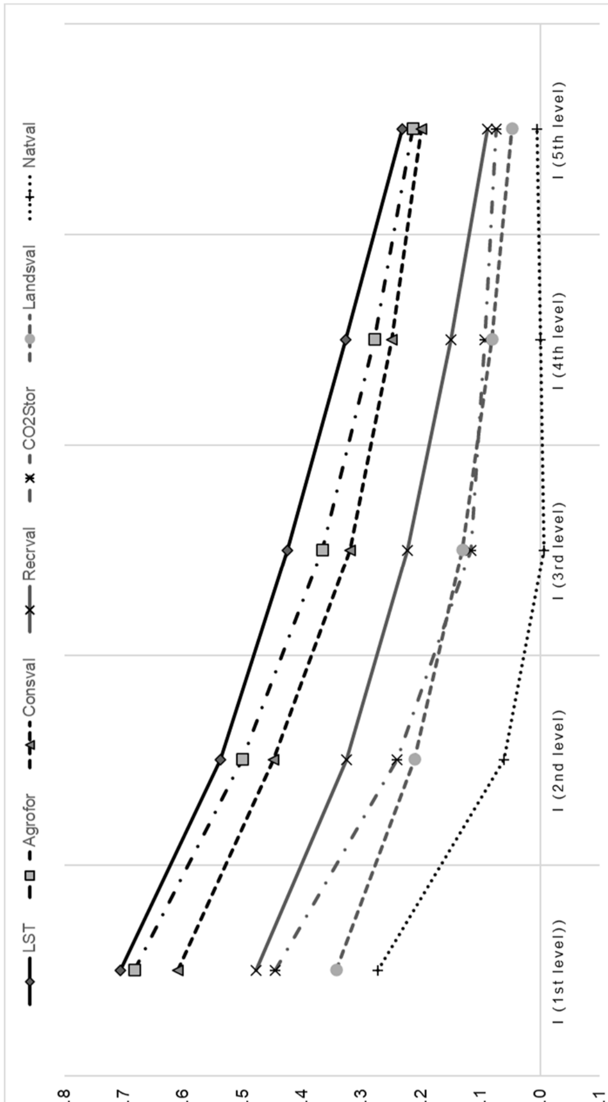


Fig. 11 - Results of the spatial autocorrelation analysis: Moran's I index

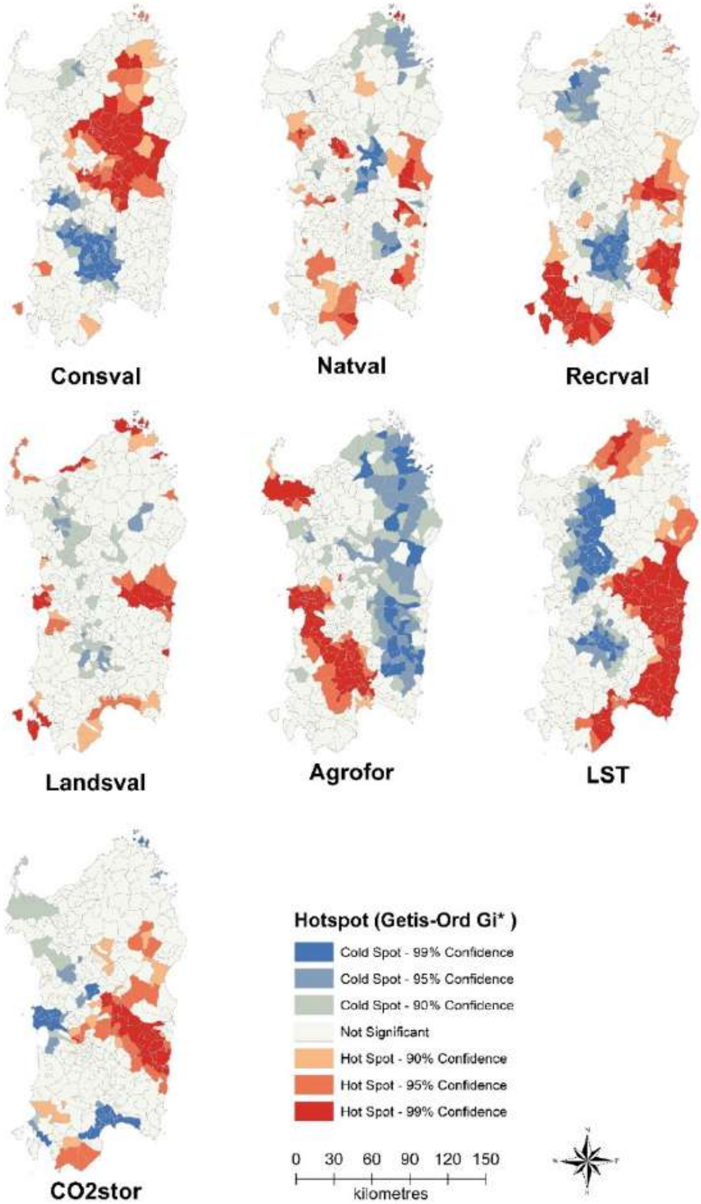


Fig. 12 - Hot spots and cold spots of ES provision (average values at the municipal level)

