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Predisposing Factors for Shallow Landslides in Alpine and Hilly/Apennines Environments: A Case Study from Piemonte, Italy

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Abstract: Landslides are the most common natural hazard in the Piemonte region (northwestern Italy). This study is focused on shallow landslides caused by the sliding of the surficial detrital-colluvial cover caused by rainfall and characterized by a sudden and fast evolution. This study investigates shallow landslide events compared with variables considered as main predisposing qualitative factors (lithology, pedology and land use) to obtain a zonation of shallow landslide susceptibility in a GIS environment. Additionally, wildfire occurrence is also evaluated as a further predisposing factor for shallow landslide initiation. The resulting susceptibility map shows a strong correlation between the first three variables and shallow landslide occurrence, while it shows a negligible, or very localized, relationship with wildfire occurrence. Through the intersection of the predisposing factors with the landslide data points, a map of homogeneous zones is obtained; each identified zone is characterized by uniform lithological, soil-type, and land-use characteristics. The shallow landslide density occurrence is computed for each zone, resulting in a four-range susceptibility map. The resulting susceptibility zones can be used to define and evaluate the hazard linked to shallow landslide events for civil protection and regional planning purposes.

Keywords: susceptibility map; slope stability; wildfire; quantitative geomorphology; GIS

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1. Introduction

The purpose of this study is a shallow landslide [1] susceptibility analysis of the Piemonte region, to provide preliminary data for hazard evaluation and input for the improvement of the Regional Landslide Early Warning System (R-LEWS). According to [2–4], an effective landslide susceptibility zonation should be carried out with respect to a specific landslide type. Hence, the slope movement data utilized in this study are restricted to shallow landslides. This landslide type develops in the shallow layer of detrital-colluvial cover on slopes and is characterized by:

- single intense rainfall event triggering, associated with a fast-triggering velocity class, often an instantaneous trigger with a scarcity of premonitory signs;
- extremely high velocities, which also characterize the post-failure stage, according to [5]; shallow landslides in the very fast velocity class, with a velocity rate between 5 m/s and 3 m/min, due to both trigger and propagation velocity [6];
- high-density landslide cluster development. For example, in 1994, a cluster of more than 200 landslides per km^2 was observed in the Langhe hills (Tertiary Piemonte Basin–TPB–south Piemonte) when an extraordinary rainfall event occurred in November [7].

Landslide susceptibility analyzed in this study is computed starting from a semi-quantitative analysis of each predisposing factor and a subsequent analysis of merged values of the predisposing factors.

The susceptibility analysis concentrates on spatial forecasting purposes (where the landslides should be expected) and not on landslide triggering-time forecasting [8–12]. For this reason, the parameters considered in this study as being relevant to predisposing shallow landslide occurrence are factors that provide qualitative information about the predisposition of the given territory. Morphometric features of the analyzed slopes (such as slope gradient and aspect) are not considered in this study, which aims for a qualitative analysis rather than a quantitative one, considering that the scale of application of Morphometric parameters are more relevant to local studies rather than regional ones [13,14]. Since the analysis presented herein is carried out on a regional scale, the parameters considered as predisposing factors are lithology, land use and soil type.

Lithology is considered because it represents information about the compositional and textural characteristics of soil that develops from the bedrock. This study also evaluates land use and soil type, the latter being taken into consideration because the variation in soil water content (saturation degree) is a direct cause of landslide triggering [15].

Study Area

The study area is located in northwestern Italy, which is well-known as a shallow landslide-vulnerable region in the Italian peninsula [16–18]. The Piemonte region hosts two complex and distinct geological and orographic environments, and for this reason the present analysis is carried out separately for landslides belonging to the Alpine system and for the hills and Apennines systems. The complex configuration of the study area implies a natural inclination for landslide processes, and therefore for landslide hazard, especially when associated with precipitation due to the orographic effect. However, humid air coming from the Mediterranean Sea evolves into four types of precipitation regimes due to the heterogeneity of the Piemonte territory: pre-alpine, subalpine, coastal, and subcontinental.

Considering this complex landscape, Piemonte (Figure 1) represents an optimal context to evaluate and test shallow landslide susceptibility mapping due to the region's high risk and due to the presence of a predisposing rainfall regime, in addition to the high spatial variability of the parameters previously mentioned (lithology, soil type and land use).

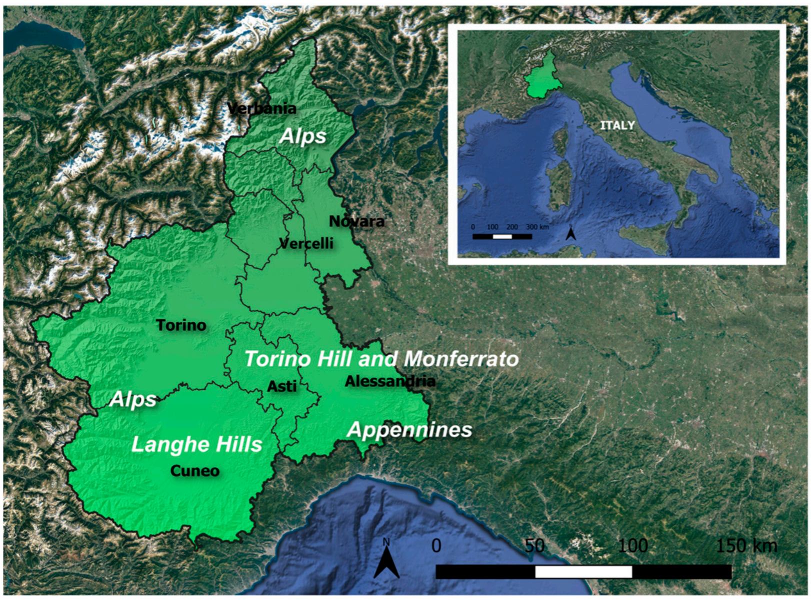

Figure 1. Study area location: Piemonte, Italy.

Shallow landslides are so common and widespread in Piemonte that the Regional Agency for Environmental Protection of Piemonte (ARPA Piemonte) developed an R-LEWS dedicated to this type of slope movement. The R-LEWS, called SLOPS (Shallow Landslides

Occurrence Prediction System), simulates landslide hazard in real time according to different rainfall thresholds; the hazard is based on the elementary zones, which are built on the following predisposing factors: lithology, soil type, environment, slope, and aspect [17].

In the investigated area, wildfire occurrence also plays a remarkable role in modifying the slopes' surficial characteristics. The effect of wildfires on slope stability is highlighted by many authors [19–22]. All cited works draw attention to the need for integrating post-fire hazard into shallow landslide prediction systems and, in broader terms, into risk mitigation studies.

Piemonte is a very complex region from geological, geomorphological, and climatic points of view. The geomorphological framework shows mountains on three sides (Alps on the northern, western, and southwestern sides, and Apennines on the southeastern side) and includes hilly areas on the southeastern part of the region. The complex framework is enriched by alluvial plains (among which is the wide Po River plain), terminal moraine systems, fluvio-glacial systems, and major glacial lakes.

The uniqueness of Piemonte's geology is derived from continuous geodynamic processes, which have, since the Rhaetian-Hettangian period (late Triassic to early Jurassic), led to the formation of two continental passive margins, the Paleo-European and the Paleo-Adriatic. Since the Late Cretaceous, the continents began converging and progressively collided. The collision gave birth to the origin of the Alpine and Apennine orogenic systems. An almost complete section of the Earth's crust surfaced, ranging from deep lithospheric mantle rocks to oceanic basalts, from volcanic continental rocks to the overlying carbonate and siliciclastic sedimentary covers, as well as many kinds of metamorphic rocks [23].

The physical conformation naturally leads to hydro-geological hazards, especially when associated with an orographic precipitation regime. The climatic variability of the Piemonte region reflects the complexity and heterogeneity of its territory.

It is important to note the different environments that characterize the Piemonte's orogenic systems. The landslide susceptibility analysis must be carried out separately for the two macro-environments to discern the different predisposing factors that take part in the total susceptibility: the Alpine environment, characterized by bedrock composed mainly of metamorphic rocks, and the Apennine and hills (Langhe, Monferrato and Torino Hill) characterized by bedrock mainly composed of sedimentary rocks (Figure 1).

