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Special Issue 1.2021

The Emergency Plan for the use and management of the territory

print ISSN 1970-9889 e-ISSN 1970-9870
University of Naples Federico II

TeMA

Journal of
Land Use, Mobility and Environment

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THE EMERGENCY PLAN FOR THE USE AND MANAGEMENT OF THE TERRITORY

Published by
Laboratory of Land Use Mobility and Environment
DICEA - Department of Civil, Architectural and Environmental Engineering
University of Naples "Federico II"

TeMA is realized by CAB - Center for Libraries at “Federico II” University of Naples using Open Journal System

Editor-in-chief: Rocco Papa
print ISSN 1970-9889 | on line ISSN 1970-9870
Licence: Cancelleria del Tribunale di Napoli, n°6 of 29/01/2008

Editorial correspondence
Laboratory of Land Use Mobility and Environment
DICEA - Department of Civil, Architectural and Environmental Engineering
University of Naples "Federico II"
Piazzale Tecchio, 80
80125 Naples
web: www.tema.unina.it
e-mail: redazione.tema@unina.it

The cover image is a photo of the landslide that hit the municipality of Amalfi (Italy) in February 2021.

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Contenets

TeMA

Journal of
Land Use, Mobility and Environment

TeMA Special Issue 1.2021 109-133
print ISSN 1970-9889, e-ISSN 1970-9870
DOI: 10.6092/1970-9870/7411
Received 13th December 2020, Accepted 25th March 2021, Available online 30th June 2021

Assessing the potential of green infrastructure to mitigate hydro-geological hazard

Evidence-based policy suggestions from a Sardinian study area

Sabrina Lai [a], Federica Isola [b], Federica Leone [c], Corrado Zoppi [d*]

[a] Department of Civil and Environmental Engineering and Architecture
University of Cagliari, Cagliari, Italy
e-mail: sabrinalai@unica.it
ORCID: https://orcid.org/0000-0002-4317-8007

[b] Department of Civil and Environmental Engineering and Architecture
University of Cagliari, Cagliari, Italy
e-mail: federica.isola@unica.it
ORCID: https://orcid.org/0000-0003-0482-0404

[c] Department of Civil and Environmental Engineering and Architecture
University of Cagliari, Cagliari, Italy
e-mail: federicaleone@unica.it
ORCID: http://orcid.org/0000-0003-1071-2768

[d] Department of Civil and Environmental Engineering and Architecture
University of Cagliari, Cagliari, Italy
e-mail: zoppi@unica.it
ORCID: https://orcid.org/0000-0003-4114-5380
* Corresponding author

Abstract

This study focuses on the relations between the definition and implementation of a green infrastructure (GI) and hydro-geological hazard. GIs 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 study 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.

Keywords

Environmental hazard; Green infrastructure; Ecosystem services; Logit models.

How to cite item in APA format

Lai S., Isola F., Leone F. & Zoppi C. (2021). Assessing the potential of green infrastructure to mitigate hydro-geological hazard. *Tema. Journal of Land Use, Mobility and Environment*, 109-133. http://dx.doi.org/10.6092/1970-9870/7411

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 & 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 & 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 raise, 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 green infrastructure (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 & 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 & 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 & 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 study 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 & Morosini, 2018). Mei et al. (2018) investigate the role of GI in mitigating flood events through the storm water 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 & 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 which are often too expensive in terms of financial resources and time needed to obtain reliable outcomes (Palmer at 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 & Gnecco, 2015; Liu et al., 2014). This article 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.

The article is structured into five 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, while the fifth section defines the implications of the study in terms of planning policy recommendations, discusses limitations and identifies future research perspectives.

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.

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). 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 study stretches over 1,306.12 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 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 study. As for floods, extreme events in recent history took place in this part of the island in 1951, 2004, 2013 (Bodini & 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) project2 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

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1 Data from the National Census as of January 1st, 2020: http://dati.istat.it/

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 from https://idrogeo.isprambiente.it/app/iffi/r/20.

topple types3 prevail (Cinus et al., 2007), while in the latter, only concerning the municipality of Tertenia, topples prevail, although some translational slides have also occurred (Cinus et al., 2007).