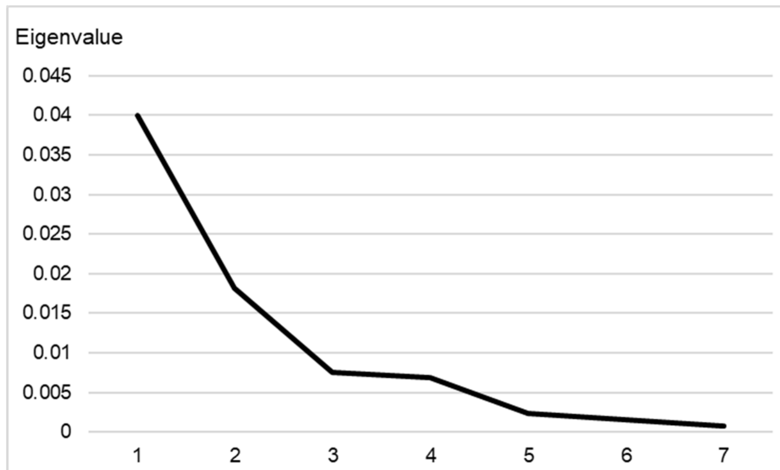


Fig. 13 - Scree plot representing the eigenvalues on the vertical axis and the components in the horizontal axis

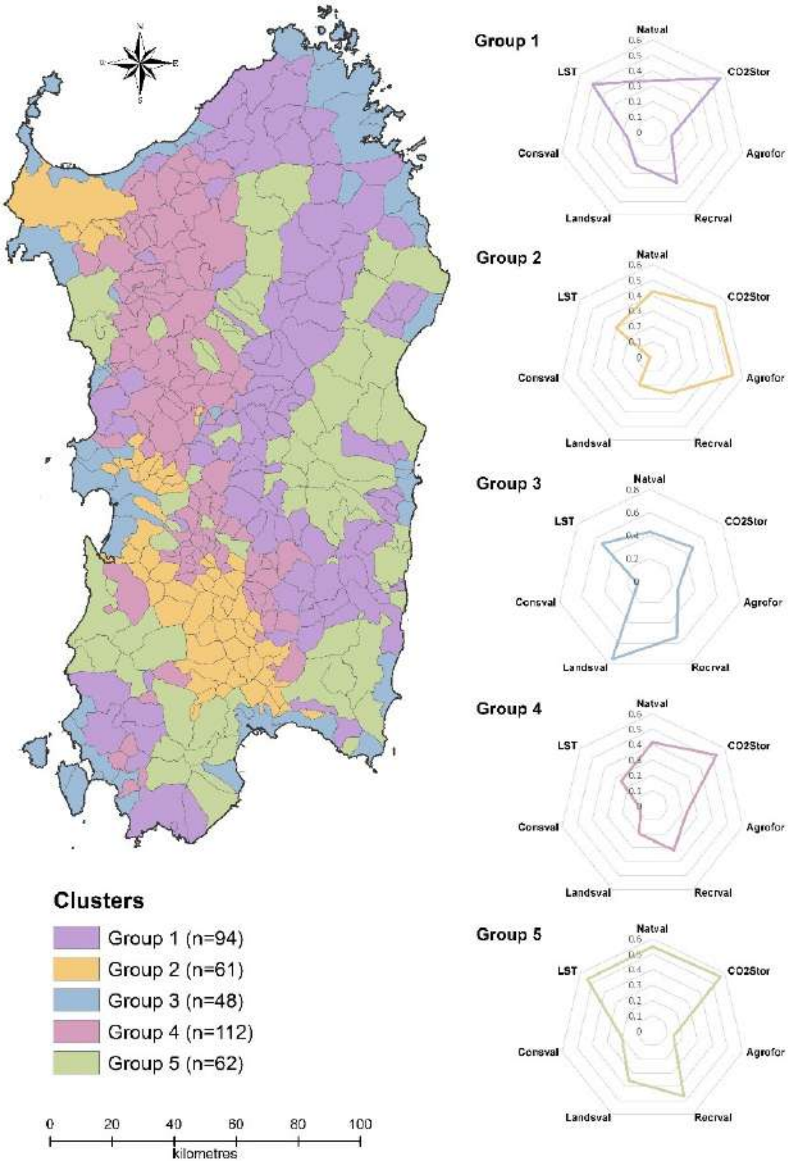


Fig. 14 - Cluster analysis: five groups of municipalities providing similar bundles of ES

