Assessing the Relation Between Land Take and Landslide Hazard. Evidence from Sardinia, Italy

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Abstract. The process of land-taking and soil sealing involves changing the way land is used, which in turn can make the land more vulnerable to landslides. This means that the land may not be able to withstand the forces of landslides as effectively as it could before. Therefore, this study examines how land-taking processes, such as urbanization, can increase the risk of landslides. The study asks the research question, "To what extent do land-taking processes increase landslide hazard?". The impact of land take is measured using a regression model that analyzes land cover variables, including artificialized land, and other land cover types grouped according to the LEAC (Land and Ecosystem Accounting) classification. The study is conducted in Sardinia and shows that land-taking processes, including urbanization, increase the size of the area prone to landslides. The study offers suggestions for planning policies to mitigate the impacts of land cover transitions on landslide hazards.

Keywords: Land Take · Landslide Hazard · Land Cover Change

1 Introduction

As per the European Environment Agency, "Land take is the process in which urban areas and sealed surfaces occupy agricultural, forest or other semi-natural and natural areas" [1] (p. 117). At the end of 2021, the European Commission approved a new Soil Strategy for 2030, which highlights how healthy soils are essential for achieving the objectives of the European Green Deal concerning climate and biodiversity. The strategy defines a general framework and concrete measures to protect and restore soils to ensure their sustainable use [2]. One of the long-term objectives to be achieved by 2050 is to reach "no net land take" [2] (p. 3). The general framework of the strategy termed "land take hierarchy" concerns four consequential actions, which are prioritized as follows: avoid, reuse, minimize, and compensate. Prioritization means that the lower level should be implemented when implementing the higher level is impossible. In this context, "Avoid" aims at preventing further land take; "Reuse" means re-using land that has already been urbanized or sealed; "Minimize" refers to curtailing the effects of land

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take by impermeabilizing land already in unfavorable conditions; "Compensate" entails applying compensation and mitigation measures. The main causes of land take are to be attributed to expansion of industrial and commercial areas, and to enlargement of residential zones and construction sites [3]. Land-taking processes entail several problems, such as the loss of multifunctional and fertile soils, biodiversity degradation and loss of ecosystem services (ESs), that is, benefits provided by ecosystems to human beings, including protection against hydrogeological hazards such as floods and landslides [4].

A landslide is the movement of materials such as rock, soil, debris, and artificial fill. Landslides primarily occur in mountainous areas, but also in low-relief zones, and can have geological, morphological, or artificial origins. Natural causes include the intrinsic properties of rocks and soils, as well as physical processes, such as heavy rains and seismic activity; artificial causes include changes in slope stability brought about, for instance, by deforestation or excessive soil sealing [5]. Therefore, landslides can be strongly connected with land use and land cover dynamics [6] and, particularly, with human-driven processes [7], such as land use/land cover changes, which alter vegetation and modify soils and hydrogeological processes [8, 9]. Land use/land cover changes can influence landside events due to their potential impacts on hydrological and mechanical processes involving soils [10, 11].

The relation between land use/land cover changes and landslides has been studied by various authors [among many: 7, 12, 13]. However, the relation between land-taking processes and landslide hazard is still under-researched. Therefore, such relationship is here explored in order to understand to what extent land-taking processes increase landslide hazard through a regression model that relates the level of landslide hazard to a set of land cover variables that includes artificialized land. The methodological approach is implemented in the Sardinia Region, Italy.

The study is structured into six sections as follows. The second section describes the study area, the methodological approach used, and the input data for the regression model. The results are presented in the third section and discussed in the fourth section. The fifth section provides recommendations and implications for spatial planning policies stemming from the results, while the sixth section provides concluding remarks and future directions of the research.

2 Materials and Methods

2.1 Study Area

The so-called "Coghinas-Mannu-Temo" subdistrict (hereafter, CMT), is the area chosen for this study (Fig. 1). It is one of the river basin districts in which the island of Sardinia, in Italy, was subdivided, and it is made up of around forty watersheds, of which the largest and most important ones are the four ones from which its name originates, i.e., Coghinas River, Mannu River, Mannu River in Porto Torres, and Temo River. The reasons for choosing the Sardinian CMT subdistrict for this study are twofold. First, Sardinia is included in the CORINE Land Cover (CLC) inventory coordinated by the European Environment Agency under the Copernicus program of the EU; this makes it possible to retrieve a regularly updated series of land cover maps, of which the most recent one refers to the year 2018 [14]. Second, a comprehensive and detailed spatial assessment

of landslide hazard and risk concerning the whole CMT was carried out and officially validated in 2014 [15] and it is publicly available from the regional geoportal.

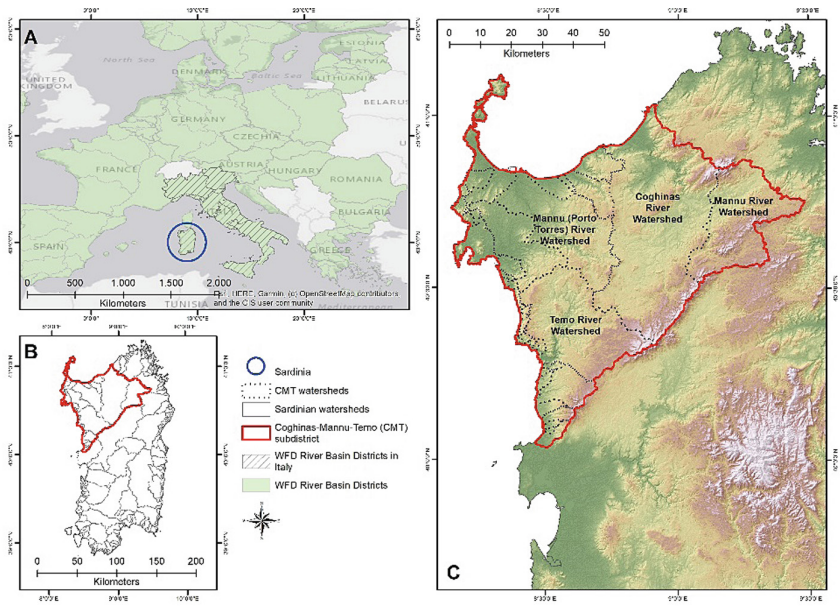

Fig. 1. River basin districts in Italy (panel A), Sardinian watersheds (panel B), and the Coghinas-Mannu-Temo subdistrict with its watersheds (panel C).

