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Forest effect on rainfall-induced landslides: a case study in Northern Slovenia

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ABSTRACT

Slovenia is a relatively small country situated in Central Europe. In August 2023, Slovenia was hit by an extreme precipitation event causing a flood disaster. The return time of the event was estimated to be up to 250 years. The extreme flood occurred from the 4^{th} to the 6^{th} of August, causing 3 casualties and 10 billion euros of direct and indirect costs. The event triggered numerous local mass movements and the estimated number of landslides that occurred in the country because of the extreme flood was around 10,000.

The study area of this research is Črna na Koroškem, a municipality located in the central-north part of the country, bordering with Austria, with a surface area of 156 km^2. It was one of the most damaged municipalities during the 2023 floods. Almost 400 landslides were detected through field observation and by comparing Digital Terrain Models from before and after the extreme event. This study aims to investigate how landslide density, size and mobility changes in forest and non-forest land use. The outcome of the calculations presented in this research will be useful for future decision-making concerning land use management and landslide risk assessment and control.

1. INTRODUCTION

1.1 Introduction of the study area – climate pattern of Slovenia

Slovenia is a country with an area of 20,271 km². It is located in Central Europe in a temperate zone (Fig. 1). It presents three main types of climates: a temperate humid climate with hot summers, a temperate continental climate and a mountain climate (Komac et al., 2020). The distribution of precipitation is primarily influenced by relief and distance from the Adriatic Sea and, more widely, from the Mediterranean Sea (Komac et al., 2020). The mean annual precipitation (measured between 1981–2010) ranges from below 900 mm in the eastern part of the country, to more than 3000 mm in the western part (Dolšak et al., 2016). More specifically, the highest amount of precipitation is in the northwest, and the lowest is in the northeast. In particular, the greatest precipitation in the Julian Alps, in the northwestern part of the country, is three times greater than that in Pannonian northeastern Slovenia (Komac et al., 2020). In Slovenia the autumn period is usually the wettest period of the year. Main flood events and big mass movements usually occur in the period from September to December (Bezak et al., 2016; Mikoš et al., 2004; Špitalar et al., 2020).

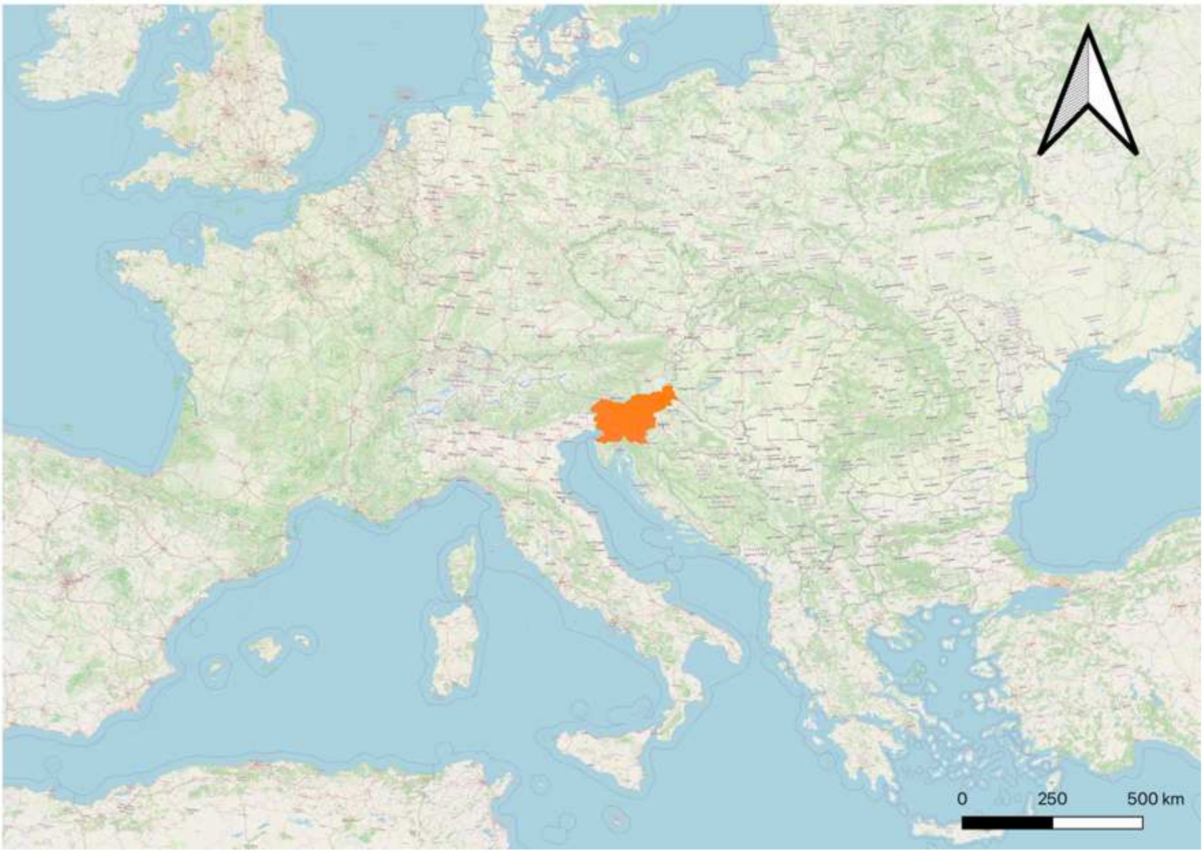

Figure 1: Location of the Republic of Slovenia.

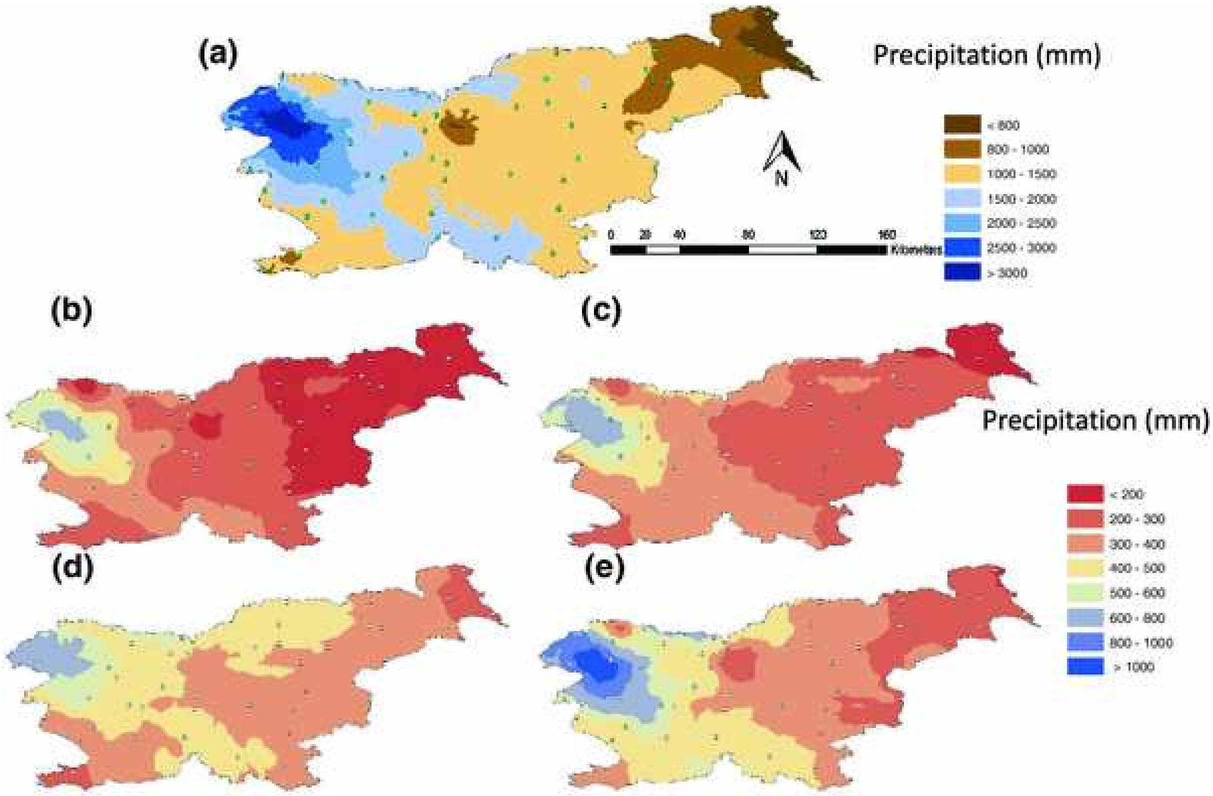

Figure 2: Average precipitation in Slovenia during the 1951–2007 period. (a) Total annual; (b) winter; (c) spring; (d) summer; (e) autumn (de Luis et al., 2014).

However, as described by Komac et al. (2020) the distribution of precipitation depends on the climate type. The region with a temperate humid climate and hot summers is characterized by spring and fall peaks. In the region with a mountain climate, most of the precipitation occurs in the fall, when Mediterranean cyclones are frequent, with a secondary peak in the late spring or at the beginning of summer. In the eastern part of the country, under the influence of a continental climate, precipitation is most abundant in the summer in the form of showers and thunderstorms caused by overheating of the atmosphere and the resulting strong convections (Fig. 2).

Compared to the rest of Europe, Slovenia is record-setting for the annual number of thunderstorm days, and the amount of precipitation is increasing, particularly in the western half of the country (Komac et al., 2020). Moreover, due to geological structures, relief and climatic conditions, Slovenia is very susceptible to the occurrence of various types of landslides (Auflič et al., 2024).

1.2 2023 extreme flood

1.2.1 Overview of the event

In 2023, Slovenia experienced two major natural disasters. The first occurred in May with over 2,000 shallow landslides triggered by prolonged heavy rainfall (from the 5th of May to the 23rd of May) mainly in the North-East of the country. The second occurred in August with heavy storms and intense rainfall causing around 10,000 landslides (Peternel et al., 2024).

As highlighted in Figure 3, most landslides were recorded north of Kamnik, in the area of Zgornja Savinjska dolina and in the Koroška region between Črna na Koroškem and Dravograd, as well as in the area of Poljanska dolina (Auflič et al., 2024).

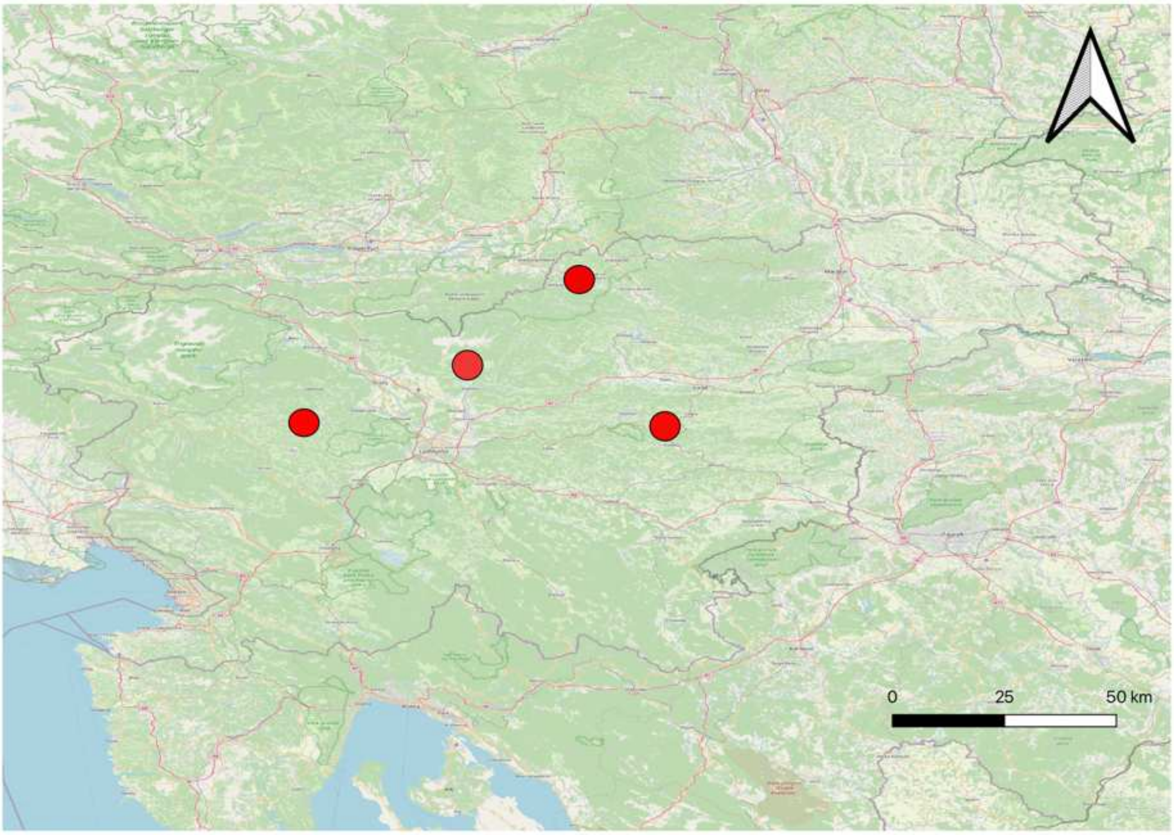

Figure 3: Location where most landslides were recorded after the extreme flood of August 2023. From left to right: in the area of Poljanska dolina; north of Kamnik; in the Koroška region between Črna na Koroškem and Dravograd; in the area of Zgornja Savi.

The natural disaster that occurred in August 2023 was a consequence of meteorological circumstances unusual for mid-summer which are more typical of the autumn or winter months, when the surface temperature of the Mediterranean Sea is not as high as it is in August (Auflič et al., 2024; ARSO, 2023a). Between the 3rd and 6th of August at some precipitation measuring stations, the monthly average amount of precipitation fell within a few hours (Auflič et al., 2024). Compared to previous years, almost all parts of the country recorded more than 50% of the total annual rainfall by the end of June, causing the soil moisture to be relatively high before the August 2023 flood event (Bezak et al., 2023). In total, during the 72-hour period up to the morning of the 6th August, between 100 and 300 mm of rain fell over most of Slovenia, with lower amounts only in parts of the Littoral region (Primorska) and along the eastern border with Croatia (ARSO, 2023a) (Fig. 4).

