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QUANTITATIVE SHALLOW LANDSLIDE RISK ASSESSMENT AT REGIONAL – SCALE: TUSCANY REGION (CENTRAL ITALY) AS CASE STUDY

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EXTENDED ABSTRACT

Le frane rappresentano uno dei pericoli geologici più diffusi a livello globale, con perdite umane, economiche e sociali in costante aumento. Tale tendenza è strettamente legata sia all'espansione urbana in aree geomorfologicamente instabili, sia all'intensificarsi degli eventi meteorologici estremi in risposta all'attuale contesto di cambiamento climatico. Di conseguenza, la crescente esigenza di stimare in modo accurato le potenziali perdite al verificarsi di eventi franosi rende centrale il tema della valutazione quantitativa del rischio da frana. In letteratura, il rischio da frana è generalmente espresso come le potenziali perdite sociali e/o economiche legate all'occorrenza di un fenomeno di una certa intensità. Questa definizione si traduce comunemente nell'analisi di tre componenti fondamentali: pericolosità, vulnerabilità ed esposizione degli elementi a rischio. Alla luce di ciò, la stima dei danni potenzialmente generati da una o più frane in un determinato territorio costituisce uno strumento di grande rilevanza per la pianificazione territoriale e la gestione del rischio. Questo approccio risulta ancora più significativo nel contesto italiano. La lunga storia di danni causati da fenomeni idrogeologici nel territorio italiano è stata ulteriormente enfatizzata dai recenti eventi meteorologici estremi che hanno colpito regioni quali Marche, Emilia-Romagna e Toscana.

Questi eventi hanno nuovamente messo in evidenza la fragilità del territorio italiano e la necessità di aggiornare le strategie di gestione dei pericoli idrogeologici. Sulla base di queste considerazioni, il presente contributo propone una valutazione quantitativa del rischio da frana per il territorio della Regione Toscana. In particolare, il rischio è stato espresso come potenziali perdite economiche (€) relative agli edifici e all'uso del suolo, dovute all'innesco di frane rapide superficiali. L'obiettivo principale dello studio è aggiornare il quadro conoscitivo del rischio da frana alla luce dei recenti eventi meteorologici estremi che hanno interessato il territorio toscano, innescando un numero significativo di frane superficiali. I risultati di questo contributo evidenziano che i valori maggiori di rischio si concentrano nei settori dell'Appennino settentrionale, in particolare tra le province di Prato e Pistoia.

Questo risultato conferma che le stime maggiori di rischio sono associate ad aree caratterizzate sia da terreni altamente suscettibili all'innesco di tali fenomeni, sia dalla presenza di insediamenti urbani in contesti potenzialmente instabili. Il valore complessivo del rischio stimato per l'intera Regione Toscana ammonta a circa 1.7 miliardi €.

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ABSTRACT

Landslides are one of the most common geohazards globally, causing considerable losses in human life and property damage. Italy is one of the European countries most severely affected by landslides due to its geological and urban setting. Moreover, as the climate continues to change, extreme rainfall events are becoming more frequent, leading to a sharp rise in landslide occurrences, often numbering in the hundreds or even thousands during a single episode. An example of this trend is represented by the Tuscany region (central Italy), which has experienced an extreme rainfall event on 2 November 2023 that triggered severe flooding and widespread landslides, highlighting the need for an updated and comprehensive assessment of landslide risk. As a result, in this contribution, we present a quantitative landslide risk assessment for the Tuscany region, focusing on rapid shallow landslides. Risk is expressed as potential economic losses (€) to building and land use. The findings show that the highest risk values are concentrated along the Apennine chain, where geomorphologically susceptible terrains overlap with urbanized and agricultural areas. The aggregation of potential losses yields a total economic risk of approximately 1.7 billion €.

Keywords: *landslides, landslide risk, Italy, Tuscany, extreme rainfall events*

INTRODUCTION

Landslides are a widespread geohazard and represent a major source of human losses, economic damage, and disruption of infrastructures (Petley, 2012; Froude & Petley, 2018). Their impacts are observed at the global scale, affecting both developed and developing countries (Turner, 2018).

Within the European context, Italy is one of the countries most severely affected by landslides (Trigila *et alii*, 2018; Rossi *et alii*, 2019; Caleca *et alii*, 2025b); indeed, the majority of landslides reported in European databases are mapped across its territory (Herrera *et alii*, 2018; Caleca *et alii*, 2025a). This pattern is mainly related to the complex geomorphological and geological setting of Italy, characterized by extensive mountain and hilly landscapes, and lithologies prone to instability. Moreover, the long history of human settlement has led to the widespread presence of urban areas, infrastructures, and cultural sites located close to sectors susceptible to landslide occurrences, thus increasing the overall risk (Caleca *et alii*, 2025b).