The prevailing morphology within the CMT is hilly, the climate is typically Mediterranean, and the vegetation is characterized by the cork tree series and the holm oak tree series. Geological instability is diffuse in the study area, where landslide events have been recorded for decades: the Italian landslide inventory (IFFI [16]) has documented 398 landslide events occurring up to 2007 in the CMT. The most prominent category is that of diffuse falls or topples, followed (in order) by simple falls or topples, by diffuse superficial instability, and by rotational or translational slides.

2.2 Regression Model

The relation between landslide hazard (LH) and the size of land taken up (L_TAKE) is assessed through a linear regression model that uses the LEAC land cover groups as explanatory variables, whose definitions are given in Sect. 2.3. The covariate representing land take is one of the LEAC groups, namely the variable associated with the artificialized land LEAC group. Dependent and explanatory variables refer to the elements of a 300-m square grid that overlays the study area, and are measured as their percentage share of a grid cell. The model operationalizes as follows:

$$\begin{aligned} \mathrm{LH} = {} & \alpha_0 + \alpha_1 \mathrm{L_TAKE} + \alpha_2 \mathrm{ARA} + \alpha_3 \mathrm{PMF} + \alpha_4 \mathrm{FOR} + \alpha_5 \mathrm{GRSH} + \alpha_6 \mathrm{DEPOQ} \\ & + \alpha_7 \mathrm{VOLSE} + \alpha_8 \mathrm{ELEV} + \alpha_9 \mathrm{HGLAGGED} \end{aligned} \quad (1)$$

where the dependent variable and covariates are identified as shown below.

- LH is for landslide hazard.
- L_TAKE is for artificialized land or land take.
- ARA is for arable land.
- PMF is for pastures and mosaic farmland.
- FOR is for standing forests.
- GRSH is for natural grasslands, sclerophyllous vegetation, and heathlands.
- DEPOQ is for ground substrate characterized by quaternary deposits.
- VOLSE is for ground substrate characterized by volcanic sedimentary rocks.
- ELEV is for the average elevation of a grid element.
- HGLAGGED is the spatially lagged dependent variable that controls for spatial autocorrelation of LH.

The estimates of the coefficients of the multiple linear regression show the correlations between landslide hazard and the land covers of the LEAC taxonomy and, in particular, the interdependence of LH and the size of land take.

The use of a multiple linear regression is motivated by the fact that prior assumptions are not available as regards the functional form of the relations between dependent and explanatory variables, which is consistent with several studies aimed at identifying the interdependence between spatial variables [17]. From this point of view, a spatial phenomenon, related to n variables, represented by a surface in an n-dimensional space whose equation is unknown, can be approximately detected, in each of its points, by the tangent hyperplane. The linear equation estimated through the regression model, which relates dependent and explanatory variables, identifies the tangent hyperplane in a small neighborhood of a point of the surface, and in such neighborhood it represents an approximation of the unknown equation of the surface [18]. Hence, model (1) represents the trace of a hyperplane on a surface in a ten-dimensional space, which reports the correlations between LH and the nine covariates listed above.

The covariates DEPOQ and VOLSE control for the ground substrate, by considering if, and to what extent, landslide hazard is influenced by the conditions of the substrate, which in the study area is mainly featured by cohesive and compact rocks such as volcanic sedimentary successions (VOLSE) and, secondly, by deposits from the quaternary era (DEPOQ), i.e., loose incoherent materials. ELEV controls for the altitude impact on landslide hazard. If the estimates of their coefficients in (1) are significant, this will entail that substrate and elevation are likely to influence LH, at least to some extent. The magnitude of the coefficients will show the size of the impacts, in terms of increase or decrease in the landslide hazard measure.

The sign of ELEV is expected to be negative, since in the study area, on average, landslide hazard conditions are more frequent in lowlands rather than in mountainous locations, as further discussed in Subsect. 3.3, whereas the expected signs of DEPOQ and VOLSE are positive and negative, respectively, since it is intuitively likely that LH will increase as long as the substrate incoherence and looseness increases, and the other way around. The variable HGLAGGED represents the spatially lagged values of LH, and controls for spatial autocorrelation of the dependent variable in model (1). The HGLAGGED definition builds on Anselin's work [19].

Moreover, a p-value test is used to check the level of significance of the estimates of the coefficients of model (1).

2.3 Input Data for the Regression Model

The dependent variable and covariates needed to feed into the regression model (1) were calculated with reference to a 300-m vector square grid that covers all of the CMT subdistrict and comprises a total of 62,231 cells, using four main input spatial datasets listed in Table 1.

Landslide Hazard. Landslide hazard levels in the study area were assessed in 2014 within a study commissioned by the Sardinian Basin Competent Authority in 2011, whose documents are publicly available on the institutional website [15]. As per the methodology used in the PAI, landslide hazard (HL) classes range in the 0–4 interval, as follows: no hazard: HL = 0; moderate hazard: HL = 1; medium hazard: HL = 2; high hazard: HL = 3; very high hazard: HL = 4. For each cell in the 300-m square grid, the dependent variable LH in model (1) was calculated as the percentage of the cell's area having non-null landslide hazard (HL $\neq$ 0) in the vector data retrieved from the geoportal. Moreover, LH's spatially lagged variable (HGLAGGED), included in model (1) as a covariate, was calculated using GeoDA (version 1.20) [20].

Table 1. Input datasets used to compute dependent and explanatory variables.

