



Dendrogeomorphological analysis of a debris flow in the Monarch Butterfly Biosphere Reserve, central Mexico

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Abstract

Debris flows are one of the most hazardous and frequent landslides in mountainous regions. In this research, we apply dendrogeomorphological techniques to analyze the debris flow that occurred in February 2010 in the Monarch Butterfly Biosphere Reserve in central Mexico. Firstly, analyzed precipitation data from two nearby meteorological stations has indicated that an extraordinary precipitation event accumulated 236.4 mm of rainfall over a 5-day period, from January 31st to February 4th, 2010. In addition, we generated a geomorphological cartography of the area at 1:600 scale by interpreting the images obtained using an Unmanned Aerial Vehicle. Subsequently, we carried out dendro-chronological sampling on 98 *Abies religiosa* trees (125 cores); the cores were dated using cross-dating and the ring width was measured for generating a chronology, in which the years with growth disturbances as a result of the debris flow could be identified and characterized. We identified three types of growth anomalies in the tree ring series: (a) traumatic resin ducts, (b) growth suppression, and (c) growth releases, related to the 2010 debris flow event. We also estimated the debris flow intensity through the scar heights recorded in the trees, which allowed us to identify that the intensity of the debris flow was greater in the transport zone. These results highlight the benefit of the dendrogeomorphological technique used in the collection of spatio-temporal information on debris flow activity in intertropical montane environments, especially where information about mass movement processes is limited. Therefore, we demonstrate that dendrogeomorphological techniques, in combination with other parameters such as scar height on the trees, as well as a detailed geomorphological survey, allows for an understanding of the dynamics of debris flows, which, in the case of Mexico have not been previously evaluated using this approach.

Keywords *Abies religiosa* · Dendrogeomorphology · Mass removal processes · Tree-ring chronology

1 Introduction

Landslides are one of the most dangerous geomorphic events (Huabin et al. 2005), causing serious damage to infrastructure, and the environment, while threatening human life (Lacasse et al. 2010). Furthermore, they are one of the most active and significant processes that modify the terrain in many regions of the world (Shroder et al. 2011). Varnes (1978) classified landslides into flows, slides, falls, spreads, or a combination of two or more of these classes, with flows being one of the most hazardous phenomena in mountainous areas, due to their impact force (Iverson 2005). In landslides classification, there are two types of flows: hyperconcentrated (turbulent subaerial flow) and debris flows (Nemec 2009). According to Iverson (2005), debris flow can be triggered by rainfall, glacial calving, dam breakage, and volcanic activity, and these can also actively influence the modifications of landforms (Procter et al. 2011) causing negative effects on society. Since the 1990s, several efforts have focused on understanding the characteristics and mechanisms that trigger debris flows from a physical and mechanical perspective (Takahashi 1981). However, an important limitation of their research is generally the lack of information about their past occurrences, which is crucial to define their relationship based on climatic variables and hydrometeorological extremes events or to predict future occurrences (Long et al. 2020). Several techniques/methods have been used to obtain temporal information on the occurrence of landslides, such as lichenometry (Crespo-Martín et al. 2023), radio-carbon (LaHusen et al. 2016), luminescence (Guo et al. 2022), and dendrogeomorphology (Stoffel and Corona 2014)—of these, dendrogeomorphology has stood out for its flexibility in terms of application costs and temporal precision of data (annual and seasonal) (Stefanini 2004). Dendrogeomorphology studies the relationship between tree growth anomalies and geomorphic processes that induce them, allowing the analysis of the frequency and spatiotemporal distribution of geomorphic events (Alestalo 1971; Šilhán 2020a). Dendrogeomorphology is based on the process-event-response model (Shroder 1978). Under this premise, trees record external perturbations in their growth rings that were induced by geomorphic processes, allowing one to obtain accurate chronometric measurements of past disturbances at annual and seasonal resolutions (Arbellay et al. 2013). In the last three decades, dendrogeomorphological methods have allowed the precise spatiotemporal assessment of slides (rotational, translational), debris flows (Šilhán 2022), lahars (Figueroa et al. 2021), avalanches (Šilhán 2021), and rock falls (Mainieri et al. 2019). Therefore, methods based on the analysis of tree rings are an effective tool for investigating debris flows (Arbellay et al. 2010; Procter et al. 2011). Although the occurrence of different types of landslides in various mountain environments has been evaluated using dendrogeomorphological techniques (Glade 2005; Rahman and Mapjabil 2017; Prasad 2021), most of these studies have been developed in temperate and cold environments (Stoffel et al. 2005; Bollschweiler et al. 2007; Szymczak et al. 2010; Lopez-Saez et al. 2012; Šilhán et al. 2018; Oven et al. 2019), without considering other environments (e.g., intertropical) where landslide occurrence is frequent and has caused major disasters (Quesada-Román 2021).

In intertropical environments, such as the Monarch Butterfly Biosphere Reserve (MBBR) in central Mexico, there are tree species with dendrochronological potential to obtain temporal data (Carlón-Allende et al. 2016, 2018). In the MBBR in February 2010, two meteorological events, which, when combined with the entry of two cold fronts and an anomalously southern jet stream, produced intense precipitation (Alcántara-Ayala et al. 2012). The intensity and duration of these rains caused several debris flows. One of the most disastrous events occurred in the town of Angangué, Michoacán, claiming the lives

of 33 people and causing up to 40% damage to the town's infrastructure (Alcántara-Ayala et al. 2012; Parrot and Ochoa-Tejeda 2013). Due to its impact, most research has focused on understanding the Angangueo event without analyzing other affected regions in which there were no victims, but where there was damage to infrastructure and economic losses. This is the case of Río Verde where human settlements are found in the lower part of the watershed. Thus, the objectives of this study are (1) to analyze the effects of this extreme precipitation and describe the spatial–temporal behavior of past events, through the application of dendrogeomorphological techniques, (2) to identify the recurrence of the debris flow activity in the MBBR, and (3) to identify the most likely triggering mechanisms.

2 Materials and methods

2.1 Study area

The MBBR is located in the central portion of the Trans-Mexican Volcanic Belt, between the border of the state of Michoacán de Ocampo and the State of Mexico, it covers an area of 562 km². It is bounded by the coordinates 19° 18' 32" N, 100° 09' 07" W, and 19° 44' 27" N, 100° 22' 26" W (DOF 2000). It covers part of the municipalities of Senguio, Angangueo, Contepec, Tlalpujahua, Aporo, Ocampo, and Zitácuaro in the state of Michoacán, and the municipalities of Villa de Allende, San José del Rincón, Temascalcingo, and Donato Guerra in the State of Mexico (DOF 2000) (Fig. 1). The landforms were generated by volcanic activity consisting mainly of andesitic breccias, basaltic andesites, rhyolite schists, and tuffs dating from the Middle and Late Cenozoic (Servicio Geológico Mexicano 2000). The altitude in the study area ranges from 2400 to 3200 m, and it has an annual rainfall between 700 and 1250 mm with an average temperature between 8° and 22 °C. Both the temperature and the precipitation vary between the southern and northern parts of the MBBR, being more humid and coldest in the northern part (Carlón-Allende et al. 2016). Among the predominant types of land cover and land use are pine-oak forest (44%), sacred fir forest (*Abies religiosa*) (27%), and agriculture (15%); the remaining areas (14%) correspond to grasslands, scrublands, human settlements and bodies of water (Carlón-Allende et al. 2015). The soil groups are Andosol, Luvisol, Regosol, and Litosol (INEGI 1978). Within the MBBR, there are 13 indigenous communities (Matlatzinca, Purépecha, Mazahua, and Otomí), and 21 small properties that house 27,346 inhabitants; most of these localities are characterized by high levels of marginalization and migration, with several of these localities being settled on slopes and foothills where runoffs converge, such as the case of Angangueo locality.