2. Materials and Methods

The Piemonte Region represents an optimal study area due to the significant number of shallow landslides that occur within its territory each year, and additionally because of the availability of a dataset covering a long time interval (from 1654 to 2014). The dataset refers to the Landslide Information System of Piemonte (SIFraP) of Arpa Piemonte (https://geoportale.arpa.piemonte.it/app/public/?pg=mappa&ids=b315c7439ffe47faa698d98e0557bdfa. Last access on 1 June 2023), which contains 36,156 shallow landslides (Figure 2).

A homogeneous map scale of 1:250,000 was applied to each cartographic dataset and factor layer (except the Corine Land Cover) to ensure scale coherence throughout the analysis. The scale of the Corine Land Cover is 1:100,000.

The lithological dataset comes from the geological map of the Piemonte region (GeoPiemonte map at 1:250,000 scale: https://webgis.arpa.piemonte.it/agportal/apps/webappviewer/index.html?id=6ea1e38603d6469298333c2efbc76c72. Last access on 1 June 2023). This layer contains information about the 22 main lithologies that can be found within the Piemonte region. To simplify this vast database, the main categories were merged into simplified classes illustrated in the map legend of Figure 3.

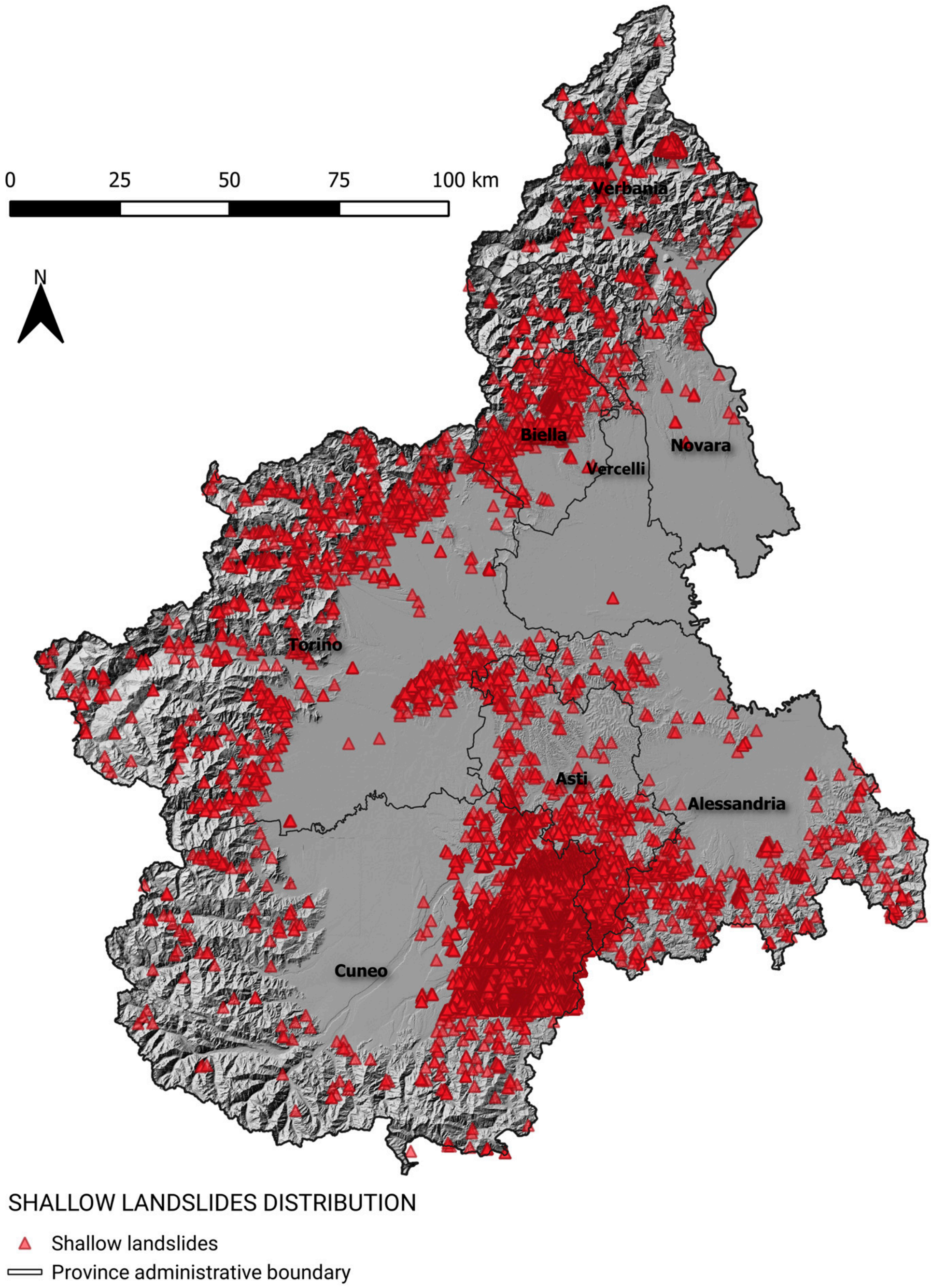

Figure 2. Shallow landslide distribution.

To collect information about the soil types of the studied area, the Piemonte Soil Map was used (from GeoPiemonte website of the Regione Piemonte governmental institution at https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/r_piemon:dl45po47-sh45-p44w-854d-58fdq6p9iu45. Last access 1 June 2023), shown in Figure 4.

The thematic layer adopted for the land use is the Corine Land Cover (2018), which includes 33 categories (third-level classification detail) of land cover and land use (Figure 5).

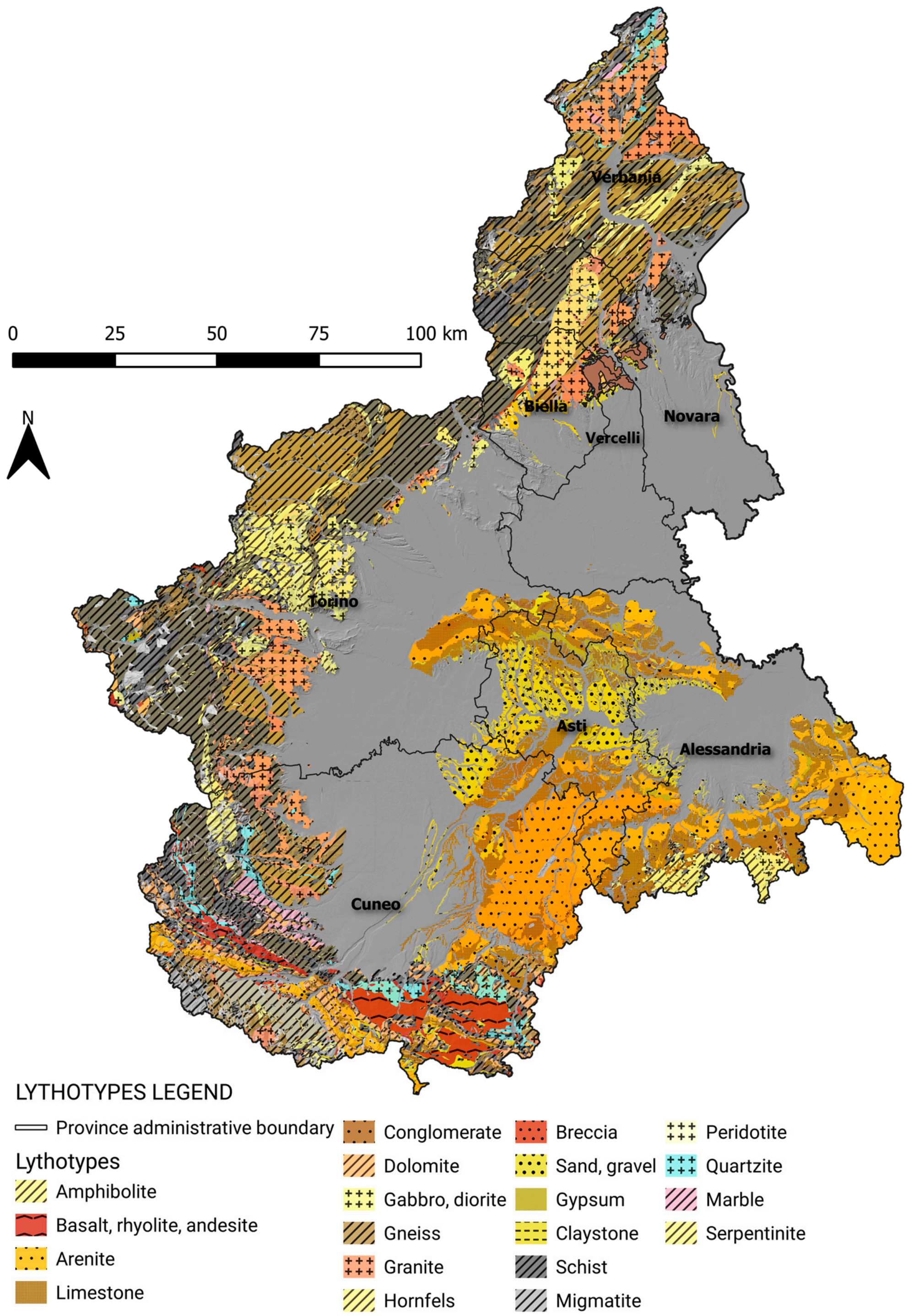

Figure 3. Lithological map of Piemonte.

