Can Planning Policies to Counter Hydro-Geological Hazard be Grounded on Ecosystem Service Assessment? Suggestions from a Sardinian Case Study

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Abstract. This study focuses on the relations between the definition and implementation of regional green infrastructure (RGI or GI, in the general case) and environmental hazard, identified by flooding and landslide phenomena. The implementation of GI within planning policies could improve the effectiveness of policies aimed at promoting landscape and environmental protection. GIs are spatial structures supplying a wide range of ecosystem services, which entail interactions with areas characterized by different levels of environmental hazard. GI is considered in this study as a provider of ecosystem services related to the following aspects: nature, natural resources and conservation and enhancement of biodiversity; landscape, culture and recreation; agricultural and forestry production; local climate regulation; and, climate change impact mitigation through capture and storage of carbon dioxide. A methodological framework is defined and implemented into a subregional spatial context located in the coastal zone of Eastern Sardinia. The methodology is aimed at assessing the relations between GI and environmental hazard through inferential analysis based on dichotomous-choice Logit models in order to increase the understanding and interpretation of the role that could be played by GI as regards control of environmental risk, and to identify policy recommendations thereof.

Keywords: Environmental hazard · Green infrastructure · Ecosystem services

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 [1]. Therefore, hydrogeological instability represents a hazard to local population, infrastructures, and the economic and productive system [2]. For instance, in 2018 in Italy 7,275 municipalities (91% of the Italian ones) were found to be exposed to landslide and/or flooding hazards. Moreover,

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16% of the national territory is classified as high-hazard area, and 1.28 million of residents live in areas featured by landslide hazard and more than 6 million in flooding hazard areas [2].

Typical consequences of hydrological phenomena are landslides, flooding, coastal erosion, subsidence, and avalanche. Although for a long time gray infrastructure has represented the only operational tool to address landslide and flooding hazard and related environmental damages [3], the implementation of nature-based solutions has more recently advocated to be very effective in mitigating the impacts of such disasters [4]. Therefore, the use of green infrastructure (GI) has gained increasing importance within the international debate. Although 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 [4]: smart growth, climate change adaptation, and social health and wellbeing [5]. The relation between GI and hydrological instability is a matter of study in the current literature. Chen et al. [6] assess the effectiveness of the implementation of practices based on GI on water supply and quality. Papathoma-Koehle and Glade [7] analyze how changes in vegetation land cover influence landslide events in terms of occurrences, consequences, and implications. However, 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 [4, 8]. Indeed, the assessment of GI-related planning policies is often based on counterfactual methodologies which imply the availability of huge databases and complex economic approaches, often too costly in terms of financial resources and time needed to obtain reliable outcomes [9].

The article is structured into four sections as follows. The second section 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 which also identifies some implications of the study in terms of planning policy recommendations.

2 Materials and Methods

This section is organized as follows. In the first subsection the study area is described. In the second, 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.

2.1 Study Area

The area chosen for this study lies on the eastern side of Sardinia, one of the main islands in the Mediterranean Sea (Fig. 1). Bordering the Tyrrhenian Sea to the East, the study area 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.

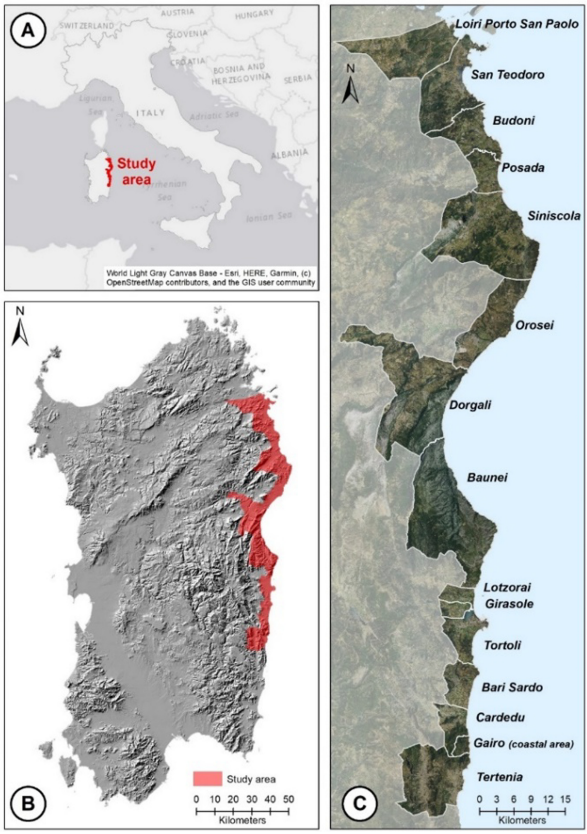


Fig. 1. Location of the study area within Italy (A) and Sardinia (B), and municipalities included therein (C).