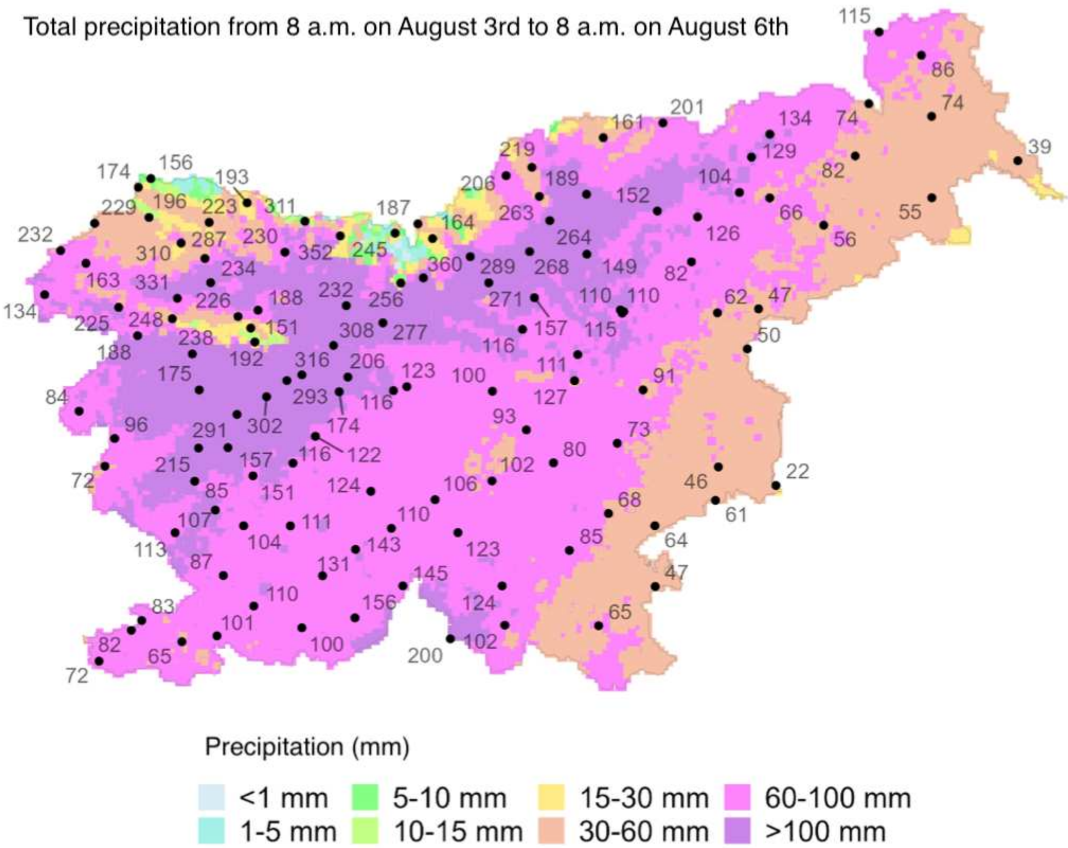

Figure 4: Map of the three-day (72-hour) precipitation totals from 8 a.m. on August 3rd to 8 a.m. on August 6th, measured at meteorological stations (rounded to the nearest mm on the figure) and estimated from radar measurements (color scale) (modified ARSO, 2023).

1.2.2 Dynamic of the event

The ARSO (Agencija Republike Slovenije za okolje - Slovenian Environmental Agency) described the dynamics of the event in their 2023 report. During the night from Thursday 3rd to Friday 4th extreme storms and heavy rainfall hit large areas of the western and northern part of the country. The flooding started early on 4th and the rainfall continued through Friday and Saturday slowly moving from the central and northern part of the country to the eastern and southeastern parts. In most parts of the country the rain stopped on Sunday 6th August.

The meteorological forecasting service issued the first warning for downpours and heavy rainfall on August 3rd at 9:00 a.m. The warning was updated in the following hours, until Friday morning at 5:30 a.m., when the weather risk level for both northern regions and central Slovenia was raised to the highest level. At 9:00 a.m., the warning was also extended to the southeastern part of Slovenia. Finally, a weather warning was also issued for the afternoon of Sunday 6th at the second-highest level for the entire country (ARSO, 2023a).

Bezak et al. (2023) highlighted the main drivers of the extreme event, being the atypical summer weather condition, the air and sea temperature in the Mediterranean, and the high previous soil moisture. In particular, the Mediterranean Sea was extremely warm, affecting the amount of water vapour in the air and thus the amount of precipitation (Auflič et al., 2024).

As reported from ARSO (2023), close to 90 % of all municipalities in Slovenia reported some kind of damage, only 30 out of 212 municipalities did not reported damage (Fig. 5).

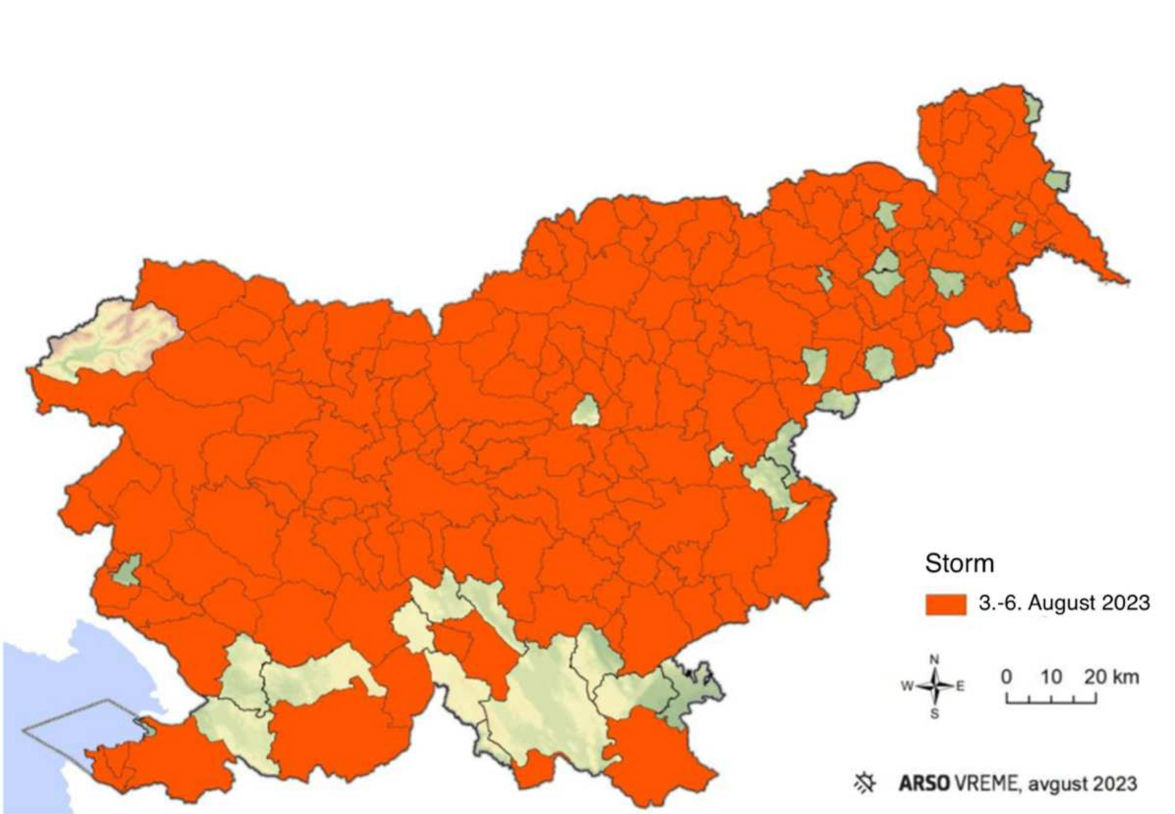

Figure 5: Map of municipalities where damage was reported due to downpours and heavy rainfall from August 3rd to 6th (ARSO, 2023a).

The August 2023 flood disaster can be regarded as relatively extreme. It was probably the most extreme flood event in Slovenia for the last several decades (since the 1980s). In particular, both daily and sub-daily precipitation extremes and peak discharges reached 250–500 years of return period (Bezak et al., 2023).

1.2.3 Consequences of the event

High soil saturation caused by heavy precipitation in July, in combination with intense precipitations at the beginning of August, induced massive disruptions in slope stability across the entire territory of Slovenia (Auflič et al., 2024). As described by Peternel et al. (2024) the hydro-meteorological conditions, such as increased water flow and rising groundwater levels, caused a large portion of the landslides to turn into mud or debris flows. The deposition areas have been detected from a few to several hundred meters away from the source areas (Fig. 6).

Figure 6: Mass movements pictured in the study area with deposited material in mountain torrents (photos: Kobal M., 2025).

In general, flooding, soil erosion, mass movements and river sediment transport processes caused major damage to buildings (more than 12 000 houses) and various infrastructure, such as roads, culverts and bridges (Bezak et al., 2023).

For what concerns the mass movement, the scale of the landslides are of a magnitude that has never been observed in the history of the Geological Survey of Slovenia (Auflič et al., 2024). During an observation visit carried out by Auflič et al. (2024), the type of slope mass movements, the extent of the events, and the causes of creep were analysed and determined. Specifically, they observed that in most cases, the rock surface was covered by clastic sediments of varying thickness, while in the Koroška region, weathering of metamorphic and magmatic rock was visible. They were able to notice that landslides occurred for very unusual geological grounds, where they would not otherwise be expected, such as steep limestone and dolomite slopes. In this case they observed shallow landslides with roots and trees, indicating that there was an exceptional amount of water liquefying the soil.

1.3 Landslides and climate change

In recent years, climate change has been intensifying, leading to an increasing occurrence of abnormal weather patterns worldwide (Asada et al., 2015).
As explained by Trenberth et al. (2003), the total amount of precipitation as well as the intensity, duration, frequency, and phase are fundamental to be taken in consideration, to determine the disposition of precipitation once it hits the ground and the generated runoff. Furthermore, they underline how the events of extreme precipitation are the ones that give rise to floods and droughts, whose changes in occurrence and severity have an enormous impact on the environment and society.
Komac et al. (2020) point out how Slovenia is characterized by an overall trend of rising temperatures, and the amount of precipitation is increasing particularly in the western half of the country, although in other parts, no noticeable trend diverging from long-term averages has been observed.
Specifically, due to climate change, extreme rainfall events will become more frequent and more intense, leading to more severe floods and mass movements (Kaitna et al., 2023; Tarasova et al., 2023). The global rising temperature from climate change is expected to increase the amount of intense rainfall events as a consequence of higher water content in the atmosphere (Allen and Ingram, 2002; Trenberth et al., 2003). It is undisputable that climate changes affect the stability of natural and engineered slopes and have consequences on landslides (Gariano and Guzzetti, 2016).
Gariano and Guzzetti, (2016) studied landslides in a scenario of future climate change. They considered changes in temperature, precipitation, and wind, for their direct and indirect effects

on stability of single slopes. They used a probabilistic landslide hazard model to appraise regional landslide changes. They predicted an increase in the number of people exposed to landslide risk as a consequence of the expected increase of the frequency and intensity of severe rainfall events, which are considered the primary trigger of rapid-moving landslides that cause many landslide fatalities.

1.4 Justification of the study

Landslides pose a severe threat to infrastructure, agricultural land, and even human life (Moos et al., 2015). Although loss of life from landslides is still poorly quantified, a global dataset of fatalities from non-seismically triggered landslides, between 2004 and 2010, recorded 2620 fatal landslides worldwide, causing a total of 32,322 recorded fatalities (Petley, 2012). Moreover, Petley (2012) explains that these numbers are an order of magnitude greater than indicated in other datasets, but analysis of the data suggests the true human costs is still underestimated. Therefore, predicting zones that are susceptible to landslide activity in a certain area and giving a better understanding of landslide triggering factors is of fundamental importance (D'Amato Avanzi et al., 2004; von Ruette et al., 2011; Piacentini et al., 2012).
Extraordinary precipitation events trigger most landslides that are among the most widespread hazards in the world. (Bogaard and Greco, 2015). The recent extreme flood event of August 2023 and its consequences are clear proofs that Slovenia is highly susceptible to landslides. Therefore, the need for implementation of preventive measures to cope with natural disasters must be underlined (Auflič et al., 2024).
Even though it is widely recognised that vegetation, particularly forest, can stabilize steep slopes, there is considerable argument about to what extent trees reduce hydro-geomorphic hazards (Rickli & Graf, 2009).

1.5 Structure of the thesis

This study will summarise the dynamics and the consequences of the extreme flood event that hit Slovenia in August 2023, describing the general climatic patterns of the country and its susceptibility to landslides. In the introduction section there is an overview of the possible future development of the mass movement natural hazard in a scenario of climate change. The importance of filling knowledge gaps in landslide risk and control management is highlighted. In the state of the art a general overview and description of mass movements is presented,

focusing on the impact that land uses, and more specifically forest covers, have on landslides. Furthermore, related knowledge gaps are pointed out. The methodology, the data collection and analyses of the study are described in the following sections.
This thesis aims to study how forest and non-forest land use have a different impact on the density, size and mobility of the landslides. The landslides parameters considered in the calculations are the area, the maximum depth, the volume and the travel distance angle. The hypothesis of this study is that the presence of forests will have a positive impact in reducing the density, the size and the mobility of the landslides. The outcome of this study can be helpful for the future developing of landslide risk management and mitigation strategies, and for the optimisation of forest management practices in landslide susceptible areas. The limitation of the study and possible improvements of the methodology are pointed out in the discussion section.

2. STATE OF THE ART
2.1 Landslides general overview
2.1.1 Landslide definition

Landslides have been defined from Cruden and Varnes (1996) as natural and potentially hazardous phenomena that move rock, debris, or earth downslope under the influence of gravity. Petley (2010a) also describes landslides as an important landscape-forming process, providing the main mechanism for sediment release from slopes to permit transportation through the fluvial system.

Cruden and Varnes (1996) identified 5 different types of movement. They highlighted the concept that the description of how movement is distributed throughout the displaced mass, is not only one of the principal criteria for classifying landslides, but it is also important to understand the appropriate response to the hazard.

The 5 different types of movement described by Cruden and Varnes (1996) are fall, topple, slide, spread and flow.