The last parameter considered is the wildfire distribution dataset built from two source databases, the Regional Forest Fire Prevention System database (available from GeoPiemonte website at https://www.geoportale.piemonte.it/geonetwork/srv/api/records/r_piemon:5d8d0dd5-c0ac-4403-afb9-c116ccefedc8#gn-tab-raster. Last access on: 1 June 2023) and the regional dataset of recent wildfire events that occurred between 2001 and 2008 (ARPA Piemonte, unpublished data). The processing and union of the two datasets results in a new dataset containing 5493 wildfire events that occurred between 1997 and 2019.

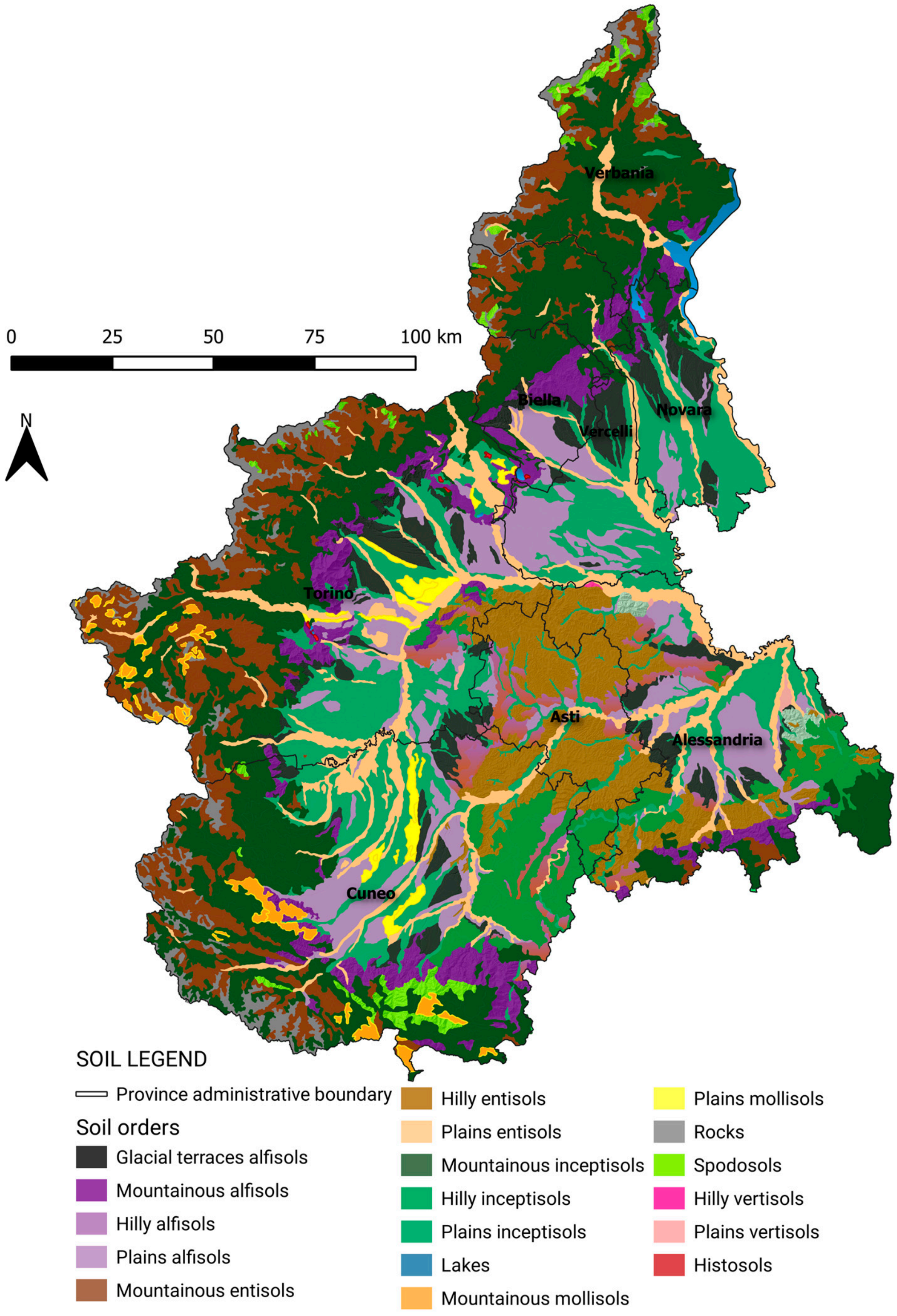

Figure 4. Soil map of Piemonte.

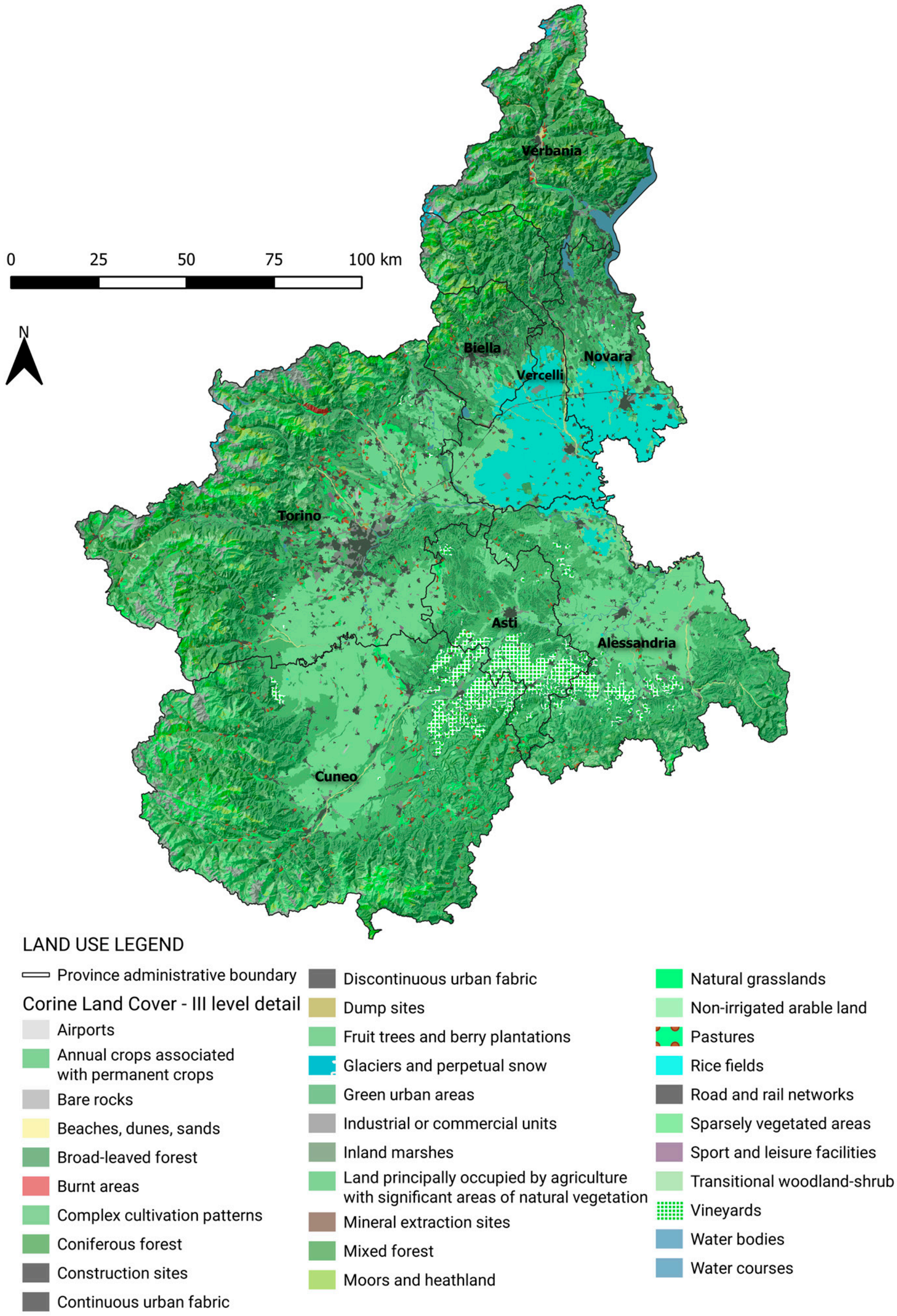

Figure 5. Land use map of Piemonte.