2.2 Methodological Framework

Building on Nerlove and Press' [10], Greene's [11], and Zoppi and Lai's [12] research, this study implements a Logit dichotomous choice model. 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:

$$\text{Prob}\,(1) = \frac{e^{\beta_1' x_1}}{1 + \sum_{k=0}^{1} e^{\beta_k' x_k}} \tag{1}$$

$$\text{Prob}\,(0) = \frac{1}{1 + \sum_{k=0}^{1} e^{\beta_k' x_k}} \tag{2}$$

where β is a vector of coefficients and x is a vector of characteristics related to the event k, k ∈{0,1}. As per Greene ([11], p. 666, 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 in Eq. (1), is estimated by solving the maximization problem of the following log-likelihood function, ln L, in the vector of coefficients β[1]:

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

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 Eqs. (1) and (2), where the Prob(k)'s are expressed as functions of vector β through Eqs. (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:

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

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{0,1}, and j ∈{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:

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

The model's estimates make it possible to derive the marginal effects of Eq. (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 Eq. (5).

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 ∈ { 0,1 }.

The characteristics which are the components of vector x = (1, x_1, …, x_N) and their descriptive statistics are reported in Table 1. The occurrences of the k's events are conditional upon the X_i's characteristics, according to a logistic distribution estimated

[1] 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 Eq. (2) ([11], p. 666).

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, recreational 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.

2.3 Data

Because the island of Sardinia is identified as a single macro-basin, a single watershed management plan and its PAI (an acronym for "Piano di Assetto Idrogeologico", verbatim

Table 1. 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 either the 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"[a], tool "Habitat quality". 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 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	0.844	0.269

(*continued*)

Table 1. (*continued*)

Variable	Definition	Mean	St.dev.
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 *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, else P = 1; - 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 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. 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] interval depending on the level of restriction. In case of overlapping protection levels, the maximum score was assigned to the parcel	0.521	0.497
Recrval	Recreation value. Continuous variable in the interval [0,1]. Recreational attractiveness of landscapes and natural habitats. The average photo-user-days per year between 2010 and 2014 was calculated using the software "InVEST" (tool "Recreation") and a 3-km grid, and subsequently normalized in the interval [0,1]	0.006	0.027
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	3.601	4.029
LST	Land surface temperature detected in August 2019 (K)	311.174	3.554
CO2Stor	Carbon dioxide storage per unit of area (Mg/(100 m^2))	1.098	0.350
Altitud	Elevation (m)	234.084	226.531

(*continued*)

Table 1. (*continued*)

Variable	Definition	Mean	St.dev.
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[b]	23.009	21.501

[a]InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) is a free software program developed by the Natural Capital Project and available from http://data.naturalcapitalproject.org/nightly-build/invest-users-guide/html/index.html.
[b]https://desktop.arcgis.com/en/arcmap/10.7/tools/spatial-analyst-toolbox/slope.htm.

"Hydrogeological Setting Plan") 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 [13].

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 making processes, because updated flood and landslide assessments concerning the whole municipal territory are prerequisite for the approval of land-use plans. Municipal assessments make use of the same hazard levels as the PAI, i.e. those listed in Table 2, and of the same methodologies as the River Basin Authority, which means that the outcomes of the regional and municipal assessments are comparable.

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[2]: 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[3] that led to an early revision of the Sardinian PAI, which means that both landslide and flood hazard data for the three

[2] http://www.sardegnageoportale.it/webgis2/sardegnamappe/?map=pai.
[3] http://www.regione.sardegna.it/index.php?xsl=509&s=1&v=9&c=9305&tb=8374&st=13.