6.2. Figures Chapter 3

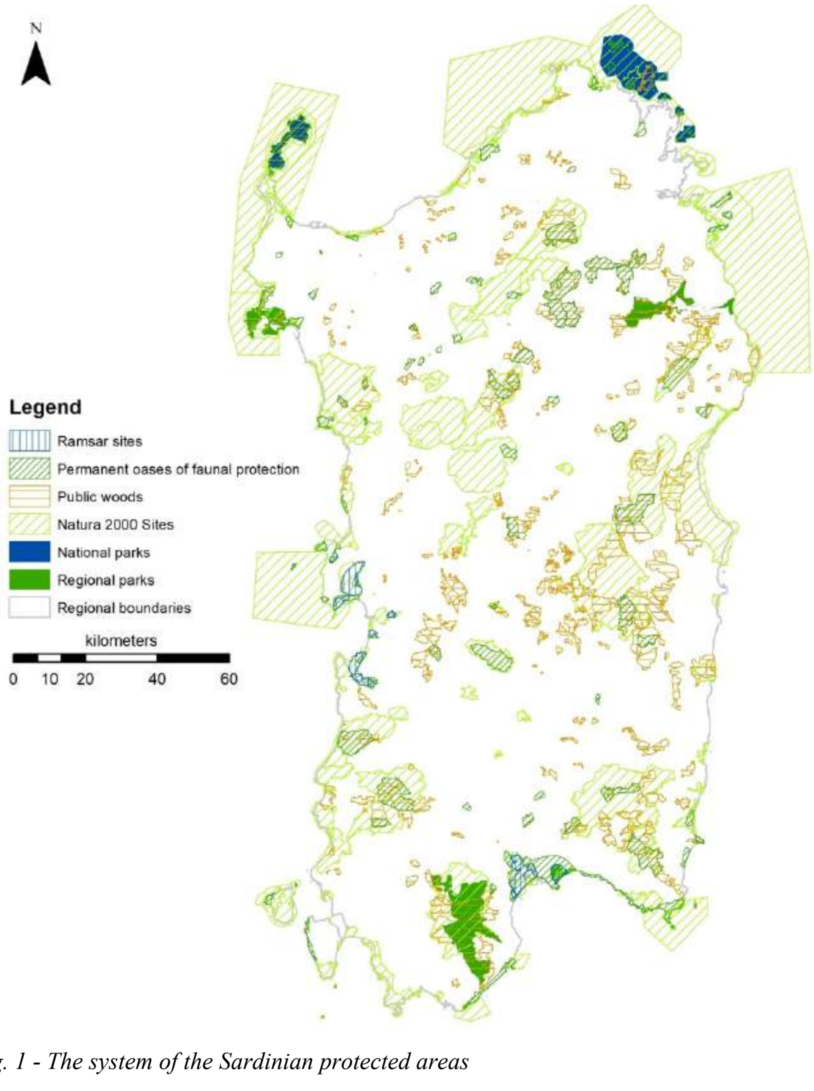


Fig. 1 - The system of the Sardinian protected areas

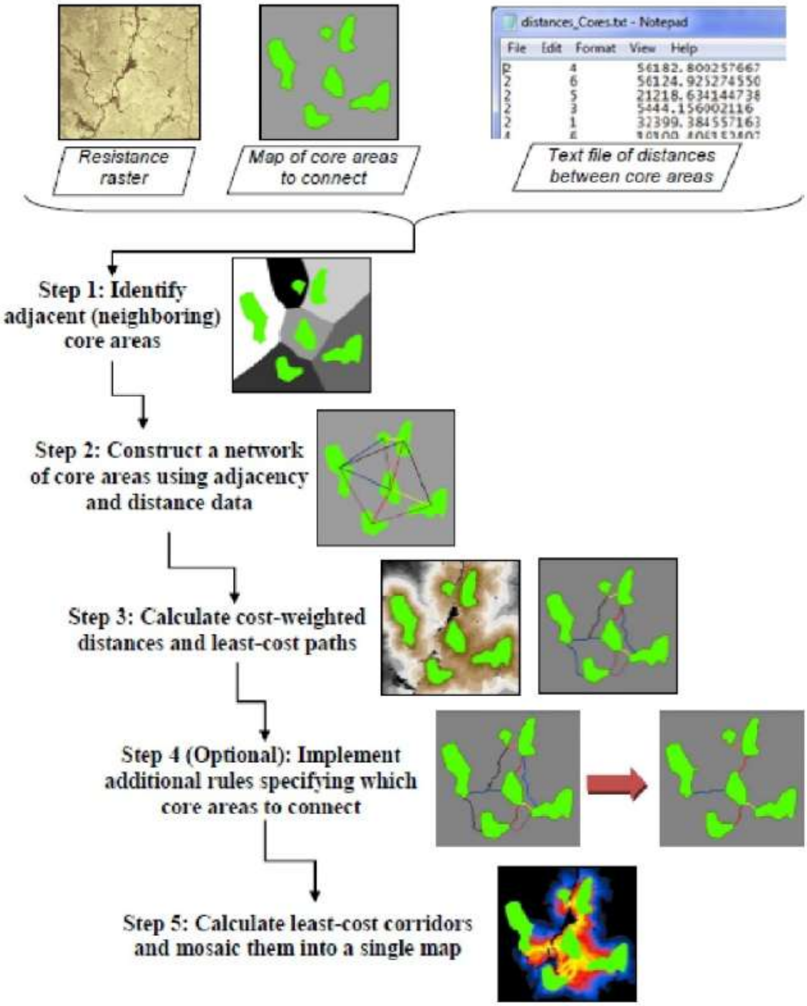


Fig. 2 - Processing process of LPT. Source: McRae and Kavanagh, 2017, p.11

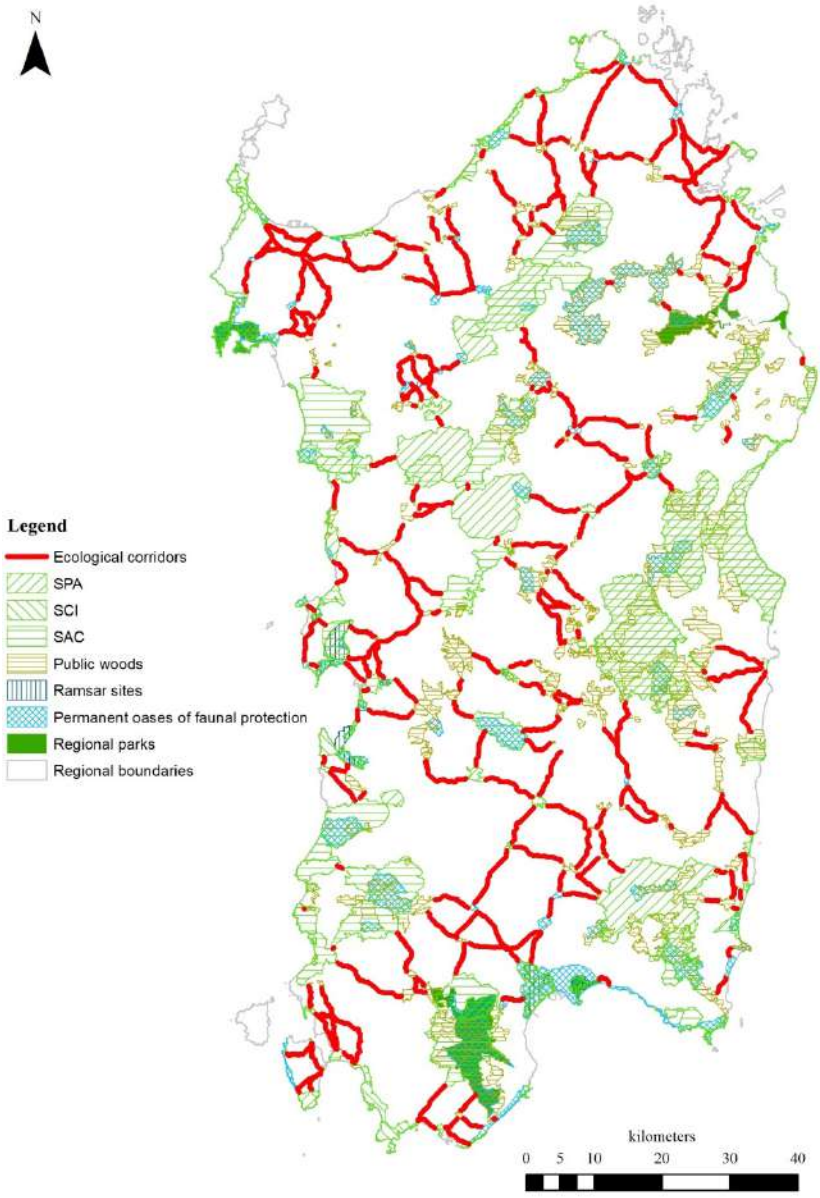