2.2 Río Verde debris flow

The Río Verde debris flow is located in the eastern part of the MBBR and to the west of the city of San José del Rincón (Fig. 1d). The area belongs to the hydrological region of Jaltepec, located within the Lerma-Toluca basin (INEGI 2010). The lithology of the area is characterized by andesitic-basaltic lavas and andesitic breccias (INEGI 1981; Servicio Geológico Mexicano 2000) that are covered by Andosol (INEGI 1981). The Río Verde debris flow deposit is located along the Río Verde creek with vegetation dominated by pine (*Pinus* spp.), and sacred fir forests (Carlón-Allende et al. 2018). The Río Verde debris flow has a length of 3,803 m and a width of 80 m on average (Fig. 1d).

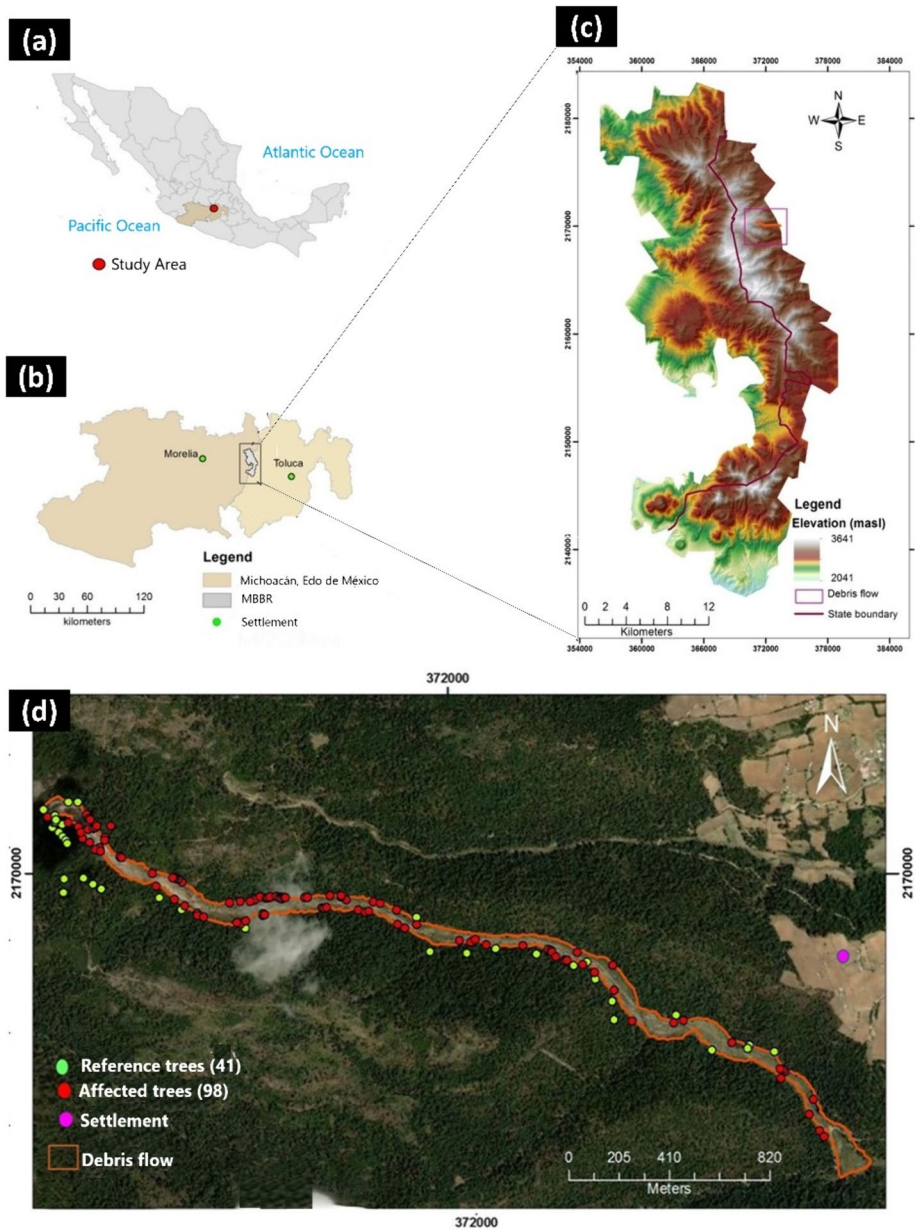


Fig. 1 Location of the study area: **a** location at the national level; **b** State of Michoacán and State of México with the polygon of the MBBR; **c** MBBR, the debris flow is shown in the red square; **d** debris flow Río Verde and located sampled trees (Source Google Earth, 2019)

2.3 Geomorphological mapping

To allow for accurate interpretation of the study area, we carried out a flight with an unmanned aerial vehicle (Mavic 2 pro model) from which we generated a 10-cm resolution

Digital Surface Model (DSM). With the DSM, we produced a slope map and a shaded model; these were used for the visual interpretation of the geomorphic units according to the methodology proposed by Cenderelli and Steven (1998). Next, we generated a geomorphological map at a 1:600 scale showing the distribution of the debris flow deposit. The deposit extension was divided into three zones: Fault Zone (FZ), Transport Zone (TZ), and Deposition Zone (DZ), following Cenderelli and Steven (1998).

2.4 Precipitation analysis

We analyzed a 100-year period of precipitation (1922–2022), in which, we identified periods of 3- and 5-day of extreme events of accumulated precipitation. Precipitation data were obtained from the Presa Brockman and Zitácuaro weather stations administered by the National Meteorological Service. This information was used to identify landslide-triggering thresholds according to Domínguez et al. (2016). These authors established the procedure to determine the levels of hazard considering the accumulated precipitation in a 5-day period for the national territory. They divided the territory in eight regions: (1) Gulf of Mexico, (2) North Gulf, (3) Trans Mexican Volcanic System, (4) Pacific South, (5) North Pacific, (6) Cal-ChD Gulf, (7) Baja California, and (8) Baja California Sur. The triggering thresholds established for the Trans-Mexican Volcanic Belt are: (a) Medium (117.07 mm), (b) High (175.61 mm), and (c) Very High (234.14 mm) (Domínguez et al. 2016). According with their procedure if the rain exceeds the Medium threshold, it will trigger a low-magnitude landslide; if it exceeds the High threshold it will generate several low-magnitude landslides, and for the Very High threshold it will trigger several large-magnitude events. In Río Verde, we used these thresholds and linked the results to hydro-meteorological events (hurricanes, tropical storms, etc.) as described in other studies of the Trans-Mexican Volcanic Belt (Capra et al. 2010).

2.5 Sampling, processing, and analysis of tree growth rings

A total of 125 sacred fir trees were sampled (98 affected trees and 27 reference trees) using an increment borer (Fig. 2a) and a chainsaw (Fig. 2b), from which 166 dendrochronological samples were extracted. For each location we obtained the coordinates, tree height, the Diameter at Breast Height (DBH), growth anomalies and/or visible alterations in the morphology of the tree, the position of the extracted sample, and scar features (height, length, width and photographic record). The 41 sacred fir tree samples of reference trees were collected outside the influence of the debris flow event, these trees showed no visual alteration or signs of disturbance, allowing us to generate a control chronology.

The increment cores were processed (mounting, drying, sanding) according to standard methodologies described in Stoffel and Bollschweiler (2008). The increment cores were dated using crossdating techniques, which are based on the identification of narrow rings from the dendrochronological series and assigning the exact year of formation for every ring (Fritts 1976). Subsequently, the width of each ring was measured using a VELMEX measuring system at a precision of 0.001 mm (Robinson and Evans 1980). The quality of dating and measurement was verified by COFECHA software; only the dendrochronological series that presented and intercorrelation value > 0.328 ($p < 0.01$) were used to generate the chronologies (Holmes 1983).