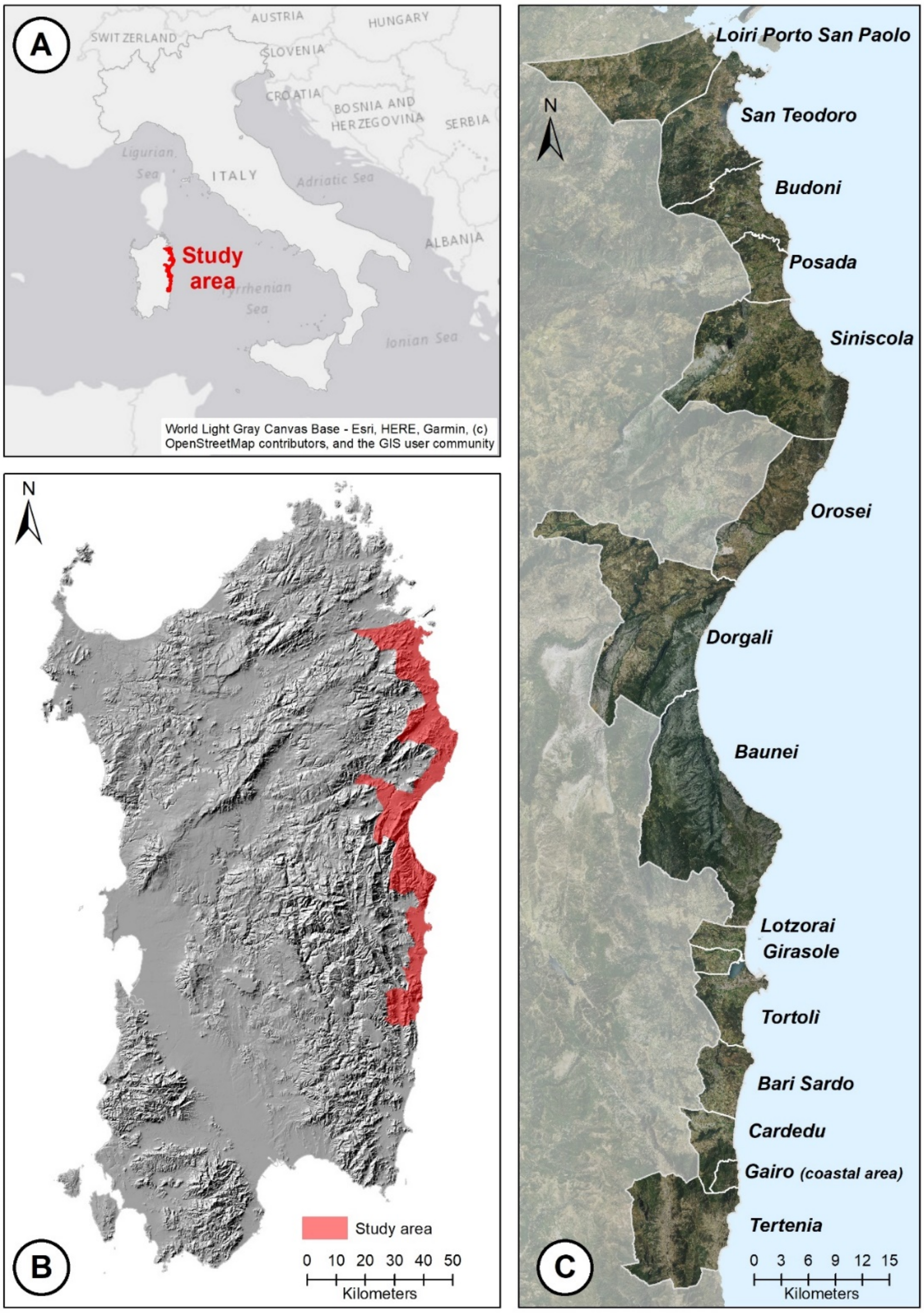

Fig.1 Location of the study area within Italy (A) and Sardinia (B), and municipalities included therein (C).