Table 2. Flood and landslide hazard classes as per the Sardinian PAI ([14], 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

aforementioned municipalities can be retrieved from the regional PAI, although in some parts of Dorgali's territory the landslide hazard map is void. For each municipality in the study area, Table 3 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 rest of this section looks briefly at the nine independent variables (defined in Table 1) and data used to map them).

For a full methodological account about the production of *Natval*, *Consval*, *Landsval*, and *Recrval* maps, the reader can refer to [15] and [16].

With regards to *Agrofor*, the value of rural plots in 2017 was estimated using the 2018 CORINE land cover map[4] as spatial reference and two main datasets for agriculture and forestry areas, both providing monetary values of the land per unit of area. As for agricultural areas, a spreadsheet[5] produced by the National Research Council of Agriculture and Agricultural Economics was used, which provides the value of land parcels based on the type of crop, on elevation area, and on location (by taking provinces, i.e. Italian NUTS3 statistical regions, as the basic spatial units). As for forestry areas, data are available from the National Revenue Agency[6] and the values are here differentiated according to type of production, provinces, and rural regions (i.e., smaller spatial units contained within provinces).

The *LST* map was developed based only on Landsat 8 satellite imagery acquired in 2019, on August 11 and 20, and available by the USGS's Earth Resources Observation and Science[7]. A full methodological account is provided in [17].

The carbon dioxide capture and storage capacity (*CO2Stor*) map was produced using the InVEST "Carbon Storage and Sequestration" model[8] fed with the regional 2008 land-cover map coupled with look-up tables associating land covers to three carbon pools as follows: i. above-ground biomass, ii. soil organic content, iii. dead organic matter; a fourth carbon pool (concerning below-ground biomass) can actually be fed into the

[4] https://land.copernicus.eu/pan-european/corine-land-cover/clc2018.

[5] https://crea-qa.cube.extrasys.it/-/banca-dati-valori-fondiari-bdvf.

[6] https://www.agenziaentrate.gov.it/portale/web/guest/schede/fabbricatiterreni/omi/banche-dati/valori-agricoli-medi/valori-agricoli-medi-sardegna.

[7] USGS. Science for a Changing World—EarthExplorer: https://earthexplorer.usgs.gov.

[8] https://storage.googleapis.com/releases.naturalcapitalproject.org/invest-userguide/latest/carbonstorage.html.

Table 3. Municipalities included in the study area: size and approval date of the most recent hazard maps.

Municipality	Area [km^2]	Approval of the hazard maps [year]	Study commissioned by
Bari Sardo	37.43	2011	Sardinian regional administration
Baunei	212.08	2011	Sardinian regional administration
Budoni	56.17	2012	Municipal administration
Cardedu	32.35	2013	Municipal administration
Dorgali	224.82	2011	Sardinian regional administration
Gairo (coastal area only)	8.62	2014	Municipal administration
Girasole	13.23	2012	Municipal administration
Loiri Porto San Paolo	118.43	2012	Municipal administration
Lotzorai	16.51	2015	Municipal administration
Orosei	90.55	2013	Municipal administration
Posada	33.07	2010	Municipal administration
San Teodoro	104.76	2015	Municipal administration
Siniscola	199.87	2013	Municipal administration
Tertenia	117.76	2015	Municipal administration
Tortolì	40.47	2011	Municipal administration

model, but no information was available. Data for the three remaining carbon pools was gathered from the 2005 National Inventory of Italian Forests[9] and from a regional pilot

[9] https://www.sian.it/inventarioforestale.

project concerning land units and soil capacity in Sardinia[10]. For a full methodological account, the reader can refer to [18].

Finally, elevation (*Altitud*) and slope (*Slope*) were retrieved from the 10-m resolution digital terrain model available from the Regional geoportal[11].

For each variable, Table 4 summarizes data inputs and their sources, tool employed (when available; otherwise, ordinary GIS tools were used), and references.

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 Sect. 2.2.

3 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.