In light of these considerations, identifying potentially unstable areas and assessing their associated consequences represents a powerful tool for land-use planning, risk mitigation strategies, and civil protection activities. These analyses belong to the framework of landslide risk assessment (Corominas *et alii*, 2014). Risk is generally defined as the expected number of lives lost, persons injured, damage to properties, and disruption of economic activities due to a phenomenon for a given area and reference period (Varnes and IAEG Commission on Landslides, 1984). Therefore, landslide risk is commonly expressed as a function of three main components: landslide hazard, vulnerability, and exposure of elements at risk (Dai *et alii*, 2002; Fell *et alii,* 2005; van Westen *et alii,* 2006; Corominas *et alii,* 2014). In this framework, landslide hazard describes the probability of landslide occurrence of a given magnitude within a specified time and area (Guzzetti *et alii,* 2005; Lombardo *et alii,* 2020; Dahal *et alii,* 2024); vulnerability expresses the degree of loss of elements at risk when affected by landslides and is strongly related to their intensity (Caleca *et alii,* 2022; Poggi *et alii,* 2026); exposure is determined by the position of the elements at risk with respect to the landslide path and is generally represented through their number or economic value (van Westen *et alii,* 2006; Pellicani *et alii,* 2014).

Furthermore, the frequency and intensity of landslide events in Italy, as well as globally, are increasing in response to ongoing climate change. Specifically, extreme rainfall events are becoming more frequent, leading to a sharp rise in landslide occurrences, which often number in the hundreds or even thousands of failures during a single event (Berti *et alii,* 2025; Confuorto *et alii,* 2025).

An example of this trend is represented by the Tuscany region, which has experienced an extreme rainfall event on 2 November 2023 that triggered severe flooding and widespread landslides, resulting in economic losses estimated at approximately 2 billion € (Masi *et alii*, 2026, in press). This event has highlighted the need for an updated and comprehensive assessment of landslide risk at the regional level.

In light of these considerations, we present in this contribution an update of the current context of landslide risk in the Tuscany region by incorporating the most recent events (Masi *et alii*, 2026, in press) and associated products (Tofani *et alii,* 2026, in press). Whereas previous contributions focused on the development of a new landslide inventory and the updating of the landslide susceptibility map, the present work moves beyond susceptibility mapping by implementing a quantitative landslide risk assessment. The analysis focuses on shallow landslides, which represent the main type of failure during the recent meteorological events. We integrate information on the likelihood of landslides with estimates of landslide intensity, vulnerability of exposed elements (buildings and land use), and their economic value. As a result, this study provides a regional-scale quantification of potential economic losses (€) to buildings and land use across the entire Tuscany region.

STUDY AREA

The landslide risk assessment we present in this study covers the whole extension of the Tuscany region, located in Central Italy. Tuscany extends over approximately 23,000 km^2 and is characterized by a highly diversified physiographic setting. The landscape ranges from the Tyrrhenian coastal plains in the western sectors to the Apennine mountain chain (Fig. 1A), which stretches from the northwestern to the southeast. The central part of the region is hilly, interspersed with flat areas (*e.g.*, Firenze-Prato-Pistoia plain). Overall, hills account for about two-thirds of the territory, while mountainous areas cover approximately 20% and plains nearly 10%.

From a geological perspective, the Tuscan setting is closely related to the geodynamic evolution of the Northern Apennine. This mountain belt is a NE-verging fold-and-thrust system, whose origin comes from the closure of a Jurassic Ocean and subsequent collision between the Corso-Sardinian block and the Adria microplate (Martini & Sagri 1993; Vai & Martini 2001; Conti *et alii*, 2020). In Tuscany, the Apennine sectors are mostly composed of marl-arenaceous or marl-calcareous flysch formations. Whereas alluvial deposits, sands, clays, and conglomerates mainly characterize the central hilly areas.

On 2 November 2023, Tuscany was affected by an intense Atlantic weather system that produced locally exceptional rainfall amounts. The most severely affected areas covered sectors of the provinces of Pistoia, Prato, and Florence (Fig. 1B) and recorded more than 200 mm precipitation within 24 hours (Masi *et alii*, 2026, in press). The extraordinary intensity led to severe flooding and triggered widespread rapid shallow landslides throughout these sectors. These phenomena resulted in 8 fatalities, the evacuation of 300 people, and estimated economic losses of about 2 billion € (Masi *et alii,* 2026, in press). The extreme severity of these impacts was further confirmed by the declaration of a national-level state of emergency. 2020). In Tuscany, the Apennine sectors are mostly composed of marl-arenaceous or marl-calcareous flysch formations. Whereas alluvial deposits, sands, clays, and conglomerates mainly characterize the central hilly areas.