- The fall is the detachment of the soil or rock from a steep slope along a surface. The material descends rapidly mainly through the air by falling, bouncing or rolling, and little or no shear displacement takes place.
- The topple is the foreword rotation out of the slope of a mass of soil or rock about a point of axis below the centre of gravity of the displacement mass, that mainly falls or slides. This type of movement can range from slow to extremely rapid.
- The slide is a downslope movement of soil or rock mass, occurring dominantly on surfaces of rupture or on relatively thin zones of intense shear strain. The displaced mass may cover the original ground surface of the slope by sliding beyond the toe or the surface of rupture (The toe is the intersection between the lower part of the surface of rupture of a landslide and the original ground surface. The surface of rupture is the surface which forms the lower boundary of the displaced material below the original ground surface).
- The spread is an extension of a cohesive soil or rock mass combined with a general subsidence of the fractured mass of cohesive material into softer, underlying material. The surface of rupture is not a surface of intense shear.
- The flow is a spatially continuous movement in which surfaces of shear are short-lived, closely spaced and not usually preserved. There is a gradation form slide to flow depending on the water content, mobility and evolution of the movement.

It is important to take in consideration that many landslides exhibit a combination of different types of movements, at the same time or during their lifetime.
Moreover, Cruden and Varnes (1996), deeply describe 20 different landslide features and 8 landslide dimensions. Such description is fundamental to create a common language and a clear reference when studying mass movements.
For this research the parameter analysed is the travel distance angle described by Hunter and Fell (2003) in Figure 7. An equivalent term of travel distance angle is “angle of reach” that, as stated by Corominas (1996), is the angle of the line connecting the head of the landslide source to the distal margin of the displaced mass (relatively defined as “Initial slide” and “Debris deposition” in Figure 7). This parameter is found to be an accurate indicator of the relative mobility of the landslide, and it is independent from the fall height.

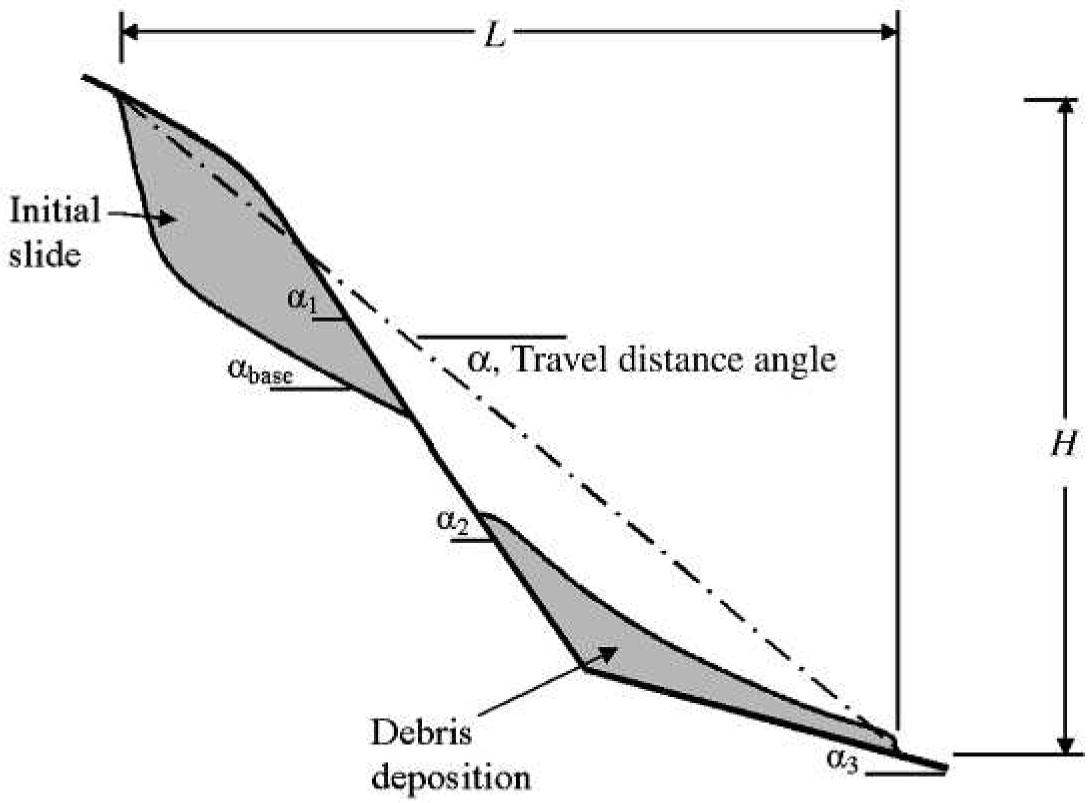

Figure 7: Definition of travel distance L, travel distance angle α, and slope geometry (Hunter and Fell, 2003).

Many other characteristics of landslides can be used to describe and classify the mass movement. For example, Cruden and Varnes (1996), emphasise the following parameters:

- the state of activity (active, inactive)
- the style of activity (complex, multiple, successive, single)
- the water content (dry, moist, wet, very wet)
- the material (rock, soil)

2.1.2 Landslide causes

Many different factors play a role in inducing mass movements, such as interactions between slope geometry, soil and rock properties, as well as surface and groundwater dynamics (Bogaard and Greco 2016).

Other phenomena that can influence the stability of slopes and cause landslides are precipitation, snow melting, temperature changes, earthquakes, volcanic activity, and various human actions (Gariano and Guzzetti, 2016). Corominas et al. (2014) developed a table describing 8 main factors controlling the occurrence of landslides (Fig. 8). The factors can be considered conditioning factors (C) or triggering factors (T) or both. Each factor contains different parameters. The 8 main factors are; topography, geology, soils, hydrology, geomorphology, land use and anthropogenic factors, earthquakes and volcanos, and weather and climate.

In particular, the identified parameters for the land use factor are the current land use, the land use changes (temporal variation in land use and land cover). The parameters related to the anthropogenic factors are transportation infrastructure, buildings, drainage and irrigation networks, quarrying and mining, and dams and reservoirs.

Corominas et al. (2014), recognize 3 different landslide mechanisms: rockfall (R), shallow landslides and debris flow (S), and large, slow-moving landslides (L). In Figure 8, it is shown how each parameter can have a crucial relevance (C), a highly important relevance (H), a moderately important relevance (M), or a less important relevance (L) for every different landslide mechanism. For example, the current land use has highly important relevance for all the landslide mechanisms, but the land-use change has a crucial relevance for the shallow landslides and debris flow, whilst a highly important relevance for the large, slow-moving landslides, and a moderately important relevance for the rockfall.

Group	Parameters	Relevance for landslide susceptibility and hazard assessment	Type of factor		Landslide mechanisms		
			C	T	R	S	L
Topography	Elevation, internal relief	Elevation differences result in potential energy for slope movements	●		H	C	H
	Slope gradient	Slope gradient is the predominant factor in landslides	●	●	C	C	C
	Slope direction	Might reflect differences in soil moisture and vegetation, and plays an important role in relation to discontinuities	●		C	M	M
	Slope length, shape, curvature, roughness	Indicator of slope hydrology, important for runout trajectory modelling	●		C	H	H
	Flow direction and accumulation	Used in slope hydrological modelling, e.g. for the wetness index	●		M	C	H
Geology	Rock types	Determine the engineering properties of rock types	●		C	H	C
	Weathering	Types of weathering (physical/chemical), depth of weathering, individual weathering zones and age of cuts are important factors	●		C	H	H
	Discontinuities	Discontinuity sets and characteristics, relation with slope directions and inclination	●		C	M	H
	Structural aspects	Geological structure in relation to the slope angle/direction	●		H	H	H
	Faults	Distance from active faults or widths of fault zones	●		H	H	H
Soils	Soil types	Origin of the soil determines its properties and geometry	●		L	C	H
	Soil depth	In superficial formations, depth determines the potential movable volume	●		L	C	H
	Geotechnical properties	Grain size, cohesion, friction angle, bulk density	●		L	C	H
	Hydrological properties	Pore volume, saturated conductivity, PF curve	●		L	H	H
Hydrology	Groundwater	Spatial and temporal variations in depth to groundwater table, perched groundwater tables, wetting fronts, pore water pressure, soil suction	●	●	L	H	H
	Soil moisture	Spatial and temporal variations in soil moisture content	●	●	L	H	H
	Hydrological components	Interception, evapotranspiration, throughfall, overland flow, infiltration, percolation, etc.	●	●	M	H	H
	Stream network and drainage density	Buffer zones around streams; in small scale assessment, drainage density may be used as an indicator for type of terrain	●		L	H	H
Geomorphology	Geomorphological environment	Alpine, glacial, periglacial, denudational, coastal, tropical, etc.	●		H	H	H
	Old landslides	Material and terrain characteristics have changed, making these locations more prone to reactivations	●		M	H	C
	Past landslide activity	Historical information on landslide activity is often crucial for determining landslide hazards and risk	●		C	C	C
Land use and anthropogenic factors	Current land use	Type of land use/land cover, vegetation type, canopy cover, rooting depth, root cohesion, weight	●		H	H	H
	Land-use changes	Temporal variations in land use/land cover	●	●	M	C	H
	Transportation infrastructure	Buffers around roads in sloping areas with road cuts	●		M	H	H
	Buildings	Slope cuts made for building construction	●	●	M	H	H
	Drainage and irrigation networks	Leakages from such networks may be an important cause of landslides	●	●	L	H	H
	Quarrying and mining	These activities alter the slope geometry and stress distribution. Vibrations due to blasting can trigger landslides	●	●	H	H	H
	Dams and reservoirs	Reservoirs change the hydrological conditions. Tailing dams may fail	●	●	L	H	H
Earthquakes and volcanoes	Seismicity	Earthquake magnitude/frequency relations, historical intensity maps linked with co-seismic landslide inventories		●	C	C	C
	Fault mechanism	Fault locations, fault type, length of fault rupture, buried or exposed, distance from fault, hanging wall/footwalls	●	●	H	H	H
	Volcano type	Height and composition of volcanic edifice, magma chamber stability	●	●	M	H	H
	Volcanic eruption types	Lateral explosions, collapse of magma chambers, pyroclastic flows, lahars	●	●	M	H	H
Weather and climate	Precipitation	Daily or continuous data, weather patterns, magnitude/frequency relations, IDF curves, rainfall thresholds, antecedent rain, PADF curves		●	C	C	C
	Temperature	Important influence on hydrology and the condition of vegetation. Rapid temperature changes, snowmelt, frost–thaw cycles, permafrost	●	●	H	H	H

Figure 8: Overview of factors controlling the occurrence of landslides, and their relevance in landslide susceptibility and hazard assessment for different landslide mechanisms (Corominas et al., 2014).

2.2 Landslides and land use

Land use refers to the purpose for which land is used and the human activities that occur on it (agriculture, residential development, industry and recreation).

As described by Corominas et al. (2014), land use is one of the factors controlling the occurrence of landslides. Concerning the current land use, the parameters that have a relevance for landslide susceptibility are; the type of land use and land cover, the vegetation type, the canopy cover, the rooting depth, the root cohesion and the weight (Fig. 8). They are considered to be conditioning factors with a highly important relevance both for shallow landslides and debris flow and for large, slow-moving landslides.

It has been observed that deforestation and cultivation alter the soil hydrological condition, especially on steep concave slopes, rendering them susceptible to saturation, and this my trigger debris flow and landslides during rainfall events (Mugagga et al., 2012).

2.3 Forest impact on landslides

2.3.1 Positive impacts of forests on landslides

As stated by Sato et al. (2023), forest cover is an important intrinsic factor influencing landslides. The presence of forests can lead to increased slope stability, due to mechanical and hydrological mechanisms, and therefore significantly reduce the landslide risk in many locations (Dorren and Schwarz, 2016).

Brang et al. (2006) highlight how the impact of forest in limiting landslide formation is most significant in the source area, which is the rock face or landslide initiation area. On the other hand, in the deposition zone (area where mass movements stop or are deposited) and the transition zone (area between the source area and the deposition area), the forest presence can only affect the transport of masses. It was observed that trees felt during the landslide forming log jams may obstruct the movement of loose sediment, while live trees situated beneath the landslide might dissipate the kinetic energy of landslide debris. Both phenomena could potentially limit the runout distance of the landslide (Johnson et al., 2000; Gomi et al., 2006; Guthrie et al., 2010).

Some results from the study of Rickli and Graf (2009) showed that landslide density was lower in forested terrain than in open land. Moreover, most forest landslides were found on steep slopes compared to open land. However, it is also important to consider that historically, settlement and agricultural fields were in flater areas, leaving forests usually on steeper slopes.

Therefore, the placement of forested and non-forested areas in relation to the terrain morphology can be seen as a consequence of the historical land use (Rickli and Graf, 2009).
Milledge et al. (2014) focused their study on shallow landslides. They defined shallow landslides as mass movement that involves low cohesion colluvial soils (less than a few meters deep) and that are often translational, falling along a sliding plane parallel to the slope surface. They observed that forests and trees modify the magnitude and rate of shallow landsliding and have been used by land managers for centuries to mitigate their effects (Philips et al., 2021).
There is a significant body of research indicating that forested mountainous regions exhibit a lower susceptibility to shallow landslides compared to non-forested slopes (e.g., Tasser et al., 2003; Persichillo et al., 2017) A research carried out by Sato et al. (2023) indicates that shallow landslides and debris flows become increasingly rare as forests mature. However the large volume of driftwood produced by landslides in mature forests may cause substantial damages when extreme rainfall events occur.

2.3.2 The role of roots

The actual degree of stabilization depends on the forest characteristics, mainly the spatial distribution of trees and more importantly their roots (cf. Schwarz et al., 2012; Hwang et al., 2015). As reported by Gehring et al. (2019) the roots contribute significantly to soil strength on hillslopes. Moreover, some investigations integrating root distribution across depth with root soil mechanical models, have highlighted the significant improvement in soil strength due to root reinforcement (Pollen 2007; Schwarz et al., 2010b; Giadrossich et al., 2019), especially in the initiation area.
Beside the mechanical effect, roots also influence hydrology by creating macro-pores, which increases infiltration and alters the underground flow of water. The effect of this mechanism is ambiguous, since root systems can create networks of preferential flow and thus influence water pressures in soils to trigger landslides (Ghestem et al., 2011).