3.1 Flood and Landslide Hazards and Their Drivers

Figure 2 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 5% of the study area; as Fig. 2 shows, they form elongated clusters along the southwest-northeast direction due to geological and geomorphological reasons, along deep canyons in 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 factors such as morphology or soil type) as the distance increases. As shown in Fig. 2, 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 concerns 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

[10] http://www.sardegnageoportale.it/index.php?xsl=2420&s=40&v=9&c=14481&es=6603&na=1&n=100&esp=1&tb=14401.

[11] http://www.sardegnageoportale.it/areetematiche/modellidigitalidielevazione/.

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 sites, 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. 2, it takes the highest values along the coastline, because the Regional Landscape

Table 4. Spatial datasets developed for this study: 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 map Protected areas map Threats to biodiversity	Regional geoportal	InVEST - Habitat quality model	[15, 16]
	Expert judgments	Questionnaires		
Consval	Habitats of Community interest	Regional administration		
	Regional monitoring report			
	Natura 2000 standard data forms	Environmental ministry's website		
Landsval	Regional landscape plan dataset	Regional geoportal		
Recrval	Study area	Regional geoportal	InVEST - Visitation: recreation and tourism model	
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		

(*continued*)

Table 4. (*continued*)

Variable	Input data	Input data source(s)	Tool	References
LST	Landsat 8 TIRS and OLI satellite imagery	USGS's Earth Resources Observation and Science's website	LST QGIS plugin [19]	[17, 20]
CO2Stor	Regional land cover raster map	Regional geoportal	InVEST - Carbon storage and sequestration model	[18]
	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		

Plan strictly protects coastal landscapes, and along some the main rivers and creeks, also protected under the national landscape law.

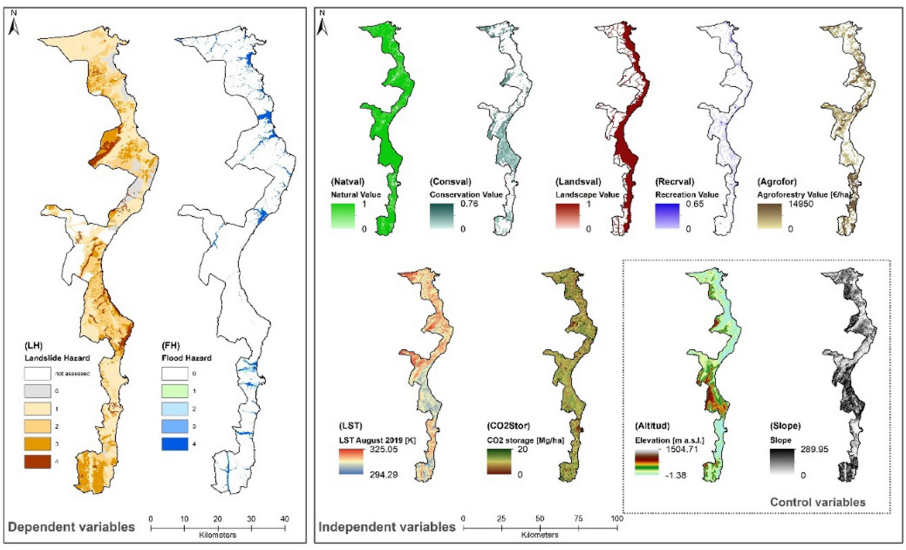


Fig. 2. Spatial distribution of dependent and independent variables in the study area.

Recrval takes the null value in most of the study area (around 78.3%), meaning that no geotagged pictures were uploaded onto Flickr in these areas. Non-zero values can be found mostly along the coastline and usually peak close to the towns and to coastal facilities, although in Dorgali and Baunei, well-renowned hikers' and climbers' destinations due to their outstanding natural characters, lighter shades of blue in Fig. 2 are visible also in inner areas across their territories.

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 high and low values are rather clustered, and the clusters mostly correspond to those having high elevation or high slope values, as the maps in Fig. 2 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.

3.2 Estimates of the Logit Models

Table 5 and Table 6 show the results of the estimates of the Logit models related to the dichotomous variables *FH* and *LH*, and their correlations with the seven environmental features that 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 opposite ways with reference to prevention and control of flood and landslide hazards. This implies that environmental and cultural attractiveness, and identification and protection of landscape and cultural resources, should be targeted 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 a negative effect on flood hazard. Therefore, 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 especially near areas characterized by a relevant landslide hazard.

