

Role of Land Cover and its Changes in Triggering Rainfall-Induced Shallow Landslides in Central Italy

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Abstract

A regional analysis of the role of land cover and its changes on landslide occurrence is carried out. Using a comprehensive dataset of shallow landslides that occurred from 2002 to 2020 in the Marche region (central Italy), hourly rainfall measurements, and different land cover maps, we evaluate how the triggering rainfall conditions change on different land covers. The impact of temporal changes in land cover on the occurrence of landslides is also studied. We find a relevant increase in landslide density in urban areas, a different seasonal distribution of landslides in areas with different land cover, and differences in rainfall thresholds for the initiation of slope failures. More rainfall is needed to trigger landslides in agricultural and forested areas than on artificial surfaces, as a sign of worsening stability conditions due to human activity. Forested areas are characterized by higher values of cumulated rainfall required to trigger landslides, an indication of the slope stabilizing effect of vegetation. Different rainfall triggering conditions are observed in different types of agricultural areas, indicating how agricultural practices can influence slope instability. The findings of this work are useful for territorial planning and

landslide risk assessment, also in view of ongoing climate and environmental changes.

Keywords

CORINE land cover · Rainfall thresholds · Landslide distribution · Shallow landslides · Marche

1 Introduction

Land cover, and their changes, influence the occurrence, distribution, and frequency of landslides (Sidle and Ochiai 2006). They act as predisposing factors for landslides and also affect the distribution of the vulnerable elements, thus influencing both landslide hazard and risk. Changes in land cover can reduce slope stability in some cases—e.g. deforestation or cutting of slopes for road or building construction—or increase it in others—e.g. new vegetation reducing soil erosion and increasing stabilizing forces through root reinforcement (Masi et al. 2021; Pacheco Quevedo et al. 2023). Furthermore, unsustainable agricultural practices characterized by heavy mechanization, such as tillage, can cause soil instabilization (Volpe et al. 2022). Therefore, evaluating the role of land cover, and its change, in the initiation of rainfall-induced landslides is relevant for landslide risk analysis and management.

The role of land cover/use on landslide occurrence has been addressed in works, considering both observed and projected changes (Glade 2003; Alcántara-Ayala et al. 2006; Beguería 2006; Reichenbach et al. 2014; Pisano et al. 2017; Gariano et al. 2018; Shu et al. 2019; Knevels et al. 2020; Ávila et al. 2021; Hürlimann et al. 2022; Pacheco Quevedo et al. 2023). Almost all works focused on evaluating the influence of land cover/use changes on landslide susceptibility assessment at the basin scale. A regional-scale analysis of the influence of land cover and its changes on rainfall

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triggering conditions of shallow landslides is missing. Such an analysis can provide significant insights into this complicated relationship, useful for landslide risk mitigation and territorial planning and management.

In this work, we consider land cover, i.e. the biological and physical materials on the Earth's surface comprising both natural elements and surfaces modified by humans, rather than land use, i.e. the socio-economic occupation of the land (Herold et al. 2006), to evaluate both natural and anthropogenic influences on landslide triggering. We use a comprehensive dataset of shallow landslides that occurred in the Marche region (central Italy) from 2002 to 2020 and different maps of land cover to evaluate whether the landslide-triggering rainfall conditions change in areas with different land cover. The effect of temporal changes in land cover on the occurrence of landslides is also assessed.

2 Data

2.1 Landslide and Rainfall Records

We use a catalogue of 1221 rainfall-induced shallow landslides that occurred between 2002 and 2020 in the Marche region, located in the eastern part of central Italy. Figure 1 shows the distribution of landslides in the regional territory. Slope failures are homogeneously distributed in both the hilly and mountainous areas of the region.

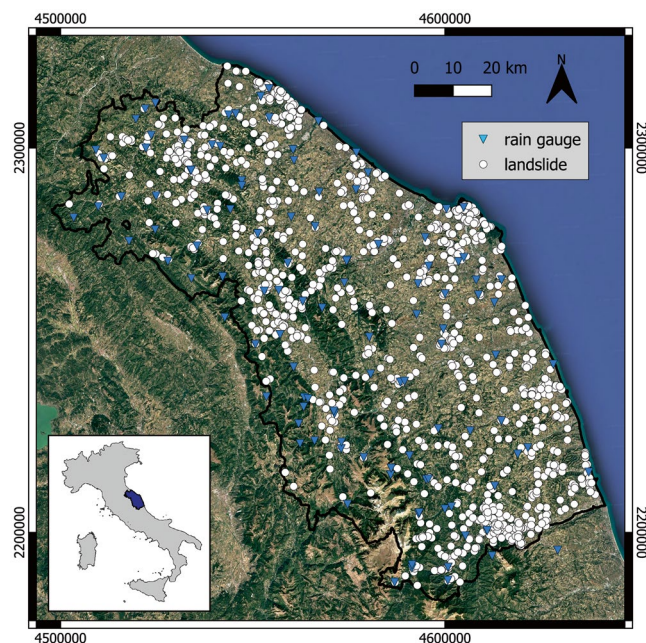


Fig. 1 Distribution of the 1221 rainfall-induced shallow landslides and the 149 rain gauges in Marche region. The inset shows the location of the region within the Italian peninsula. Background from Bing. EPSG: 3035