All input layers are described in Table 1.

The analysis consists of two parts: first, a general distribution and density analysis of the input data (landslides and wildfires); and second, a more accurate investigation of the predisposing factors associated with the shallow landslide events. This second part results in a thematic analysis intended to show each parameter's contribution to shallow landslide occurrence and a final susceptibility map for the entire region.

Table 1. Input data and information layers used in the analysis.

Input Data	Source	Scale	Data Type	Temporal Extent
Shallow landslides (ARPA Piemonte landslide database)	Geoportale ARPA Piemonte	Accuracy: maximum 2 m	vector	1654–2014
Lithology (Geopiemonte)	Geoportale ARPA Piemonte	1:250,000	vector	2017
Pedology (Soil Map)	Geoportale Regione Piemonte	1:250,000	vector	2005
Land use (CLC 2018)	ISPRA	1:100,000	vector	2018
Forest fires	Geoportale Regione Piemonte	Accuracy: maximum 2 m	vector	1997–2019
Administrative limits	Geoportale Regione Piemonte	1:10,000	vector	2011
Slope environments	Geoportale Regione Piemonte	1:50,000	vector	2017
DTM	Geoportale Regione Piemonte	1:10,000	raster	2008

The distribution analysis aims to examine the areas in which a large number of shallow landslides occurred, whereas the density analysis consists of a heatmap, a GIS-based method for visualizing the clustering of a phenomenon. This tool helps to show where higher-than-average concentrations of landslides occur.

The regional landslide susceptibility is primarily established for every predisposing factor. Every lithological class, soil, or land-use category that intersects with areas affected by shallow landslides is analyzed. The susceptibility associated with each class is computed and classified into three density ranges (Tables 3–4).

Secondly, the landslide density associated with each parameter is represented in the thematic maps (Figures 8–11).

After having examined each predisposing factor separately, the total landslide susceptibility is determined through the intersection of the three thematic layers, resulting in a regional landslide susceptibility map that summarizes all the combined factors. The resulting classes of joint predisposing factors are computed and represented in a four-range zonation map.

With reference to wildfire occurrence, the first step was to verify the consistency of the datasets expressed as event density. The event density (both wildfire and shallow landslides) was developed through the generation of 1-km wide buffer areas of wildfire geometries to better identify the landslide proximity to burnt areas. An overlay of the wildfire density map with the shallow landslide susceptibility map demonstrates the contribution of wildfires to predisposing slope movements.

3. Results

The analysis shows that 84% of shallow landslides occurred in the province of Cuneo (southwestern sector of Piemonte). In this province, most of the territory is hilly and characterized by sedimentary bedrock with a predominance of unstable slopes. Moreover, the analysis shows that 22.4% of the landslides in the region are in wildfire-affected territories.

The density analyses are summarized in Figures 6 and 7. As previously disclosed, the landslide and wildfire density heatmaps do not show a high correlation. According to [22], in the Western Alps, a close correlation has been found for debris flow events in small alpine catchments that were previously affected by wildfires. However, the correlation of the shallow landslides with wildfires is verified only for some local cases in the Biella and Verbano provinces (north Piemonte) and Lanzo valleys (north-western Piemonte).

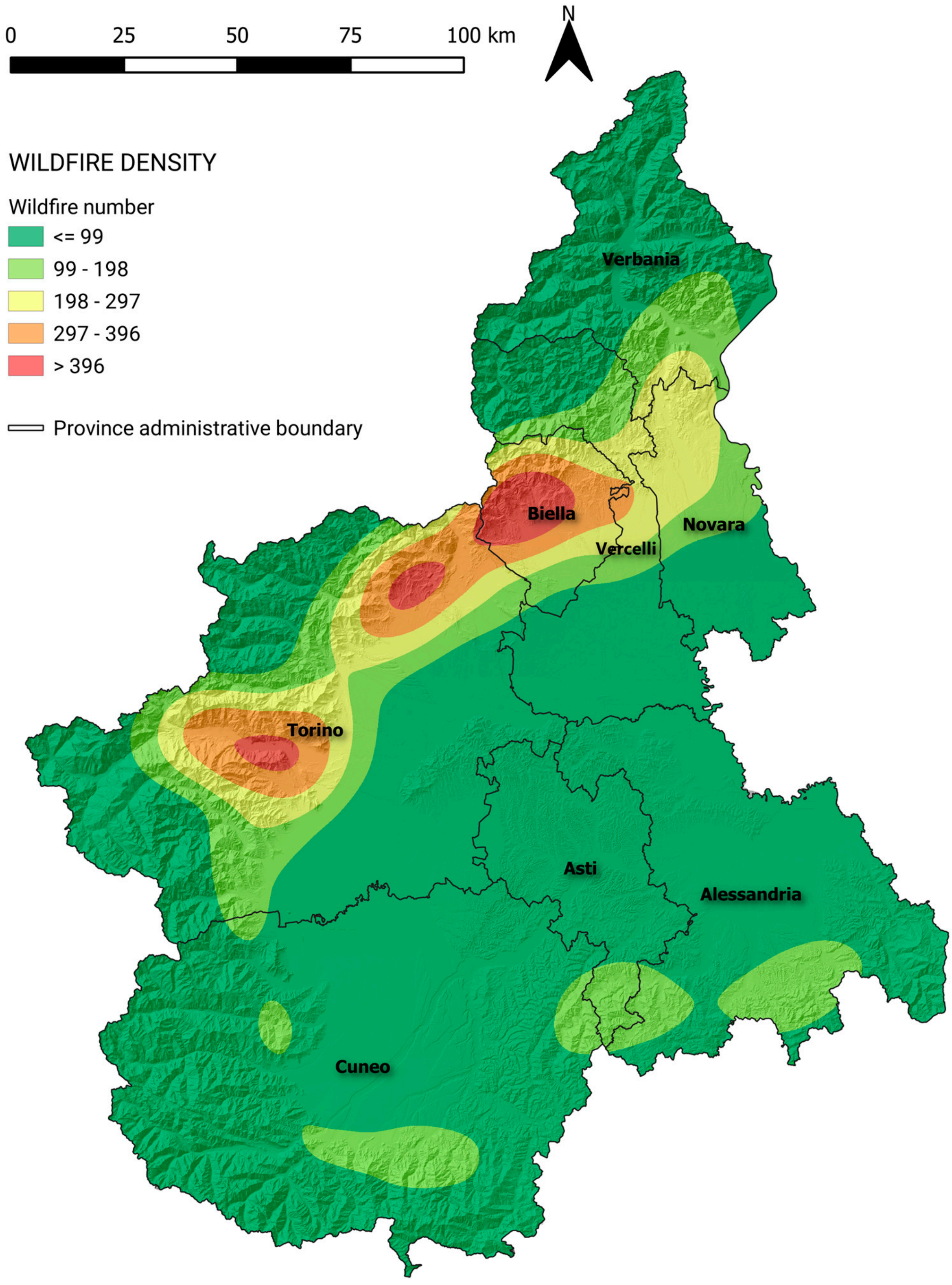

Figure 6. Wildfire density map of Piemonte.

Based on this information, subsequent analyses were concentrated on the three factors that effectively influence landslide occurrence. Below are the results related to each predisposing factor.

Lithology: the 21 lithological classes associated with landslide development are displayed in Table 2.