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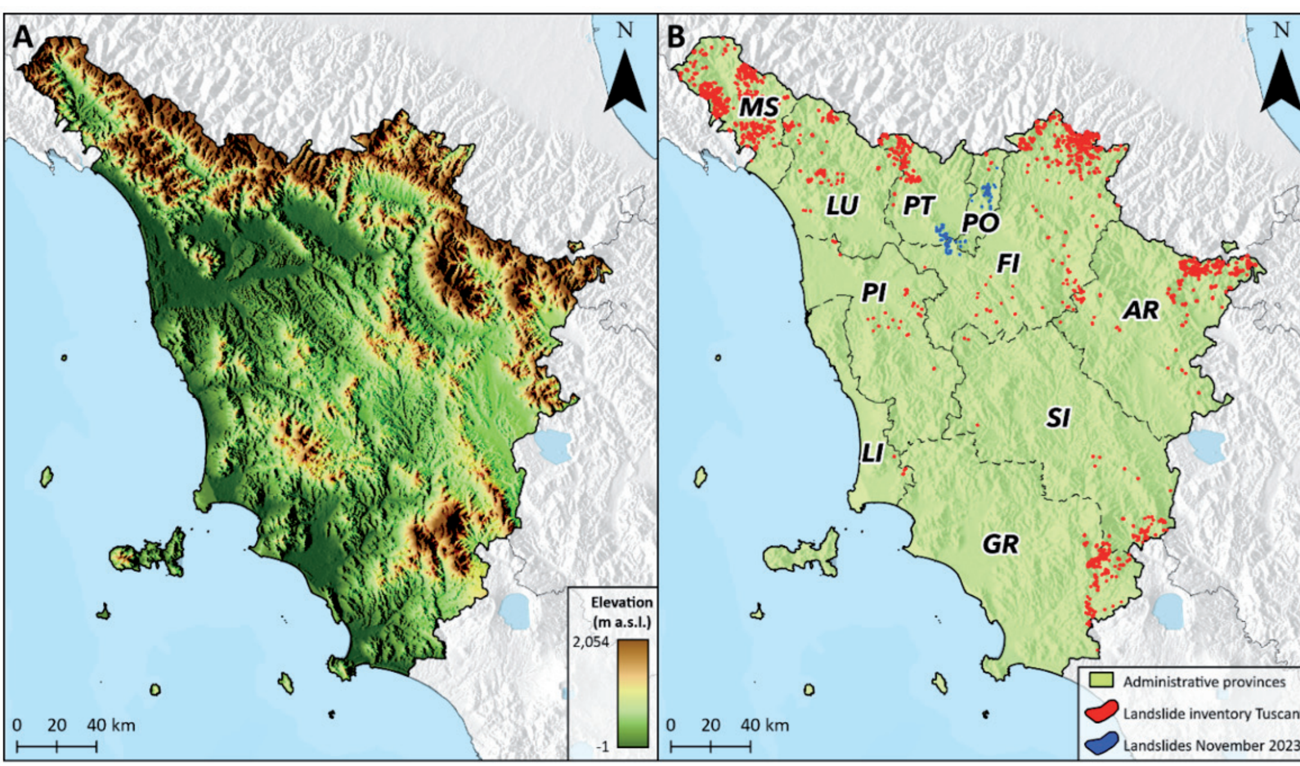

AR: Arezzo; **FI**: Florence; **GR**: Grosseto; **LI**: Livorno; **LU**: Lucca; **MS**: Massa-Carrara; **PI**: Pisa; **PO**: Prato; **PT**: Pistoia; **SI**: Siena.

Fig. 1 - A) The elevation of the Tuscany region. B) Administrative units (provinces) of the region and spatial distribution of rapid shallow landslides in the IFFI database (red color) and shallow landslides triggered on 2 November 2023 (blue color)

DATA AND METHODS

In this section, we describe the input data and the methodological phases adopted to assess landslide risk for the Tuscany region. All analyses are performed using slope units (hereafter SUs) as the spatial mapping unit of our work. This choice mainly relies on the need to ensure consistency with the landslide susceptibility mapping recently developed for the same study area by Tofani *et alii* (2026, in press), whose product is directly integrated into this work. Moreover, SUs represent geomorphologically meaningful terrain partition, as they delineate single or groups of adjacent slopes. The partition into SUs is done using the r.slopeunits (Alvioli *et alii*, 2016) software, which requires a DEM as the only input data. Specifically, the software generates SUs by clustering slope exposition through hydrological criteria. This is done by setting several parameters that r.slopeunits requires, such as the circular variance or the flow accumulation threshold. For a technical description of these parameters, we refer the reader to Alvioli *et alii* (2016). Overall, our partition results in 37,756 SUs with a mean planimetric area of 0.49 km^2. Additionally, flat areas are removed from the analysis as landslides typically do not occur in these sectors.

The landslide risk assessment we propose focuses on rapid shallow landslides. Specifically, we decide to direct our analyses on these phenomena because they represent the main landslide type observed during the recent extreme rainfall events in Italy as well as in Tuscany (Berti *et alii,* 2025; Confuorto *et alii,* 2025; Masi *et alii,* 2026, in press).

The methodology we adopt relies on procedures previously proposed by other contributions (Caleca *et alii,* 2022, 2025b). However, we introduce a few updates through the integration of new datasets, such as the landslide inventory compiled after the November 2023 event by Masi *et alii* (2026, in press) and the landslide susceptibility map provided by Tofani *et alii* (2026, in press). As a consequence, the introduction of these recent products allows for an up-to-date representation of the landslide risk context in Tuscany.

Landslide hazard

Landslide hazard is commonly defined as the combination of three conditional probabilities describing the spatial occurrence, temporal frequency, and size of landslides (Guzzetti *et alii*, 2005; Lombardo *et alii,* 2020; Dahal *et alii,* 2024). In other words, hazard is generally quantified by integrating landslide susceptibility, temporal probability of occurrence, and landslide magnitude. In this study, we represent hazard exclusively through its spatial component (*i.e*., susceptibility), while the temporal and magnitude components are not explicitly considered due to data availability and methodological limitations.