All landslides are mapped as points and for each record several information is known, including: source of information, landslide type (if available), geographic coordinates, location and municipality, day and approximate or exact time of occurrence, classes of spatial and temporal accuracy. Information is gathered mostly from local and national newspapers (mainly online) and technical reports from Fire Fighters. Almost all landslides (97%) are classified as generic shallow movements, with only a few mud flows, earth flows and rock falls (1% each) (Hungr et al. 2014). More than 40% of the landslides (492) are localized with a high mapping accuracy (uncertainty $<1 \text{ km}^2$) while 692 movements (57%) are mapped with a medium accuracy (uncertainty $<10 \text{ km}^2$). Only 37 records (3%) are mapped with a low accuracy (uncertainty between 10 and 100 km^2). For half of the landslides (619 out of 1221) the exact time of occurrence is known; for 147 landslides (12%) the part of the day and for 455 landslides (37%) only the day is known. Regarding the monthly distribution, landslides occurred mostly in spring (530 records, 43%, in March–April–May) and winter (298, 24%, in December–January–February). Only 21% and 12% of the records occurred in autumn (251 landslide) and summer (142), respectively. The average number of landslides per year is 64, with a peak in 2013 and 2014 with 206 and 246 records, respectively (Fig. 2).

The landslide records are included in the ITALian rainfall-induced Landslides Catalogue (ITALICA), an extensive and spatially and temporally accurate catalogue of 6312 rainfall-induced landslides that occurred in Italy between 1996 and 2021 (Peruccacci et al. 2023). The ITALICA catalogue is freely downloadable from Zenodo (Brunetti et al. 2023).

To reconstruct the rainfall responsible for the initiation of each landslide, we use the hourly rainfall data recorded by

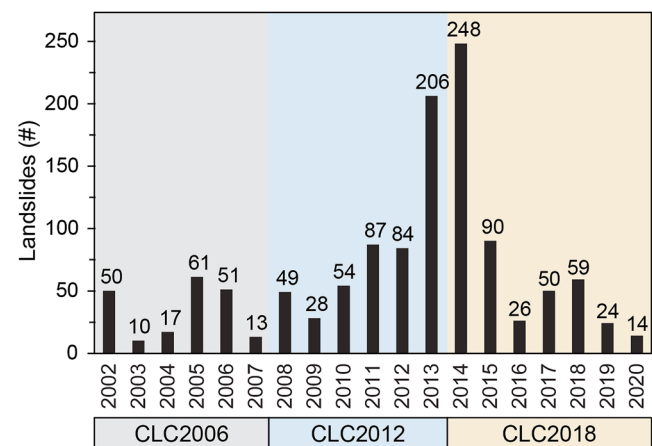


Fig. 2 Annual distribution of the analyzed landslides and scheme used for the association of the CLC classes from three Corine releases to the landslide records

Table 1 Percentage of area per CLC class in the region. The percentages for wetlands and water bodies are not reported

CLC class (level 1)	Percentage of regional area (%)		
	CLC 2006	CLC 2012	CLC 2018
Artificial surfaces	4.7	4.8	4.9
Agricultural areas	64.4	63.8	63.7
Forested areas	30.8	31.3	31.3

149 rain gauges in the regional network managed by the regional Civil Protection Office (triangles in Fig. 1).

2.2 Land Cover Maps

We use three releases of the Corine (Coordination of Information on the Environment) Land Cover (CLC) maps, for the years 2006, 2012, and 2018 (namely CLC2006, CLC2012, and CLC2018). CLC is a vector-based dataset of 44 land cover/use classes, derived from different satellite missions, providing information at a pan-European scale, with a minimum mapping unit of 25 hectares and updates every six years (Corine Land Cover 2021).

We consider the first and the second levels of the maps, which include five and 15 fields, respectively. For each CLC release, Table 1 lists the percentages of regional areas covered by the three first-level land cover classes, i.e., artificial surfaces (AS), agricultural areas (AA) and forested areas (FA). The variations in the percentages of the three first-level classes are minimal in the CLC releases +0.2% for AS, −0.7% for AA and + 0.5% for FA).

3 Methods

3.1 Attribution of Land Cover to Landslides

Each landslide in the catalogue is associated with a land cover class according to its spatial and temporal features. An overlay between the landslide points and the CLC maps is made according to the year of occurrence of the landslides. To consider the land cover of the year closest to the year of occurrence, landslides between 2002 and 2007 are assigned to CLC2006, those between 2008 and 2013 to CLC2012, and those between 2014 and 2020 to CLC2018 (Fig. 2).

Landslide points are converted into circles depending on their mapping accuracy. The radius of the circles is set to 0.6 km, 1.8 km and 5.6 km (corresponding to circular areas equal to 1 km², 10 km², and 100 km²) for landslides mapped with a high, medium and low accuracy, respectively. The landslides are then intersected with the CLC class layers and the proportion of each CLC class within each buffer is calcu-

lated. A CLC class is attributed to each landslide if it covers at least 75% of the area (Peruccacci et al. 2017).