2.3.3 The role of canopy interception

Previous studies indicated that root water uptake and canopy rainfall interception benefit slope stability (Hemmati et al., 2012; Sidle and Ziegler, 2017; Ni et al., 2017; Francis et al., 2022). Specifically, canopy interception captures rainfall, reducing the amount that reaches soil surface, slowing soil saturation, which is a critical factor in triggering shallow landslides (Keim

et al., 2003). In general, soil saturated with water can lose mechanical strength and become more prone to sliding. Forests increase the threshold amount of precipitation required for landslides to occur. Specifically, interception and evapotranspiration can reduce the amount of water that reaches the soil.
However, it has also been observed that the rainfall interception ability of the canopy and root uptake is minimal during heavy rainfall (Gonzalez-Ollauri and Mickovski, 2017; Liu et al., 2018). During heavy rainfall events, the soil loses its cohesion, and the weight of the soil increases (Meusburger and Alewell, 2014).

2.3.4 Negative impacts of forests on landslides

Other sources report how forests can also have a negative impact on landslide risk, from the weight of the biomass and the effects of the wind on the soil through the trees (Steinacher et al., 2009; Pawlik, 2013). The effect of the biomass weight affects terrain stability depending on the type of terrain. The effect is neutral or slightly positive when; the soil is unconsolidated and shallower than the root system, and when the sliding surface is parallel to the slope. Otherwise, the weight effect is unclear on well-consolidated soils and negligible in areas with deep sliding surfaces (Steinacher et al., 2009). Wind can negatively affect slope stability in forested areas since the tree movement under the action of the wind can cause loosening of the soil, influencing the slope stability. Landslides can also be triggered with tree uprooting (Pawlik, 2013), however Steinacher et al. (2009) consider the positive effects of the root mat being much greater than the negative effects of wind and weight.
Other studies report how landslides in forested slopes can be deeper due to the entanglement of roots within the soil matrix, leading to larger failure areas compared to grasslands (Bathurst et al. 2007; Koyanagi et al. 2020). In fact, as described by Bingli et al. (2024), the area near the lower boundary of root growth is the area with the lowest soil strength, therefore the role of vegetation is considered limited for failures occurring deeper than the root system (Liu et al., 2021).

2.4 Knowledge gaps of impacts of forests on landslides

The protective function of forests against gravitational natural hazards in mountainous regions is one of their most important ecosystem services (Gehring et al., 2019). However, when studying landslide susceptibility, the influence of forests on their mobility is often overlooked, despite their significance. A comprehensive quantitative evaluation of the impact of forests on landslide mobility remains absent in current research (Bingli et al., 2024).

Brang et al. (2006) define the effectiveness of protection of forests as a combination of the type of natural hazard with its frequency and intensity, and the state of the forest. Forest stand species composition and structure imply considerable differences in the resistance and resilience of forest systems against disturbances (Dazio et al., 2018). For example, some result from Murgia et al. (2024) research showed that species with deep root systems, such as oaks, provide more effective slope stability than other species, such as pines. It has also been observed how beech is more suitable than spruce in slope stabilization, mainly due to beech's deeper root system and higher water consumption (Norris et al., 2008; Chiaradia et al., 2016). Chiaradia et al. (2016) underline the importance to select species suited to the habitat rather than choose the species solely based on properties such as root depth and water consumption. Species diversity and adaptation to the habitat are key factors for forests resistance to disturbances. Still very little is known about the effect of different forest structures on slope stability (Moos et al., 2015).

Bischetti et al. (2009) underline that although the effect of forests in preventing and mitigating hydrogeomorphic hazards in mountainous landscapes are particularly relevant, its quantification is a relatively new challenge.

3. DATA AND METHODS

3.1 Study area

This study aims to investigate forest and non-forest land use effect on landslide density, size and mobility. The study area of the research is in the Municipality of Črna na Koroškem in the Koroška Region, northern Slovenia, bordering with Austria. According to the statistical data for 2023 the municipality counts 3160 inhabitants in a total surface area of 156 km^2 (Črna na Koroškem - Slovenian regions and municipalities in numbers. Last access: 7 August 2025 https://www.stat.si/obcine/sl/Municip/Index/23).

3.2 Data collection

3.2.1 Data sources

The data used for this study are the georeferenced airborne lasers scanning data (3D point cloud) of the ground of the municipality of Črna na Koroškem from the years 2014 and 2023, after the flood events.
For the year 2014, the data was downloaded from the Environmental Atlas of the Slovenian Environment Agency (ARSO- Agencija RS Za Okolje) (Atlas Okolja ARSO - Environmental Atlas of the Slovenian Environment Agency. Last access: 7 August 2025 https://gis.arso.gov.si/atlasokolja/profile.aspx?id=Atlas_Okolja_AXL@Arso). The Atlas Okolja is a map-interface of Slovenia that presents data of various indicators (for example environment, climate, land use). The lidar data fishnet in D96TM projection was used, in which each cell is 1 km^2. Almost 200 cells cover the surface area of municipality Črna na Koroškem. For each cell, the data georeferenced and classified point cloud GKOT (D96TM) in LAZ format was downloaded.
For the year 2023, the data was downloaded from the public national data viewer, CLSS - Slovenia's Cyclical Laser Scanning (Ciklično Lasersko Skeniranje Slovenije), which is a web application designed to provide access to spatial data obtained through laser scanning. For each cell covering the study area, the georeferenced and classified point cloud GKOT (D96TM) in LAZ format was downloaded.
The land use data was taken from the RABA Land Use database (RABA archive database. **RABA** Grafični podatki RABA za celo Slovenijo (shape.zip ~ 638 MB) KoordSistem: D96/TM https://rkg.gov.si/vstop/ Last access: 8 August) which is a national record of land

cover and land use in which the delineation of forest areas is coordinated with Slovenian Forest Service (SFS).

3.2.2 Point cloud conversion to digital terrain model (DTM)

The two sets of classified georeferenced point cloud are downloaded. The first set of data is from 2014 and the second is from 2023 after the extreme flood event that happened between the 3rd and the 6th of August 2023.

In the program QGIS (Quantum Geographic Information System) it is possible to create a model, which is a custom processing workflow, by using the Graphical Modeler. It allows to connect multiple processing steps in a visual interface. A model is used to convert all the point cloud data of each cell into a DTM – Digital Terrain Model, and to create the hillshade DTM. The DTM is a 3D digital representation of the bare ground surface of a certain area, that shows the elevation of the terrain. In the DTM, trees, buildings, objects and other above-ground features are removed.

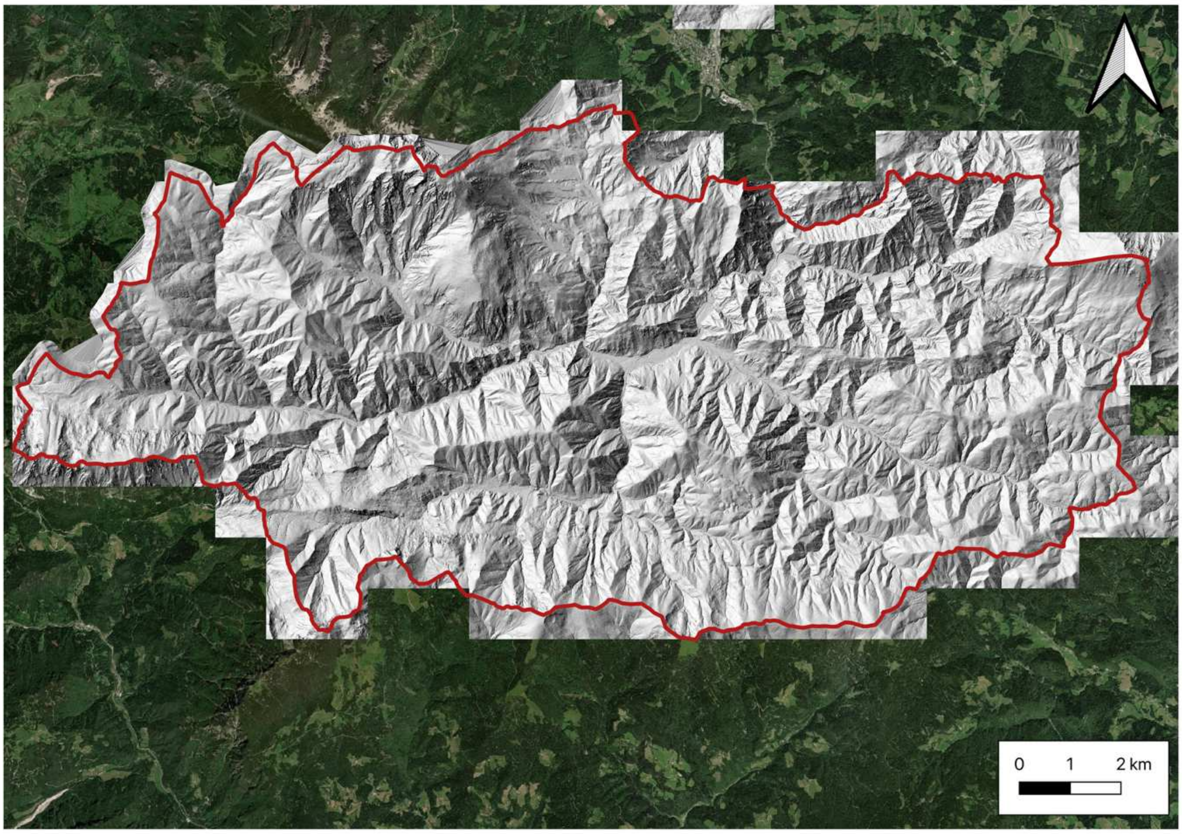

Figure 9: Hillshade 2023, output of the second step of the QGIS workflow applied to every cell of the study area. The red line represents the borders of the municipality of Črna na Koroškem.

The hillshade is a raster layer styled with a scale of grey colour plate representing the ground elevation by simulating the effect of the sunlight on the terrain. The pixels values represent the intensity of the light in each point of the terrain as if it was illuminated by a source of light at a certain angle and height.
The workflow on QGIS consists of two steps applied to every cell of the study area. The input of the first step is the point cloud data that undergoes the point cloud conversion, which is a data conversion function transforming the point cloud data form LAZ format the DTM raster layer. In the second step the input is the DTM obtained in the first step and the Hillshade raster analyses tool is applied, giving the hillshade layer as an output.
Therefore, 4 sets of data for each cell were created as an output after the script ran twice, one for every year considered; DTM 2014, DTM 2023 hillshade 2014, hillshade 2023 (Fig. 9).

3.2.3 DoD - Difference of DTMs

The DoD (Difference of DTMs) is a raster layer obtained by subtracting two different DTMs (or Digital Elevation Model (DEM)) allowing the detection and measure of elevation changes over time in the observed area.
In QGIS the Graphical Modeler is used to create a model giving the DoD raster layer as an output of the study area (Fig. 10). The processing workflow is applied to every cell covering the area of the Municipality of Črna na Koroškem and it consists of a raster calculation where the DTM of 2014 is subtracted from the DTM of 2023.
The DoD allows to detect where the zones of erosion and accumulation are, therefore, thus identifying where landslides occur. This approach is also described in general terms by Cruden and Varnes (1996). They define the zone of erosion as the area over which the elevation of the ground surface decreases because of landsliding, whereas the zone of accumulation is the area over which the elevation of the ground surface increase. Based on this definition, when the DTM of the landslides is available before and after the mass movement, the zone of erosion and accumulation can be found from the differences between the models. In particular, the volume decrease over the zone of erosion and increases over the zone of accumulation. They also point out how accumulation is expected to be larger than erosion as the ground generally dilates during landslides.

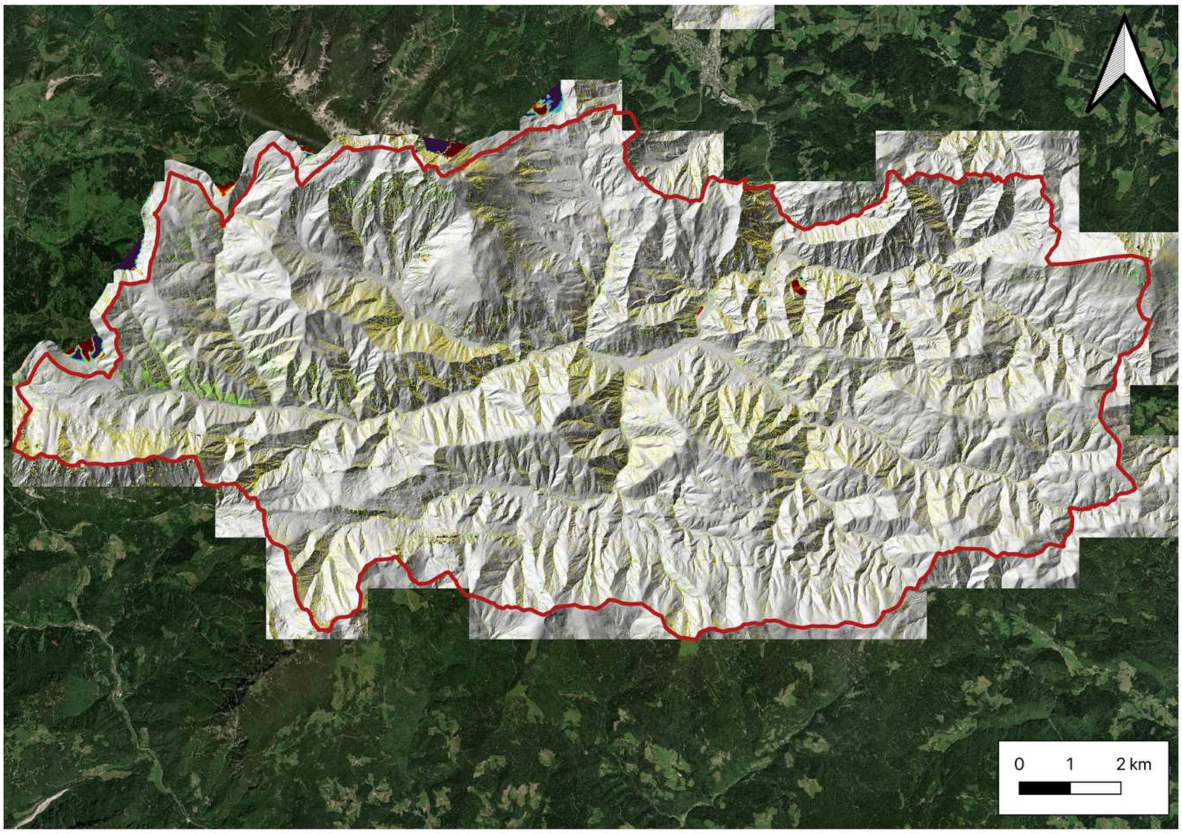

Figure 10: The raster layer representing the DoD of the study area. The red line represents the borders of the municipality of Črna na Koroškem.