Fig. 3 - Ecological corridors connecting the NPA

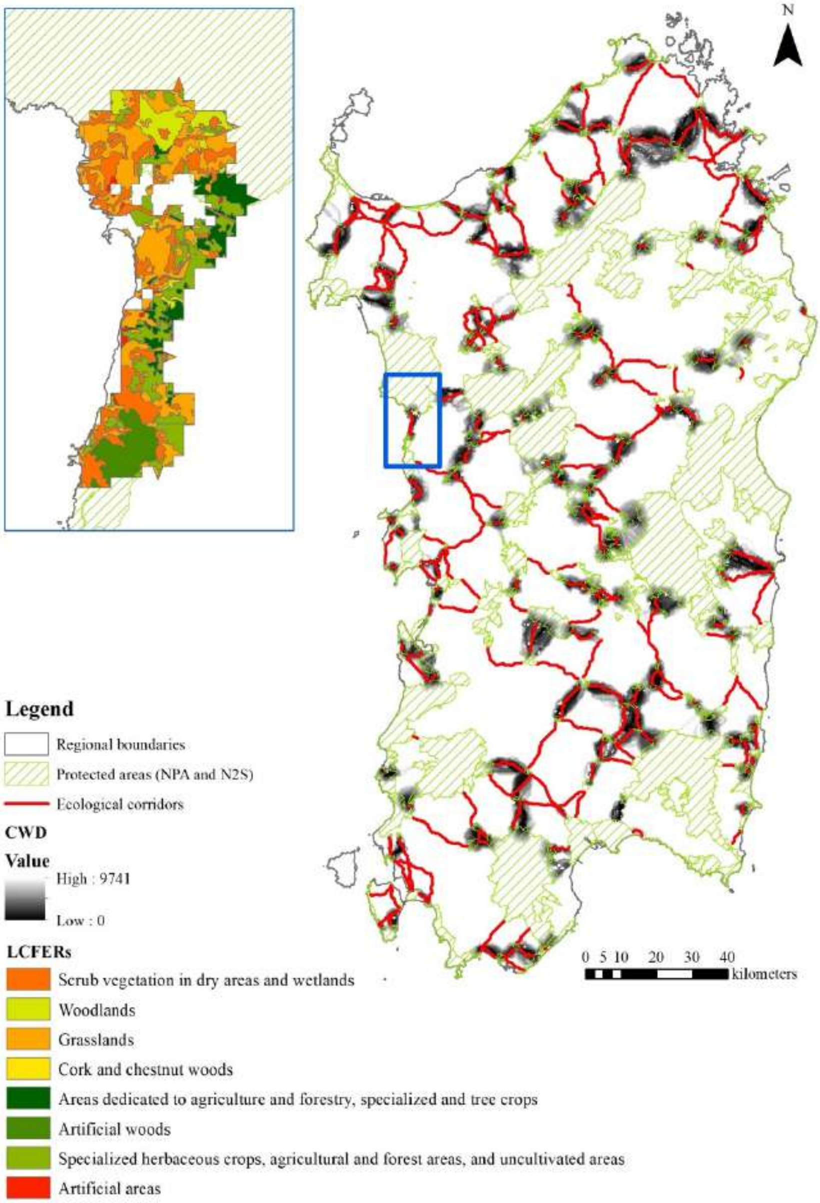


Fig. 4 - Identification of ecological corridors and of CWD values included in the second's upper limit decile (map on the right), and the overlapping map of CWD values and the LCFER (upper-left map)