The number and density of landslides in each class are evaluated for the time intervals associated with CLC2006, CLC2012 and CLC2018. All landslides associated with each CLC class are grouped to assess monthly and seasonal variations in landslide occurrence as a function of land cover. Finally, we reconstruct and analyze the rainfall conditions that triggered the landslides in the different CLC classes.

3.2 Evaluation of Rainfall Triggering Conditions

To automatically reconstruct the rainfall conditions responsible for landslide initiation and to calculate rainfall thresholds, we use CTRL-T (Calculation of Thresholds for Rainfall-induced Landslides—Tool) introduced by Melillo et al. (2018). Using continuous rainfall measurements, rain gauge and landslide locations, and landslide triggering time, CTRL-T (1) identifies the representative rain gauges, (2) reconstructs the triggering conditions (in terms of rainfall duration D and cumulated event rainfall E), and (3) calculates frequentist rainfall thresholds and their associated uncertainties.

Rainfall thresholds at different non-exceedance probabilities are defined adopting the frequentist method (Brunetti et al. 2010), which assumes a power law curve linking D (in h) and E (in mm) in the equation:

$$E = (\alpha \pm \Delta\alpha) D^{(\gamma \pm \Delta\gamma)} \quad (1)$$

where, α is a scaling constant (the intercept), γ is the shape parameter (that defines the slope), and $\Delta\alpha$ and $\Delta\gamma$ are the uncertainties of α and γ , respectively. Uncertainties associated with the threshold parameters are calculated using a “bootstrap” non-parametric statistical technique (Peruccacci et al. 2012) and depend on the number and distribution of the empirical data points. As an example, the threshold at 5% non-exceedance probability leaves 5% of the (D, E) points below itself.

4 Results

4.1 Spatial and Temporal Variations of Landslides

Figure 2 shows the number of landslides per year divided into the time intervals associated with CLC2006, CLC2012 and CLC2018. In total there are 202 landslides for CLC2006, 508 for CLC2012 and 511 for CLC2018. Two maxima with more than 200 landslides are visible in the years 2013 and

2014. Table 2 lists the number of landslides in each CLC class (AS, AA and FA) based on the maps released in 2006, 2012, 2018.

Fig. 3a shows the percentage of landslides in the three CLC classes, and Table 2 lists the number of landslides per CLC class for the 2006, 2012 and 2018 Corine releases. In all periods, more than 65% (806) of the recorded landslides take place in agricultural areas, and about 20% (238) and 15% (177) in artificial surfaces and forested areas, respectively. No significant percentage changes in the three main CLC classes are observed between the different releases, apart from a slight increase in AS and a slight decrease in FA. The density of landslides per class (number of landslides per 100 km²), shown in Fig. 3b, exhibits a huge increase in all CLC classes from 2006 to 2012. In particular, landslide density in AA and FA more than doubled, while almost tripled in AS. From 2012 to 2018, landslide density did not change significantly across the three CLC classes.

Table 2 Number of landslides per CLC class

CLC class (level 1)	Landslides (#)		
	CLC 2006	CLC 2012	CLC 2018
Artificial surfaces	35	102	101
Agricultural areas	136	328	342
Forested areas	31	78	68

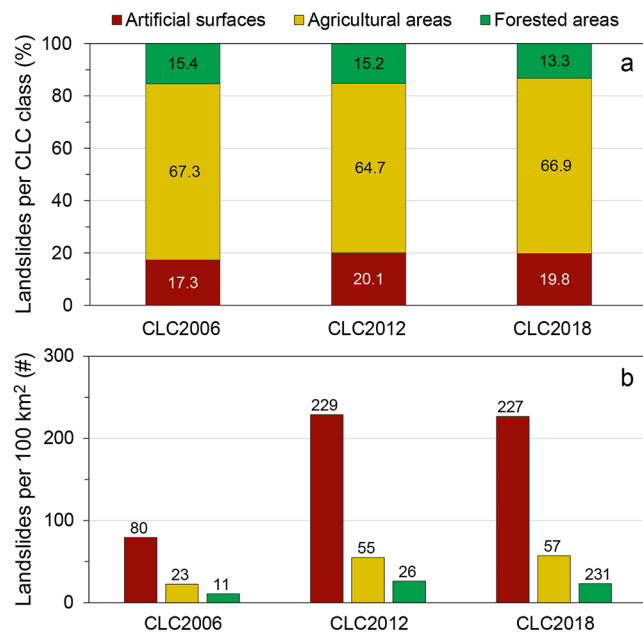


Fig. 3 (a) percentage of landslides per CLC class, first level, related to the Corine maps released in 2006, 2012, and 2018; (b) number of landslides per 100 km² in each CLC class

Figure 4 shows the monthly distribution of landslides and Table 3 lists seasonal number of landslides in AS, AA and FA, respectively. The monthly distribution of landslides varies in the three classes: in AS, landslides occur mainly in March, and December; in AA, landslides take place primarily in early spring (March and May) and secondarily in autumn (September, November, December). In FA, slope failures occur mainly in December and May. Overall, most landslides occur in the spring season (MAM) regardless of CLC class (Table 3).