In QGIS it is possible to style the raster layer choosing different colours for different erosion and accumulation intervals. Small scale changes in elevation can be neglected, to highlight only the main mass movement that happened in the study area.

In this study the elevation ranges from 0.50 m -0.50 m are not shown in the map (transparent). As shown in the legend in Figure 11 erosion areas are divided in five elevation intervals, from light yellow to dark red. The accumulation areas are divided in five intervals from light green to dark blue.

Both intervals of the negative and positive values are:

- from 0.5 m to 1.0 m
- from 1.0 m to 3.0 m
- from 3.0 m to 5.0 m
- from 5.0 m to 10.0 m
- above/below 10.0 m

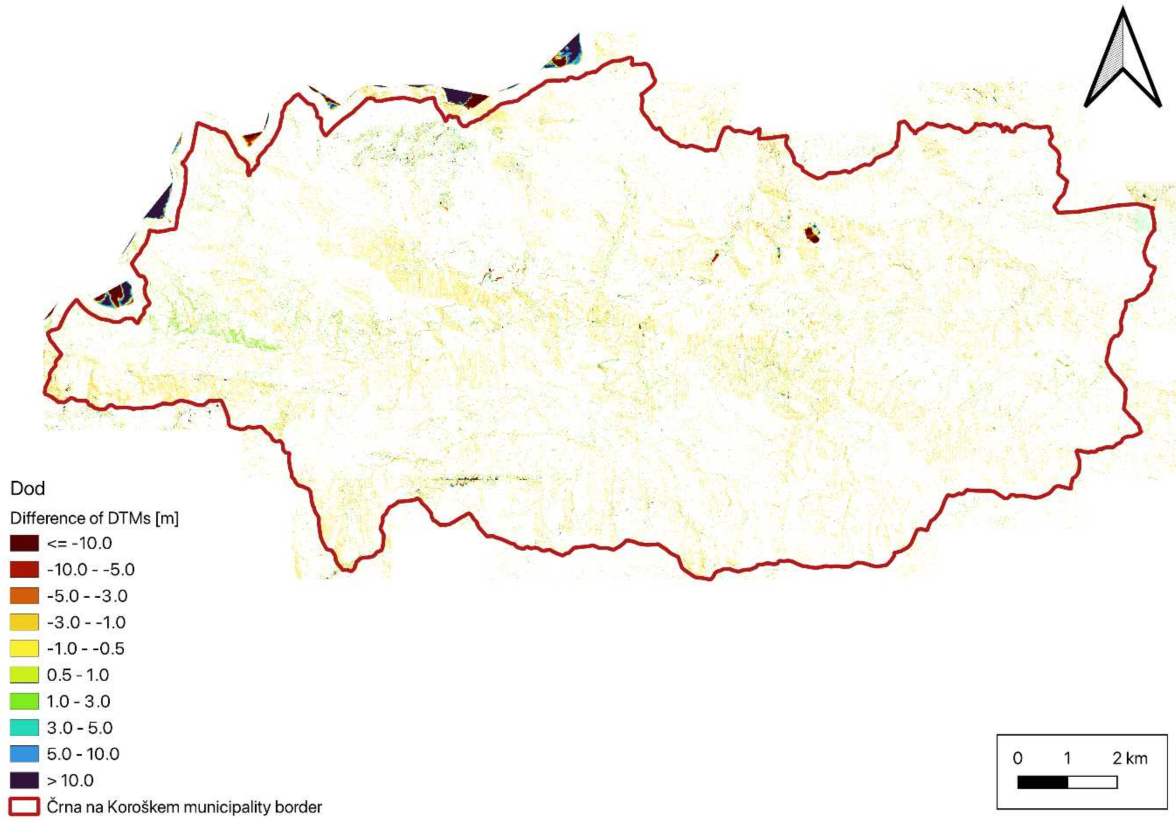

Figure 11: The raster layer representing the DoD over the study area. The red line represents the borders of the municipality of Črna na Koroškem. The legend in the bottom left of the map shows how the elevation intervals are divided and styled.

3.2.4 Landslide detection and vectorisation

There are different approaches that can be used to detect the landslides in the study area. It is possible to observe the erosion and deposition processes highlighted by the DoD (Fig. 12). A red to yellow usually smaller surfaces indicates the erosion area, which must be followed by a green to blue usually bigger surface indicating deposition. Where the DoD highlights what may look like a landslide, it is useful to; compare the hillshade layer from the two different years (Fig. 13), to check satellite image (Fig. 14), and to carry out observation in the field (Fig. 15).

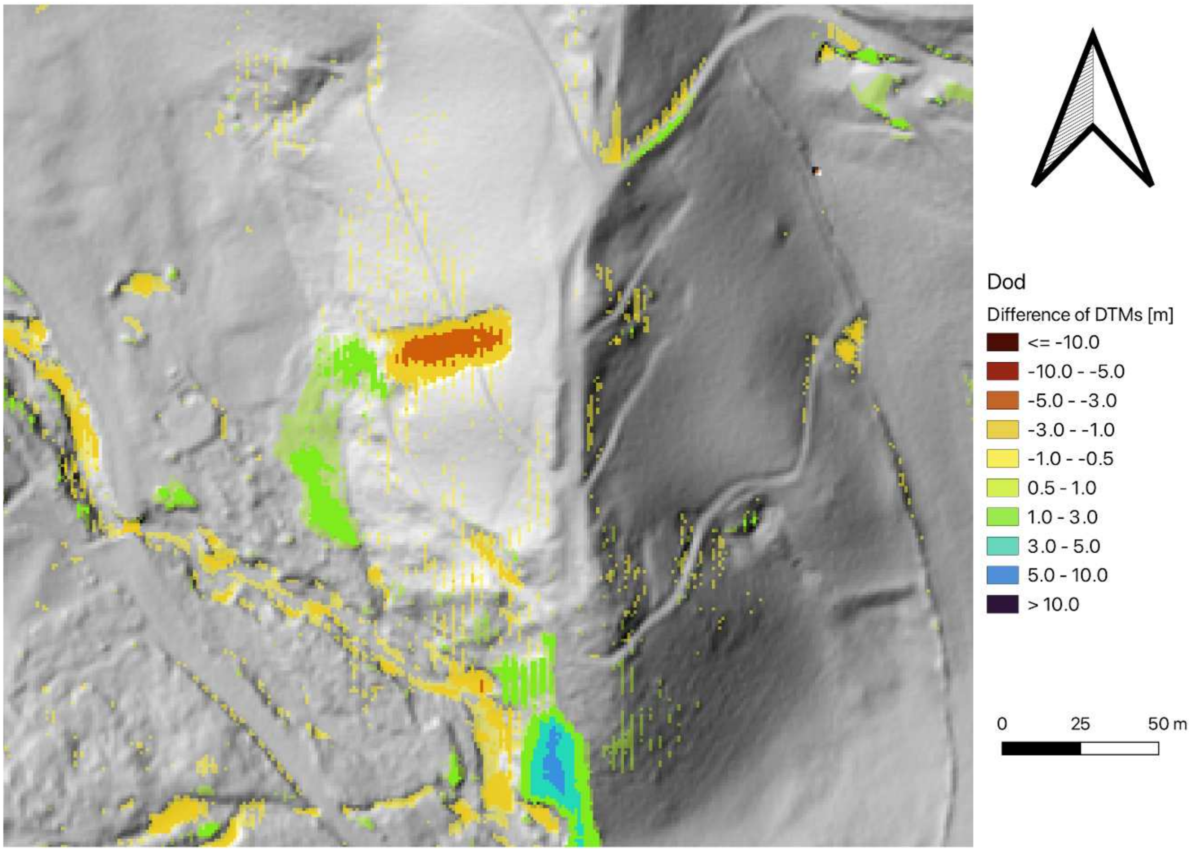

Figure 12: The DoD layer highlights a landslide. The source area is yellow and orange above the transport and accumulation area in green.

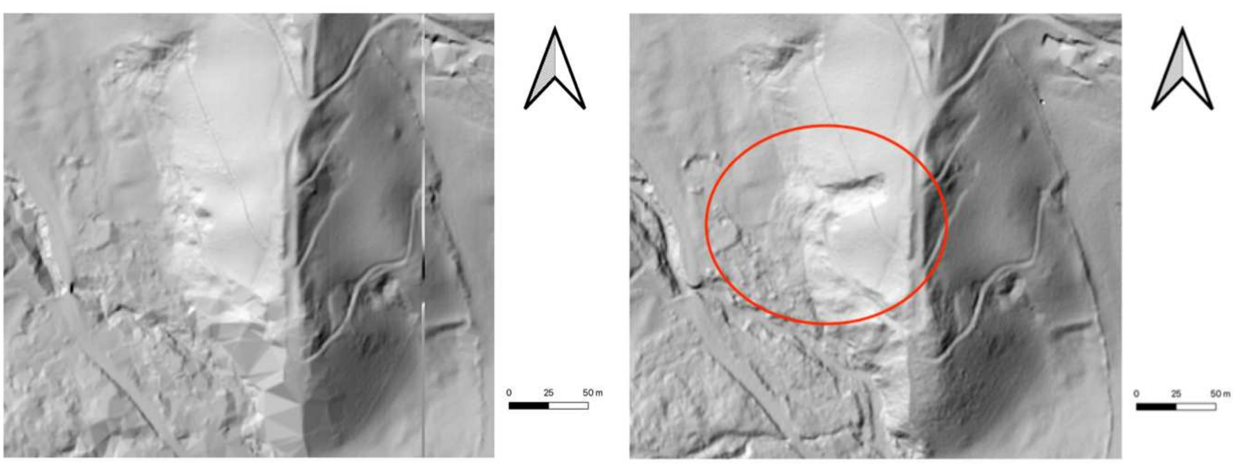

Figure 13: The comparison between the hillshade 2014 (on the left) and 2023 (on the right) where it is possible to see the landslide.

Figure 14: The landslides observed on satellite image (photo source: Google Earth).

Figure 15: Landslide observed in the field (photo: Kobal M., 2025).

In QGIS is possible to create a vector layer which consists of spatial data representing geographic features using point, lines or polygons with the related attributes. The detected landslides can be vectorised by drawing a polygon around the perimeter of the landslide surface area (Fig. 16).

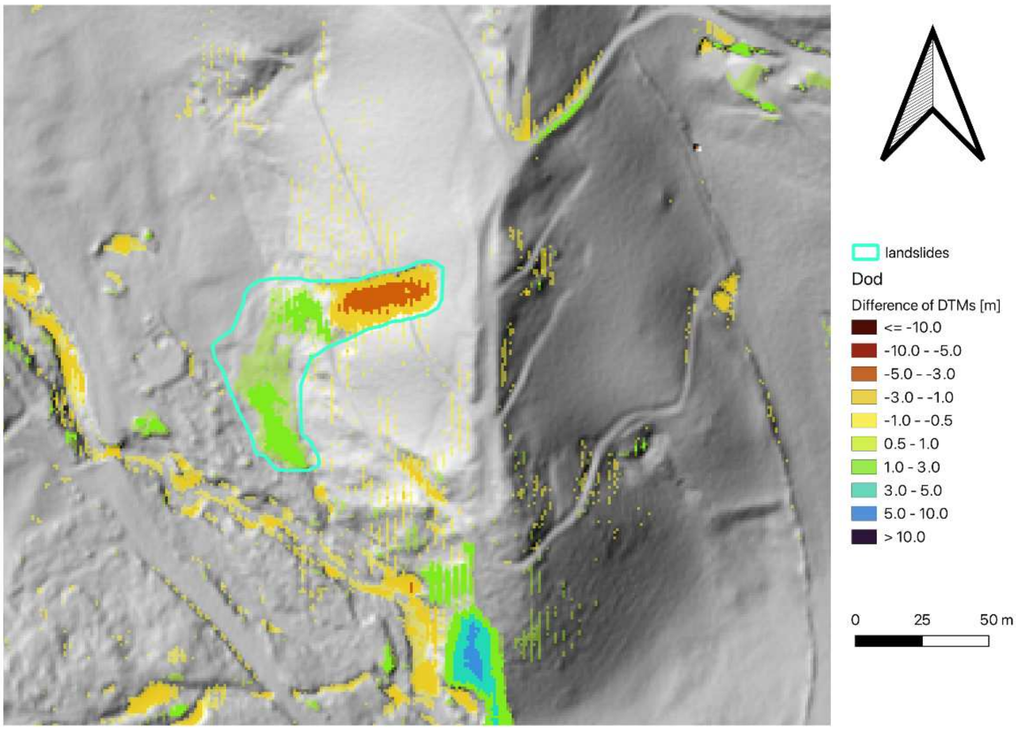

Figure 16: Landslide detected and vectorised on QGIS vector layer.

It is important not to base the landslide vectorisation only on the difference of DTM layers, but also to consult satellite images (Fig. 17), and to compare the hillshade layers from the two different years (Fig. 18 and 19), in order to understand if the mass movement is related to a natural rain-induced landslide or is the result of an anthropic intervention, for example excavations.