The ring-width series were standardized by fitting negative exponential curves to the series, while ring-width indices were created by dividing the ring-width measurements



Fig. 2 Photographs of dendrochronological sampling. **a** Extraction of incremental cores from affected trees, **b** Use of a chainsaw to extract wedges and slices

between the curve values (Fritts 1976). During this process, the variance between the measurements of the dendrochronological series related to age is reduced and it allows for transforming the ring widths into dimensionless indices (Briffa 1995). The chronologies were generated using the dplR library in R (Bunn 2008).

2.6 Dendrogeomorphological analysis for detection of landslides

The event analysis was based on the process-event-response model and the semi-quantitative concept of the standard event response rate approach proposed by Shroder (1978, 1980). An annual rate value was established to define the relationship between trees showing growth responses and all living trees sampled. To avoid the overestimation of Growth Disturbances (GD) in the tree ring series, we calculated an index value (I_t) according to the following equation:

$$I_t = \left(\left(\sum_{i=1}^n R_t \right) / \left(\sum_{i=1}^n A_t \right) \right) * 100$$

I_t = index value.

R_t = trees that display a response in the year t .

A_t = trees sampled alive in the year t .

An index threshold of 20% was considered, considering the number of trees sampled in all the debris flow deposit and avoiding an overestimation caused by low tree numbers in the event-response calculations. The index value (I_t) has been widely used and is reliable for event reconstructions, to assess debris flows and snow avalanches (Šilhán 2022) and for the analysis with the *Abies* (Chiroiu et al. 2015). In the case of Mexico, a similar index has

been used to analyze debris flows event with the species *Pinus leiophylla*, *Abies religiosa*, and *Alnus jorullensis* and has given acceptable results (Franco-Ramos et al. 2019).

2.7 Event frequency and growth disturbances

We calculated the frequency of debris flow events by dividing the elapsed time by the number of analyzed events (Casteller et al. 2011). To demonstrate the effects of geomorphic events and disturbances with larger certainty in the growth rings, the samples were classified according to the criteria described by Stoffel and Corona (2014), who grouped the samples based on the intensity and type of reaction observed in the trees. The intensity of growth disturbances presented here represents a synthesis of indicators commonly used in dendrogeomorphic. According to the proposal, intensities are distinguished between weak, moderate, and strong, and as a general rule, strong reactions should be prioritized over weak ones in trees (Stoffel and Corona 2014).

Thus, we based the identification of the events on (a) the number of trees showing GD in the same years, (b) the precision of the position of the GD within the tree rings, (c) the intensity of the signal within the series of rings of trees, and (d) the spatial distribution of the affected trees (Bollschweiler et al. 2008).

2.8 Analysis of the scar height

The scar height was measured by considering the base of the tree up to the central height of the scar (Ballesteros et al. 2011). With the scar height data, different statistical analyses were performed (Shapiro–Wilk test, Kruskal–Wallis test, Mann–Whitney Post-hoc comparison test). The scars on trees were used as paleostage indicators that can be accurately dated (Ballesteros et al. 2011) and used to determine the magnitude estimations of flow events (Stoffel et al. 2011; Ballesteros et al. 2011). The Kruskal–Wallis test analysis and Mann–Whitney Post-hoc comparison test was carried out to determine the value of the significance of the heights of the scars between the three zones and to know whether the behavior of the flow presented differences between zones. Through this test, they hypothesized that scars were inflicted by rock materials and pieces of wood, implying that scar heights represent maximum flow depths at a given time during the debris flow (Ballesteros et al. 2011).

3 Results

3.1 Geomorphological cartography

The geomorphological analysis of the Río Verde debris flow shows that it started at an altitude of 3410 m and finished at 2909 m. The debris flow is 3.8 km long, 65–128 m wide, and covers an area of 22.42 ha. The channel (runoff) has a slope of 7° and a well-developed scarp (Fig. 3). The debris flow fault zone is steep with an angle of 34° (Fig. 3). This part is unstable due to rock weathering and the humidity conditions produced by rainfall and perennial runoff.

The analysis indicated that the February 2010 debris flow deposit displays post-emplacment erosion, evidenced by terraces formed on the margins of the channel. Throughout the debris flow, two types of erosive terraces were identified: those with scarce

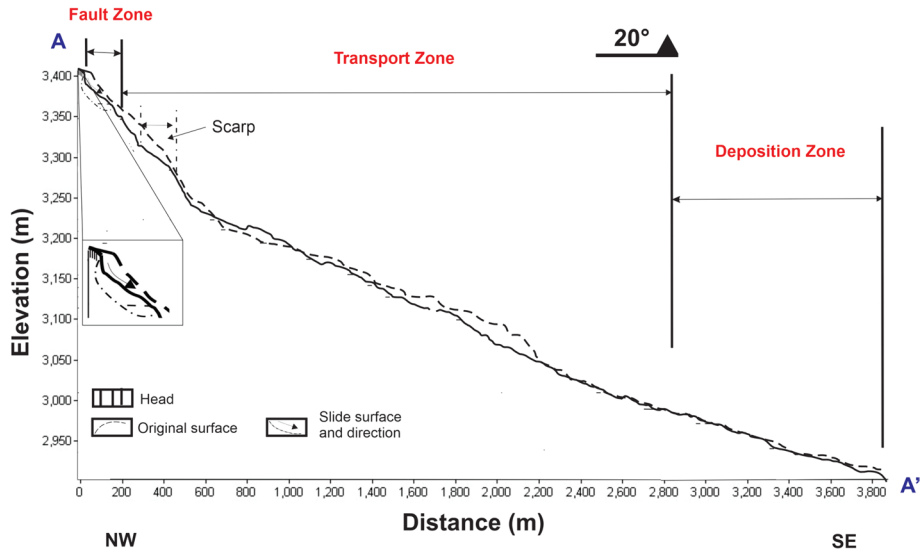


Fig. 3 Geomorphological longitudinal section (A-A') of the Río Verde debris flow in the Monarch Butterfly Biosphere Reserve

vegetation (Fig. 4a) and those with abundant vegetation (Fig. 4b). For those with abundant vegetation, over 50% of the terrace is covered with trees and shrubs, which is an indication that the terraces are stable and that a greater amount of material has been deposited (less eroded). In contrast, those with scarce vegetation expose a deposit with thin soil or none.

We classify the debris flow deposit in three zones: Fault, Transport, and Deposition (Fig. 5). The Fault Zone (FZ) is the area of the detachment of the material (Figs. 5 and 6a) with evidence for the occurrence of a rotational landslide associated with the debris flow (Fig. 6a). The FZ exhibits lobules and crowns, as well as tension cracks; the latter may be influenced by an inferred fault that extends from 23 m above the crown to 68 m below the main escarpment from the crown. A few meters below the escarpment there is a five-meter-high stepping-stone (not very perceptible due to the vegetation). In this zone there appears

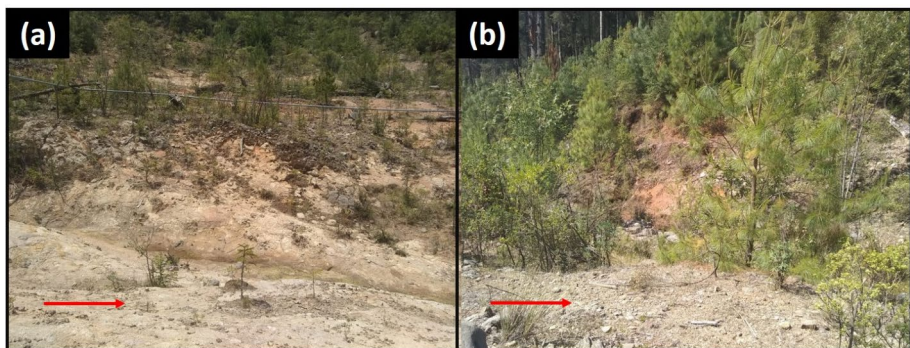


Fig. 4 Aspects of different terraces exposed along the Río Verde debris flow deposit. **a** Terraces with little vegetation; mostly grasses and herbs. **b** Terraces with a greater presence of vegetation, with pine regeneration between 5 and 8 years. The red arrow indicates the position of the terrace