4.2 Changes in Landslide-Triggering Rainfall Conditions

Using CTRL-T, a triggering rainfall condition is calculated and associated with 703 landslides. The triggering conditions are reconstructed using rain gauges located at an average distance of 6.2 km from the landslides, with a maximum distance of 20 km. The landslide-triggering rainfall conditions have duration D ranging between 1 h and 306 h and cumulated rainfall E values between 5.4 mm and 446.0 mm (with a mean value of 71.6 mm). The corresponding mean

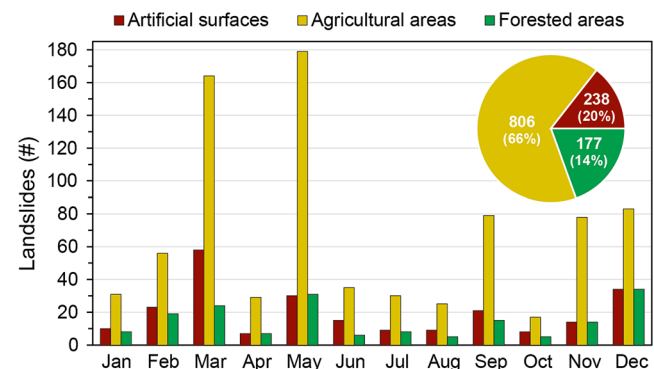


Fig. 4 Monthly number of landslides in the three first-level CLC classes. The pie chart in the inset shows the total number and percentage of landslides in the three classes

Table 3 Seasonal distribution of the landslides in the three CLC classes (first level). Key: DJF, December–January–February; MAM, March–April–May; JJA, June–July–August; SON, September–October–November

CLC class (level 1)	Landslides (#)			
	DJF	MAM	JJA	SON
Artificial surfaces	36	59	17	26
Agricultural areas	95	217	50	94
Forested areas	32	41	13	22

rainfall intensity values range between 0.2 mm/h and 41.2 mm/h (mean value 3.4 mm/h).

For 518 landslides, it was not possible to reconstruct a rainfall condition for various reasons: (1) unlikely amount of rainfall to justify triggering the landslide movement (i.e., cumulated rainfall values too low and inconsistent with the information source), or (2) malfunctioning rain gauges or unreliable rainfall measurements. It is possible that several landslides are triggered by the same rainfall event and reconstructed using the same representative rain gauge. In order to keep only the first triggered landslides and to avoid duplicates, such records were excluded from the analysis.

Overall, 138, 456, and 109 rainfall conditions are reconstructed and associated with landslides that occurred in AS, AA and FA, respectively.

Figure 5 shows the box-and-whiskers plots of the duration and cumulated event rainfall of the rainfall conditions that have triggered landslides the three CLC classes. The landslides that occurred in AA are characterized by a lower rainfall duration median value, while those in FA are triggered by longer rainfall conditions. On the other hand, the cumulated rainfall needed to trigger landslides on AS is on average lower than in AA and FA.

Similar results can be seen by looking at Fig. 6, which shows the kernel density distribution of the *ED* rainfall conditions that induced landslides in the three main CLC classes. In general, landslides occurring in urbanized areas are trig-

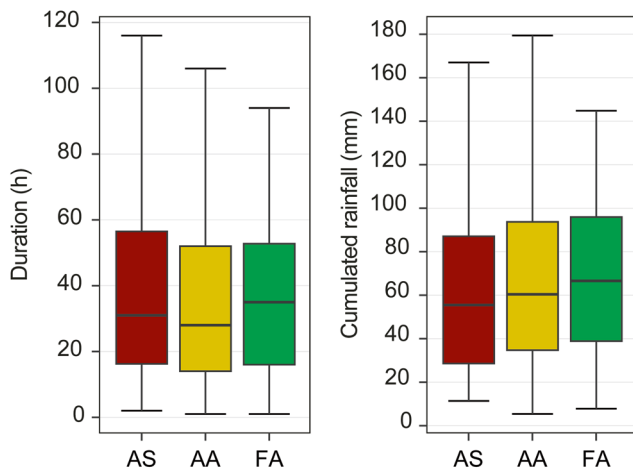


Fig. 5 Box-and-whiskers plots of duration (h) and cumulated event rainfall (mm) of the rainfall conditions that have triggered landslides in artificial surfaces, agricultural areas, and forested areas. Graphs show the median values (horizontal lines inside the boxes), the 25th and 75th percentiles (bottom and top of rectangular boxes), and the value range of 1.5 times the interquartile range (whiskers)