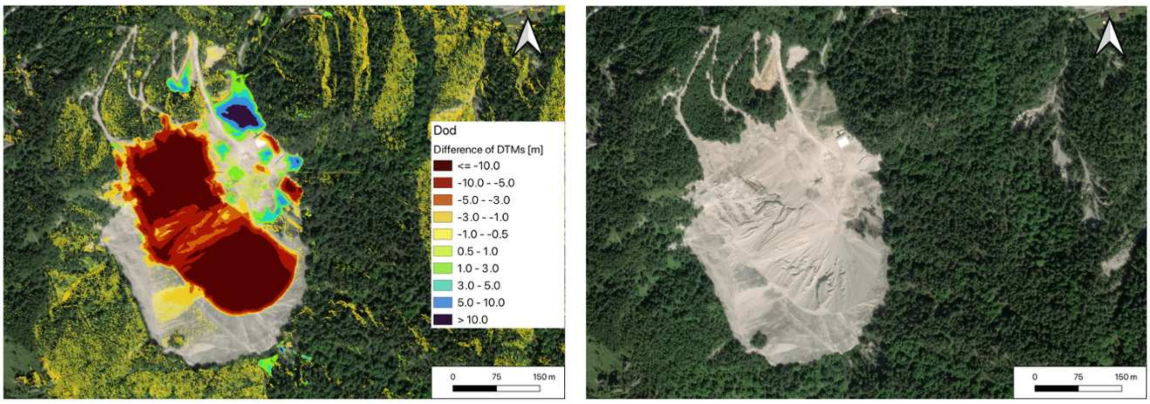

Figure 17: Detected difference of terrain elevation due to anthropic intervention. By looking at the satellite image it is possible to state that the highlighted erosion is due to anthropic excavation activities.

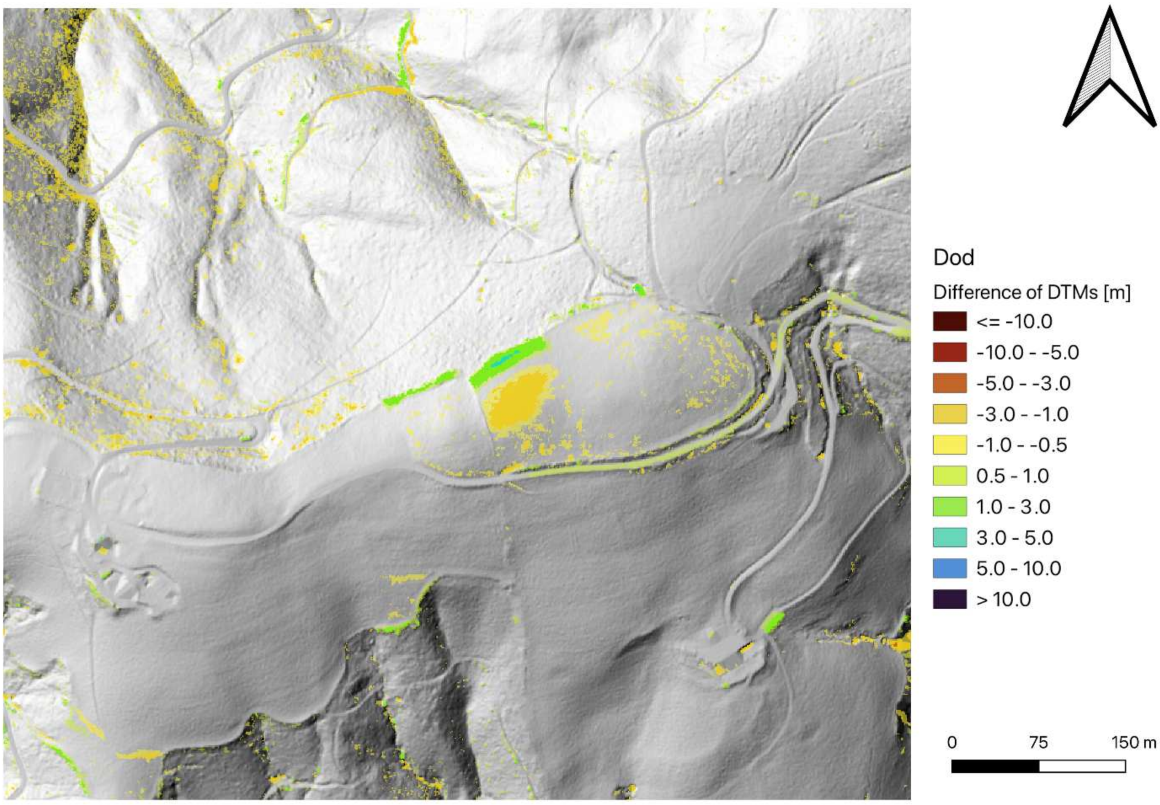

Figure 18: DoD highlight a difference in elevation due to anthropic intervention.

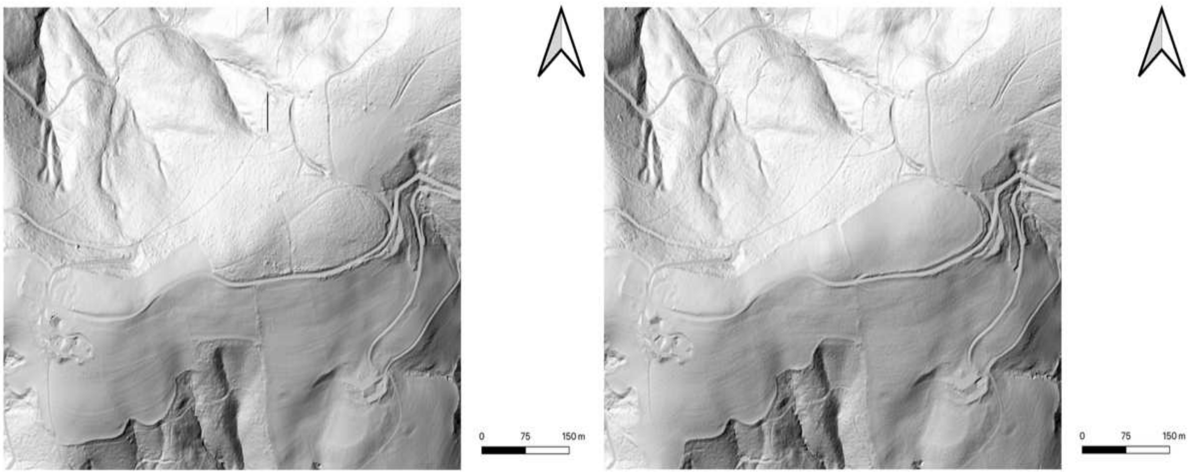

Figure 19: Comparison of the hillshade that shows a difference in elevation due to an anthropic intervention. Hillshade 2014 on the left, hillshade 2023 on the right.

3.2.5 Landslides parameters values collection

QGIS data were used to obtain values of landslide number, size and mobility. The number of landslides is taken from the vector file where every detected landslide in the study area is marked with a vector polygon around its perimeter.

The travel distance angle is calculated with the ratio L/H. H is the difference between the maximum and minimum elevation point of the 2014 DTM within the landslide polygon. L is the line connecting these two points, representing the maximum elevation difference (i.e. the slope between the upper and lower part of the landslide). A bigger ratio corresponds to a smaller angle, which indicates a longer travel distance.

The landslide surface area is taken from the attributes of the vector polygon.

The maximum depth and volume values are taken from the DoD raster layer. The negative values of the volume represent erosion, and the positive ones represent accumulation.

The values of the slope are obtained from the 2014 DTM layer since the slope before the landslides occur is the one that has to be considered.

3.3 Data analysis

The data analysis aims to observe how different parameters concerning the landslide density, size and mobility change in different land use. All the calculations have been carried out in R (Software environment for statistical computing and graphics - programming language).

For this research, the land use classified as agricultural land include arable land, greenhouses, vineyards, intensive orchards, extensive orchards, permanent grasslands, and uncultivated agricultural land. The land use classified as forest include overgrown agricultural areas, forest plantations, trees and shrubs, forest trees and agricultural land and forests. The land use classified as 'other' consists of built-up area and related surface, dried open area with special vegetation, open area with little or no vegetation, and water.

The calculation estimates the number of landslides in each land use, the landslide density in each land use, as well as the percentage of the land use area over the whole Municipality and the landslide percentage in every land use. The mean accumulated and deposited volumes and their mean maximum depth are compared for each land use. Moreover, more analyses were carried out by using R.

First, the relationship between the density of the landslides and the slope of the terrain in forest and non-forest land use was analysed. For the density, the distribution of the variable was estimated with R's kernel density estimator via the density() function (stats::density in stats package). The method computes a smooth estimate of the probability density based on the data and a chosen bandwidth (automatically selected unless specified).

The relationship between the empirical cumulative probability of landslides and the slope of the terrain in forest and in non-forest land use was calculated. Specifically, the empirical cumulative distribution function (ECDF) was obtained in R using the function stats::ecdf in stats package, which use the following function:

$$F(x) = \frac{1}{n}\sum_{i=1}^{n} 1(x_i \leq x)$$

In this case the proportion of the observations is less than or equal to x (i.e. the value at 30° refer to the probability of landslides in a slope gradient equal or lower than 30°).

The relationship between the density of the landslides and the travel distance angle in forest and non-forest land use was analysed using the above descripted methods to obtain the considered values (section 3.2.5).

Closing the relationship between the slope of the terrain and the percentage of forest covering the landslide polygon was calculated. For this last value the land-use dataset RABA was used. The intersected landslide polygons with the forest classes from RABA database were considered to obtain the percentage of forest cover over the landslide area with the following formula:

$$\%forest = 100 \times \frac{area\ of\ (polygon\ \cap forest)}{area\ of\ polygon}$$

4. RESULTS

4.1 Data collection results

In the Municipality of Črna na Koroškem, measuring a surface area of 156 km^2, 389 landslides were detected and vectorised (Fig. 20). There is not a clear spatial pattern in the distribution of the detected landslides, even though there seems to be a higher density of landslides in the south western part of the study area and a lower density in the north eastern part.

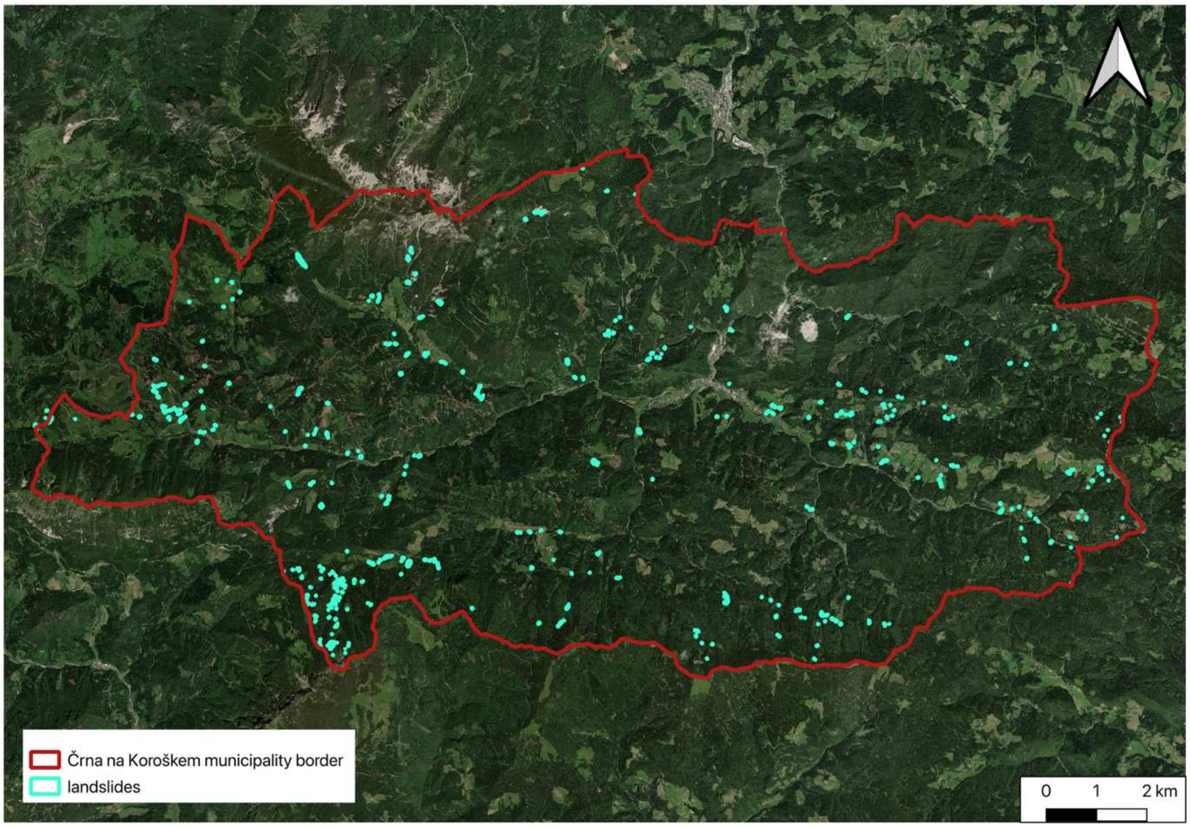

Figure 20: The shape file showing the 389 landslides detected and vectorised in the light blue lines. The red line represents the borders of the study area: the Municipality of Črna na Koroškem.

4.2 Data analysis results

As reported in Table 1 most landslides occurred in forested areas (339 events, which corresponds to about 87% of the total number). Agricultural areas accounted for 39 events (about 10 %), while the 'other' category contributed to only 11 events (about 3 %). This distribution suggests that forests are the most affected land use type, which could be due to their larger spatial extent in the study area, particular geomorphological conditions or both.

Table 1: Number of landslides in each land use.

Land use	Agricultural land	Forest	Others
No. landslides	39	339	11

Although most landslides were recorded in forested areas (339 events), this pattern must be interpreted in the context of the much larger forested area, which accounts for 138.43 km² or about 89% of the study area. Agricultural areas cover 13.23 km² (about 8.5% of the area) and recorded 39 landslides, while the 'other' category covers 4.12 km² (about 2.6%) with a total of 11 events. Normalised by area, the density of landslides is approximately 2.95 landslides/km² in agricultural areas, 2.45 landslides/km² in forests and 2.67 landslides/km² in the 'other' category. This shows that although forests recorded the highest absolute number of landslides, the relative susceptibility per unit area is higher in agricultural areas (Tab. 1 and 2).

Table 2: Surface area of each land use expressed in km^2, and their percentage area in the Municipality, landslide density expressed in No./km^2 and percentage in each land use.