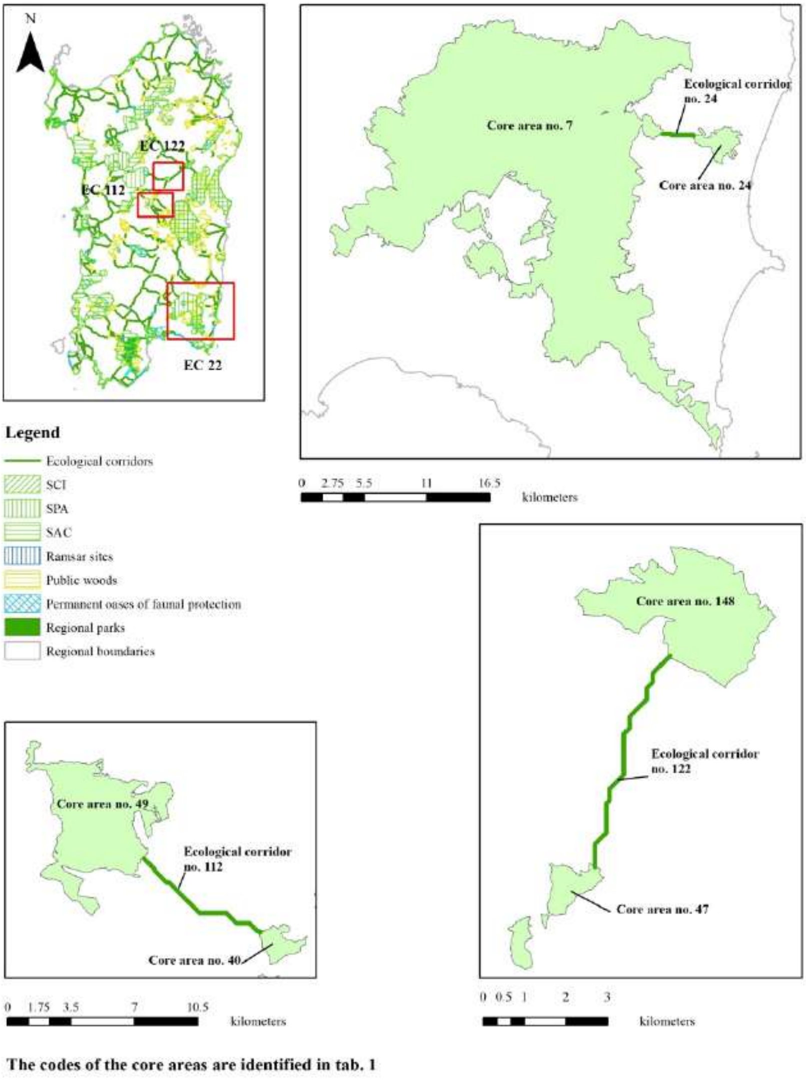
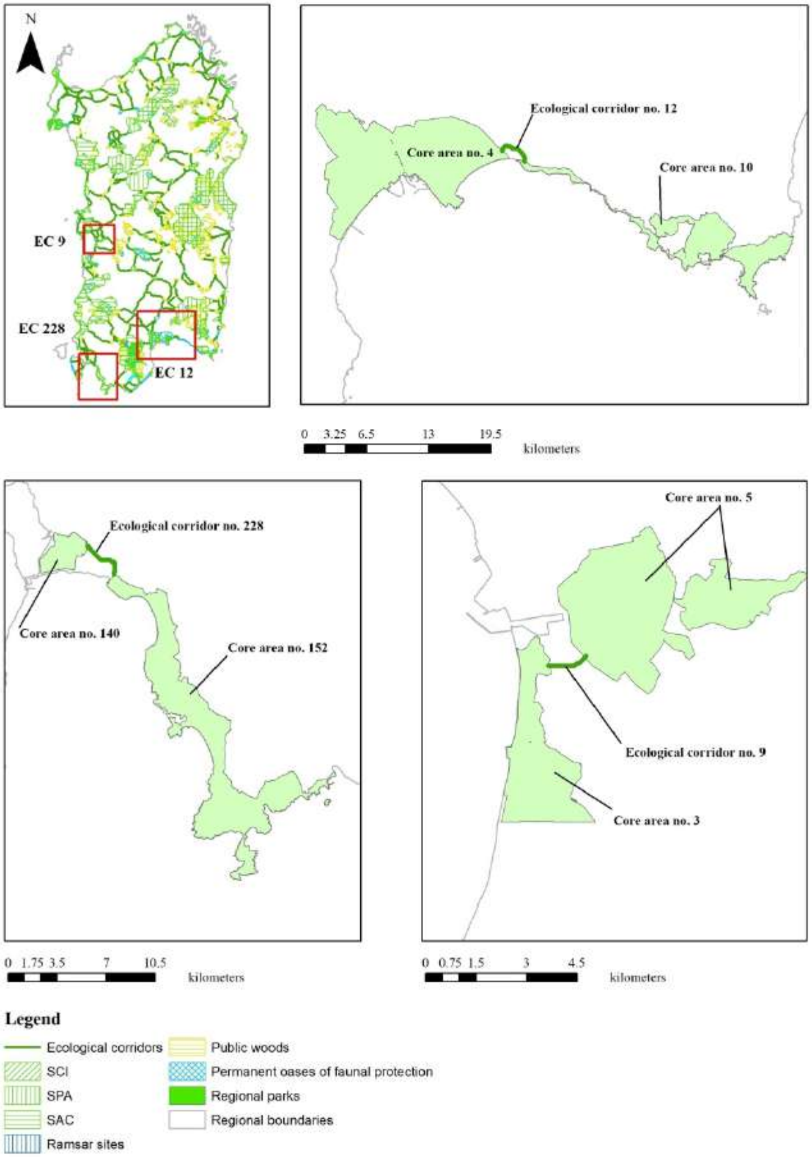