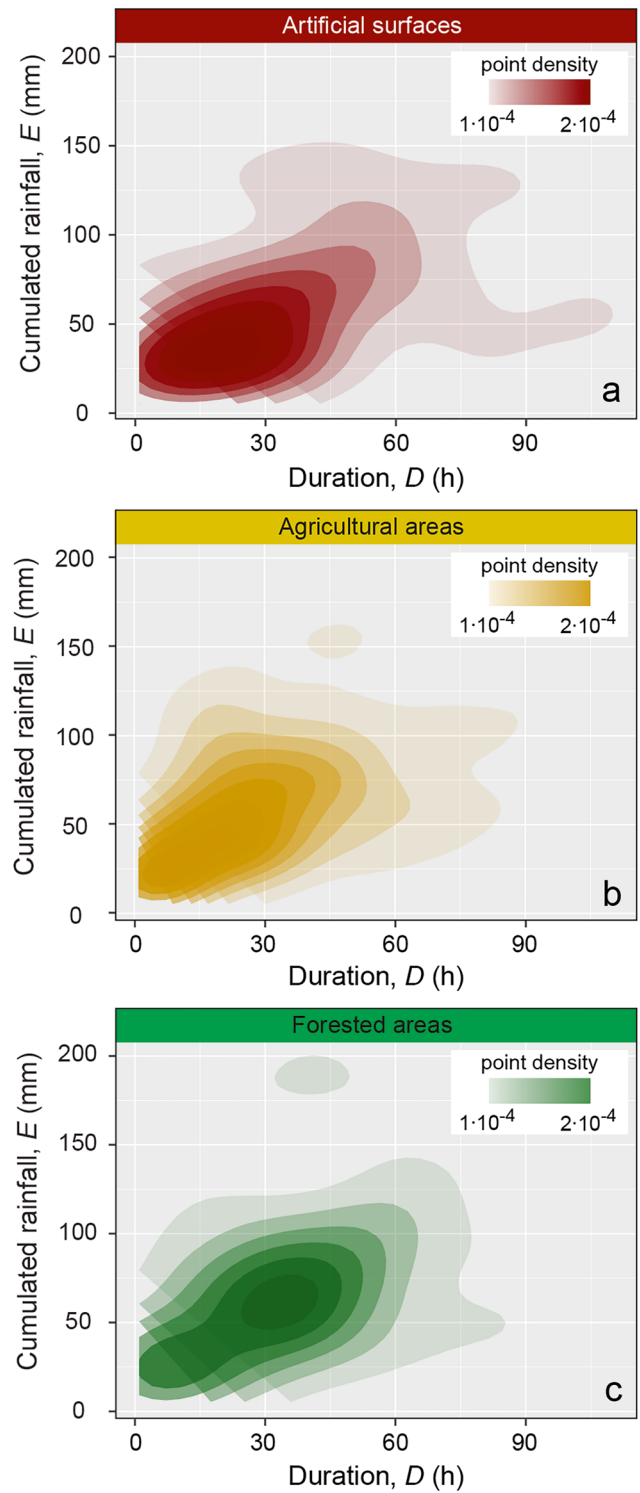


Fig. 6 Kernel density distributions of the cumulated rainfall-duration (*ED*) conditions that triggered landslides in (a) artificial surfaces, (b) agricultural areas, and (c) forested areas

gered by significantly shorter and less intense rainfall conditions than those localized in vegetated areas. On the other hand, longer and wetter conditions are required to trigger landslides in forested areas.

4.3 Changes in Rainfall Thresholds

Figure 7 shows the cumulated rainfall-rainfall duration (ED) conditions that have resulted in landslides in AS (Fig. 7a), AA (Fig. 7b) and FA (Fig. 7c), and the corresponding frequentist thresholds at 5% non-exceedance probability level (T_{AS} , T_A , T_{FA}), according to Eq. 1. The threshold equations are listed in Table 4.

The thresholds allow a quick comparison between the rainfall conditions that are likely to trigger a landslide in each land cover area. It can be observed that less rainfall is required to trigger a landslide on AS than on AA. The threshold for FA is less steep than that for AA, meaning that for longer duration ($D > 24$ h) a landslide can be triggered with less rainfall in forests than in agricultural areas.

The number of landslide records collected allows a more detailed analysis of the role of land cover in the rainfall conditions that can trigger landslides. Therefore, further analysis is carried out at the second and third levels of the CLC (Corine Land Cover 2021). Here we report the results only for those fields where enough landslides are found. In AS, almost all landslides occur in areas classified as *discontinuous urban fabric* (CLC code 1.1.2, 119 movements). In AA, they are found mostly on arable land (code 2.1 in CLC) and heterogeneous agricultural areas (code 2.4). In even more detail, several landslides occur in areas classified as *non-irrigated arable land* (code 2.1.1 in CLC, 191 landslides), *complex cultivation patterns* (code 2.4.2, 156 landslides) and *land principally occupied by agriculture* (code 2.4.3 in CLC, 103 points). In FA, most landslides occur in *broad-leaved forests* (CLC code 3.1.1, 71 landslides). Threshold equations are listed in Table 4.