Land use	Agricultural land	Forest	Others	Total
Area [km^2]	13.23	138.43	4.12	155.78
Landslides density [No./km^2]	2.95	2.45	2.67	2.50
Land use percentage [%]	8	89	3	100
Landslides percentage [%]	10	87	3	100

The characteristics of landslides differ depending on the type of land use (Tab. 3). On agricultural land, the events are generally smaller, with smaller amounts of eroded (385.05 m³) and accumulated (74.90 m³) material, shallower depths (-2.59 m and 1.07 m) and smaller area (610.50 m^2). Landslides in forests are moderately larger (567.73 m³ of eroded material, 122.03 m³ of accumulated material, depths of -3.23 m and 1.60 m, 639.95 m^2 of mean area), while the 'other' category has the largest events (1,278.96 m³ of eroded material, 165.70 m³ of accumulated material, maximum depths of -4.54 m and 2.29 m, mean surface area of 1228.49

m^2). This indicates that smaller landslides occur in agricultural areas, bigger ones occur in forests while 'other' land use is affected by the largest and deepest landslides.

Table 3: Mean area, mean eroded and accumulated volume and maximum depth in erosion and accumulation area of landslides in each land use.

Land use	Agricultural land	Forest	Others
Mean area [m^2]	610.50	639.95	1228.49
Mean eroded volume [m^3]	385.05	567.73	1278.96
Mean accumulated volume [m^3]	74.90	122.03	165.70
Mean maximum depth [m]	-2.59	-3.23	-4.54
Mean maximum depth [m]	1.07	1.60	2.29

In Figure 21 the relationship between landslide density and slope angle is shown for forest and non-forest land uses. The results indicate that the maximum density of landslides occurs at 26.1° in non-forest areas and at 33.4° in forested areas. Overall, landslides in non-forest areas tend to develop on gentler slopes, with a peak around 30°, whereas in forests they occur more frequently on steeper slopes, peaking around 35–40°. This pattern suggests that slope gradient exerts a stronger control on landslide occurrence in forests, while in non-forest land uses, landslides are more common on lower slope gradients.

In Figure 22 it is possible to observe the relationship between the empirical cumulative probability of landslides and the slope of the terrain in forest and in non-forest land use.

The result shows that the cumulative probability of landslides below 20° slope in forests is low (under 6%), while in non-forest land use it is above 25%.

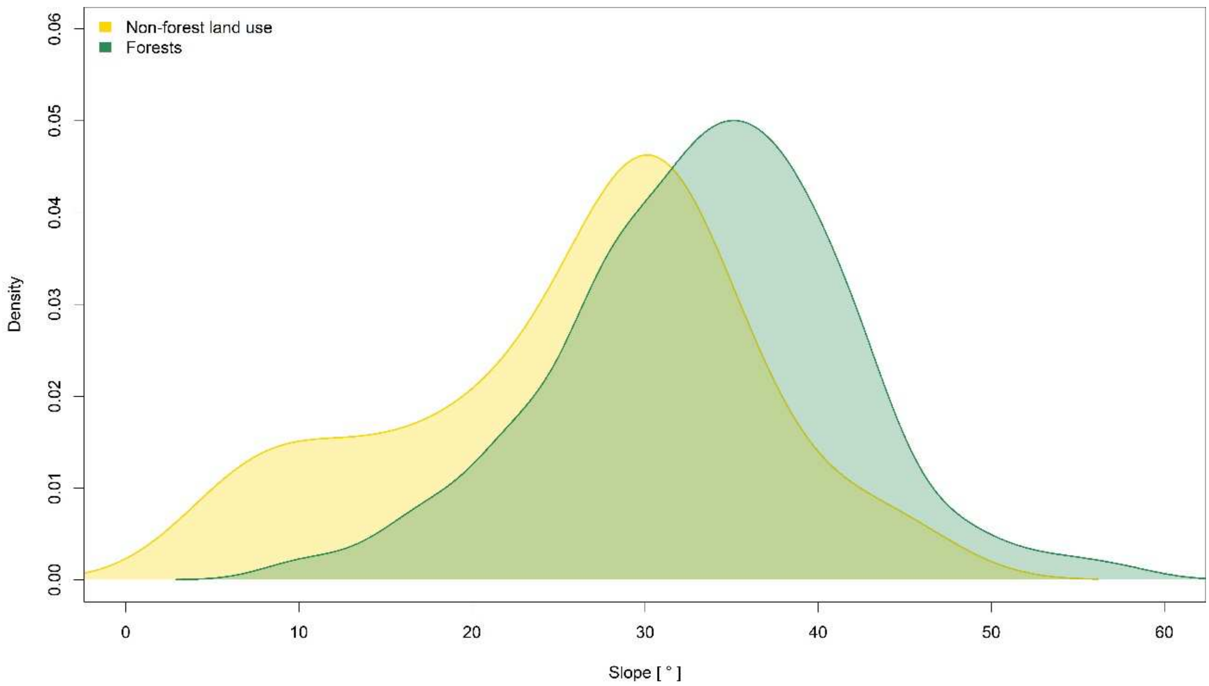

Figure 21: Graph showing the relationship between the density of the landslides and the slope of the terrain in forest and non-forest land use.

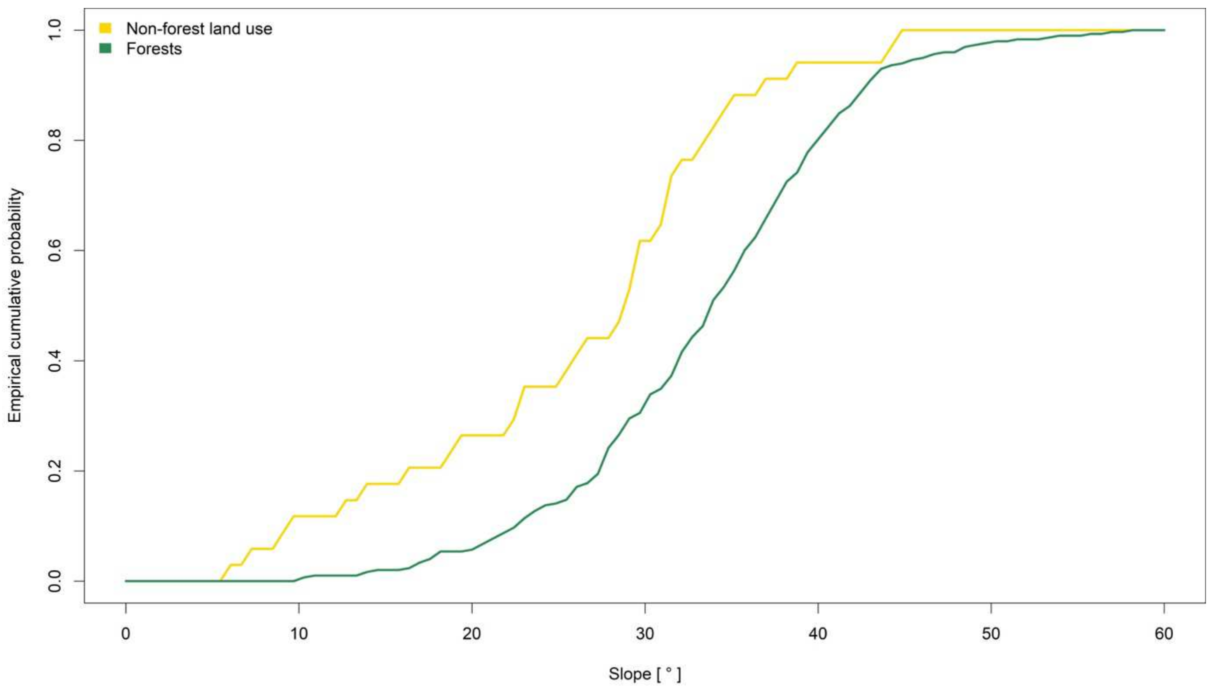

Figure 22: Graph showing the relationship between the empirical cumulative probability of landslides and the slope of the terrain in forest and in non-forest land use.

Values of the graph in Figure 22 are presented in Table 4. It repors the landslides empirical cumulative probability, expressed as a percentage, in forest and non-forest land use and their difference in percentage points, in relation with the slope gradient. The results indicate that the lowest difference in percentage points occur at the lowest (0.00% at 5°) and highest (1.01% at 55°) slopes, while between 20° and 35° the difference of cumulative probability exceeds 20 percentage points. In particular, the highest difference in percentage points (32.19) occurs at 35° where the forest protection effect is at its highest. At 30° it is still high (29.55 points) while at 40° it drops to 13.92 points.

Table 4: Percentage of landslides in forest and non-forest land use and their difference in percentage points, in relation with slope gradient.

Slope [°]	Landslides in non-forest land use [%]	Landslides in forest land use [%]	Difference in percentage points
5	0.00	0.00	0.00
10	11.76	0.67	11.09
15	17.65	2.01	15.63
20	26.47	5.70	20.77
25	35.29	14.43	20.86
30	61.76	32.21	29.54
35	88.24	56.04	32.19
40	94.12	80.20	13.92
45	100.00	94.30	5.70
50	100.00	97.65	2.35
55	100.00	98.99	1.01

Figure 23 shows the percentage of forest area within the landslide surface in relationship with the slope of the terrain. The landslides considered for this analysis are the ones with a percentage of forest cover ranging from 1% to 99%. The graph indicates the tendency of landslides with higher forest cover to be found on higher slopes. When forest cover is less than half of the landslide area, the slope of occurrence is on average slightly above 20°. The slope of occurrence is around 30° when the forest covers more than half of the landslide area. This suggests that areas with a lower forest cover can be susceptible of landslides also at milder slopes.

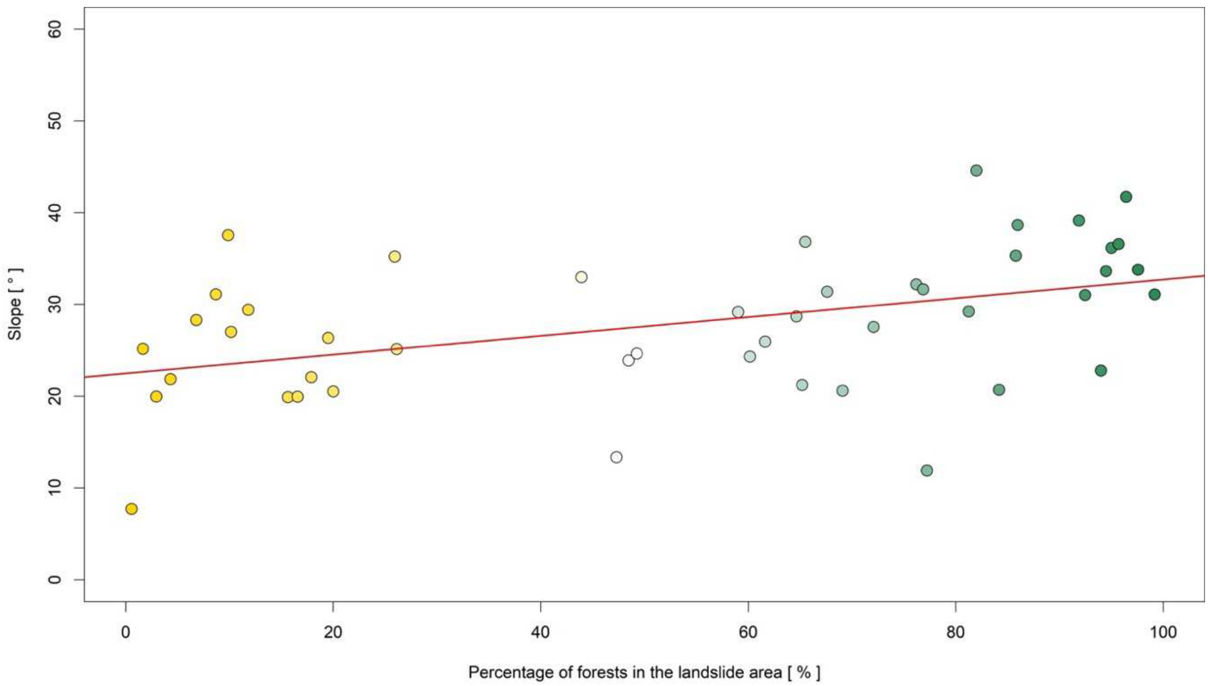

Figure 23: Graph showing the relationship between the percentage of forest land use in the landslide area and the slope of the terrain.

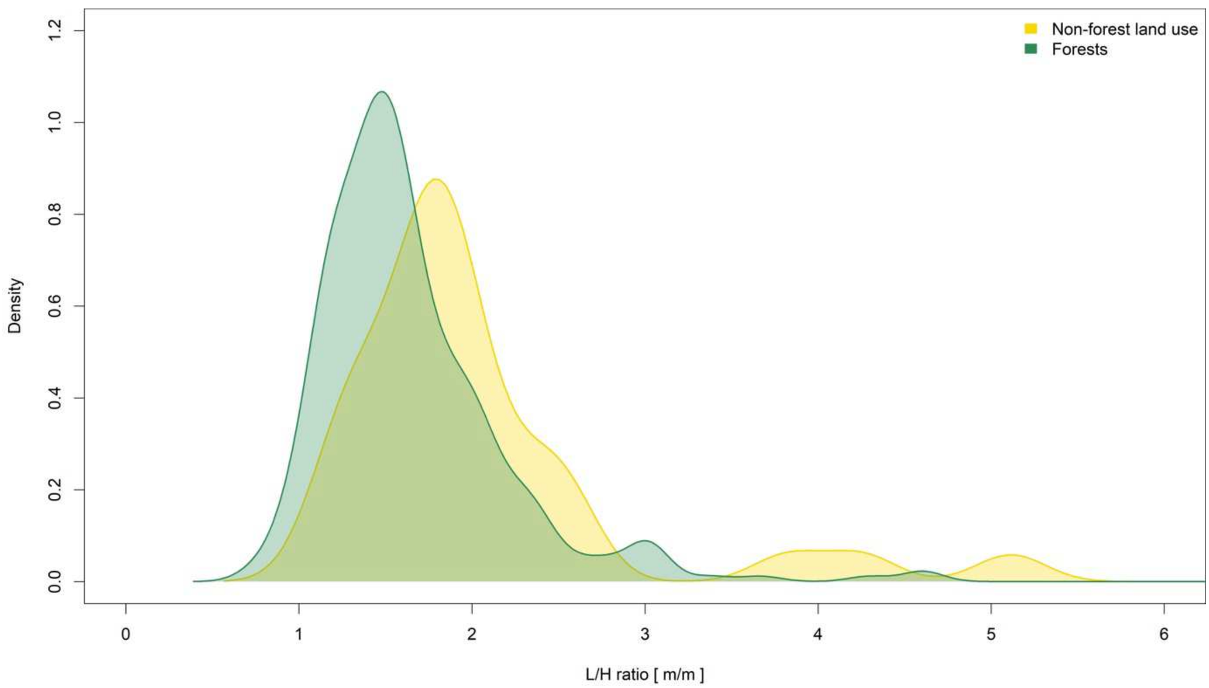

Figure 24: Graph showing the relationship between the landslide density and the L/H ratio, representing the travel distance angle, indicator of landslide mobility, in forest and non-forest land use.