Fig. 5 - Spatial identification of the EC which show the lowest values of the CWD/ED index



The codes of the core areas are identified in tab. 1

Fig. 6 - Spatial identification of the EC which show the highest values of the CWD/ED index

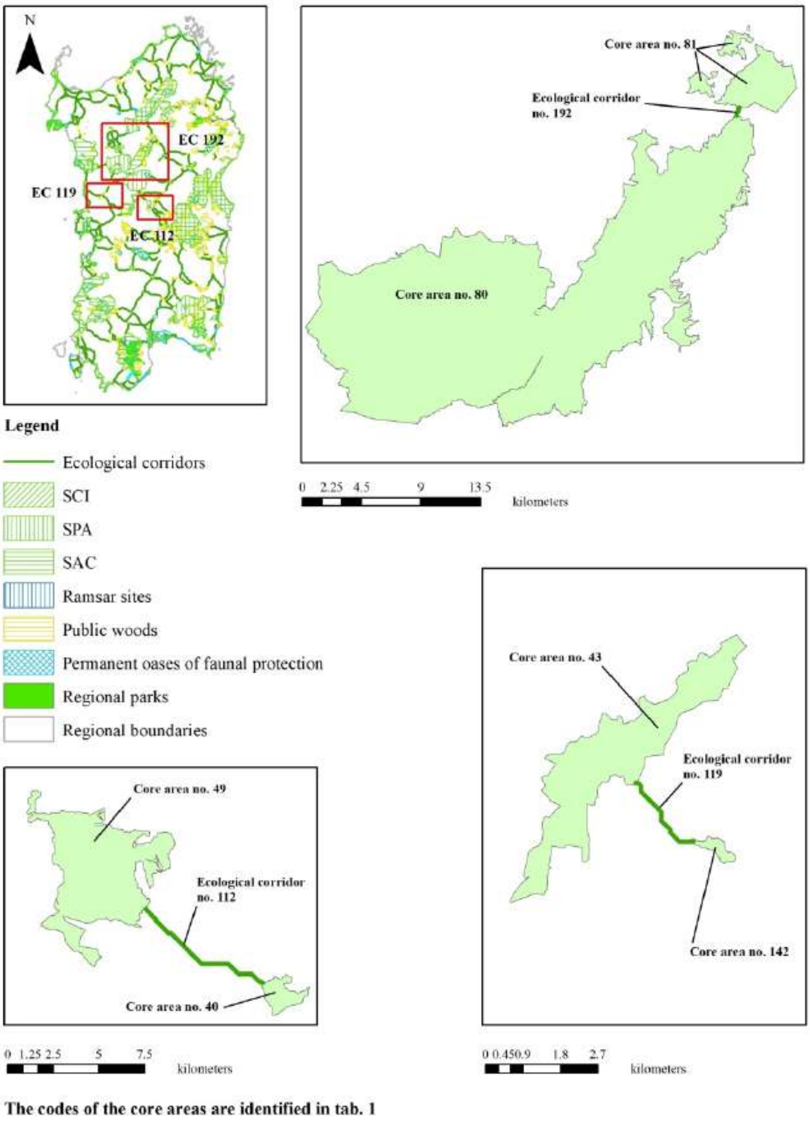


Fig. 7 - Spatial identification of the EC which show the lowest values of the CWD/LCP index