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 rural and urban environments [17]. As in the cases of *Recrval* and *Landsval*, the estimates of the two Logit models reveal impacts on the probability of weak flood and landslide hazards consistent with each other and positive,

Table 5. Marginal effects on the probabilities of $FH = 1$ of variables described in Sect. 2, whose definitions and descriptive statistics are reported in Table 1.

Variable	Marginal effect	z-statistic	p-value
Marginal impact on $FH = 1$ probability, ∂Prob ($FH = 1$)/dx$_i$, Prob ($FH = 1$) = 9.00%			
Natval	−0.0043	−13.042	0.0000
Consval	0.0132	22.859	0.0000
Landsval	0.0113	30.012	0.0000
Recrval	−0.0042	−1.867	0.0619
Agrofor	0.0014	36.580	0.0000
LST	−0.0020	−35.729	0.0000
CO2Stor	−0.0055	−21.299	0.0000
Altitud	−0.0001	−72.983	0.0000
Slope	−0.0003	−22.713	0.0000
Log-likelihood goodness-of-fit test			
Log-likelihood ratio = 72946.20 – Prob. > chi-square = 0.00000 (9 degrees of freedom)			

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. Therefore, as climate-change mitigation and adaptation focus on policies to decrease *LST*, it can be concluded that the issue of *LST* is not relevant to address landslide and flood hazard.

Furthermore, *CO2Stor* shows opposite impacts on the probability of a parcel to be associated to either a relevant or a weak hazard level. This is entirely consistent with expectations: 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 already mentioned with reference to *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

Table 6. Marginal effects on the probabilities of $LH = 1$ of variables described in Sect. 2, whose definitions and descriptive statistics are reported in Table 1.

Variable	Marginal effect	z-statistic	p-value
Marginal impact on $LH = 1$ probability, ∂Prob ($LH = 1$)/dxi, Prob ($LH = 1$) = 44.80%			
Natval	0.3351	64.191	0.0000
Consval	−0.2787	−46.522	0.0000
Landsval	0.0155	7.137	0.0000
Recrval	−0.6352	−12.970	0.0000
Agrofor	−0.0170	−56.433	0.0000
LST	−0.0274	−72.544	0.0000
CO2Stor	0.0533	17.930	0.0000
Altitud	0.0002	44.439	0.0000
Slope	0.0087	128.132	0.0000
Log-likelihood goodness-of-fit test			
Log-likelihood ratio = 122653.10 – Prob. > chi-square = 0.00000 (9 degrees of freedom)			

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 are excellent, as shown by the two log-likelihood ratios measures.

4 Conclusions

Some policy implications and recommendations can be derived from the outcomes of the study, as follows. 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 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. Therefore, 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" [21]. Since Natura 2000 sites within Sardinia include most coastal wetlands, estuaries, waterways, and large stretches of coastal areas, it is 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 [22]. To sum up, the methodological approach proposed in this study 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. A promising direction for future research should focus on 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.

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References

1. Margottini, C., Un contributo per gli Stati Generali dei cambiamenti climatici e l'arte della difesa del territorio [A contribution to General States of climate change and soil