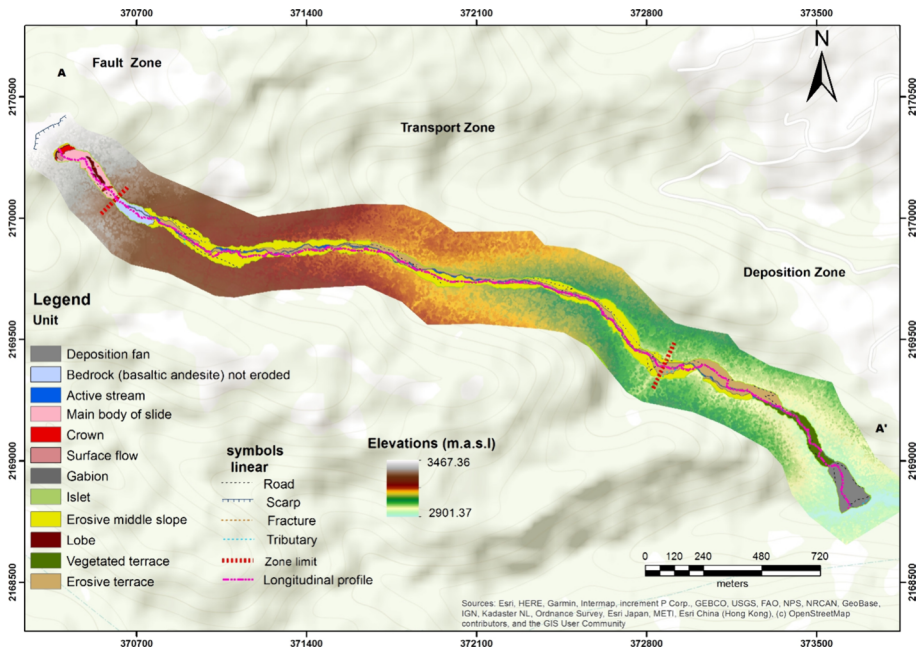


Fig. 5 Geomorphological map of the Río Verde debris flow deposit with the altitudinal gradient. The map shows the different zones, and units with their boundaries along the main channel and their corresponding symbols

to be a creeping process, which is evidenced by leaning trees (Figs. 5, 6a, and b) and fallen rocks (1.5–3.0 m in maximum length) indicating that the zone is active.

The Transport Zone (TZ) is located between 2998 and 3310 m a.s.l. with a length of 2475 m and an average width of 50 m. The detached material moved in the form of a debris flow, carrying a significant amount of rock blocks and finer material. In this area, there are jointed basaltic andesitic lavas that are barren of vegetation or soil (Figs. 5 and 6c). The TZ contains an active channel that is observed in the deposition fan.

The Deposition Zone (DZ) extends 1150 m in length and has an average width of 65 m. This zone is characterized by the presence of massive moderately consolidated deposits that are composed of dispersed chaotic heterolithologic fragments of various sizes, mainly between 0.2 m and 1.0 m in maximum length (Fig. 6d). In the riverbed, there still are jointed basaltic andesitic lavas and abundant blocks with diameters varying from 0.7 to 1.0 m in maximum length (Figs. 5 and 6d).

3.2 Analysis of precipitation events

The analysis of precipitation data from 1922 to 2022 (100 years) from the Presa Brockman and Zitácuaro meteorological stations, has allowed us to identify extraordinary precipitation events. For instance, light to heavy intensity winter rains during the first days of February 2010 were caused by an anomalously southern jet stream and cold fronts number 28 and 29; these meteorological events triggered the Río Verde debris flow.

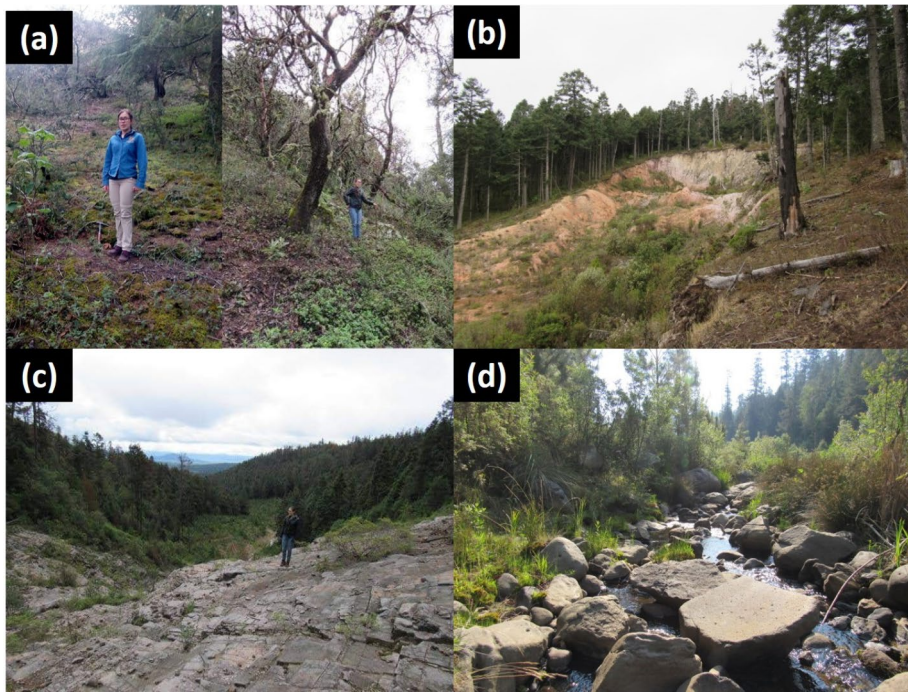


Fig. 6 **a** Fault Zone, creeping movement evidenced by the presence of leaning trees; **b** stepping close to the escarpment; **c** Transport Zone, the exposed jointed and non-eroded rock unit; **d** Deposition Zone, characterized by the presence of rocks of various sizes

The rainfall data analysis showed that for 3 days (January 31st–February 2nd, 2010) a total precipitation of 98 mm accumulated (Fig. 7a). While, for 5 days (January 31st–February 4th, 2010) a total of 236.4 mm, accumulated, this amount of rain exceeded the “Very High” threshold (Fig. 7b). This amount of rainfall (236.4 mm) represents 25% of the total annual rainfall (946 mm) and exceeds July’s rainfall amount, which is the rainiest month (Appendix 1A). We did not identify years before 2010 with accumulated precipitations in 3 or 5 consecutive days that exceed the “Very High” and “High” thresholds (Fig. 7a and b). However, we documented years with accumulated rains of 5 days in June 1925, July 1932, July 1937, and September 1998; as well as, accumulated rains of 3 days in June 1925 that exceeded the “Medium” threshold (117.07 mm) (Fig. 7b).

3.3 Chronology of events and pre and post flow activity

The mean age of the sacred fir trees was 69 years, with a standard deviation of 20 years. The oldest tree has an age of 130 years while the youngest is just 31 years old. The chronology of generated geomorphic events spans from 1923 to 2020. The series intercorrelation was 0.428 (>0.328 , which is the significant acceptable threshold), indicating reliable dating and an average mean sensitivity of 0.311. The total number of samples analyzed was 125, all of which had evidence of GD.