Input Datasets	Sources	Link
Landslide hazard	Regional geoportal	https://webgis2.regione.sardegna.it/geonetwork/srv/ita/catalog.search#/metadata/R_SARDEG:eb38d6c0-b51f-4df1-acdc-f7a752e7664c
LEAC land cover groups	Copernicus—Europe's Eyes on Earth program	https://land.copernicus.eu/pan-european/corine-land-cover/clc2018
Elevation	Regional geoportal	https://www.sardegnageoportale.it/areetematiche/modellidigitalidielevazione
Geological characteristics	Regional geoportal	https://www.sardegnageoportale.it/index.php?xsl=2420&s=40&v=9&c=14479&es=6603&na=1&n=100&esp=1&tb=14401

LEAC Land Cover Groups. In this study the 2018 CORINE Land Cover vector map (CLC2018) was used. The map provides information on land covers, i.e., on the biophysical characteristics of the Earth's surface, through a hierarchical classification that

comprises 44 classes at the third (and lower) level, 17 at the second level, five at the first level, with a minimum mapping unit equaling 25 hectares. The CLC2018 was next reclassified so as to group the third-level land cover classes following the taxonomy used by the European Environment Agency for land cover accounts [21] and comprising eight groups. Detailed information on how the reclassification was performed is provided in [22].

Geological Characteristics and Elevation (Control Data). A 1:25,000 regional geological map of Sardinia was produced at the beginning of the year 2000 building upon geological data collected by the former regional agency for mines and quarries. The spatial dataset, available from the regional geoportal [23], identifies geological characters in compliance with the "CARG" national mapping program initiated in the 1980s by the Italian Geological Society. The taxonomy of the Sardinian geological map is hierarchically structured into five main classes and five levels ([24], pp. 49–108), and a simple reclassification was carried out in this study, whereby i., first-level classes only were considered and, ii., three main groups were retrieved by merging first-level classes. The three groups are as follows: i., quaternary deposits (also comprising lakes); ii., volcanic sedimentary successions; iii., intrusive complexes and metamorphic basements. Finally, for each cell in the 300-m square grid, the explanatory variables DEPOQ and VOLSE were calculated as the shares of the cell occupied, respectively, by quaternary deposits and by volcanic sedimentary successions. For any terrestrial cell in the grid, the share occupied by the third group is, fairly obviously, the difference between 100 and the sum of DEPOQ and VOLSE.

Elevation was retrieved from the 10-m resolution digital terrain model (DTM) available "off the shelf" from the regional geoportal [25]: for each cell in the 300-m square grid, the explanatory variable ELEV in model (1) was calculated as the average elevation in the cell.

3 Results

3.1 Landslide Hazard in the Study Area

In the vast majority of CMT (i.e., 80.29% of the CMT land mass) the hazard level was assessed as null by the PAI, while around a fifth of the subdistrict is prone to landslides, mostly of medium (10.40%) or high severity (6.67%); a very small share of the CMT (1.92%) features moderate landslide hazard and a negligible one (0.71%) is characterized by very high hazard levels. Within the 300-m grid used in this study, LH is greater than zero in 30,775 out of the total 62,231 300-m grid cells (Fig. 2, panel B); hence, in nearly half of the cells, landslide hazard, of whichever level, affects a certain share of the cell.

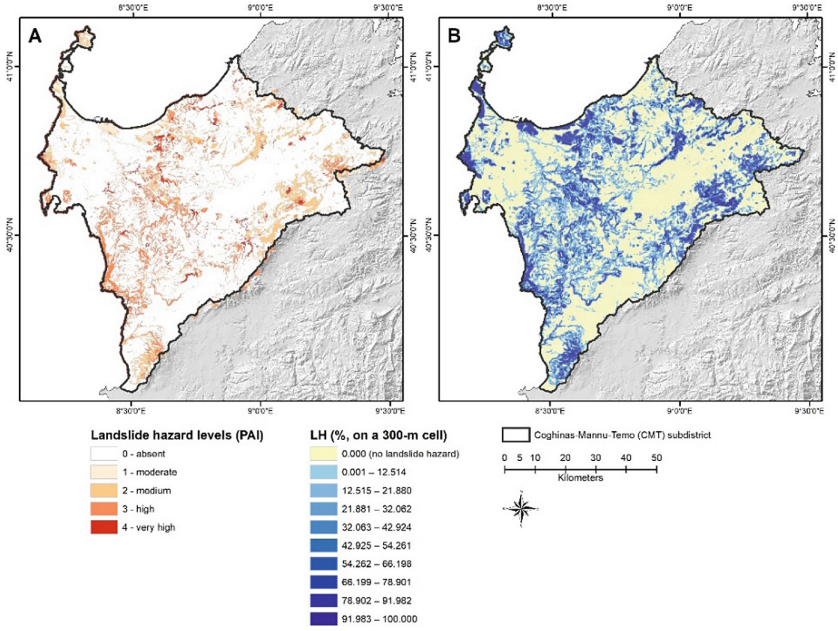

Fig. 2. Landslide hazard levels as assessed by the regional PAI in the CMT subdistrict (panel A), and spatial distribution of the LH variable in the 300 m grid used in this study (panel B).

3.2 The Spatial Framework of the LEAC Groups

Three LEAC groups prevail in the CMT subdistrict, as shown in Table 2 and Fig. 3: arable land and permanent crops (32.09%); pastures and mosaic farmland (26.68%); natural grasslands, sclerophyllous vegetation and heathlands (23.19%). Together, they make up 81.96% of the study area. Next come standing forests (14.98%), while artificialized land amounts to 2.37% of the study area, and a negligible share (0.69%) is that of waters, which are not listed in Table 2 because they were not relevant for this study.

Table 2. LEAC groups as share of the Coghinas-Mannu-Temo subdistrict.

LEAC Groups	Area (% CMT)
Artificialized land (land taken by development)	2.37
Arable land and permanent crops	32.09
Pastures and mosaic farmland	26.68
Standing forests	14.98
Natural grasslands, sclerophyllous vegetation, and heathlands	23.19

Panels B-F in Fig. 3 show the spatial layout of the share of each LEAC group in the 300-m grid cells used within this study. Cells having non-null values of L_TAKE

form small and spatially disarticulated bundles. Cells where a share of arable land and permanent crops (ARA) is present cluster especially along the main plains; however, they are spread across the subdistrict, except for the Asinara Island to the north and the mountain areas that delineate the borders of the watersheds. In the latter, clusters of cells hosting standing forests (FOR) are clearly visible in the map, while the Asinara Island is a hotspot for natural grasslands, sclerophyllous vegetation, and heathlands (GRSH), which also feature along the rugged western coast and are scattered across CMT. Finally, cells hosting pasture and mosaic farmland (PMF) are diffuse across the subdistrict, with the larger assemblage along the Marghine mountain chain to the southern border.