The susceptibility component is derived from a recent regional-scale product developed by Tofani *et alii* (2026, in press), which provides a landslide susceptibility map designed for rapid landslides

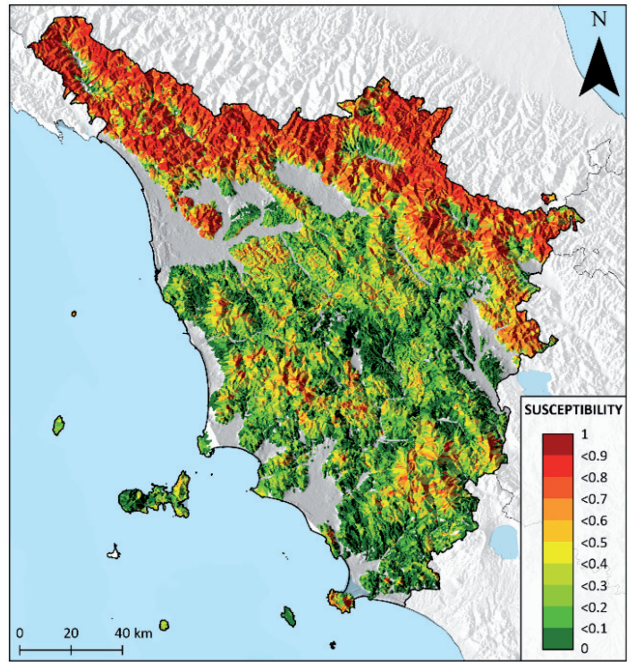

Fig. 1 - Rapid landslide susceptibility map of the Tuscany region from Tofani et alii (2026, in press)

in Tuscany, including shallow landslides. The susceptibility probabilities (Fig. 2) range from 0 to 1, where the former indicates non-susceptible conditions and the latter points out mapping units prone to failure. Overall, the probabilities were modeled across the region using an interpretable machine learning model, namely Explainable Boosting Machines (EBMs; Nori *et alii,* 2019), whose applications in susceptibility studies have been recently demonstrated (Maxwell *et alii,* 2021; Caleca *et alii,* 2024). The model was trained by combining landslide data from the Italian Landslide Inventory (IFFI; Trigila *et alii,* 2007) with the landslide inventory compiled after the November 2023 rainfall event (Masi *et alii*, 2026, in press), together with a set of environmental variables describing the main predisposing factors for rapid landslides in the study area. These environmental predictors include geomorphological parameters (*e.g*., slope steepness, eastness, and northness), as well as lithological and soil property information. Model performance was evaluated using the Area Under the Curve (AUC), which yielded a value of 0.86. According to Hosmer and Lemeshow (2000), this value indicates very good predictive capabilities.

For a detailed description of the model configuration, input variables, and model outcomes, we refer the reader to Tofani *et alii* (2026, in press).

Landslide intensity

Landslide intensity represents the destructive power of landslides (Hungr, 1997) and is a key parameter for vulnerability assessment (Uzielli *et alii*, 2008; Li *et alii,* 2010; Caleca *et alii,* 2022). Owing to its dynamic nature, landslide intensity can be defined by using different parameters depending on the landslide typology. In this work, landslide intensity is estimated following the approach proposed by Caleca *et alii* (2025b). Specifically, we express landslide intensity as a function of landslide density and landslide velocity via a semi-quantitative approach.

Landslide density is computed as the percentage of area affected by landslides within each SU. The spatial extent of landslides is derived by integrating information from the IFFI inventory together with the landslide inventory compiled after the November 2023 event (Masi *et alii,* 2026, in press).

The velocity component is estimated using a morphometric approach originally developed by Marinelli *et alii* (2022) and subsequently refined and applied at the national scale by Caleca *et alii* (2025b). This methodology leverages the Heim energy lines model, which allows for estimating the landslide velocity based on the slope morphology. Notably, the landslide body is considered as a rigid block moving down a slope, and a theoretical energy line connecting the highest point of the source area to the most distal accumulation point is defined. As a consequence, the inclination of this line with respect to the horizontal plane can then be used to derive a representative velocity value. Therefore, we apply this approach to estimate a velocity value for SUs with landslide presence. Conversely, for SUs without landslides, velocity values are inferred through a correlation-based criterion. Specifically, the relationship between the velocities computed for SUs with landslides and a set of geomorphological and geometrical parameters is analysed. Among the tested variables, the mean elevation of each SU shows the strongest correlation with velocity and is therefore adopted as a proxy. Accordingly, SUs with similar elevation values is assumed to report comparable velocities. In other words, for each SU without a landslide, a representative velocity is estimated by computing the mean velocity of SUs with landslides falling within a similar elevation value. For further technical details on this approach, we refer the reader to Caleca *et alii* (2025b).

As previously mentioned, landslide intensity is evaluated using a semi-quantitative approach based on the combined contribution of landslide density and landslide velocity. This implies the application of a contingency matrix that integrates the two components at the SU-level. Specifically, we classify the landslide density within each SU into four levels, from D_0 to D_3, following the Jenks method (Jenks & Caspall 1971). Similarly, the landslide velocities are divided into four distinct classes (from Vel_1 to Vel_4) according to the following ranges: Vel_1 (velocity < 12 m/s), Vel_2 (12 m/s < velocity < 15 m/s), Vel_3 (15 m/s < velocity < 21 m/s) and Vel_4 (velocity > 21 m/s). As a result, the matrix allows us to identify five different intensity levels: from I_0 to I_4.