We identified a difference in the rings’ growth by comparing the samples obtained from reference trees and affected trees. In the reference samples, ring growth was

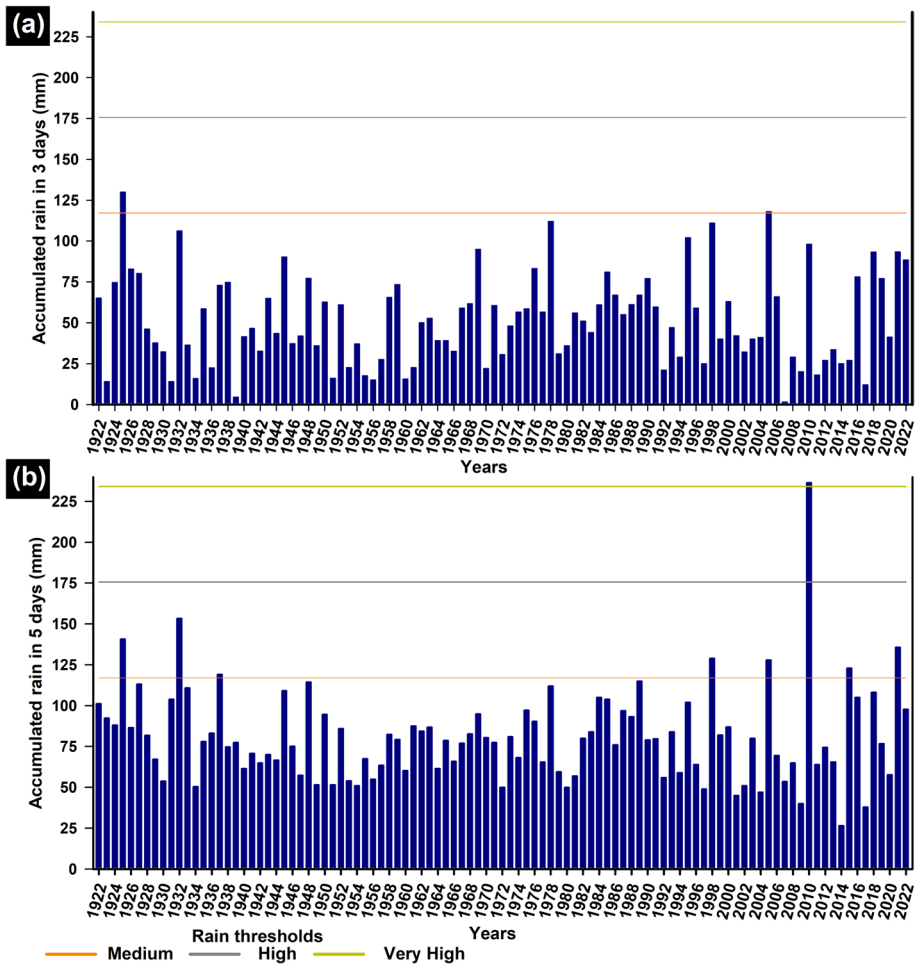


Fig. 7 Analysis of maximum precipitation events (1922–2022); **a** accumulated precipitation for 3 consecutive days; **b** accumulated precipitation for 5 consecutive days

normal in 2010, while in the samples of the affected trees, there is a clear ring suppression from 2010, which lasted the next three years (Fig. 8) a response to the debris flow that occurred in February of that year. The affected trees were located on the edges of the channel, while young vegetation (between 9 and 10 years old) was found inside the channel, a product of post-event reforestation (for example, the lack of a canopy allowed more sunlight).

Comparing the chronology of the affected trees with that of the reference trees (undamaged trees) we observed regular and homogeneous ring growths up to the year 2009; however, in 2010 we identified a distinct change in the ring growth (Fig. 9). From 2011 to 2013, occur a suppression in both chronologies (Figs. 8b and 9). We identify this 2010 suppression to be a consequence of the Río Verde debris flow event occurred in February (Fig. 9).

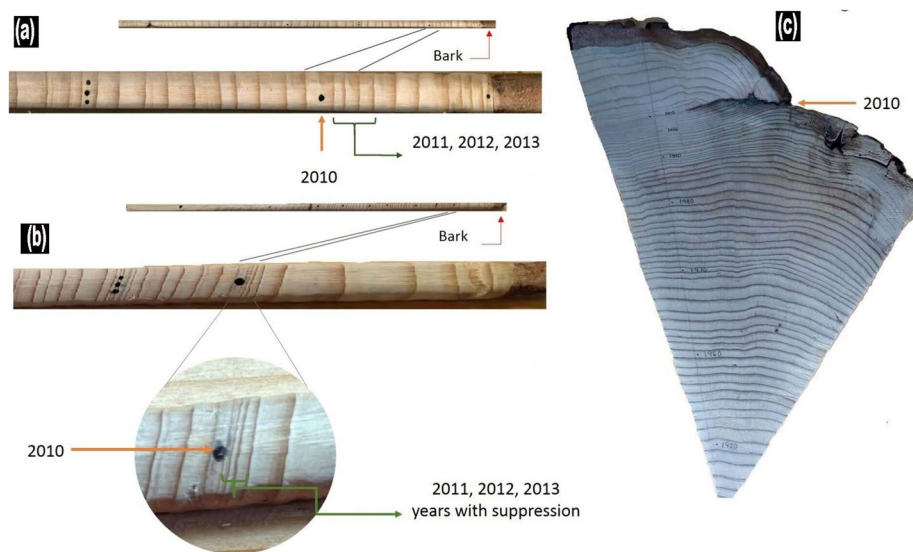


Fig. 8 Dendrochronological samples. Here, the rings of the year 2010 stand out; **a** core of undamaged reference tree (collected at the beginning of 2021); **b** core of the affected tree (collected at the end of 2019) shows a suppression in the 2010–2013 rings; **c** section of affected tree “wedge” (collected at the beginning of 2021) with a span of 75 years. The year 2010 is indicated by the orange arrow

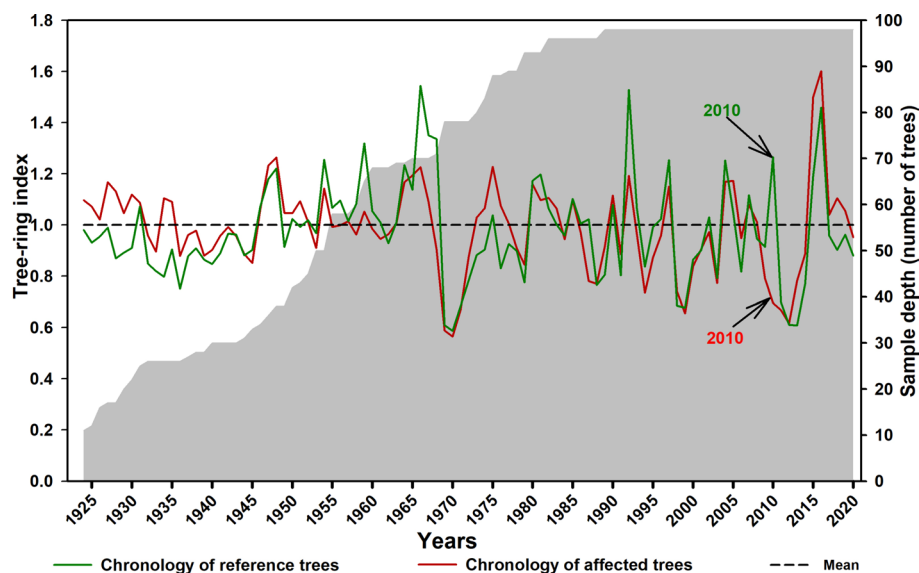


Fig. 9 Ring-width chronologies. The red line represents the chronology of the trees affected by the debris flow, the green line represents the reference chronology generated from undisturbed trees, and the black line represents the mean. The right axis shows the sample size

3.4 Analysis of events identified in tree ring growth

Figure 10 shows the event-response of all the reactions recorded in the trees along the debris flow. In this analysis Traumatic Resin Duct (TRD) is not included in the growth disturbances count and is shown in red bars to assess debris flow events, also displaying the threshold value of the 20% index that was used. This approach helped us to isolate the debris flow occurrence to the year 2010. Although other events were identified before 2010, the growth disturbances were not nearly as significant ($n=1$ and 2), we therefore believe they are not related to debris flow events. The evidence for debris flow was particularly high in 2010 ($n=98$) suggesting the occurrence of a large-magnitude event, with a mean return interval of 103 years.