Given the number of ED conditions, the thresholds for discontinuous urban fabric ($T_{CL1.1.2}$) and forests ($T_{C3.1.1}$) are quite similar to the corresponding thresholds for artificial surfaces (T_{AS} and T_{FA}). On the

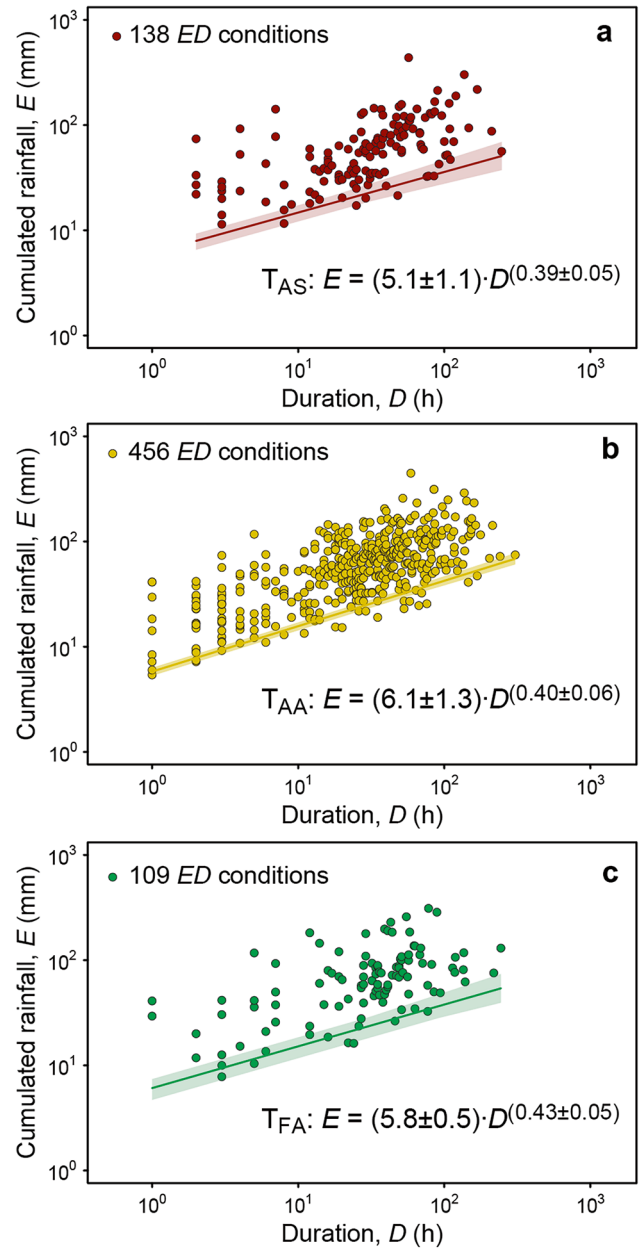


Fig. 7 ED conditions that have resulted in landslides in (a) artificial surfaces (T_{AS}), (b) agricultural areas (T_{AA}), and (c) forested areas (T_{FA}), and corresponding frequentist thresholds at 5% non-exceedance probability level, according to Eq. 1. Shaded areas show uncertainty of the thresholds. Data shown in logarithmic coordinates

Table 4 Parameters (Eq. 1) of the *ED* rainfall thresholds for the possible initiation of landslides in areas with different CLC classes (third level). The thresholds are defined for durations in hours and cumulated event rainfall in mm. Key: #, number of rainfall conditions used to calculate the thresholds; T_{AS} , threshold for *artificial surfaces*; T_{AA} , threshold for *agricultural surfaces*; T_{FA} , threshold for *forested areas*; $T_{C1.1.2}$, threshold for *discontinuous urban fabric* CLC1.1.2; $T_{C2.1.1}$, threshold for *non-irrigated arable land* CLC2.1.1; $T_{C2.4.2}$, threshold for *complex cultivation patterns* CLC2.4.2; $T_{C2.4.3}$, threshold for *land principally occupied by agriculture* CLC2.4.3; $T_{C3.1.1}$, threshold for *broad-leaved forests* CLC3.1.1

Label	#	Threshold parameters				D range (h)
		α	$\Delta\alpha$	γ	$\Delta\gamma$	
CLC first level						
T _{AS}	138	5.1	1.1	0.39	0.05	2–247
T _{AA}	456	6.1	1.3	0.40	0.06	1–306
T _{FA}	109	5.8	0.5	0.43	0.05	1–244
CLC third level						
T _{C1.1.2}	119	5.0	1.0	0.38	0.05	2–247
T _{C2.1.1}	191	6.3	0.9	0.42	0.04	1–204
T _{C2.4.2}	156	6.4	0.8	0.40	0.05	1–306
T _{C2.4.3}	103	4.5	0.8	0.50	0.05	1–204
T _{C3.1.1}	71	5.9	1.6	0.41	0.07	2–244

other hand, significant differences are found among the thresholds defined for the three third-level agricultural classes. The thresholds for classes 2.1.1 and 2.4.2 (*non-irrigated arable land* and *complex cultivation patterns*) are similar, while the threshold defined for the class 2.4.3 (*land principally occupied by agriculture*) is lower and steeper.

5 Discussion and Conclusions

Using a comprehensive catalogue of rainfall-induced shallow landslides in the Marche region, hourly rainfall measurements and three releases of Corine land cover maps, we observe differences in the distribution of landslides at different land cover levels and in landslide triggering conditions.

A high landslide density in urban areas is observed in the examined period (Table 2, Fig. 3). This result has relevant implications for landslide risk assessment. In general, the link between urbanization and landslide risk is known, but poorly quantified (Ozturk et al. 2022). Human modifications to slopes (e.g., slope cutting for building construction, vegetation removal, changes in hydrogeological conditions due to poor drainage or leaking pipes) can increase their instability. On the other hand, it should be acknowledged that landslides

information in urban areas may be more frequent and easier to obtain than in agricultural and forested areas, often non urbanized (Peruccacci et al. 2023).