3.3 The Outcomes of the Regression Model

The strength and significance of correlations between the explanatory variables in model (1) were preliminarily assessed through the Pearson product–moment correlation coefficient. The outcomes of this assessment, which was carried out on the attribute table of the shapefile containing the 30,775 cells having non-null values of LH, show that the strongest correlation is that between PMF and GRSH (-0.4033, $p < 0.01$), while $|r| < 0.4$ for the remaining couples of variables. The lack of strong correlations between the explanatory variables highlights the absence of issues of multicollinearity in model (1).

The estimates of the coefficients of DEPOL and VOLSE are significant and show the expected signs, since comparatively higher values of LH are associated with the incoherent and loose substrates that characterize quaternary deposits, and comparatively lower LH values are correlated with the solid and resistant substrates that feature volcanic sedimentary rocks. Moreover, lower altitudes are associated with higher landslide hazard, and a decrease of 100 m is correlated with an increase of 1.8% in landslide hazard. While this outcome may seem counterintuitive, the reason lies in the peculiar spatial taxonomy of landslide hazard in the study area, where high-landslide-hazard zones are concentrated in locations characterized by comparatively low and medium elevation. Finally, as regards the control variables, the spatially lagged variable shows a positive and significant sign, in terms of p-values, which shows an effective control of the spatial autocorrelation of the dependent variable.

The estimated coefficients of the five explanatory variables are significant at 1% and entail the following results, provided that everything else is equal.

Agricultural land, whether characterized by extensive or intensive production, is negatively associated with landslide hazard, showing comparatively low correlations, since, on average, a 10% increase in pastures and mosaic farmland or in arable land corresponds to a 0.7% decrease or to a 1% decrease in landslide hazard.

Positive correlations are shown by the coefficient of FOR, since 10% increases in FOR and GRSH are associated with 1.4% and 0.9% increases in LH, respectively. Increases in forests, natural grasslands, sclerophyllous vegetation, and heathlands are associated with higher values of LH, which entails that such land covers are likely to identify buffer zones with respect to areas characterized by relevant landslide hazard. The spatial contexts featured by these land covers are usually almost totally devoid of human settlements, which highlights a virtuous spatial organization, which aims at protecting urbanized areas from the negative impacts generated by landslides, by preserving natural forests and grasslands from land-taking processes.

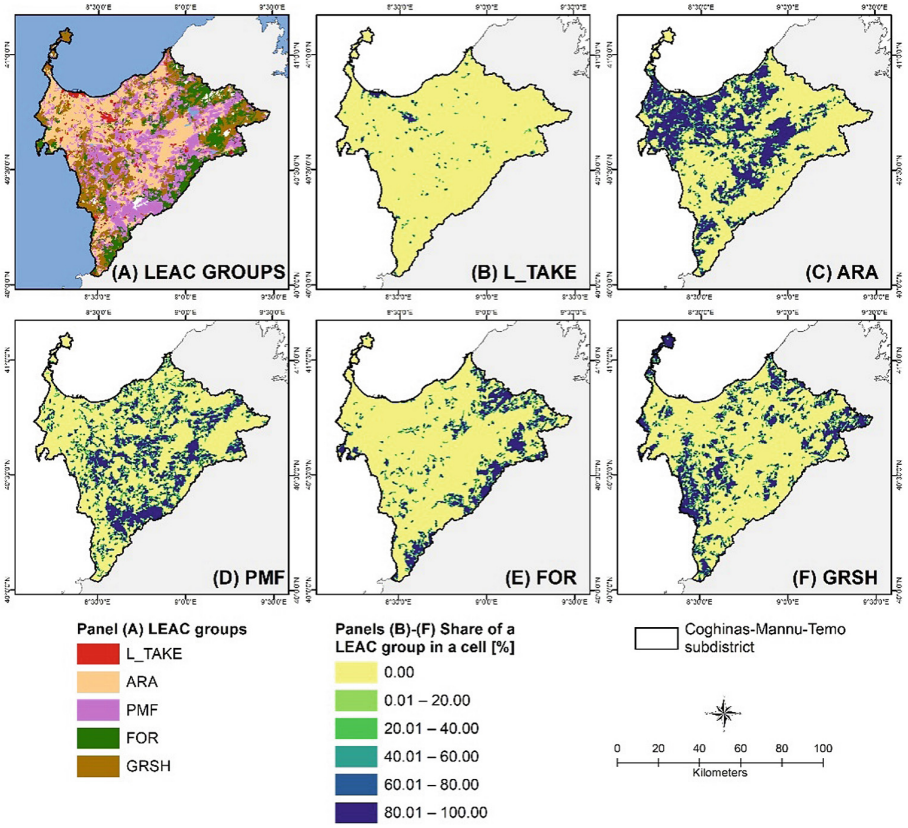

Fig. 3. Spatial distribution of land covers in CMT classed through the LEAC groups (panel A), and share of each LEAC group within the 300 m grid used in this study (panels B, C, D, E, F).

All in all, crop production is not associated with increases in LH. On the other hand, forests are the LEAC group that reveals the most relevant positive correlation with landslide hazard, whereas natural grasslands, sclerophyllous vegetation, and heathlands are less relevant in terms of association with LH.

Finally, the regression model identifies the association of LH and L_TAKE as a relevant positive correlation; namely, a 10% increase in L_TAKE is associated with a 0.8% increase in LH. In other words, the higher the size of the land take-related covariate, the higher the size of areas characterized by relevant landslide hazard. This finding highlights that the spatial structure of the study area is characterized by artificialized areas intertwined with areas featured by relevant landslide hazard, or that land-taking processes have taken place in locations that should have been preserved free from urbanization processes due to the magnitude of landslide hazard. Table 3 reports the results of the estimate and relevant statistics of regression model (1).

Table 3. Estimate of regression model (1).