Vulnerability of elements at risk

Vulnerability represents the degree of loss of the elements within the area affected by landslides (Corominas *et alii*, 2014) and is a non-dimensional parameter ranging from 0 (no damage) to 1 (total damage). In this contribution, the landslide risk assessment relies on two types of elements at risk: buildings and land use. As a consequence, we estimate vulnerability separately for the two assets following the procedures proposed by Caleca *et alii* (2025b).

The vulnerability of buildings is evaluated as a function of both landslide intensity and their structural resistance. Specifically, the latter is computed by using a modified version of the method proposed by Li *et alii* (2010). Structural resistance depends on structural factors derived from the ISTAT database, which provides detailed information at the census-section level across Italy. Different values are assigned to the structural factors according to the literature, and these values are then used to calculate the structural resistance of each census section. Subsequently, we aggregate the resistance values to the SU-level using an area-weighted average. For the complete description of the procedure, we refer the reader to Caleca *et alii* (2025b). Finally, building vulnerability is assessed through a semi-quantitative approach by classifying structural resistance into five levels using the Jenks criterion (from R_0 to R_4): R_0 (resistance < 0.76), R_1 (0.76 < resistance < 0.90), R_2 (0.90 < resistance < 0.98), R_3 (0.98 < resistance < 1.07) and R_4 (resistance > 1.07). Structural resistance classes are combined with landslide intensity classes using a contingency matrix (Tab. 2) to derive five discrete vulnerability values ranging from 0 to 1.

The vulnerability of land use is defined as a function of the spatial distribution of land use classes and landslide intensity. The spatial distribution of land use classes is derived from the CORINE Land Cover database (Bossard *et alii*, 2000).

		Landslide velocity			
		Vel_1	**Vel_2**	**Vel_3**	**Vel_4**
Landslide density	**D_0**	I_0	I_0	I_0	I_0
	D_1	I_1	I_2	I_2	I_3
	D_2	I_1	I_2	I_3	I_4
	D_3	I_2	I_3	I_4	I_4

Tab. 1 - Contingency matrix for the landslide intensity assessment

		Landslide intensity				
		I_0	I_1	I_2	I_3	I_4
Structural resistance	**R_4**	0	0	0.25	0.25	0.50
	R_3	0	0.25	0.25	0.50	0.50
	R_2	0	0.25	0.50	0.50	0.50
	R_1	0	0.25	0.50	0.75	0.75
	R_0	0	0.25	0.75	0.75	1
	R N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

Tab. 2 - Contingency matrix of the building vulnerability.

		Landslide intensity				
		I_0	I_1	I_2	I_3	I_4
Land use	**Arable lands**	0	0.05	0.40	0.70	0.90
	Permanent crops	0	0.10	0.30	0.50	0.70
	Pasture – agricultural areas	0	0.10	0.30	0.50	0.70
	Forests	0	0.05	0.10	0.20	0.30
	Shrubs – open spaces	0	0	0	0.05	0.10

Tab. 2 - Contingency matrix of land use vulnerability

Specifically, the land use classes are arable lands, permanent crops, pastures and heterogeneous agricultural areas, forests, shrubs and open or sparsely vegetated areas, and wetlands. For each land use class, a vulnerability value (Tab. 3) is assigned based on the landslide intensity of the corresponding SU. The final land use vulnerability for each SU is then computed as an area-weighted average of the vulnerability values of the land use classes present within the SU.

Exposure of elements at risk

Exposure is an attribute of people, properties, or other elements placed in the area that might be affected by landslides. As a result, exposure is directly related to the position of the element at risk with respect to the landslide path. In this contribution, we assume that all the elements placed within a SU would be affected in the event of a landslide. This assumption is due to methodological limitations in estimating the landslide runout at the regional level. We express exposure in monetary terms and estimate it separately for buildings and land use.

Building exposure is estimated by integrating both their spatial distribution (m^2) and market values (€/m^2) for our mapping units. The building footprint (m^2) within each SU is computed by leveraging a dataset available on the geoportal of the Tuscany region (https://www502.regione.toscana.it/geoscopio/cartoteca.html). The real estate market values (€/m^2) are retrieved from the Osservatorio Mercato Immobiliare (OMI) database. Specifically, we assign a different market value depending on the several types of buildings reported by both datasets. As a result, we compute a monetary exposure of buildings (€) by combining this information for each SU, by summing the value of all the buildings placed in its domains.

Equally, the land use exposure is obtained through their spatial distribution of land use classes and their market values for each SU. In this case, the spatial distribution is computed for each land use class through the CORINE Land Cover database. Whereas the land prices are acquired from the Valori Agricoli Medi (VAM) database. As a result, the total monetary exposure of land use within each SU is then computed by summing the values of all land use classes present.

Landslide risk assessment

The landslide risk assessment relies on the theoretical framework outlined by several contributions (Dai *et alii*, 2002; Fell *et alii,* 2005; van Westen *et alii,* 2006; Corominas *et alii,* 2014). Notably, landslide risk can be expressed as follows:

$$R = \sum(H \sum (VE))$$

where the total risk (R) is expressed in € and is given by the landslide hazard (H), vulnerability (V), and exposure (E) of elements at risk. Additionally, we recall here that landslide hazard is considered solely in terms of its spatial component (*i.e.*, susceptibility).