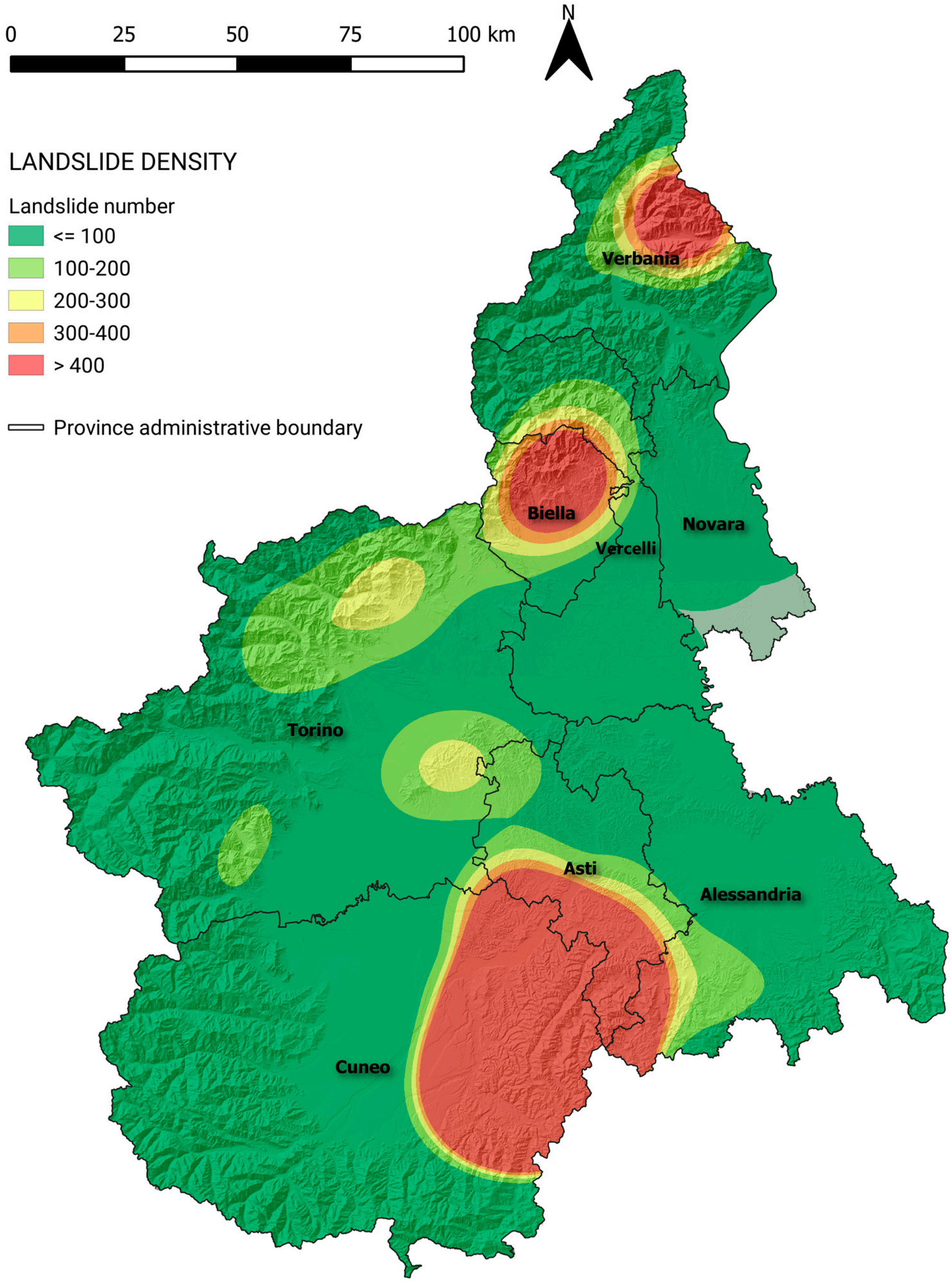

Figure 7. Shallow landslide density map of Piemonte.

Soil type: the 14 soil categories that predispose shallow slope movements and the density analysis associated with each soil class are displayed Table 3. A higher density is found with soils that develop in hilly environments, such as inceptisols, where the density class corresponds to more than 15 landslides per km^2.

Table 2. Landslide density per lithological class.

Lithotype	Area (km^2)	Landslides n°	Density (Landslides/km^2)	Density Class
Arenite	1531.13	26351	17.21	HIGH ($d \geq 15$ landslides/km^2)
Limestone	913.4	4916	5.38	MODERATE ($2 \leq d \leq 15$ landslides/km^2)
Marble	13.18	18	1.37	
Peridotite	129.34	151	1.17	
Granite	728.37	843	1.16	
Gabbro, diorite	292.62	303	1.04	
Sand, gravel	549.53	559	1.02	
Gypsum	53.98	46	0.85	LOW ($d \leq 2$ landslides/km^2)
Breccia	1.39	1	0.72	
Dolomite	58.66	35	0.60	
Migmatite	180.28	109	0.60	
Hornfels	26.44	12	0.45	
Conglomerate	212.73	78	0.37	
Schist	2255.40	596	0.26	
Quartzite	86.17	22	0.26	
Gneiss	1481.96	373	0.25	
Serpentinite	353.09	90	0.25	
Claystone	25.15	6	0.24	
Vulcanite	92.45	17	0.18	
Amphibolite	50.85	6	0.12	
Basalt, rhyolite, andesite	280.36	25	0.09	

Table 3. Landslide density per soil-type class.

Soil Type	Area (km^2)	Landslides n°	Density (landslides/km^2)	Density Class
Hilly inceptisols	1167.55	24273	20.79	HIGH ($d \geq 15$ landslides/km^2)
Hilly alfisols	534.45	4708	8.81	MODERATE ($2 \leq d \leq 15$ landslides/km^2)
Hilly entisols	1802.48	2696	1.50	
Plains entisols	785.82	671	0.85	LOW ($d \leq 2$ landslides/km^2)
Mountainous entisols	948.12	806	0.85	
Mountainous alfisols	1191.14	758	0.64	
Plains alfisols	495.95	293	0.59	
Mountainous inceptisols	4264.46	1430	0.34	
Glacial terraces alfisols	846.55	277	0.33	
Plains inceptisols	664.50	182	0.27	
Lakes	17.98	3	0.17	
Spodosols	127.20	17	0.13	
Mountainous mollisols	116.06	8	0.07	
Rocks	369.39	7	0.02	

Land use: 22 categories are reported. Most landslides occur in pastures and transitional woodland shrub environments (the 3rd level Corine Land Cover code is, respectively, 231 and 324) (Table 4).

Table 4. Landslide density per land-use class.

Land Use	Area (km^2)	Landslides n°	Density (Landslides per km^2)	Density Class
Pastures	76.488	2050	26.80	HIGH ($d \geq 15$ landslides/km^2)
Transitional woodland/shrubs	183.553	2238	12.19	
Mixed forest	457.973	4735	10.34	MODERATE ($2 \leq d \leq 15$ landslides/km^2)
Land principally occupied by agriculture, with significant areas of natural vegetation	1150.38	11,443	9.95	
Mineral extraction sites	0.251	2	7.97	
Vineyards	536.882	3475	6.47	
Fruit trees and berry plantation	42.268	264	6.25	
Industrial or commercial units	3.671	15	4.09	
Discontinuous urban fabric	200.829	535	2.66	
Complex cultivation patterns	970.898	2119	2.18	
Broad-leaved forest	4535.448	8699	1.92	
Continuous urban fabric	2.809	4	1.42	
Water courses	28.99	32	1.10	
Natural grassland	176.663	129	0.73	LOW ($d \leq 2$ landslides/km^2)
Moors and heathland	56.784	39	0.69	
Burnt areas	9.973	6	0.60	
Coniferous forest	327.019	160	0.49	
Annual crops associated with permanent crops	2.749	1	0.36	
Sparsely vegetated areas	670.316	101	0.15	
Non-irrigated arable land	2040.379	96	0.05	
Water bodies	113.431	4	0.04	
Bare rock	180.904	4	0.02	

The shallow landslide density computed in the analysis is then classified into three ranges from high to low. Each lithology, soil-type and land-use category is associated with a density range that has been elaborated and represented in a density map associated with the lithological parameter, a density map related to soil type and a density map showing which land-use categories contribute most to predisposing shallow landslide occurrence (Figures 8–10).

The intersection of these three considered factors describes the shallow landslide susceptibility zonation for the Piemonte region, classified into four susceptibility ranges (Table 5). The final output is shown in Figure 11.

Table 5. Shallow landslide susceptibility classes.