Figure 24 shows the relationship between the density of the landslides and the travel distance angle (L/H ratio) in forest and non-forest land use. The distribution of the L/H ratio differs slightly between forested and non-forested land use. In forested areas, most landslides accumulate at lower values, with a peak value equal to 1.7 L/H (a drop in elevation of 10 m reflect in 17 m travel distance), while in non-forested areas the distribution shifts towards higher ratios, with a peak value equal to 2.5 L/H (a drop in elevation of 10 m reflect in 25 m travel distance). The peak represents the mode of the distribution, therefore the most frequent value. This suggests that landslides in forests tend to be shorter compared to their height, while landslides in non-forested areas are more elongated, hence with greater mobility.

5. DISCUSSION

5.1 Interpretation of the obtained results

389 landslides have been detected in the study area. Most of the landslides (87%) occurred in forested areas. However, forest land use is the most common in the municipality covering 89% of the total surface area. The results indicate that the density of landslides in the whole study area (2.50 No./km^2) is higher than the density of landslides in forest areas (2.45 No./km^2) and lower than the one observed in agricultural areas (2.95 No./km^2), which makes this type of land use the most affected by landslides (Tab. 3). It is also important to consider that usually settlement and agricultural fields are located in flatter areas, leaving forests in steeper slopes (Rickli & Graf, 2009). This pattern is also widely observed in the Municipality of Črna na Koroškem. Forests represent the wider land use in the municipality, and they occupy a terrain morphology characterized by a higher slope gradient, which is one of the predominant factors triggering and causing mass movements (Corominas et al., 2014).

The results indicate that in non-forest land use, landslides are more commonly found in milder slopes (below 25°) than in forested areas (below 35°). This can be due to the pattern of distribution of the different land use types in the study area, however few landslides (5.7%) happen in forested areas with a slope gradient below 20°. For non-forested land use 26.47% of the landslides occurred at a slope gradient below 20° (Tab. 4). This result can be an indication of the protective role of forests in stabilizing the soil and reducing the landslides probability, expecially at milder slopes. Moreover, it has been observed that forests have the highest protective function at 35° where the difference of landslide density in percentage points between forest and non-forest land use is the highest (32.19). Therefore it is possible to assume that terrain chatacterized by higher slope gradients are more susceptible to mass movement when the forest cover is little or absent. In fact, it has been observed that deforestation and cultivation can alter the soil hydrological condition, especially on steep concave slopes, increasing the risk of soil saturation inducing mass movements during rainfall events (Mugagga et al., 2012).

In line with this observation, some results of this research (Fig. 23), indicate that landslides with a lower percentage of forest cover are more common in lower slope gradients rather than the ones with a higher percentage of forest cover. On one side, it is possible to assume that higher slope gradients are required for landslides to occur in forested areas, however it must be considered that forests are usually more present in steeper terrain.

In agricultural areas the detected landslides have a smaller mean area, volume and maximum depth than in forests. This can be explained by the negative effect that weather conditions, such as wind and extreme precipitation, can have on the stability of the forests. This could cause uprooting, affecting larger areas compared to grasslands, due to the entanglement of roots within the soil matrix (Pawlik, 2013; Bathurst et al. 2007; Koyanagi et al. 2020). However, the size parameters are the highest for landslides that occuer in ‘other’ land use, for example areas with little or no vegetation where soil stabilisation from the root systems is minimum or absent, and the low rain interception can accelerate soil saturation.
The analysis focusing on landslide moility indicates that landslides with a higher travel distance angle are more common in non-forest land use (L/H peak at 2.5) rather than in forested areas (L/H peak at 1.7) (Fig. 24). It is possible that the presence of the forest has an effect in reducing the mobility of the landslides, by hindering and stopping the moving material closer to the source area, rather than in non-forest land use. Forests can limit the landslide formation in the source area, and they can dissipate the kinetic energy of landslide debris in the transition zone. In addition, the trees felled during the landslide could form log jams obstructing the movement of loose sediment. All these phenomena can potentially limit the runout distance of the landslide (Johnson et al., 2000; Gomi et al., 2006; Guthrie et al., 2010, Brang et al., 2006).

5.2 Comparison with the hypothesis and previous studies

The hypothesis of this study is that the presence of forests will have a positive impact in reducing the density, the size and the mobility of landslides. There is not a clear idea about the effect of forests on landslides. Many studies underlined the function of soil stabilisation carried out by the root systems (Gehring et al., 2019) and the function of rain interception of the canopy cover (Keim et al., 2003). However, some research identified the weight of the forest itself as a possible conditioning and triggering factor, especially under the action of the wind (Steinacher et al., 2009; Pawlik, 2013). By interpretating the obtained results related to the study area, it seems that forests have an effect in reducing the mobility of the landslides, as well as the density in milder slopes. It has been observed that in non-forest land use lower slopes with respect to forests can be susceptible of mass movement. The results also indicates that the landslides occurred in forest land use are larger (in terms of mean area, volume and maximum depth) rather than in agricultural areas, but smaller than in ‘others’ land use.

In conclusion, the results for this study are partially in line with the hypothesis, since the forests seem to have a positive effect in reducing the density and mobility of the landslides, but not in reducing the size.

5.3 Limitations of the study

The limitation of this study is related to the density of the point cloud dataset used to create the DTM layer. In particular, the low point cloud density and lack of ground points in the process of interpolation can create unrealistic values in the DTM raster layer, affecting the clarity of the DoD. Figure 25 report and example of the hillshade layers obtained by the DTMs from 2014 and 2023. In the hillshade from 2014, on the left it is possible to notice the irregularity of the layer. In this case the values of the DoD obtained with the DTMs raster subtraction, cannot be considered reliable.

In Figure 26, the DoD shows some areas with a deposition exceeding 10 m of elevation, highlighted by the dark blue colour. These results are not realistic and cannot be considered in the calculation. As described in section 3.2.4, during the procedure to detect the landslides, it was fundamental to compare the hillshade from the two different years, whilst observing satellite photos to distinguish between natural and anthropogenic mass movement. However, when the DoD showed a change in elevation, it was also important to check the respective hillshade layer, especially from 2014, to ensure erosion and accumulation were realistic. The analysis through DoD is a useful and widely used approach to study the mass movement, like the erosion and accumulation processes. The quality of the data makes the difference in the speed of the procedure, the possible spatial scale of the analyses and the accuracy of the results.

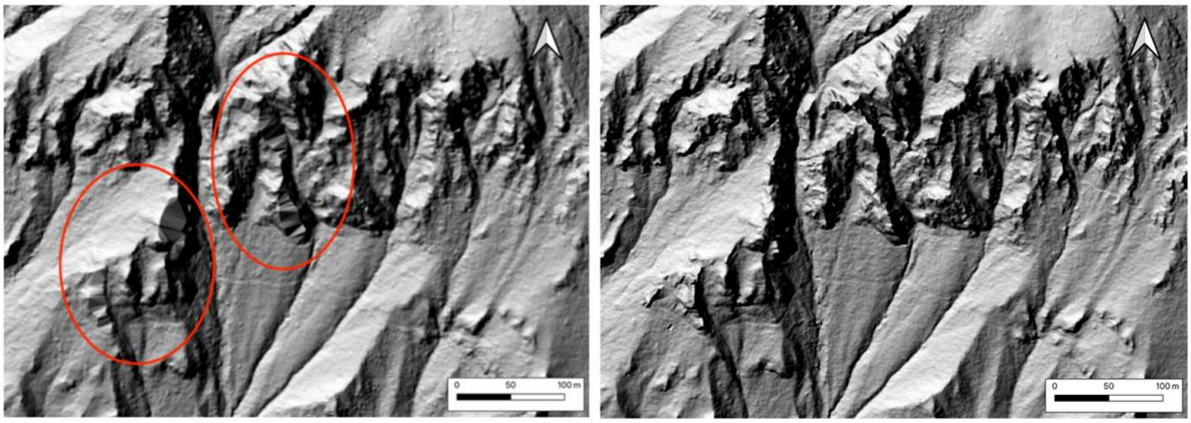

Figure 25: Comparison between the hillshade layer (2014 on the left and 2023 on the right). The hillshade 2014 shows the irregularity from the DTM 2014 caused by the low density of the point cloud data set from the year 2014.

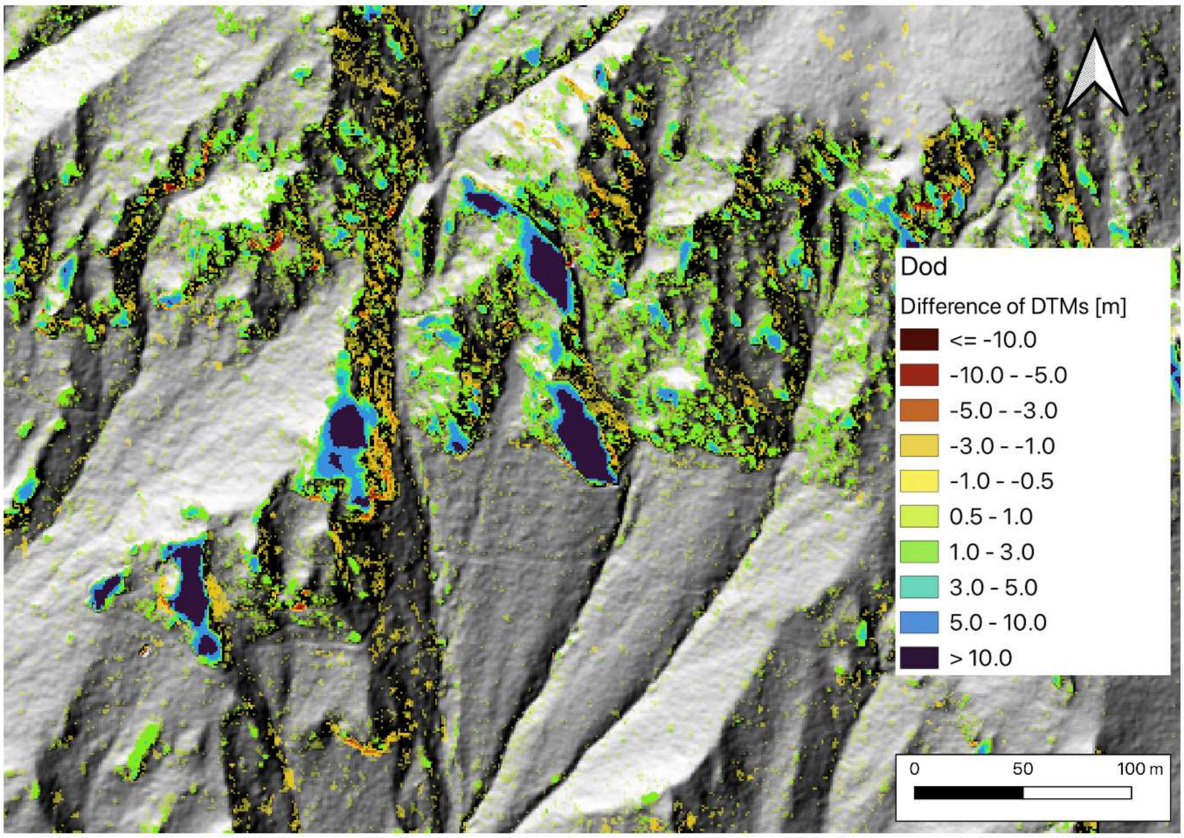

Figure 26: Unrealistic representation of the DoD between the years 2014 and 2023 due to the low density of the point cloud data set from the year 2014 causing irregularities in the interpolation processes to generate the DTM layer from 2014.

5.4 Possible future developments

As well as improvements in data quality, as discussed in section 5.3, there are other possible future developments that could help to improve and deepen this study.

To improve decision making in land use management it could be helpful not only to analyse the different impact of forest and non-forest land use, but also to analyse the effect of different forest stand structures, spices composition, forest stage and forest management on landslides. Moreover, it would be also advisable to study the incidence of forest roads in landslides.

In conclusion, to develop a clearer literature about the forest effect on mass movements, it is useful to broaden the research over a wider study area, within different forest landscapes, ecosystems, soil types, slope gradient, and climatic areas.

6. CONCLUSIONS

This study aimed to analyse the effects of forests on rainfall-induced landslides. The study area is the municipality of Črna na Koroškem, located in the north centre of the country. Most of the municipalities of the country were hit by an extreme flood between the 4^{th} and the 6^{th} of August 2023. The extreme event caused 3 casualties, 10 billion euros of direct and indirect costs. The rainfall-induced landslides were estimated to be around 10,000 throughout the country.

In this research, 389 landslides have been detected and vectorised in the 156 km^2 wide study area. The focus of the study was to analyse the effect of forest and non- forest land use on the density, size and mobility of the landslides. Overall, the results showed that forests have an effect in reducing the density of landslides (2.45 No./km^2 in forest land use and 2.95 No./km^2 in agricultural land), and their mobility (1.7 L/H in forest land use and 2.5 L/H in non-forest land use). From the analysis it is possible to observe that landslides are found to be larger in forests than in agricultural land, but they are smaller than landslides in 'other' land use, such as build-up areas and areas with little or no vegetation.

Overall, this study highlights the protection function that forests can have in limiting the density of landslides, especially below 35°. A higher forest cover can increase the slope gradient at which mass movement can occur.

This study can be helpful for the future development of landslide risk management and mitigation strategies, and for the optimisation of forest management practices in landslides susceptible areas. Further studies are needed to clarify the effects of land use on mass movements. More detailed research should focus on the impact that the structure, composition, and management of forests can have on landslide density, size and mobility.

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