RESULTS

In this section, we present the results derived from the landslide risk assessment, in which risk is expressed as potential economic losses (€) to buildings and land use. As outlined, the analysis focuses exclusively on rapid shallow landslides.

Fig. 3 displays the spatial distribution of landslide risk values across the Tuscany region. The estimated potential economic losses range from 0 to a maximum of approximately 54 million €. The overall distribution of risk values can be summarized by a mean of 0.05 million € and a single standard deviation of 0.64 million €. The analysis of Error! Reference source not found. indicates that the majority of the Tuscan territory is characterized by very low risk estimates; approximately 97% of SUs report potential economic losses equal to zero. When these zero-value units are excluded, the mean potential economic loss increases to 1.8 million €, with a corresponding standard deviation of 3.6 million. The aggregation of risk values across all SUs yields a total estimated economic risk from rapid shallow landslides in Tuscany of approximately 1.7 billion €. Notably, about 93% of this total risk is associated with potential losses to buildings, while the remaining 7% is related to land-use categories, highlighting the dominant role of buildings in the overall risk assessment.

From a geomorphic perspective, the highest risk values are predominantly concentrated along the Apennine chain, particularly in the sectors between the provinces of Prato and Pistoia (Fig. 1B). For instance, the SU reporting the highest value of potential economic losses is located in the municipality of Vaiano (Fig. 3B), which is also one of the municipalities severely affected by landslides in November 2023 (Masi *et alii*, 2026, in press).

From an exposure perspective, elevated risk values correspond to areas where geomorphologically susceptible terrain overlaps with built-up areas and agricultural land. While the main urban centers are primarily located in coastal and flat areas that generally show lower risk values or are removed from our analysis.

Overall, the results highlight a spatially heterogeneous distribution of landslide risk in Tuscany, characterized by widespread zero or very low values and a limited number of SUs contributing disproportionately to the total economic risk. This pattern indicates that regional landslide risk is controlled by the combined effects of geomorphological predisposition and the spatial distribution of exposed elements.

To further investigate the spatial distribution of landslide risk estimates, we analyze the data at two different administrative levels, namely the municipal and provincial scales (Fig. 4). For each administrative unit, we compute the mean landslide risk (€/m^2) as the ratio between total estimated risk (€) and the surface area (m^2) of the unit.

Fig. 4A displays the aggregation at the municipal level. As previously discussed, municipalities reporting the highest landslide risk values are mainly located along the Apennine