Landslide Susceptibility	Density (Landslides/km^2)
Very high	$d \geq 20$ landslide points/km^2
High	$10 \leq d \leq 20$ landslide points/km^2
Moderate	$2 \leq d \leq 10$ landslide points/km^2
Low	$d \leq 2$ landslide points/km^2

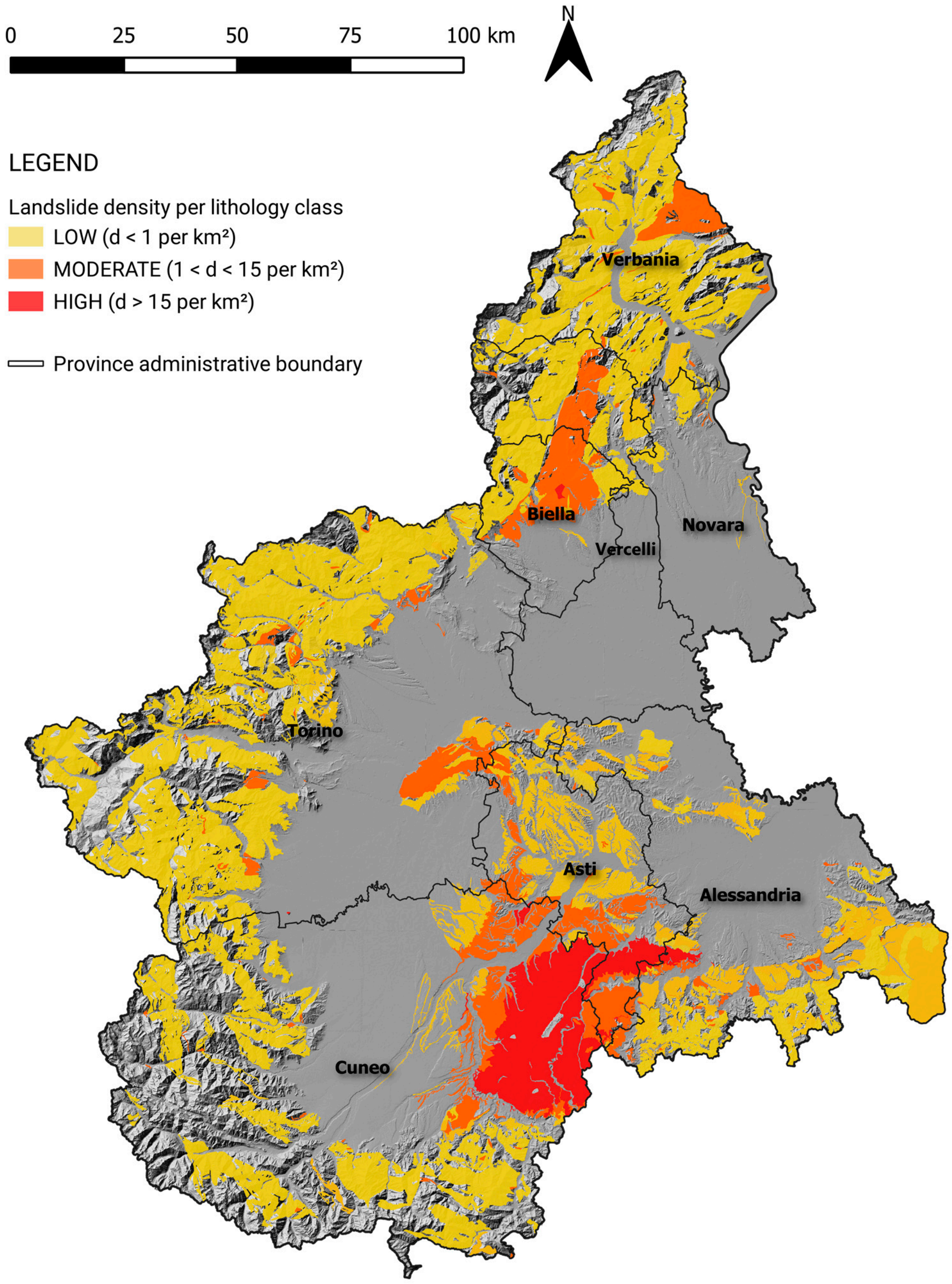

Figure 8. Shallow landslide density per lithotype.

The relationship between shallow landslides and wildfire occurrence is summarized as follows:

- the density analysis depicts four ranges of wildfire occurrence: from a very high (more than five wildfires per km^2) to low occurrence (density lower than one wildfire per km^2);
- the overlay of the landslide susceptibility map with the wildfire occurrence map (Figure 12) clarifies the correlation between shallow landslides and wildfires. The correlation does not seem to be significant for the landslide type evaluated in this work. The relationship between wildfire-affected slopes and consequent slope movements is negligible in this regional analysis, but it is important to deepen the analysis to a local scale.

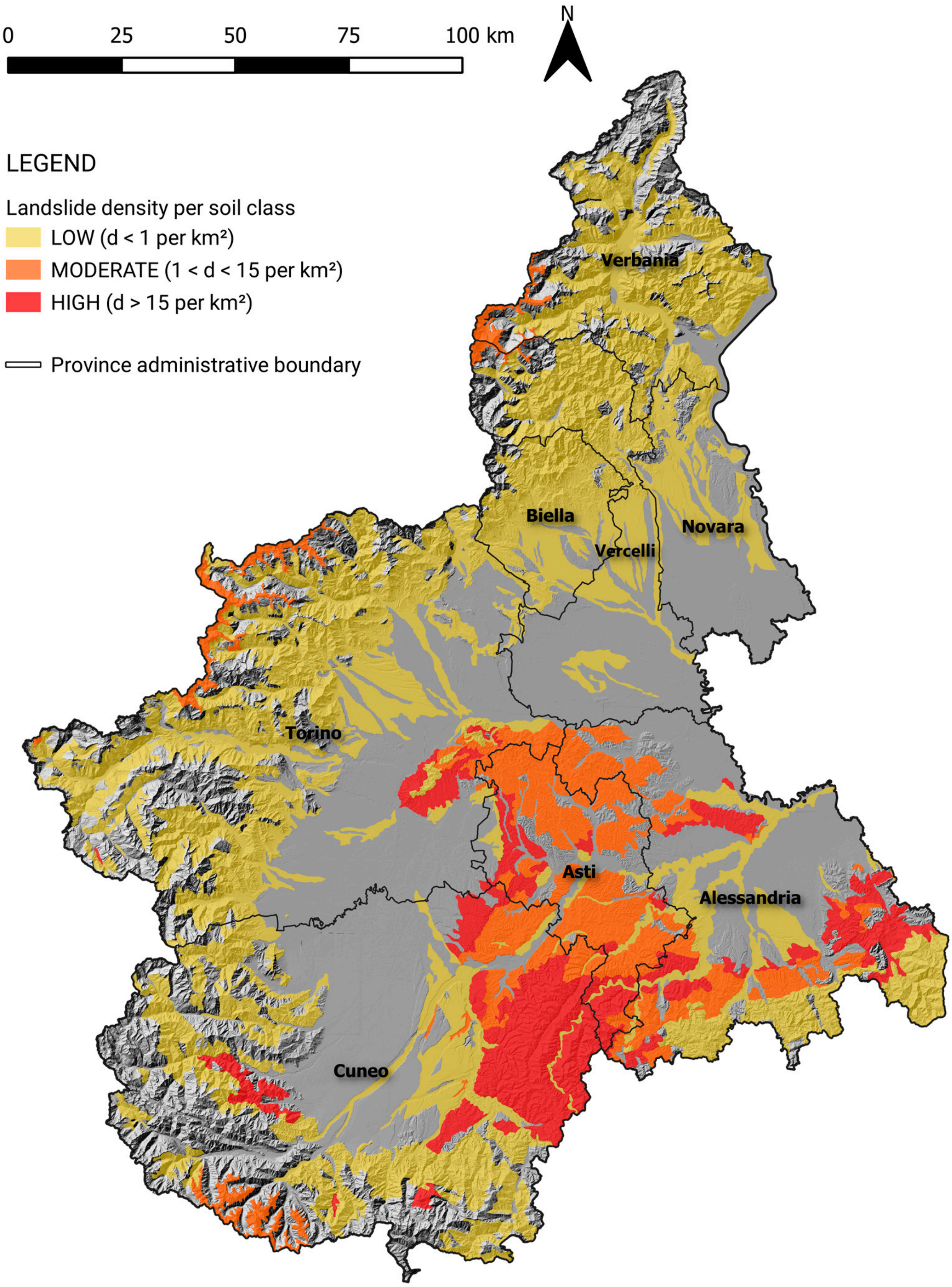

Figure 9. Shallow landslide density per soil type.