Various seasonal distributions are observed in the CLC classes (Table 3, Fig. 4). Almost all landslides occurring in agricultural areas are concentrated in spring, while the slope failures occurring in forested areas are distributed between late autumn and mid spring. The information available in the catalogue does not allow an evaluation of the relationship between the land cover and the type of landslide movement. It is worth noting that this analysis was previously done for an event landslide inventory for about two thousand landslides that occurred in the Marche region after an extraordinary rainfall event in September 2022 (Donnini et al. 2023). In that case, almost all the landslides classified as falls and three quarters of those classified as flows occurred in forested areas, while most slides occurred in agricultural areas. The results of such different analyses made with different datasets could (and should) be combined to provide information on the occurrence of landslides of different types are expected in different land covers.

Relevant differences in the rainfall conditions able to trigger shallow landslides in the study area are also found. In detail, more rainfall is needed to trigger a landslide in agricultural and forested areas than on artificial surfaces (Fig. 5). Again, human modifications to natural environments may have worsened the stability conditions of the terrains covered by artificial surfaces. Forested areas are characterized by the higher values of cumulated rainfall needed to trigger landslides, particularly for duration longer than 24 h (Figs. 6 and 7). This is linked to the stabilization action played by vegetation on the slopes, mainly due to: (1) reduction of effective rainfall and infiltration, by interception and evapotranspiration; (2) increase in shear strength and additional soil cohesion due to root reinforcement; (3) changes in soil suction through root water uptake; (4) stabilization of the shallowest soil layers (Schmaltz et al. 2017; Masi et al. 2021).

Looking in more detail, different landslide-triggering conditions are observed in three agricultural areas. Less rainfall is needed to initiate a landslide in areas classified as *land principally occupied by agriculture* than in areas defined as *non-irrigated arable land* and *complex cultivation patterns* (Table 4). This could be an indication of some agricultural practices that may favor soil degradation and shallow slope instability (Tarolli and Straffellini 2020; Volpe et al. 2022).

The evaluations and the outcomes of this work will be even more relevant in a climate change context. In addition to the evident worldwide rise in temperature, global warming may increase extreme rainfall events due to an enhanced atmospheric moisture retention and consequently affect land cover, for example by changing agricultural and forestry practices. These changes have a direct and indirect impacts on slope stability and landslide occurrence (Sidle and Ochiai 2006; Gariano and Guzzetti 2016).

The results of this work are of interest for regional land-use planning and landslide risk assessment in the short and long term. The findings can also be used for a future evaluation of changes in landslide triggering conditions in response to projected land cover changes. The addition of new records to the landslide catalogue will allow further analysis at the second and third Corine levels to evaluate more specific differences in landslide triggering conditions in various types of crops and different forest species. Finally, the release of a new CLC map will allow new temporal analyses to look for recent most changes and trends in the density and distribution of the landslides.