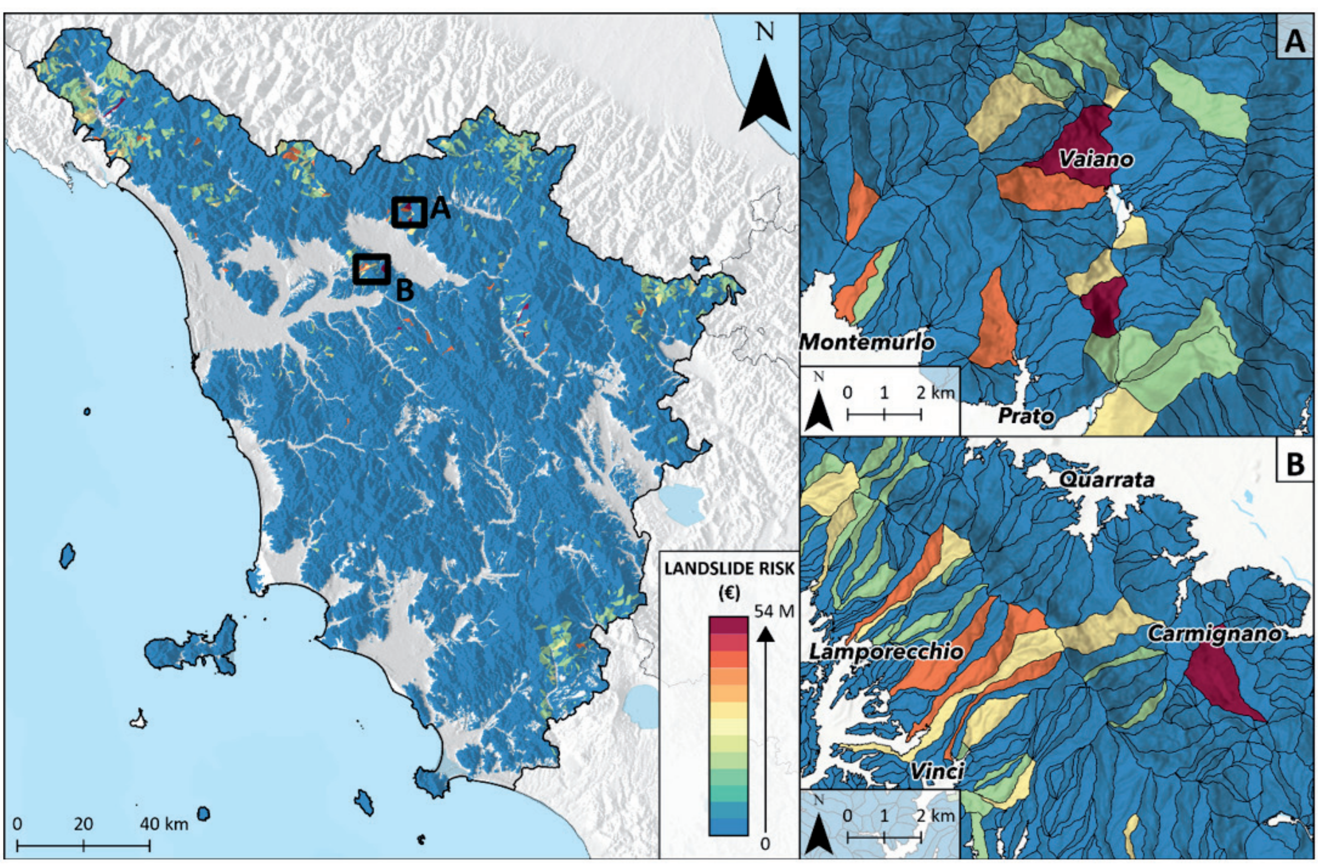

Fig. 3 - Spatial distribution of estimated landslide risk values for the Tuscany region

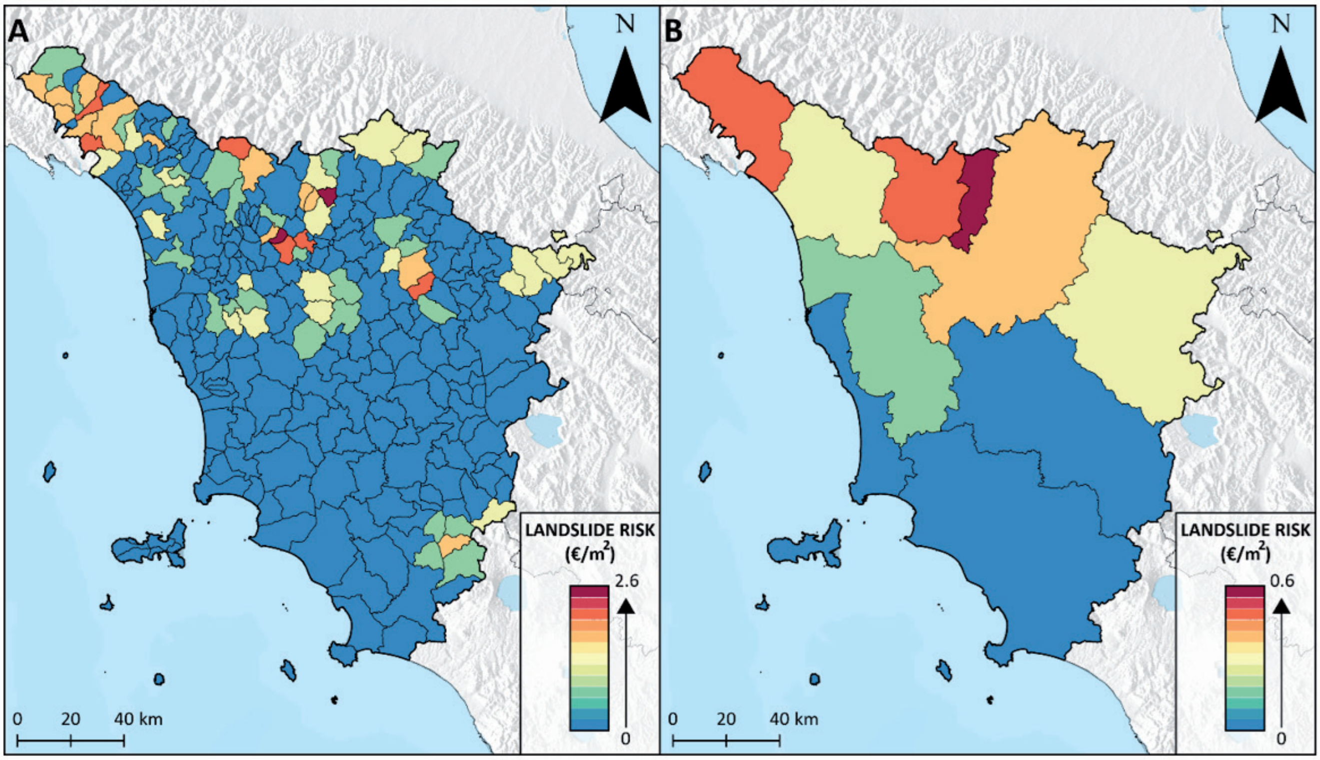

Fig. 4 - Overview of landslide risk across the administrative levels of Tuscany. A) Municipal level. B) Provincial level

sectors. The ten municipalities with the highest mean risk are all situated within or in proximity to the Apennines. Among them, Vaiano (province of Prato) records the highest mean value of potential economic losses, equal to 2.6 €/m^2.

Fig. 4B depicts the aggregation of landslide risk at the provincial level. Even in this context, provinces within the Apennine sectors display the highest mean risk values. Notably, the province of Prato reports a mean value of potential economic losses of approximately 0.6 €/m^2. Compared with Fig. 4A, the aggregation at the provincial level presents a smoothed pattern, reflecting the effects of coarser spatial aggregation.