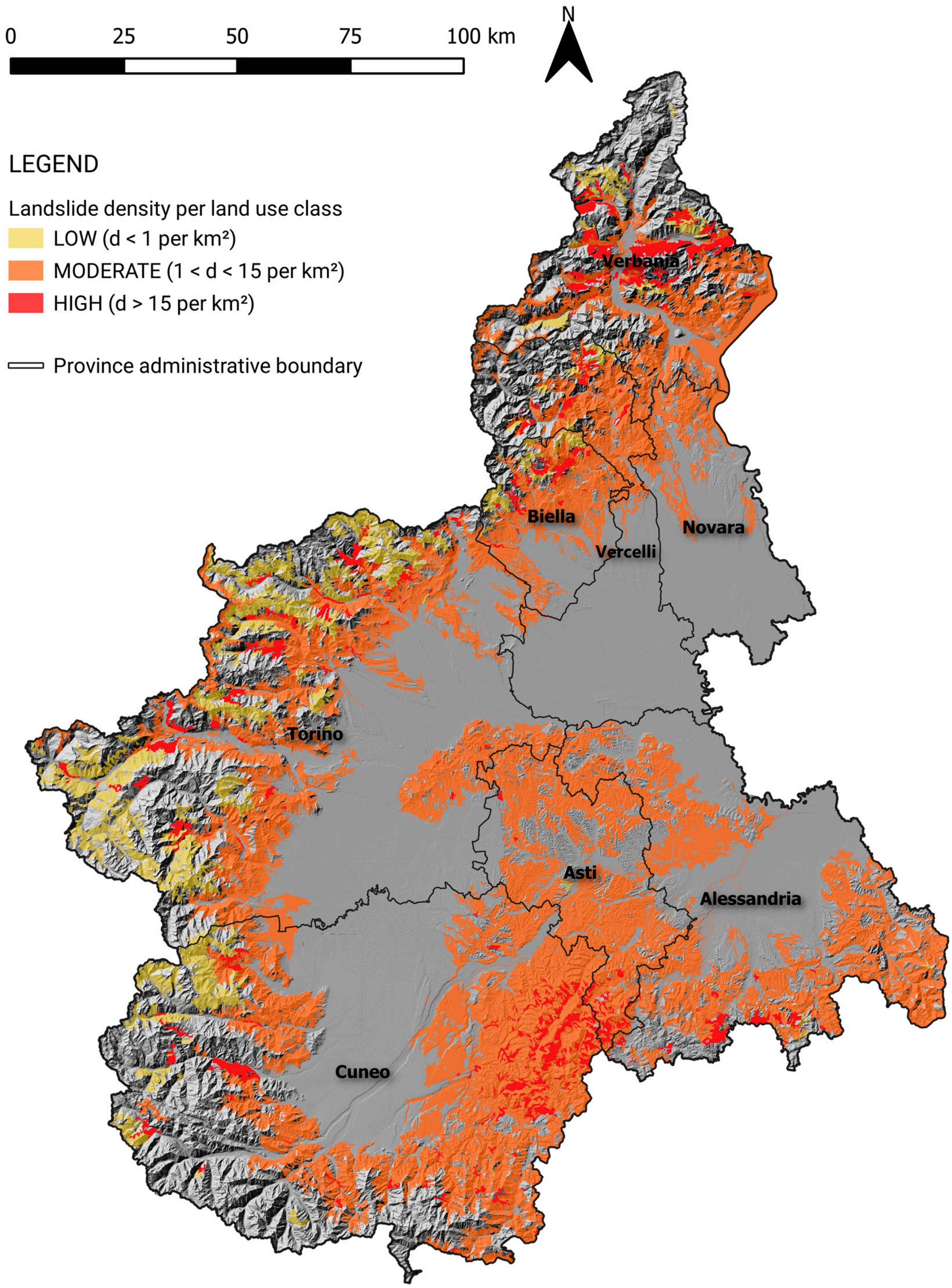

Figure 10. Shallow landslide density per land use.

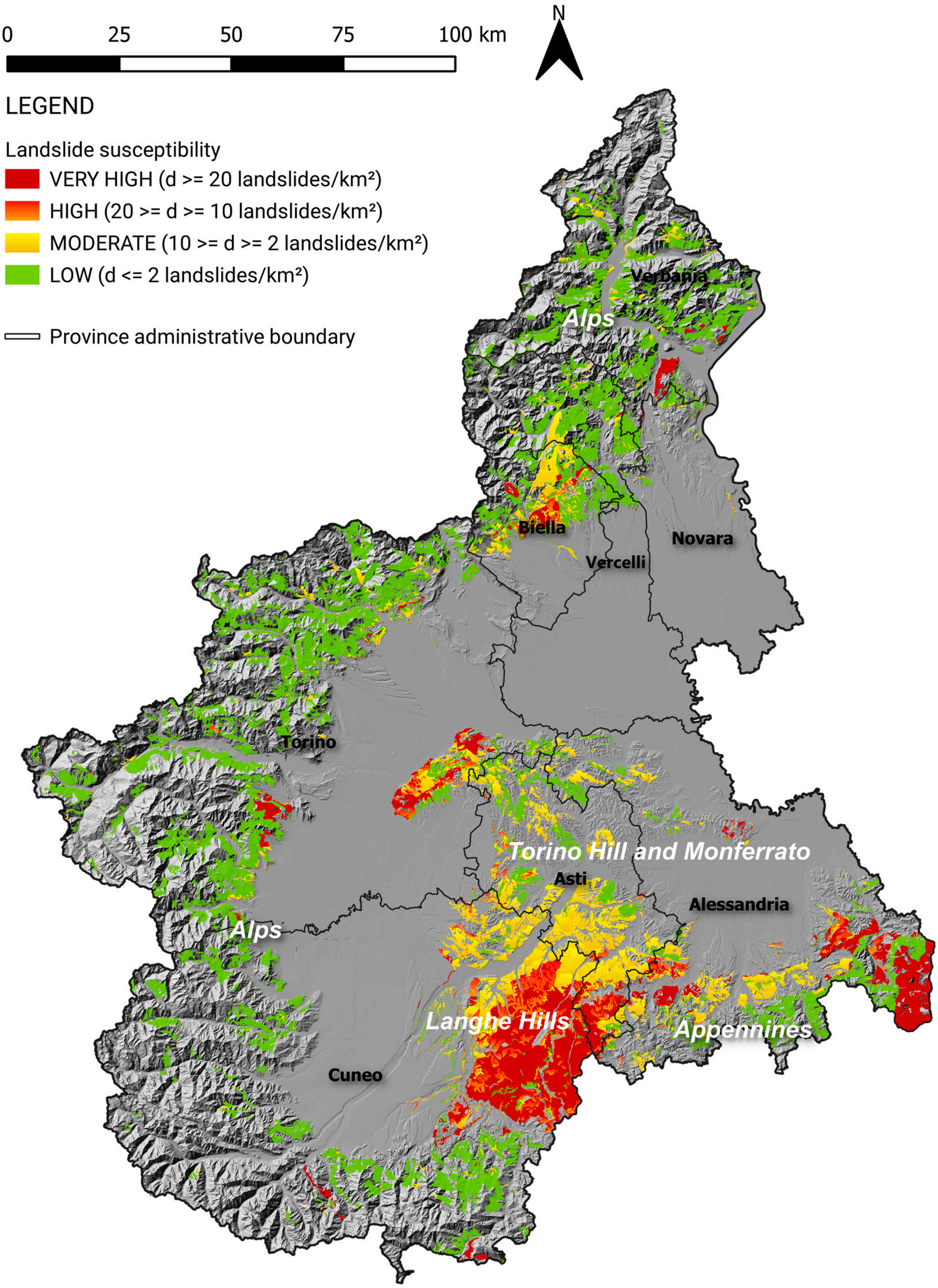

Figure 11. Shallow landslide susceptibility map of the Piemonte region.