Moreover, we found evidence in the years 2011 and 2012 of TRD in a considerable number of trees (16 and 8 trees, respectively). However, these TRDs were not considered as evidence of the 2010 debris flow occurrence because the damage could have persisted for some years after the event.

3.5 Changes in tree ring growth

The analysis of 98 samples allowed the identification of 261 GD with different intensities (Table 1), from 1919 to 2020. The most common response was Traumatic Resin Ducts (TRD, 52.49%), Growth Suppression (GS 40.61%), Growth Release (GR, 6.89%), and Callous Tissue or Lesions (L, 2.68%). This response has different intensities (Low, Moderate and High; Table 1), the TRDs dominated in the three areas. In the Fault Zone, most of the TRD (14) were of low intensity, in the Transport Zone, 33 low-intensity TRD were found and in the Deposition Zone dominated of TRD (11) moderate intensity (Table 1).

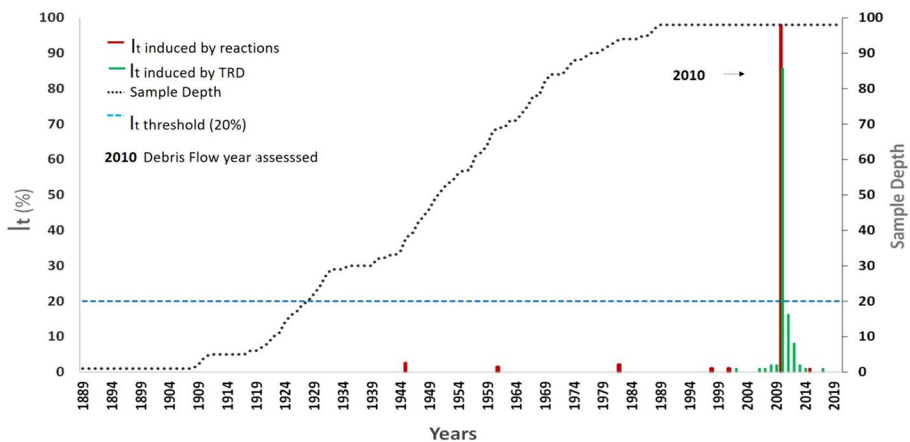


Fig. 10 Analysis of debris flow using Growth Disturbances (GD) in damaged trees as a reference. The analyses of debris flows were calculating using the Index Value (I_t) according to the methodology proposed by Shroder (1980)

Table 1 Record of the type, number, and intensity of growth alterations of the chronology of affected trees, differentiated by zones based on the proposal of Stoffel and Corona (2014)

Zone	Type of disturbance	Number of disturbances	Intensity of disturbances		
			Low	Moderate	High
Fault zone	TRD	29	14	12	3
	GR	4	4	–	–
	L	1	1	–	–
	GS	22	10	5	7
Transport zone	TRD	89	33	30	26
	GR	15	9	3	3
	L	3	3	–	–
	GS	60	27	21	12
Deposition zone	TRD	23	4	11	8
	GR	1	1	–	–
	L	3	–	–	–
	GS	11	1	2	7

TRD, Traumatic Resin Ducts; GR, Growth Release; GS, Growth Suppression; L, Lesion

3.6 Scar height analysis

The results of Kruskal–Wallis analysis of the scar height indicate that, in the FZ there is a greater symmetry in the distribution of the sample in other words, the height of the tree scar does not vary throughout the zone. The scar at the lowest height was identified at 10 cm, while the highest one was found at 110 cm; 50% of the scars have a height of 30 cm.

The height of the scars in the Transport Zone (TZ) and Deposition Zone (DZ) presented an asymmetric distribution, which skewed to the left. In the TZ, scars with the minimum and maximum heights corresponding to 20 and 240 cm (average scar height of 93 cm). In the DZ, the minimum and maximum heights were 20 cm and 250 cm (average scar height of 89 cm). These heights suggest that the impact of the material was more intense in the transport zone (mainly found above 200 cm in height). Further, the size of blocks was large enough to cause considerable damage to tree stems. It should be noted that the scars were found oriented in the direction of the debris flow (Northwest–Southeast) with an oval shape at the top and back (Fig. 11).

The average number of scars recorded for each tree was 1.68 throughout the study area, ranging between 1.7 (FZ), 1.83 (TZ), and 1.4 (DZ). The frequency histogram and the Shapiro test revealed an asymmetrical distribution of the scar heights (Fig. 12), for which the non-parametric Kruskal–Wallis test was used to check the differences in height by zone. This test yielded a value of $p=0.03347$, indicating that there are statistically significant differences in scar height between the FZ and TZ zones. In addition, the Post-hoc Mann–Whitney comparison analysis yielded the highest statistical significance ($p=0.03$), whereas the FZ and DZ had a value of $p=0.18$. These results demonstrate that there are no significant differences in scar height for the TZ and DZ ($p=1.00$).

Scar height analysis reveals that TZ scars are found at a higher level—meaning that in the channeling of the detached material and the intensity of the water current, the slope, and the characteristics of the basaltic andesitic lava (which acted as a kind of lubricant), intensified the effects of the debris flow. In contrast, Kruskal–Wallis analysis between DZ and TZ showed no significant difference for this variable (Fig. 13).

Fig. 11 Scar on impacted tree due to the Río Verde debris flow. The yellow arrow shows the height. The red dotted line indicates the contour on the acquired form of the scar. The red arrow indicates the direction of flow with respect to the position of the channel

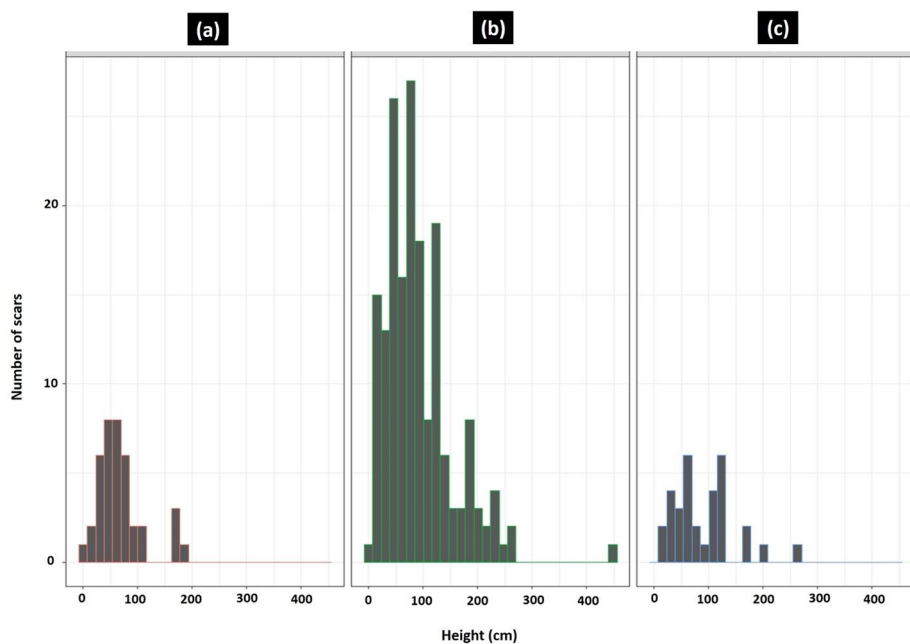
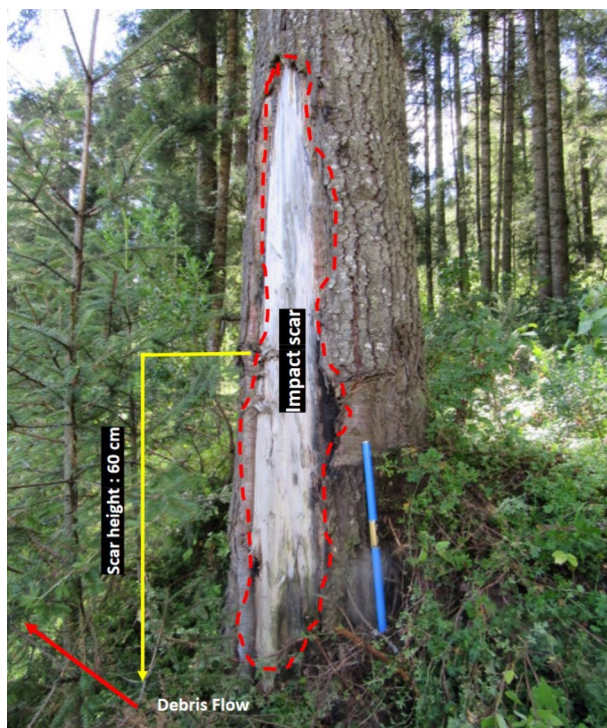