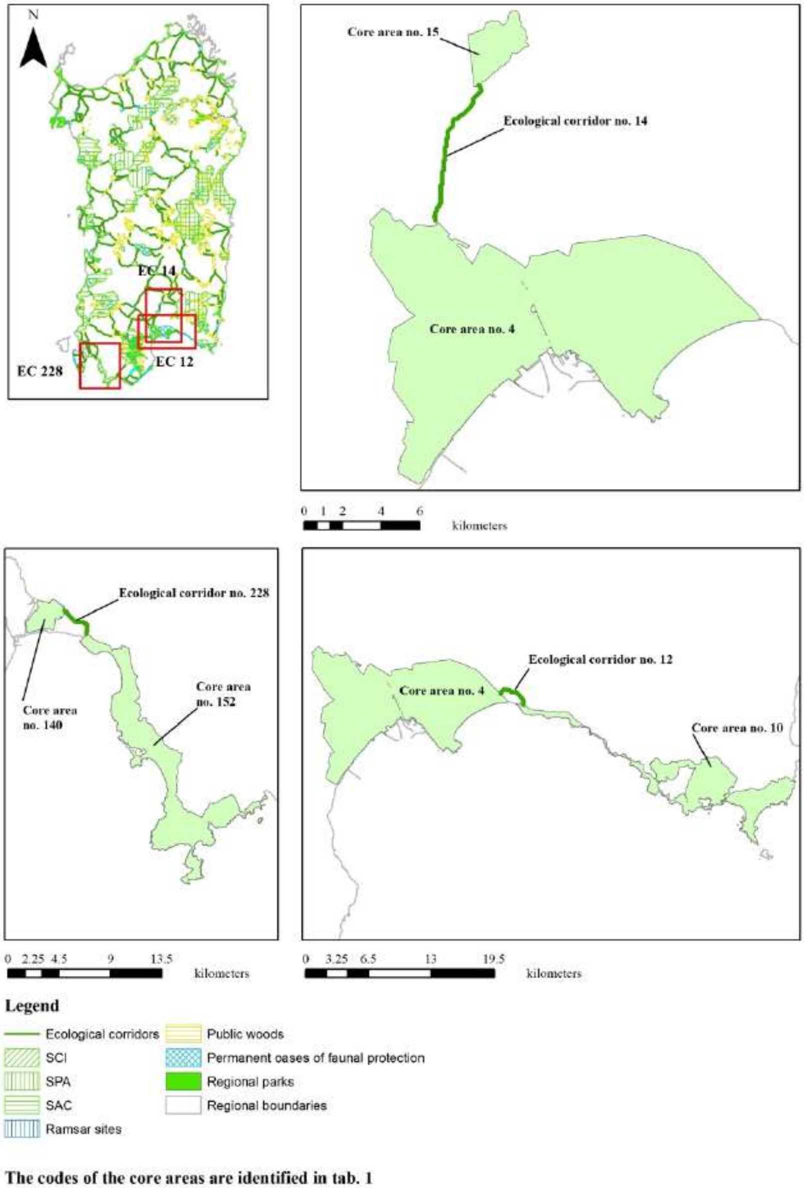


Fig. 8 - Spatial identification of the EC which show the highest values of the CWD/LCP index

6.3. Figures Chapter 4

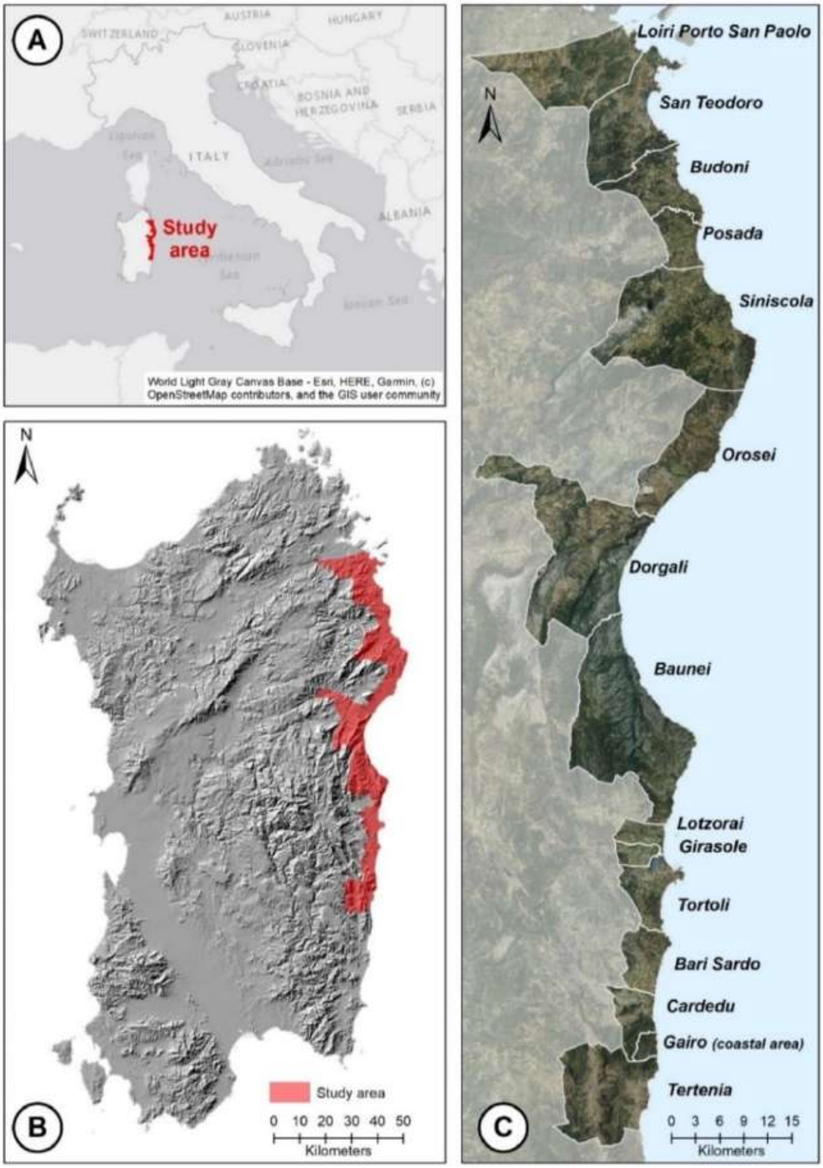


Fig. 1 − Location of the study area within Italy (A) and Sardinia (B), and municipalities included therein (C)