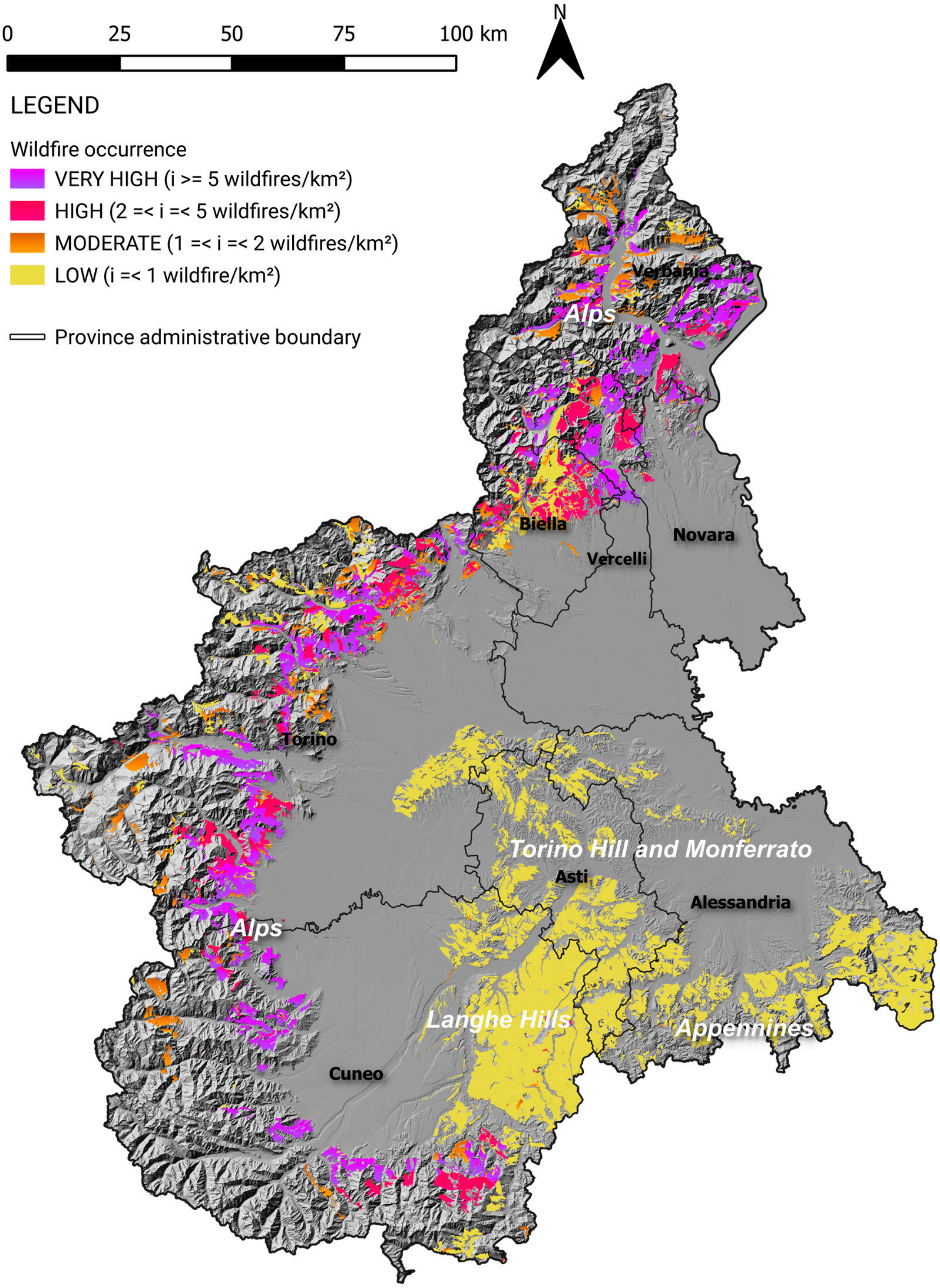

Figure 12. Wildfire occurrence map of the Piemonte region.

4. Discussion

The regional susceptibility zonation reveals that lithological, soil, and land-use parameters are the predisposing factors that provide the greatest contribution to a slope's natural predisposition to shallow landslides.

It is important to clarify that the lithological factor plays an indirect role in predisposing shallow landslides because this type of gravitational movement does not involve the bedrock but only develops within the shallow alteration layer. However, the soil characteristics in which shallow landslides develop are directly influenced by the underlying lithology. Indeed, lithology determines the characteristics of soil, such as grain size, texture, porosity, permeability, and cohesion, which control shallow landslide occurrence.

Arenites are the lithological class with the most significant contribution to landslide susceptibility for the studied area, with 51% of the landslides occurring on this lithotype.

As previously described, a high susceptibility is associated with hilly-environment soils. Inceptisols correspond to more than 20 landslides per km^2. They are poorly developed soils, typically found on abandoned and formerly agriculturally exploited slopes.

Pasture and transitional woodland shrub land covers are associated with a high landslide susceptibility at the regional scale, related to 28% and 13%, respectively, of the total landslide dataset. The landslide density for these two land-use classes is higher than 15 landslides per km^2.

Regarding the analysis of the total susceptibility, derived from the combination of the considered predisposing factors, the Piemonte region is classified into four susceptibility ranges: from very high ($\geq$20 landslide points/km^2) to low ($\leq$2 landslide points/km^2).

A total of 140 predisposing factor classes and 2658 shallow landslides are associated with the Alpine environment in an area of 2632.48 km^2. Nevertheless, 90% of the alpine slopes are classified in the lowest susceptibility class (low), while the very high susceptibility class corresponds to 0.71% of the study area, the high susceptibility class represents 0.59%, and the moderate susceptibility class corresponds to the remaining 7.20%. Some examples of the factor classes are shown in Table 6.

Table 6. Higher susceptibility class resulting from the sum of all predisposing factors for the Alpine environment.

Sum of Higher Predisposing Factors (Alpine Environments)	Area (km^2)	Landslides n°	Landslide Density	Susceptibility Class
Artificial surfaces; vulcanite; alfisols	0.02	1	50.00	HIGH (d > 20 landslides per km^2)
Pastures; granite; entisols	0.11	5	45.45	
Pastures; basalt, rhyolite, andesite; afisols	0.03	1	33.33	
Transitional woodland/shrubs; granite; entisols	9.07	292	32.19	
Pastures; serpentinite; entisols	0.04	1	25,00	
Forest; granite; entisols	9.18	193	21.02	
Sparsely vegetated areas; quartzite; entisols	0.2	4	20.00	

In contrast, most shallow landslides, corresponding to 36,816 points, occur in hilly environments, mostly located in the southeastern Piemonte region (total area of 2528.36 km^2). The analysis utilizes 322 predisposing factor classes for hilly environments, making it clear that this kind of environment guides the regional susceptibility to shallow landslides. Indeed, 30% of the hills in the Torino, Monferrato, Langhe, and Roero territories are classified in the very high landslide susceptibility range, with an average density of 26 shallow landslides per km^2. The high susceptibility class corresponds to 6.5% of hilly areas, whereas 26% and 34% are in the moderate and low susceptibility classes, respectively. Some of the most predisposing factor classes can be observed in Table 7.

Perhaps most importantly, 20% of the entire Piemonte region is exposed to landslide hazards, with a susceptibility ranging from low (two landslides per km^2) to very high (more than 20 landslides per km^2).

Ultimately, the overall analysis reaffirms that wildfire occurrence is a minor factor in the region's predisposition to shallow landslides, while the other factors strongly influence the regional shallow landslide susceptibility.

Table 7. Higher susceptibility class resulting from the sum of all predisposing factors for the hilly and Apennines environments.

Sum of Higher Predisposing Factors (Hilly/Apennines Environments)	Area (km^2)	Landslides n°	Landslide Density	Susceptibility Class
Artificial surfaces; limestone; inceptisols	0.04	6	150.00	HIGH (d> 20 landslides per km^2)
Forest; arenite; entisols	0.51	69	135.29	
Transitional woodland/shrubs; arenite; inceptisols	9.18	1130	123.09	
Transitional woodland/shrubs; limestone; inceptisols	2.92	358	122.60	
Transitional woodland/shrubs; arenite; entisols	2.07	225	108.70	
Artificial surfaces; limestone; alfisols	0.16	17	106.25	
Forest; limestone; inceptisols	0.03	3	100.00	
Transitional woodland/shrubs; limestone; inceptisols	0.22	21	95.45	
Pastures; arenite; entisols	2.14	167	78.04	
Artificial surfaces; arenite; alfisols	0.09	7	77.78	

5. Conclusions

The predisposing factors examined (lithology, soil type and land use) have a reputation for being strong conditioning factors for slope instability in Piemonte.

The investigation was carried out for each factor individually, starting with the landslide density associated with each predisposing lithological-class, soil-group or land-use category.

The present analysis confirms these dynamics through the development of a regional susceptibility map (Figure 11). The last phase of the analysis was to consider the influence of wildfire occurrence on the total susceptibility. Wildfire was revealed to be a negligible factor on a regional scale, while shallow landslide susceptibility clearly appeared to be more influenced by the lithology, soil-type, and land-use factors.

The susceptibility investigation carried out in this study is a valid tool for landslide hazard evaluations for the Piemonte region and can be used to undertake hazard analysis for the ultimate purpose of civil protection and regional planning.

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