Variable	Coefficient	t–Statistic	p–value
ARA	−0.10613	−11.28802	0.00000
PMF	−0.07235	−7.81156	0.00000
FOR	0.14146	14.72390	0.00000
GRSH	0.09436	10.44108	0.00000
L_TAKE	0.08803	5.85287	0.00000
DEPOL	0.01569	1.68502	0.09201
VOLSE	−0.07308	−15.41213	0.00000
ELEV	−0.00978	−10.60318	0.00000
HGLAGGED	0.96762	23.96984	0.00000
Adjusted R-squared: 0.83247			

4 Discussion

The mapping of landslide hazard in the study area is quite consistent with the taxonomies of similar spatial contexts described and discussed in the current literature. Hilly spatial contexts intertwined with plain areas, such as the CMT, are often associated with limited zones characterized by relevant landslide hazard and by diffused geological instability, as demonstrated by the regional screening of landslide phenomena in the lowlands of Calabria, Southern Italy [26]. The European screening study by Jaedicke et al. [27] identifies the European hotspots concerning landslide hazard, based on the implementation of the models defined by the International Center for Geohazards (ICG) and the Joint Research Center of the European Commission (JRC), which are often located in hilly and plain areas, i.e., with morphological characteristics similar to the CTM subdistrict, sometimes featured by high levels of precipitation and seismic activity. The European screening is quite consistent with what was detected in the case of the landslide inventory implemented by Solís-Castillo et al. [28] as regards the Mexican tropical region of Sierra Costa, characterized by low precipitation rates and landslide hazard diffused over mountainous and plain zones. Analogous findings are shown in many recent studies (among which [29] and [30]).

The spatial distribution of the LEAC groups in the study area is consistent with the spatial taxonomies reported in other studies concerning landslide hazard in hilly spatial contexts intertwined with plain areas. As in the case of the CTM subdistrict, important relations between landslide hazard and farming production in hilly and plain zones have been identified in the literature [31]. Landslide hazard and related events in hilly spatial contexts intertwined with plain areas are mainly related to soil erosion phenomena [32], which should be addressed by increasing soil retention capacity [26], and the endowment of ecosystem services such as ground and superficial water resources quality and recharge, ground and underground biodiversity, and soil resilience to the impacts of climate change and of landslide events [33].

The outcomes of the regression model can be straightforwardly discussed in the theoretical and technical context of the current literature.

Negative correlations are associated with agricultural land, whether it is characterized by intensive or extensive crop farming. This is consistent with the results of several studies which relate the effectiveness of soil conservation practices based on agriculture (among many, [34]). In particular, the mapping of the quoted study by Santangelo et al. [34] is consistent with the regression outcomes related to the covariates that identify forests (FOR), and natural grasslands, sclerophyllous vegetation, and heathlands (GRSH). Since the latter two LEAC groups characterize non-urbanized areas, it has to be put in evidence that a virtuous approach to land use planning brings together Central Italy and the Sardinian CMT subdistrict, since areas with relevant landslide hazards have been kept almost totally settlement-free.

The outcomes related to the DEPOQ covariate are consistent with previous studies [35, 36], where significant landslide hazard is correlated to inland wetlands, whereas coastal wetlands are associated with low LH, which brings together the CMT and the Central Italy coastal wetlands, as characterized by Santangelo et al. [34].

As for forests, woodlands, and shrubs, not only do they almost totally feature the non-urbanized areas of the CMT district, but also, they act as spatial contexts whose management is crucial to implement planning policies aimed at decreasing the environmental risk associated with landslide hazard. The enhancement and strengthening of forests and woodlands is related to the protection of primary forests, to forest recovery activities, to sustainable management of forests and woodlands, and to tree planting in spatial contexts characterized by different prevailing ecosystems, such as urban and agricultural areas, where these LEAC groups play a decisive role in mitigating the impact of landslide hazard [37]. FAO identifies forest sustainable management as the most important operational category to enhance economic, social, and environmental quality of rural areas, mainly because of its impact on improvement of crop production and productivity connected to protection from flood and landslide effects [38]. Forest and woodlands' recovery and new arboreal plantations are particularly relevant for the definition and implementation of spatial planning policies since the assessment of their economic impact in terms of mitigation and adaptation to climate change is generally recognized as particularly effective in the medium and long runs, especially due to decrease in flood and landslide risk [39], as well as for biodiversity protection and enhancement [40].

Finally, the regression model shows that landslide hazard is significantly associated with land take in the CMT subdistrict. This finding is supported by the fact that the other results of the regression are consistent with the outcomes of several studies available in the current literature, which implies that the definition and implementation of spatial planning policies aimed at addressing landslide hazard in the study area are almost entirely an issue of countering the ongoing land-taking processes and of deurbanizing at least a part of the areas located in landslide-prone zones. This is a key issue in the current scientific and technical debate (among many, [41, 42]), and it is widely discussed in the fifth section.

5 Policy Implications

The results show a positive correlation between coefficient of FOR and landslide hazard due to virtuous spatial organization aimed at protecting urbanized areas and at preserving natural forests and grassland from land-taking processes. Forests have positive effects on reducing impacts of landslide. In shallow soils, deep-rooted trees and shrubs may reduce the occurrence of rapid landslide, while trees may represent a physical barrier to contrast rocks and debris. Two main policy implications can therefore be identified as follows. First, forest management should consider the potential of forests and woodlands for landslide protection by restoring and protecting natural forests [43] and by maintaining forest cover. Secondly, spatial planning should localize forest in high-risk areas in order to support a virtuous spatial organization that locates human settlements and activities in zones characterized by low levels of landslide hazard.

The most prominent result is, however, the significant positive correlation concerning L_TAKE; therefore, as far as land covers and their effects on landslide hazard are concerned, controlling land-taking processes is the main road to mitigating the hazard. On this premise, three main groups of policy implications, respectively concerning land densification, land recycling, and strategic environmental assessment, can be identified as follows.