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 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

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

unit of area, and in terms of land taken per capita (Tab. 1, penultimate and last column respectively). 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.

Municipality	Area [km^2]	Population (*)	Population density [residents/km^2]	Land take [%] (**)	Land take [m^2/inhabitant]
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 (http://dati.istat.it/).
(**) As of 2019. Source: Munafò, 2020. Defined as "Consumed soil" in the supplementary materials (http://groupware.sinanet.isprambiente.it/uso-copertura-e-consumo-di-suolo/library/consumo-di-suolo/indicatori/).
(***) Data in this table refer to the whole municipality, but in this study 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.

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

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 & Lerman 1985; Ortúzar & Willumsen 2001; Train 2009), which assume imperfection of agents' rationality and information incompleteness (Tversky 1972).

In this article, 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 flow 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 & Lai's (2013), this study 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:

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

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

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

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 & 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;

[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).

- Var(ε) = σ^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 ∈ {0,1}.

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], 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 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	0.844	0.269
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, 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. 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
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

Tab. 2 Definition of variables and descriptive statistics

5 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 [accessed 4 November 2020].

6 https://desktop.arcgis.com/en/arcmap/10.7/tools/spatial-analyst-toolbox/slope.htm [accessed 4 November 2020]

The characteristics which are the components of vector x = (1, x_1, …, 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, 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

Flood hazard and landslide hazard in Italy are mapped at the sub-national 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 identifies through hydraulic models (RAS, 2000). Hazard classes within the PAI range in the 0-4 interval, as per Tab. 3.

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

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

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

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

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. 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.

Title of the spatial dataset (original)	Content of the spatial dataset	Latest update	Metadata and download URL
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

Tab. 4 Landslide and flood hazard datasets used within this study.

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

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

8 http://www.sardegnageoportale.it/webgis2/sardegnamappe/?map=pai

9 http://www.regione.sardegna.it/index.php?xsl=509&s=1&v=9&c=9305&tb=8374&st=13

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 study 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 rest of this section looks briefly at the nine independent variables and data used to map them.
Natval value was assessed though the InVEST model "Habitat Quality"[11] based on the following input data:

- land cover types as per the 2008 Regional land cover raster map;
- raster maps of ten spatial threats (cultivation; grazing; removal of forest undergrowth; salt works; paths, tracks, and cycling tracks; roads and motorways; airports; urbanized areas; discharges; fire and fire suppression). The threats were selected based on the Sardinian standard data forms for the Natura 2000 sites among those having spatial character;
- 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 value was assessed using the following datasets:

- vector raster map of habitats of Community interest, provided by the Sardinian regional administration;
- Natura 2000 standard data forms, available as MS-Access database from the website of the Italian ministry for the environment, and land and sea protection[12];
- a regional monitoring (unpublished) report on the conservation status of habitats and species of Community interest, provided by the Sardinian regional administration.

Landsval was assessed using the spatial dataset of the Regional Landscape Plan, retrievable from the Regional geoportal[13], and providing the spatial distributions of areas protected because their environmental and/or cultural and historic qualities and significance.
Recrval was mapped using the InVEST model "Visitation: Recreation and Tourism"[14], which only requires the area of interest as input data, used by the tool to retrieve geotagged pictures uploaded by Flickr users within a chosen time frame.
For a full methodological account about the production of *Natval*, *Consval*, *Landsval*, and *Recrval* maps, the reader can refer to Lai & Leone (2017) and to Cannas et al. (2018).
With regards to *Agrofor*, the value of rural plots in 2017 was estimated using the 2018 CORINE land cover map[15] 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[16] produced by the National Research Council of Agriculture and Agricultural Economics was used, which provides the value of land parcels based