defense] (2015). https://www.minambiente.it/sites/default/files/archivio/allegati/italiasicura/114Contributodisses.pdf. Accessed 25 March 2021
2. Trigila, A., Iadanza, C., Bussettini, M., Lastoria, B.: Dissesto idrogeologico in Italia: pericolosità e indicatori di rischio [Hydrogeological instability in Italy: hazard and risk indicators]. ISPRA, Rome, Italy (2018)
3. Badiu, D., Nita, A., Ioja, C., Nita, M.: Disentangling the connections: a network analysis of approaches to urban green infrastructure. Urban Forestry & Urban Greening **41**, 211–220 (2019)
4. Caparrós-Martínez, J.L., Milán-García, J., Rueda-López, N., de Pablo-Valenciano, J.: Green infrastructure and water: an analysis of global research. Water **12**(6), 1760 (2020)
5. United States Environment Protection Agency: What is green infrastructure?. https://www.epa.gov/green-infrastructure/what-green-infrastructure. Accessed 25 March 2021
6. Chen, J., Liu, Y., Gitau, M.W., Engel, B.A., Flanagan, D.C., Harbor, J.M.: Evaluation of the effectiveness of green infrastructure on hydrology and water quality in a combined sewer overflow community. Sci. Total Environ. **665**, 69–79 (2019)
7. Papathoma-Köhle, M., Glade, T.: The role of vegetation cover change for landslide hazard and risk. In: Renaud, G., Sudmeier-Rieux, K., Marisol, E. (eds.) The Role of Ecosystems in Disaster Risk Reduction, pp. 293–320. UNU-Press, Tokyo (2013)
8. European Commission Green infrastructure (GI)—Enhancing Europe's natural capital: communication from the commission to the European Parliament, the council, the European economic and social committee and the committee of the regions (2013). https://eur-lex.europa.eu/resource.html?uri=cellar:d41348f2-01d5-4abe-b817-4c73e6f1b2df.0014.03/DOC_1&format=PDF. Accessed 25 March 2021
9. Palmer, M., Liu, J., Matthews, J., Mumba, M., D'Odorico, P.: Water security: gray or green? Science **349**(6248), 584–585 (2015)
10. Nerlove, M., Press, S.: Univariate and multivariate log-linear and logistic models. Report no. R1306-EDA/NIH. RAND Corporation Santa Monica, CA, United States (1973)
11. Greene, W.H.: Econometric Analysis. Macmillan, New York, NY, United States (1993)
12. Zoppi, C., Lai, S.: Differentials in the regional operational program expenditure for public services and infrastructure in the coastal cities of Sardinia (Italy) analyzed in the ruling context of the regional landscape plan. Land Use Policy **30**, 286–304 (2013)
13. Regione Autonoma della Sardegna: Attività di individuazione e di perimetrazione delle aree a rischio idraulico e geomorfologico e delle relative misure di salvaguardia. Linee guida. [Identifying and mapping areas subject to flood risk and landslide risk, and delineation of safeguard measures. Guidelines] (2000). http://www.regione.sardegna.it/documenti/1_26_20060913170604.pdf. Accessed 25 March 2021
14. Regione Autonoma della Sardegna: Piano Stralcio per l'Assetto Idrogeologico (PAI). Relazione generale. [Hydrogeological Setting Plan. Comprehensive Report] (2004). http://www.regione.sardegna.it/documenti/1_26_20060913170906.pdf. Accessed 25 March 2021
15. Lai, S., Leone, F.: Bridging biodiversity conservation objectives with landscape planning through green infrastructures: a case study from Sardinia, Italy. In: Gervasi, O., et al. (eds.) ICCSA 2017. LNCS, vol. 10409, pp. 456–472. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-62407-5_32
16. Cannas, I., Lai, S., Leone, F., Zoppi, C.: Green infrastructure and ecological corridors: a regional study concerning Sardinia. Sustainability **10**(4), 1265 (2018)
17. Lai, S., Leone, F., Zoppi, C.: Spatial distribution of surface temperature and land cover: a study concerning Sardinia, Italy. Sustainability **12**(8), 3186 (2020)
18. Floris, M.: I servizi ecosistemici nella pianificazione spaziale come strumenti interpretativi per la definizione di tassonomie territoriali innovative [Ecosystem services within spatial planning as knowledge-interpreting tools for the definition of innovative spatial taxonomies], unpublished doctoral thesis discussed at the University of Cagliari on March 6 (2020)

19. Ndossi, M.I., Avdan, U.: Application of open source coding technologies in the production of Land Surface Temperature (LST) maps from Landsat: a PyQGIS Plugin. Remote Sens. **8**(5), 413 (2016)
20. Lai, S., Leone, F., Zoppi, C.: Policies to decrease land surface temperature based on land cover change: an assessment related to Sardinia, Italy. TEMA – J. Mobility Land Use Environ. **13**(3), 329–351 (2020)
21. Commission of the European Communities: White paper. Adapting to climate change: towards a European framework for action (2009). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52009DC0147. Accessed 25 March 2021
22. European Commission: Promoting the socio-economic benefits of Natura 2000. Natura 2000 (2010). https://ec.europa.eu/environment/nature/info/pubs/docs/nat2000newsl/nat29_en.pdf. Accessed 25 March 2021