Fig. 12 Scar height histogram. The three zones present the same type of distribution: left asymmetry; **a** Fault Zone; **b** Transport Zone; **c** Deposit Zone

4 Discussion

The debris flow triggered in the Rancho Verde area in February 2010 is the longest recorded in the Monarch Butterfly Biosphere Reserve. Our analysis provides a limited-in-scope but objective vision role that dendrochronology plays in determining the spatio-temporal dynamics of debris flows in the area, as well as the relationship between conditioning elements such as lithology and hydrological characteristics, and the proximate causal elements (e.g., precipitation). These findings are important because debris flows are a constant hazard in Latin America (García-Martínez and López 2005; Valdés Carrera et al. 2021). For example, in Mocoa, Colombia, a catastrophic debris flow killed 333 people, with 398 injured, and 76 missing (García-Delgado et al. 2019). Likewise, in China, Mei et al. (2001) has documented how the combination of rock characteristics and conditions, which are influenced by water flows, caused intense erosive activity. This modified the slope profiles in mountainous areas, leading to causal conditions that were similar to those of the debris flow of MBBR (Río Verde) as we discuss below.

4.1 Precipitation-triggered debris flows

Analysis of precipitation data from two weather stations indicates that in early 2010 two cold fronts and a pronounced jet stream caused the accumulation of 236.4 mm in just five

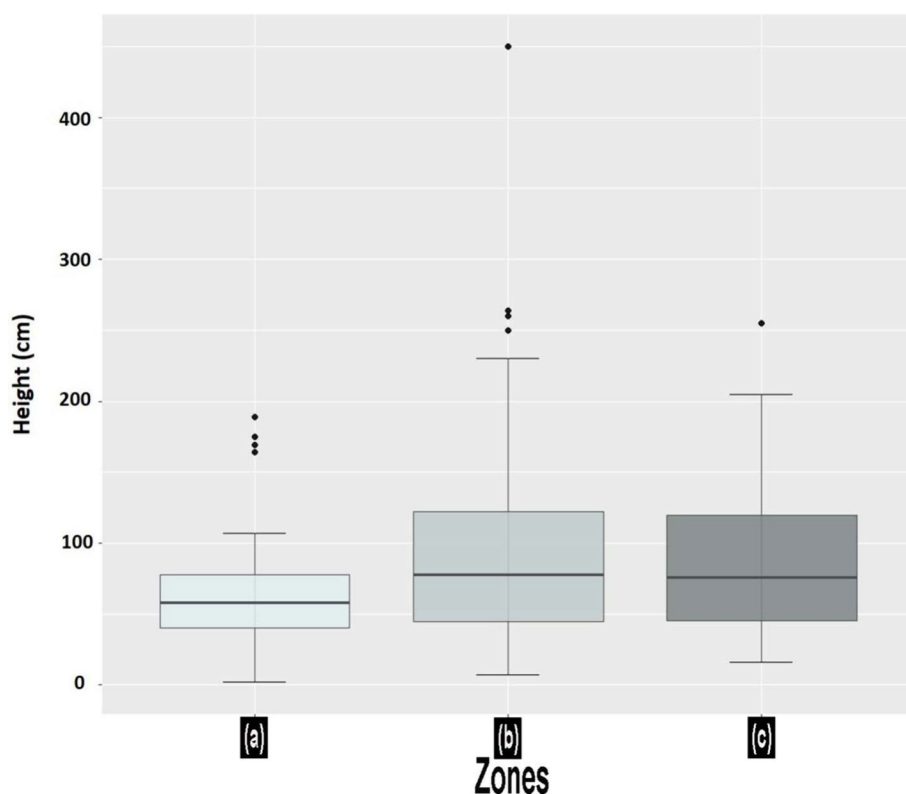


Fig. 13 Scar height variability observed in **a** Fault; **b** Transport; and **c** Deposition zones of the 2010 debris flow

days, leading to various debris flows in the MBBR. However, only those that occurred in Anganguero village have been documented (Alcántara-Ayala et al. 2012; Morelli et al. 2017). This debris flow caused the death of 33 people (Parrot and Ochoa-Tejeda 2013; Sánchez-Nuñez et al. 2021). Based on our results of the Río Verde debris flow (MBBR), we attribute its occurrence to the high amounts of subsurface water that saturated the soil and to the entrance of water into faults and cracks in the bedrock. These conditions likely saturated the upper few meters of the terrain, which is formed by highly altered basaltic andesitic rocks. Although a quantitative study of the level of degradation of the lithological material was not carried out, we can infer that the rock is in state of grade IV and V weathering in the FZ. Consequently, more than 50% of the rocky material is disintegrating or has already disintegrated to the ground (Hearn 2011).

In the MBBR, the rainfall started on January 31st and finished on February 4th, accumulating 236.4 mm in over a five-day period. This amount of rainfall had not been recorded for the previous 96 years, and in our analysis, it was classified as light to intense rainfall exceeding the threshold “Very High” with 236.14 mm of rain (Fig. 7b), sufficient to trigger several large magnitude landslides in the Trans Mexican Volcanic Belt (Domínguez et al. 2016).

The rains that occurred in February 2010 caused soil saturation, thus increasing the interstitial pore pressure, and subsequently decreasing the shear strength of the uppermost altered rocks and soil that form the slopes. These conditions affect the force of friction and promote the initial movement of the water-saturated mass, leading to a debris flow; similar results have been reported in other areas (Alcántara-Ayala et al. 2012; Sun et al. 2021; Lu et al. 2011).

4.2 Disturbance intensity a dendrogeomorphological approach

Our analysis of the intensity of the Growth Disturbances along the Río Verde debris flow path clearly shows that the 2010 growth suppression evident in tree rings was a consequence of the debris flow. According to Stoffel and Corona (2014), the analysis of Growth Disturbances in tree rings provides the elements to identify if the anomalies found are the product of the impact of a hazardous event (hydrogeomorphological or of another nature), thus reducing potential confusion caused by other processes (anthropogenic or climatic disturbances). With the intention of minimizing the noise generated by other causal factors, only growth disturbances of intensity equal to or greater than 20% are considered to be due to debris flows.