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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.
11 https://storage.googleapis.com/releases.naturalcapitalproject.org/invest-userguide/latest/habitat_quality.html
12 ftp://ftp.minambiente.it/PNM/Natura2000/TrasmissioneCE_dicembre2017/
13 http://www.sardegnageoportale.it/webgis2/sardegnamappe/?map=ppr2006
14 https://storage.googleapis.com/releases.naturalcapitalproject.org/invest-userguide/latest/recreation.html
15 https://land.copernicus.eu/pan-european/corine-land-cover/clc2018
16 https://crea-qa.cube.extrasys.it/-/banca-dati-valori-fondiari-bdvf

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[17] 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 TIRS and OLI satellite imagery acquired in 2019, on August 11 and 20, and made available by the USGS's Earth Resources Observation and Science[18]. A full methodological account is provided in Lai et al. (2020b).

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	Regional geoportal	InVEST - Habitat quality model	Lai & Leone, 2017 Cannas et al., 2018
	• Threats to biodiversity (spatial data only)			
	• 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		
LST	• Landsat 8 TIRS and OLI satellite imagery	USGS's Earth Resources Observation and Science's website	LST QGIS plugin by Ndossi & 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		---

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

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

18 USGS. Science for a Changing World—EarthExplorer: https://earthexplorer.usgs.gov

The carbon dioxide capture and storage capacity (*CO2Stor*) map was produced using the InVEST "Carbon Storage and Sequestration" model[19] 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 model, but no information was available. Data for the three remaining carbon pools was gathered from the 2005 National Inventory of Italian Forests[20] and from a regional pilot project concerning land units and soil capacity in Sardinia[21]. For a full methodological account, the reader can refer to Floris (2020).

Finally, elevation (*Altitud*) and slope (*Slope*) were retrieved from the 10-m resolution digital terrain model available from the Regional geoportal[22].

For each variable, Tab.6 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 Section 2.2.

Fig.2 provides a complete overview of the methodology presented in Sections 2.2 and 2.3.