As for land densification, it implies that land is developed within existing settlements so as to take advantage of existing infrastructure without using undeveloped land [44], Therefore, national and regional administrations should promote land recycling strategies within regional plans, to be further downscaled at the local level through municipal masterplans where new development should be allowed only if its impacts on land take are negligible. Moreover, regional strategies should promote a compact urban model based on the land densification concept to reduce demand for undeveloped areas. However, this should not be regarded as a "one size fits all" solution, as local specificities need to be taken into account. Indeed, such measures have been found to be particularly effective in developed countries, whereas in Latin America and Sub-Saharan Africa, as well as in already hyper-dense Asian megacities, further urban densification can bring about negative effects in terms of inequality of spatial distribution and social conditions of the local communities [45].

With regard to land recycling, this is mainly supported through financial and regulatory tools. Concerning the former, financial support through publicly funded programs [46] and subsidies generated through impact fees, soil sealing fees, or improvement levies [47] are among the most common tools to promote land recycling. However, national and regional governments should diversify the set of fiscal tools that usher in creative and innovative ways to manage land uses effectively and efficiently. For example, the transfer of development rights can be used to direct development towards already taken up and well-serviced areas, rather than towards greenfield areas that are poorly connected in terms of transport, infrastructures, facilities, and services. As for regulatory tools, such as zoning schemes and land use regulations, these could successfully promote the participation of the private sector within land recycling projects. Furthermore, flexible and performance-based zoning regulations could be adopted within municipal masterplans [48]: these should pursue strict limits and constraints on land take, while allowing land uses that do not result in artificial land, hence in turn promoting mixed land uses where

different functions coexist. Due to the complexity of interests at stake, measures concerning land-take prevention and limitation, be they finance-based or regulation-based, call for active involvement of local communities and municipalities [49], and for effective vertical and horizontal cooperation between governments and other public bodies [50].

A third important policy implication concerns strategic environmental assessment (SEA), an appraisal planning tool that is mandatory in EU countries, which ensures that environmental considerations and sustainable-oriented goals are integrated into plan-making processes by assessing their likely effects on the environment, by considering reasonable and more sustainable alternatives, and by taking into account the mutual relations between the environment and the economic and social sectors [50]. Through the comparison of alternative land uses, the identification of areas that are more suitable for certain uses, and the evaluation of cumulative, direct, and indirect impacts of land-based investments, SEA can pave the way for the integration, within spatial plans, of measures aimed at preventing or minimizing land take.

In areas prone to landslide hazard (as well as in areas prone to flood hazard, which are not the object of this study), in Sardinia the PAI maps serve as a spatial reference for the PAI regulations, which restrict land uses and prevent land transformations depending on the magnitude of the hazard. In this way, the PAI provides a legally binding framework for municipal masterplans, whose zoning choices must comply with the PAI regulations, contrary to what has been reported in other countries [51], where new development in landslide hazard areas is not prohibited [52]. Hence, this higher-level regional planning tool contributes to limiting land-taking processes in fragile areas, while also providing relevant spatial information to planners in charge of drafting land use plans and appraising them through the SEA. Moreover, because the PAI maps are publicly available through the regional geoportal, they also contribute to raising local authorities' and local communities' awareness of landslide hazard and, by doing so, to granting transparency and legitimacy to restrictions that otherwise would be, in principle, quite conflictual.

6 Conclusions

In this study a novel methodological approach was proposed with a view to analyzing the relations between land-taking processes and landslide hazard in order to understand whether, and to what extent, land-take phenomena are associated with landslide hazard. The outcomes of this analysis were next used to define policy suggestions that, by preventing or minimizing land take, can help mitigating landslide hazard, therefore indirectly preventing the human and economic losses that might result from land mismanagement. The methodological approach here proposed as a tool to support decision-making processes can be exported to other European contexts, since the CLC inventory is available for 39 European countries [14], among them the 27 EU Member States, provided that a detailed landslide hazard or landslide susceptibility spatial dataset is available, which is not the case for all of the EU Member States, as reported in a recent study by Mateos et al. [51].

Moreover, the methodological approach shows a certain degree of flexibility, allowing for the inclusion of further context-specific spatial or normative variables that might

be appropriate or needed in other contexts. In our selected case study, the influence of two LEAC groups (open space with little or no vegetation; transitional woodland and shrub) on landslide hazard could not be assessed because they were not relevant in the study area, hence this might be a matter for future investigation in other contexts. In addition, the impact of specific land cover classes on landslide hazard was here not assessed due to the simplified classification of the LEAC taxonomy, where the 44 CORINE land covers are aggregated into eight groups. Future directions of the research might therefore include a more detailed analysis, where the LEAC groups are (completely or partly) replaced by the CLC classes, which might, however, result in a more complicated implementation of the model and interpretation of its results.

This study has analyzed the relations between land-taking processes and landslide hazards in a cross-section terms; therefore, dynamic issues, such as the evolution process of land covers or the development through time of different forms of urbanization are not within the scope of this work. However, these are relevant future directions related to the research work proposed in this article, which may entail the assessment of the dynamics of the relationship between landslide hazard and land-taking processes. The advantages in analyzing how land cover changes are correlated to landslide hazard are connected with the outstanding dynamicity that characterizes land cover change processes. Although different factors influence landslide hazard in the long run, such as geological and geomorphological phenomena, land covers are also characterized by short-term dynamics, which stresses the relevant added value which may be provided by a time-series-based contextualization of the cross-section assessment here implemented. As regards the dynamic relationships between urbanization processes and landslide hazard, further important research directions are represented by the assessment of landslide phenomena in different cities and towns characterized by diversified urban morphologies, ranging from dense and compact urban fabrics to sparse and widespread urbanization, in order to define and implement planning policies and measures aimed at countering and mitigating landslide hazard.