We have identified several growth anomalies in other years (1945, 1961, 1982, 1998, 2001, 2002, 2006, 2007, 2008, 2009, 2013, 2011, 2012, 2014, 2015, and 2017). However, it is not certain that these growth disturbances were caused by geomorphological processes because most of them are weak to moderate (insignificant growth disturbances, and mostly growth suppression). Such disturbances may have been caused by climatic dry conditions (Stahle et al. 2016) or other biotic events such as pests or tree competition. The most frequent type of anomalies in the three zones (FZ, TZ, and DZ) were TRDs. TRDs have also been common in tree rings observed in other studies carried out with *Abies religiosa* in volcanic areas of Mexico, such as Malinche, Pico de Orizaba, and Popocatepetl (Stoffel et al. 2008; Bollschweiler et al. 2010; Franco-Ramos et al. 2016; Vázquez-Ríos and Franco-Ramos 2022). TRDs have also been reported for other species (*Larix decidua* Mill), located to the south of the Simplon Pass in the Valais Alps, Switzerland (Bollschweiler et al. 2008). Therefore, TRDs are considered as the most reliable evidence of past geomorphic disturbances. In our case, the TRD recorded in the years 2011 and 2012 was not considered as an evidence of some debris flow in 2011 and 2012, but it is rather a delayed effect of the debris flow occurred in 2010. This delayed effect

damage could have persisted for some years after the event, similar results have been identified in other studies with *Abies alba* (Stoffel and Corona 2014).

We associate the suppression of radial growth (Fig. 8) with the debris flow of Río Verde, as confirmed by the retrospective evaluation of ring-width indices of affected trees and of the reference chronology (Fig. 9). The control chronology indicated that under normal conditions tree rings (including 2010) were consistent. However, both chronologies revealed that the suppressions in 2011, 2012, and 2013 events may not only have been caused by the impact of the debris flow, but also by droughts that occurred in northern and central Mexico in 2011 (Stahle et al. 2016).

We observe that the impact of debris shifted from lower (FZ) to higher intensity (DZ), identified by scar height analysis (Figs. 12 and 13) and in the volume of the material deposited. In the TZ, the flow was faster, and with a greater particle load (thus greater force). However, when the dragged material reached the breaking point on the slope, it decreased its speed and load capacity, causing it to expand, and lose height, as evident by the scars of lower height in the DZ. The scar sizes show clear evidence of this impact from zone to zone as found in the FZ (~30 cm), the TZ (~93 cm), and the DZ (~89 cm). These results clearly show that the impact was more intense in the TZ. Furthermore, we found trees that presented stem curvature (Fig. 5b), as well as a slight lean in the FZ, so it is presumed that the hillside was already unstable (creep movement) before 2010. The curvature and tilting of trees growing near a slope that is affected by creep movements gradually compensates for the continuous tilting of their trunks (Fig. 6a); similar results have been reported elsewhere, where they identified reaction wood and tree-ring eccentricity (Šilhán 2015, 2020b; Šilhán et al. 2024). It is important to mention that creep movement can be very slow (mm per year) and that it affects the soil and rock mantle to a maximal depth of one meter (Saunders and Young 1983; Sabir et al. 2016), for shallow slope creep. Therefore, we recommend that future studies analyze the eccentricity of the rings, which could reveal signs of fracturing and identify areas of reactivation that represent hazards. This has been done in other studies that used methods derived from dendrometry, allowing for the identification of low-magnitude movements and occasional detachments (Šilhán 2014). In addition, this information could be useful to determine the debris flow frequency (Tichavský and Fabiánová 2022), which contributes to the spatio-temporal evaluation of the hazard, a key issue in territorial planning. The present investigation contributes to the understanding of debris flow in temperate intertropical zones of Mexico such as the MBBR, given that most dendro-chronological studies have been applied to the analysis of lahars and rock falls in volcanic areas of temperate-cold environments (Franco-Ramos et al. 2016, 2018, 2019).

Finally, we would like to point out that the application of dendrogeomorphological techniques comes with some limitations when identifying landslides. In this study, we found that due to the magnitude of the event, there is a spatio-temporal sampling bias, caused by the elimination of trees that may have been affected by events of lesser magnitude. Moreover, some trees that were affected by the Río Verde debris flow in 2010 were removed by the process, and so couldn't be studied. On the other hand, due to constant river erosion, some of the original geomorphological features were considerably modified, to the point of being barely visible or recognizable. In addition to this, we consider the use of the Digital Terrain Model instead of the Digital Surface Model to be essential, since, in the particular case of this study, it represented a great limitation when identifying the geomorphological units that characterize the debris flow.

5 Conclusions

In this study, we analyzed the debris flow activity in the Monarch Butterfly Biosphere Reserve using dendrogeomorphic methods. Data from 125 tree ring series of affected trees allowed the identification of the 2010 Río Verde debris flow event. Detailed analysis of the induced growth disturbances on the affected trees provided comprehensive insights into the flow's basic characteristics, its behavior, providing an understanding of the dynamics of debris flows during their trajectories. Flow intensity varied across the study area, with the transport zone being the one with the highest intensity, shown clearly by the fact that it had the highest, largest, and most frequent scars. The debris flow identified in the tree ring series in 2010 was triggered by intense hydrometeorological events that occurred in late January and early February 2010 (cold fronts 28 and 29, and a pronounced jet stream), which together caused a cumulative rainfall of 236.4 mm in just five days.

This investigation provides the first temporal analysis data of a debris flow in the Monarch Butterfly Biosphere Reserve with an annual resolution. We highlight the use of dendrogeomorphological techniques in the collection of spatio-temporal information on debris flow activity in intertropical montane environments—in the case of Mexico, until now the analysis of debris flows using a dendrogeomorphology approach has been barely addressed. We encourage increasing research on the It index thresholds in intertropical environments. Further studies could benefit from this approach, as it can also be applied to other hillsides, not only in the MBBR but other sites in the Trans Mexican Volcanic Belt, where debris flows may be a threat.

Appendix

See Fig. 14.

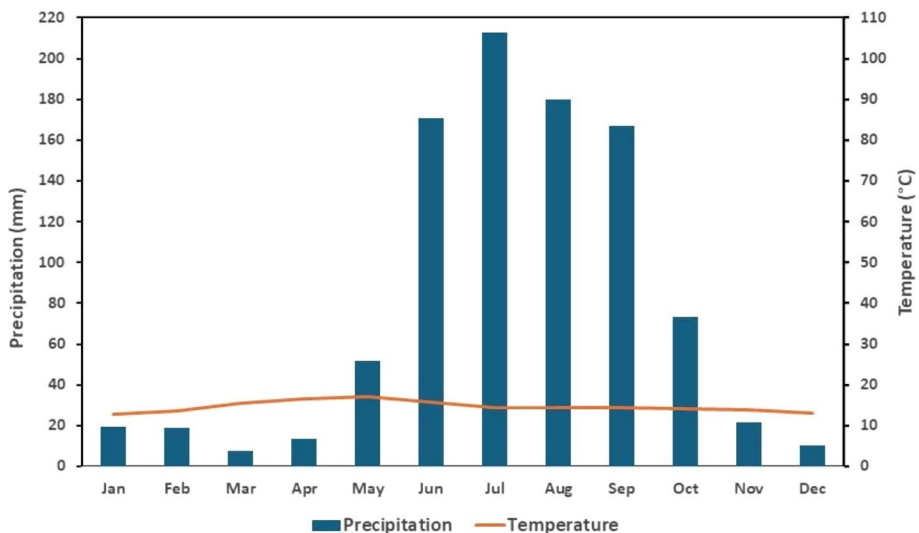


Fig. 14 Climograph of the Monarch Butterfly Biosphere Reserve, data period from 1922 to 2022.

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Author's contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Karla Aurora De La Peña Guillen and Teodoro Carlón Allende. The first draft of the manuscript was written by Karla Aurora De La Peña Guillen and Teodoro Carlón Allende. José Luis Macías, Manuel E. Mendoza and José Villanueva Díaz commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Conflict of interest The authors declare that they have not conflict of interest

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