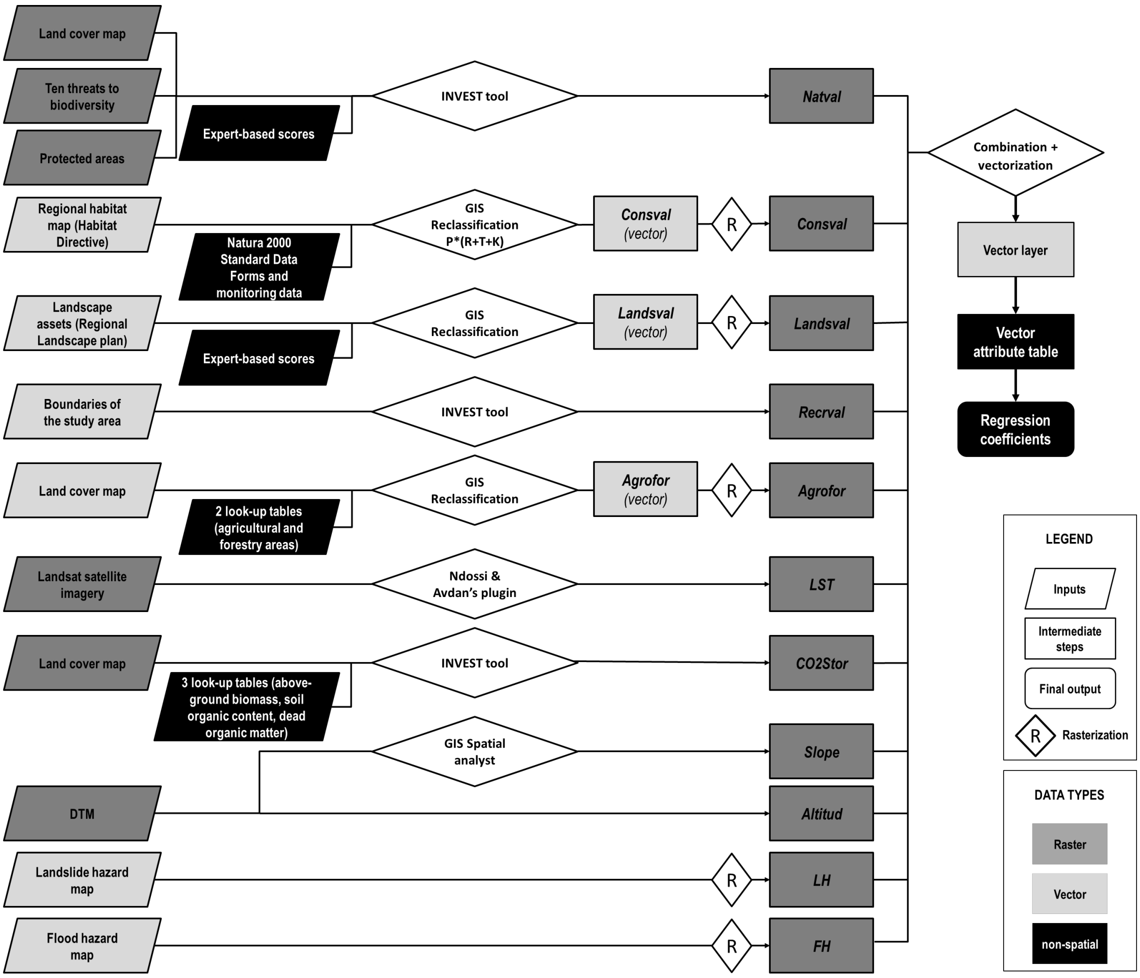

Fig. 2 Full overview of the methodology.

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

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

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

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

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

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.

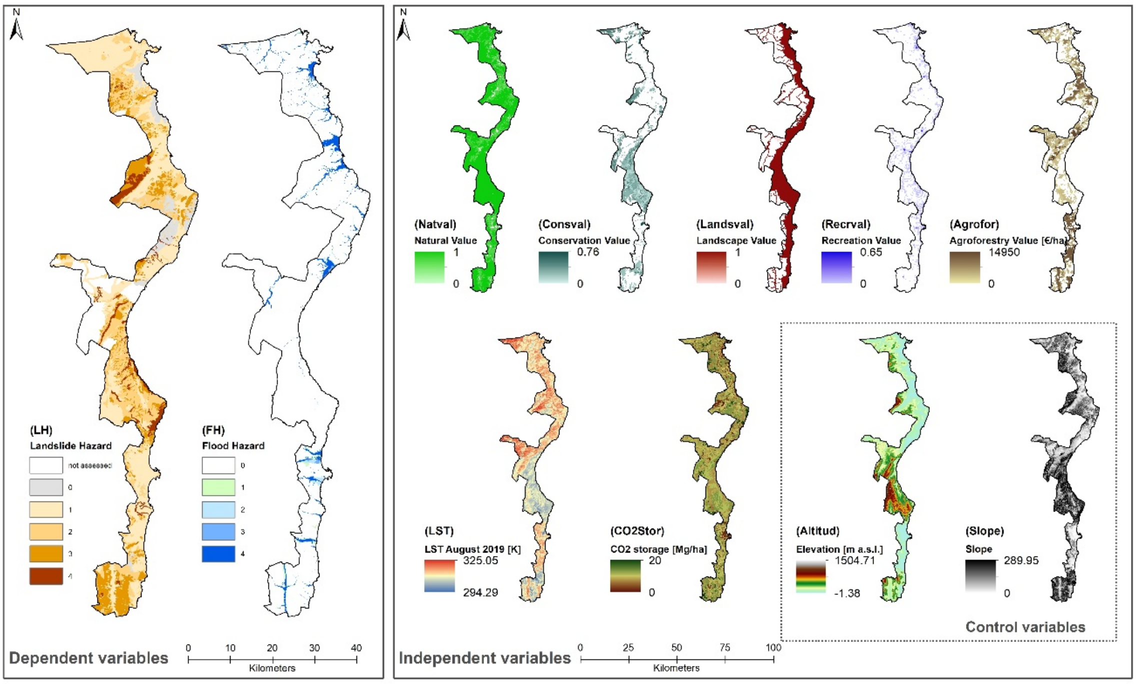

Fig. 3 Spatial distribution of dependent and independent variables in the study area.