DISCUSSION

The landslide risk assessment highlights a heterogeneous spatial distribution of potential economic losses across the Tuscany region, with most of SUs exhibiting null or low risk. This implies that a limited number of areas account for most of the total estimated losses. This pattern reflects the combined effects of geomorphological controls on landslide occurrence and the uneven spatial distribution of exposed assets, such as buildings.

The concentration of high-risk values along the Apennine chain, especially between the provinces of Prato and Pistoia (Fig. 3), is consistent with the geomorphological and lithological context of these sectors. These areas are locally characterized by steep slopes and high local relief, which facilitate unstable conditions. From a lithological perspective, these sectors are largely composed of sand, which has high permeability and a rapid hydrological response to intense rainfall events. Under such conditions, rainfall infiltration can lead to an increase in pore pressure and reduce the stability of a slope. As a result, the combination of the morphological setting and such soil properties mainly contributes to the high susceptibility and also explains the spatial correspondence between high potential economic losses. Moreover, the high-risk estimates observed in the Apennine sectors are strongly related to the patterns of human exposure. In these areas, human settlements are frequently located along valley bottoms or on mid-slope positions, often in proximity to unstable areas. This spatial distribution reflects historical land-use practices, but it also increases the exposure component in the landslide risk assessment. As a result, the overlapping of geomorphologically susceptible areas and exposed elements contributes significantly to the concentration of higher risk values in these sectors.

Conversely, the large proportion of SUs with risk equal to zero can be mainly related to lithological and geomorphological conditions. From a lithological perspective, these sectors are mainly characterized by lithological units less susceptible to shallow landslides, while being more prone to deep-seated slides and slow-moving phenomena (Segoni *et alii*, 2015; Rosi *et alii*, 2018). Furthermore, hilly areas are typically characterized by lower slope steepness and relief energy compared to the

Apennine sectors. This implies that both landslide intensity and the corresponding vulnerability of elements at risk might be lower. This explains the widespread occurrence of SUs with potential economic losses equal to zero.

Despite the several key points highlighted by this study, a few limitations should be acknowledged. Our landslide risk assessment relies on the assumption that all elements within a SU would be affected in the event of a landslide. As a consequence, exposure, particularly that of buildings, plays a fundamental role in the analysis and strongly influences the estimated potential economic losses. This effect mainly arises from the difference in magnitude between exposure and the other risk components, such as landslide hazard and vulnerability. In our case, landslide hazard, approximated by susceptibility, ranges from 0 to 1, and a similar range applies to vulnerability. Conversely, exposure can vary by several orders of magnitude, from 0 to billions of euros. Therefore, while hazard controls the probability of landslide occurrence, exposure largely determines the scale of potential economic losses. This role of exposure is further emphasized at the regional scale, where data and methodological constraints do not allow the adoption of run-out models for identifying which elements are likely to be impacted by a landslide. If run-out processes could be explicitly modelled, exposure estimates would be reduced and more realistic, as the analysis would no longer rely on the assumption that all elements within a spatial unit are affected.

A further shortcoming, which may pave the way for future improvements, is related to the nature of landslide risk. Here, risk is expressed solely in terms of direct losses, based on the market value of buildings and land use. However, the impacts of natural hazards extend beyond direct damage and also include indirect effects on society, such as economic disruption and social consequences. Therefore, future work could focus on integrating indirect damages into landslide risk assessments to provide a more comprehensive evaluation.

Overall, our risk assessment represents a valuable first step in identifying areas at risk by providing a regional-scale overview of potential economic losses across the Tuscany region. Although the adopted scale of analysis does not allow for direct site-specific applications, our estimates are meant to support the identification of potentially critical sectors. Specifically, the regional-scale assessment highlights areas where more detailed investigations and analyses should be planned. In short, the landslide risk estimates are not designed to assist mitigation measures or funding allocation at the local scale, but rather to support land use planning policies and to orient future site-specific studies.

CONCLUSION

In this study, we present a quantitative landslide risk assessment at the regional scale in Italy, focusing on rapid shallow landslides within the geographical extent of Tuscany. Landslide risk is expressed in terms of potential economic losses to buildings and land-use.

Our results reveal a highly heterogeneous spatial distribution of landslide risk across the region. Most of the Tuscan territory is characterized by very low or zero risk values, while a limited number of mapping units account for the majority of the total estimated risk. The aggregation of potential losses yields a total economic risk of approximately 1.7 billion €, largely associated with the risk of buildings. From a geographical perspective, the highest risk values are concentrated along the Apennine chain, where geomorphologically susceptible terrains overlap with urbanized and agricultural areas. These findings indicate that landslide risk in Tuscany is primarily controlled by the combined effects of geomorphological conditions and the spatial distribution of exposed elements.

However, several future improvements can already be listed. Future works should include the assessment of indirect damages to provide a more comprehensive evaluation of landslide impacts, as well as the incorporation of road networks among the exposed elements.

Overall, this study contributes to updating the current understanding of landslide risk in Tuscany and provides a quantitative framework that is particularly relevant in light of recent extreme rainfall events, which have highlighted the increasing frequency and severity of landslide-related impacts in the region.

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