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References

1. European Environment Agency: The European environment—State and outlook 2020. Knowledge for transition to a sustainable Europe. Publications Office of the European Union, Luxembourg (2019)
2. European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. EU soil strategy for 2030, Reaping the benefits of healthy soils for people, food, nature and climate (2021). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0699. Accessed 17 Jan 2023
3. European Environment Agency: Land take and land degradation in functional urban areas, EEA Report n. 17/2021. Publications Office of the European Union, Luxembourg (2021)
4. Notaro, S., Paletto, A.: The economic valuation of natural hazards in mountain forests: an approach based on the replacement cost method. J. Forest Econ. **18**, 318–328 (2012). https://doi.org/10.1016/j.jfe.2012.06.002
5. Huber, S., et al. (eds.): Environmental assessment of soil for monitoring. Volume I, Indicators & Criteria. EUR 23490 EN/1. Office for the Official Publications of the European Communities, Luxembourg (2008)
6. Meneses, B.M., Pereira, S., Reis, E.: Effects of different land use and land cover data on the landslide susceptibility zonation of road networks. Nat. Hazards Earth Syst. **19**, 471–487 (2019). https://doi.org/10.5194/nhess-19-471-2019
7. Hao, L., van Westen, C., Rajaneesh, A., Sajinkumar, K.S., Martha, T.R., Jaiswal, P.: Evaluating the relation between land use changes and the 2018 landslide disaster in Kerala, India. CATENA **216**(106363), 1–13 (2022). https://doi.org/10.1016/j.catena.2022.106363
8. Tasser, E., Mader, M., Tappeiner, U.: Effects of land use in alpine grasslands on the probability of landslides. Basic Appl. Ecol. **4**, 271–280 (2003). https://doi.org/10.1078/1439-1791-00153
9. Vuillez, C., Tonini, M., Sudmeier-Rieux, K., Devkota, S., Derron, M.H., Jaboyedoff, M.: Land use changes, landslides and roads in the Phewa Watershed, Western Nepal from 1979 to 2016. Appl. Geogr. **94**, 30–40 (2018). https://doi.org/10.1016/j.apgeog.2018.03.003
10. García-Ruiz, J.M.: The effects of land uses on soil erosion in Spain: a review. CATENA **81**, 1–11 (2010). https://doi.org/10.1016/j.catena.2010.01.001
11. Glade, T.: Landslide occurrence as a response to land use change: a review of evidence from New Zealand. CATENA **51**, 297–314 (2003). https://doi.org/10.1016/S0341-8162(02)00170-4
12. Pisano, L., Zumpano, V., Malek, Ž, Rossokopf, C.M., Parise, M.: Variations in the susceptibility to landslides, as a consequence of land cover changes: a look to the past, and another towards the future. Sci. Total Environ. **601–602**, 1147–1159 (2017). https://doi.org/10.1016/j.scitotenv.2017.05.231
13. Muñoz-Torrero Manchado, A., Ballesteros-Cánovas, J.A., Allen, S., Stoffel, M.: Deforestation controls landslide susceptibility in Far-Western Nepal. CATENA **219**(106627), 1–11 (2022). https://doi.org/10.1016/j.catena.2022.106627
14. Copernicus Europe's Eyes on Earth 2022. CORINE land cover. https://land.copernicus.eu/pan-european/corine-land-cover. Accessed 17 Jan 2023
15. Autorità di Bacino Regionale della Sardegna. Studio di dettaglio e approfondimento del quadro conoscitivo della pericolosità e del rischio da frana nel sub bacino n° 3 Coghinas–Mannu–Temo. https://www.regione.sardegna.it/index.php?xsl=509&s=1&v=9&c=12097&tb=8374&st=13. Accessed 17 Jan 2023
16. IFFI—Inventario dei fenomeni franosi in Italia. https://www.progettoiffi.isprambiente.it. Accessed 17 Jan 2023

17. Zoppi, C., Argiolas, M., Lai, S.: Factors influencing the value of houses: estimates for the city of Cagliari. Italy. Land Use Policy **42**, 367–380 (2015). https://doi.org/10.1016/j.landusepol.2014.08.012
18. Byron, R.P., Bera, A.K.: Linearized estimation of nonlinear single equation functions. Int. Econ. Rev. **24**, 237–248 (1983). https://doi.org/10.2307/2526125
19. Anselin, L.: Spatial econometrics. In: Baltagi, B.H. (ed.) A companion to Theoretical Econometrics, pp. 310–330. Blackwell, Oxford (2003)
20. Anselin, L., Syabri, I., Kho, Y.: GeoDa: an introduction to spatial data analysis. Geogr. Anal. **38**, 5–22 (2006). https://doi.org/10.1111/j.0016-7363.2005.00671.x
21. European Environment Agency. Land accounts for Europe 1990–2000: Towards integrated land and ecosystem accounting. European Environment Agency Report no. 11. Office for Official Publications of the European Communities, Luxembourg (2006)
22. Isola, F., Lai, S., Leone, F., Zoppi, C.: Land take and landslide hazard: spatial assessment and policy implications from a study concerning Sardinia. Land **12**(359), 1–23. https://doi.org/10.3390/land12020359
23. Regione Autonoma della Sardegna. Sardegna Geoportale. Carta Geologica di base della Sardegna in scala 1:25.000. https://www.sardegnageoportale.it/index.php?xsl=2420&s=40&v=9&c=14479&es=6603&na=1&n=100&esp=1&tb=14401. Accessed 17 Jan 2023
24. Regione Autonoma della Sardegna. Linee Guida per l'Adeguamento dei Piani Urbanistici Comunali al PPR e al PAI. Assetto ambientale. Bozza 2008. https://www.sardegnaterritorio.it/documenti/6_83_20081007095546.zip. Accessed 17 Jan 2023
25. Regione Autonoma della Sardegna. Sardegna Geoportale. Modelli digitali del terreno e delle superfici. https://www.sardegnageoportale.it/areetematiche/modellidigitalidielevazione. Accessed 17 Jan 2023
26. Vennari, C., et al.: Rainfall thresholds for shallow landslides occurrence in Calabria, Southern Italy. Nat. Hazards Earth Syst. Sci. Discuss. **1**, 5141–5179 (2013). https://doi.org/10.5194/nhessd-1-5141-2013
27. Jaedicke, C., et al.: Identification of landslide hazard and risk 'hotspots' in Europe. Bull. Eng. Geol. Env. **73**(2), 325–339 (2013). https://doi.org/10.1007/s10064-013-0541-0
28. Solís-Castillo, B., Mendoza, M.E., Vázquez Castro, G., Bocco, G.: Landslide inventory map of the tropical dry Sierra Costa Region, Michoacán México. Phys. Geog. **40**, 554–577 (2019). https://doi.org/10.1080/02723646.2019.1574136
29. Lahai, Y.A., Anderson, K.F.E., Jalloh, Y., Rogers, I., Kamara, M.: A comparative geological, tectonic and geomorphological assessment of the Charlotte, Regent and Madina landslides, Western area, Sierra Leone. Geoenviron. Dis. **8**(1), 1–17 (2021). https://doi.org/10.1186/s40677-021-00187-x
30. Bradbury, T.: Whitsunday landslide study. Landslide susceptibility investigation and mapping. Cardno, Paget, Australia (2019). https://www.whitsundayrc.qld.gov.au/downloads/file/367/08-whitsunday-landslide-study-2019. Accessed 17 Jan 2023
31. Rendon, P., Steinhoff-Knopp, B., Burkhard, B.: Linking ecosystem condition and ecosystem services: a methodological approach applied to European agroecosystems. Ecos. Serv. **53**(101387), 1–16 (2022). https://doi.org/10.1016/j.ecoser.2021.101387
32. Panagos, P., et al.: Projections of soil loss by water erosion in Europe by 2050. Environ. Sci. Pol. **124**, 380–392 (2021). https://doi.org/10.1016/j.envsci.2021.07.012
33. Lal, R.: Soil conservation and ecosystem services. Int. Soil Water Conserv. Res. **2**, 36–47 (2014). https://doi.org/10.1016/S2095-6339(15)30021-6
34. Santangelo, M., et al.: Exposure to landslides in rural areas in Central Italy. J. Maps **17**, 124–132 (2021). https://doi.org/10.1080/17445647.2020.1746699
35. Sasaki, N., Sugai, T.: Distribution and development processes of wetlands on landslides in the Hachimantai volcanic group, NE Japan. Geogr. Rev. Jap. Ser. B **87**, 103–114 (2015). https://doi.org/10.4157/geogrevjapanb.87.103