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 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 among hikers and climbers for their outstanding natural characters, lighter shades of blue in Fig. 3 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 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.

3.2 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.

Variable	Marginal effect	z-statistic	p-value
Marginal impact on FH=1 probability, $\partial Prob(FH=1)/dx_i$, 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)			

Tab. 7 Marginal effects on the probabilities of FH=1 of variables described in subsection 2.3, whose definitions and descriptive statistics are reported in Tab. 2

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, which indicates that these two features of the RGI should be enhanced and strengthened in order to promote prevention and control. 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 *Agroforest* 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.

Variable	Marginal effect	z-statistic	p-value
Marginal impact on LH=1 probability, ∂Prob (LH=1)/dx_i, Prob (LH=1) = 44.80%			
Natval	0.3351	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)			

Tab. 8 Marginal effects on the probabilities of LH=1 of variables described in subsection 2.3, whose definitions and descriptive statistics are reported in Tab. 2

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 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, 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.

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

4. Discussion

The methodological approach proposed in this study analyzes the relations between RGI and environmental hazards, represented by landslides and floods. In particular, the study 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 & 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 study'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 & 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).

5. Conclusions

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

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., 2020a). 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 & 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 study 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 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.

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).

Authors' contribution

Sabrina Lai (S.L), Federica Isola (F.I.), Federica Leone (F.L.), and Corrado Zoppi (C.Z.) collaboratively designed this study. Individual contributions are as follows: F.I. and F.L. jointly wrote Section 1; S.L. wrote Sections 2.1, 2.3, and 3.1; C.Z. wrote Sections 2.2, and 3.2; F.I. wrote Section 4; F.L. wrote Section 5.

Acknowledgments

The study was implemented within the Research Program "Paesaggi rurali della Sardegna: pianificazione di infrastrutture verdi e blu e di reti territoriali complesse" [Rural landscapes of Sardinia: Planning policies for green and blue infrastructure and spatial complex networks], funded by the Autonomous Region of Sardinia for the period 2019–2021, under the provisions of the call for the presentation of "Projects related to fundamental or basic research" of the year 2017, implemented at the Department of Civil and Environmental Engineering and Architecture (DICAAR) of the University of Cagliari, Italy.

Conflicts of Interest: The authors declare no conflict of interest.

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Author’s profiles

Sabrina Lai

She is a civil engineer, a Doctor of Research in Land Engineering (Italy, 2009), and an MSc in International Planning and Development (UK, 2008). She is an Assistant Professor at the University of Cagliari (Sector ICAR/20 – Spatial planning), where she is presently teaching at the Department of Civil and Environmental Engineering and Architecture of the University of Cagliari in the Graduate Program in Environmental and Territorial Engineering (module leader for the Strategic Planning course).

Federica Isola

She is a building engineer, and a Doctor of Research in Engineering and Natural Sciences (Italy, 2012). She is currently a research fellow at the Department of Civil and Environmental Engineering and Architecture of the University of Cagliari.

Federica Leone

She is a building engineer, a Doctor of Research in Land Engineering (Italy, 2013), and an MSc in International Planning and Development (UK, 2012). She is currently a research fellow at the Department of Civil and Environmental Engineering and Architecture of the University of Cagliari.

Corrado Zoppi

He is a civil engineer, a Doctor of Philosophy in Economics (USA, 1997), a Doctor of Research in Territorial Planning (Italy, 1992), and an MSc in Economic Policy and Planning (USA, 1990). He is a Professor at the University of Cagliari (Sector ICAR/20 – Spatial planning). He is presently teaching at the Department of Civil and Environmental Engineering and Architecture of the University of Cagliari in the Undergraduate and Graduate Programs in Environmental and Territorial Engineering and in Sustainable Tourism Management and Monitoring (Regional and Urban Planning, Strategic Planning and Environmental planning).