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References

- Alcántara-Ayala I, Esteban-Chavez O, Parrot JF (2006) Landsliding related to land-cover change: a diachronic analysis of hillslope instability distribution in the sierra Norte, Puebla. Mexico *Catena* 65(2):152–165. <https://doi.org/10.1016/j.catena.2005.11.006>
- Ávila FF, Alvalá RC, Mendes RM, Amore DJ (2021) The influence of land use/land cover variability and rainfall intensity in triggering landslides: a back-analysis study via physically based models. *Nat Hazards* 105:1139–1161. <https://doi.org/10.1007/s11069-020-04324-x>
- Beguiria S (2006) Changes in land cover and shallow landslide activity: a case study in the Spanish Pyrenees. *Geomorphology* 74(1–4):196–206. <https://doi.org/10.1016/j.geomorph.2005.07.018>
- Brunetti MT, Melillo M, Gariano SL, Guzzetti F, Bartolini D, Brutti F, Bianchi C, Calzolari C, Denti B, Gioia E, Luciani S, Martinotti ME, Palladino MR, Pisano L, Roccati A, Solimano M, Vennari C, Vessia G, Viero A, Peruccacci S (2023) ITALICA (ITALian rainfall-induced Landslides CAtalogue). Zenodo. <https://doi.org/10.5281/zenodo.8009366>
- Corine Land Cover (2021) CORINE land cover product user manual (version 1.0). European Environment Agency (EEA), Copenhagen
- Donnini M, Santangelo M, Gariano SL, Bucci F, Peruccacci S, Alvioli M, Althuwaynee O, Ardizzone F, Bianchi C, Bornaetxea T, Brunetti MT, Cardinali M, Esposito G, Grita S, Marchesini I, Melillo M, Salvati P, Yazdani M, Fiorucci F (2023) Landslides triggered by an extraordinary rainfall event in Central Italy on September 15, 2022. *Landslides* 20:2199–2211. <https://doi.org/10.1007/s10346-023-02109-4>
- Gariano SL, Guzzetti F (2016) Landslides in a changing climate. *Earth-Sci Rev* 162:227–252. <https://doi.org/10.1016/j.earscirev.2016.08.011>
- Gariano SL, Petrucci O, Rianna G, Santini M, Guzzetti F (2018) Impacts of past and future land changes on landslides in southern Italy. *Reg Environ Chang* 18:437–449. <https://doi.org/10.1007/s10113-017-1210-9>
- Glade T (2003) Landslide occurrence as a response to land use change: a review of evidence from New Zealand. *Catena* 51:297–314. [https://doi.org/10.1016/s0341-8162\(02\)00170-4](https://doi.org/10.1016/s0341-8162(02)00170-4)
- Herold M, Latham JS, Di Gregorio A, Schmullius CC (2006) Evolving standards in land cover characterization. *J Land Use Sci* 1:157–168. <https://doi.org/10.1080/17474230601079316>
- Hungr O, Leroueil S, Picarelli L (2014) The Varnes classification of landslide types, an update. *Landslides* 11:167–194. <https://doi.org/10.1007/s10346-013-0436-y>
- Hürlimann M, Guo Z, Puig-Polo C, Medina V (2022) Impacts of future climate and land cover changes on landslide susceptibility: regional scale modelling in the Val d'Aran region (Pyrenees, Spain). *Landslides* 19:99–118. <https://doi.org/10.1007/s10346-021-01775-6>
- Knevels R, Petschko H, Proske H, Leopold P, Maraun D, Brenning A (2020) Event-based landslide modeling in the Styrian Basin, Austria: accounting for time-varying rainfall and land cover. *Geosciences* 10(6):217. <https://doi.org/10.3390/geosciences10060>
- Masi EB, Segoni S, Tofani V (2021) Root reinforcement in slope stability models: a review. *Geosciences* 11:212. <https://doi.org/10.3390/geosciences11050212>
- Ozturk U, Bozzolan E, Holcombe EA, Shukla R, Pianosi F, Wagener T (2022) How climate change and unplanned urban sprawl bring more landslides. *Nature* 608(7922):262–265. <https://doi.org/10.1038/d41586-022-02141-9>
- Pacheco Quevedo R, Velastegui-Montoya A, Montalván-Burbano N, Morante-Carballo F, Korup O, Daleles Rennó C (2023) Land use and land cover as a conditioning factor in landslide susceptibility: a literature review. *Landslides* 20:967–982. <https://doi.org/10.1007/s10346-022-02020-4>
- Peruccacci S, Brunetti MT, Luciani S, Vennari C, Guzzetti F (2012) Lithological and seasonal control of rainfall thresholds for the possible initiation of landslides in Central Italy. *Geomorphology* 139–140:79–90. <https://doi.org/10.1016/j.geomorph.2011.10.005>
- Peruccacci S, Brunetti MT, Gariano SL, Melillo M, Rossi M, Guzzetti F (2017) Rainfall thresholds for possible landslide occurrence in Italy. *Geomorphology* 290:39–57. <https://doi.org/10.1016/j.geomorph.2017.03.031>
- Peruccacci S, Gariano SL, Melillo M, Solimano M, Guzzetti F, Brunetti MT (2023) The ITALian rainfall-induced Landslides CAtalogue, an extensive and accurate spatio-temporal catalogue of rainfall-induced landslides in Italy. *Earth Syst Sci Data* 15:2863–2877. <https://doi.org/10.5194/essd-15-2863-2023>
- Pisano L, Zumpano V, Malek Z, Roskopf CM, Parise M (2017) 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. <https://doi.org/10.1016/j.scitotenv.2017.05.231>
- Reichenbach P, Busca C, Mondini AC, Rossi M (2014) The influence of land use change on landslide susceptibility zonation: TheBriga catchment test site (Messina, Italy). *Environ Manag* 54:1372–1384. <https://doi.org/10.1007/s00267-014-0357-0>
- Schmaltz EM, Steger S, Glade T (2017) The influence of forest cover on landslide occurrence explored with spatio-temporal information. *Geomorphology* 290:250–264. <https://doi.org/10.1016/j.geomorph.2017.04.024>
- Shu H, Hürlimann M, Molowny-Horas R, González M, Pinyol J, Abancó C, Ma J (2019) Relation between land cover and landslide susceptibility in Val d'Aran, Pyrenees (Spain): historical

- aspects, present situation and forward prediction. *Sci Total Environ* 693:133557. <https://doi.org/10.1016/j.scitotenv.2019.07.363>
- Sidle RC, Ochiai H (2006) Landslides: processes, prediction, and land use. *Water Resour Monogr* 18:312. <https://doi.org/10.1029/WM018>
- Tarolli P, Straffelini E (2020) Agriculture in hilly and mountainous landscapes: threats, monitoring and sustainable management. *Geogr Sustain* 1:70–76. <https://doi.org/10.1016/j.geosus.2020.03.003>
- Volpe E, Gariano SL, Ardizzone F, Fiorucci F, Salciarini D (2022) A heuristic method to evaluate the effect of soil tillage on slope stability: a pilot case in Central Italy. *Land* 11(6):912. <https://doi.org/10.3390/land11060912>

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