36. Akumu, C.E., et al.: Inland wetlands mapping and vulnerability assessment using an integrated geographic information system and remote sensing techniques. Global J. Environ. Sci. Manag. **4**, 387–400 (2018). https://doi.org/10.22034/gjesm.2018.04.001
37. Cariñanos, P., Calaza, P., Hiemstra, J., Pearlmutter, D., Vilhar, U.: The role of urban and peri-urban forests in reducing risks and managing disasters. Unasylva **69**, 53–58 (2018)
38. FAO (Food and Agriculture Organization of the United Nations): Global Forest Resources Assessment 2020. Main Report. FAO, Rome, Italy (2020). https://doi.org/10.4060/ca9825en
39. de Groot, R.S., Blignaut, J., Van der Ploeg, S., Aronson, J., Elmqvist, T., Farley, J.: Benefits of investing in ecosystem restoration. Conserv. Biol. **27**, 1286–1293 (2013). https://doi.org/10.1111/cobi.12158
40. Morecroft, M.D., et al.: Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems. Science **366**(eaaw9256), 1–6 (2019). https://doi.org/10.1126/science.aaw9256
41. Segoni, S., Caleca, F.: Definition of environmental indicators for a fast estimation of landslide risk at national scale. Land **10**(621), 1–14 (2021). https://doi.org/10.3390/land10060621
42. Fiorini, L., Zullo, F., Marucci, A., Romano, B.: Land take and landscape loss: Effect of uncontrolled urbanization in Southern Italy. J. Urban Manag. **8**, 42–56 (2019). https://doi.org/10.1016/j.jum.2018.09.003
43. Zhang, Y., Shen, C., Zhou, S., Luo, X.: Analysis of the influence of forests on landslides in the Bijie Area of Guizhou. Forests **13**(1136), 1–27 (2022). https://doi.org/10.3390/f13071136
44. European Environment Agency. Indicator Assessment. Land recycling and densification. https://www.eea.europa.eu/data-and-maps/indicators/land-recycling-and-densification/assessment-1. Accessed 17 Jan 2023
45. Li, M., Verburg, P.H., van Vliet, J.: Global trends and local variations in land take per person. Landsc. Urban Plan. **218**(104308), 1–13 (2022). https://doi.org/10.1016/j.landurbplan.2021.104308
46. Dull, M., Wernstedt, K.: Land recycling, community revitalization, and distributive politics: an analysis of EPA brownfields program support. Policy Stud. J. **38**, 119–141 (2010). https://doi.org/10.1111/j.1541-0072.2009.00347.x
47. Tobias, S., Conen, F., Duss, A., Wenzel, L.M., Buser, C., Alewell, C.: Soil sealing and unsealing: state of the art and examples. Land Degrad. Dev. **29**, 2015–2024 (2018). https://doi.org/10.1002/ldr.2919
48. Voghera, A., Giudice, B.: Defining a social-ecological performance to prioritize compensatory actions for environmental regeneration. The experimentation of the environmental compensation plan. Sustain. Cities Soc. **61**(102357), 1–15 (2020). https://doi.org/10.1016/j.scs.2020.102357
49. Kovács, E., et al.: Understanding the links between ecosystem service trade-offs and conflicts in protected areas. Ecosyst. Serv. **12**, 117–127 (2015). https://doi.org/10.1016/j.ecoser.2014.09.012
50. Floris, M., Zoppi, C.: Ecosystem services and spatial planning: a study on the relationship between carbon sequestration and land-taking processes. Arch. Studi Urbani Reg. **127**, 11–33 (2020). https://doi.org/10.3280/ASUR2020-127-S1002
51. Mateos, R.M., et al.: Integration of landslide hazard into urban planning across Europe. Landsc. Urban Plan. **196**(103740), 1–12 (2020). https://doi.org/10.1016/j.landurbplan.2019.103740
52. Bucała-Hrabia, A., Kijowska-Strugała, M., Śleszyński, P., Rączkowska, Z., Izdebski, W., Malinowski, Z.: Evaluating the use of the landslide database in spatial planning in mountain communes (the Polish Carpathians). Land Use Policy **112**(105842), 1–15 (2022). https://doi.org/10.1016/j.landusepol.2021.105842