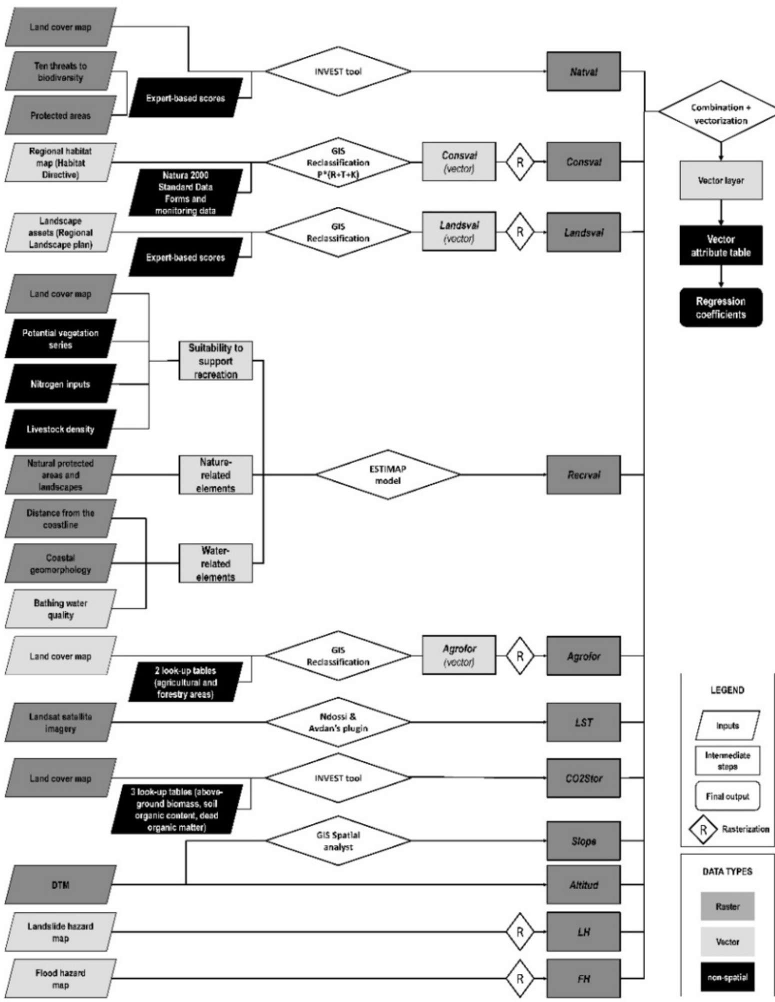


Fig. 2 − Full overview of the methodology

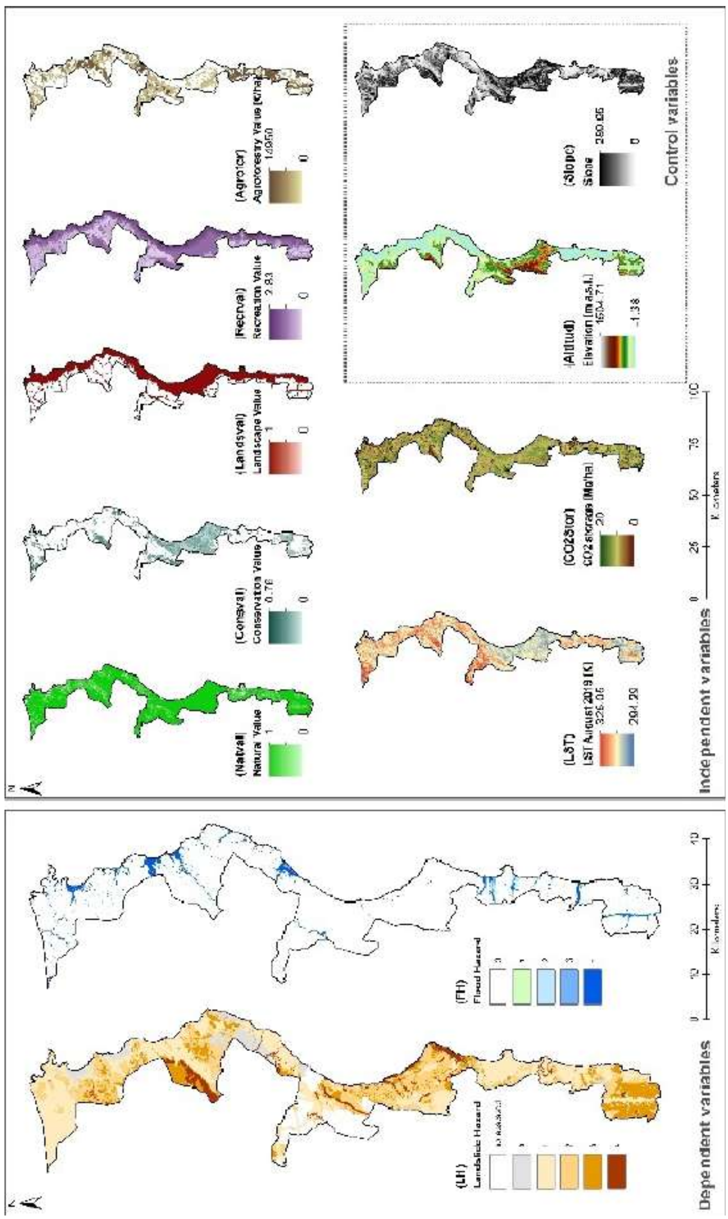


Fig. 3 – Spatial distribution of dependent and independent variables in the study area

Identifying and planning green infrastructures at the regional scale can be considered an intentional way of spreading the positive impacts of environmental conservation policies across spatial contexts much more complex and larger than protected areas.

In this volume, a methodological approach is defined and experimentally implemented into the Sardinian region (Italy), in order to identify both a regional green infrastructure, and a network of ecological corridors, conceived as edges connecting the regional protected areas. This approach supports spatial decision-making processes aimed at addressing environmental hazards connected to landslides and floods, as well as at establishing effective spatial planning rules.

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FrancoAngeli
La passione per le conoscenze