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Active Geomorphic Hazards in the Sâmbăta Valley, Făgăraș Mountains (Romania): a Tree-ring Based Approach

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Abstract

The present study addresses, for the first time, the problem of spatio-temporal reconstruction of geomorphic processes using tree-rings in the Sâmbăta Valley (Romanian Carpathians). The dendrogeomorphic analysis was conducted in two different sites, one affected by snow avalanches and the other by rockfall. A total number of 130 *Picea Abies* were sampled in the two sites. The results yield 13 major snow avalanches between 1950 and 2020 and a return period of 3.3 years. The winters with the highest activity index were 1988, 1997 and 2012. The rockfall reconstruction highlights several years of intense activity: 1952, 1955, 2003 and 2012. Thus, the results of the present study provide evidence of active geomorphic processes in the studied area, indicating that tourists are highly exposed to geomorphic hazards, as both sites interfere with popular hiking trails. (Because Sâmbăta Valley is one of the most intensely frequented by tourists in the Făgăraș Mountains, it is a need for warning signs to be installed on the exposed trails.

Keywords: snow avalanches; rockfall; natural hazards; dendrogeomorphology; Romania

Introduction

In mountainous regions all over the world, slope processes such as snow avalanches, debris flows and rockfall can pose a serious threat to human lives and activities (Bollati et al., 2018). A better understanding of geomorphic processes, in terms of past occurrences, is an important task for the assessment of natural hazards and the associated risks, in areas where information on past process behavior is sparse or missing. The Romanian Carpathians have long been a mountainous region repeatedly affected by geomorphological hazards (Bălteanu, 1997). Several active geomorphological processes have frequently caused damage to tourism infrastructure, human activities and human fatalities (Micu et al., 2017). Due to the rapid development of the tourism infrastructure in the Carpathians in the XXth century, geomorphological processes like landslides, debris flows, rockfall, snow avalanches and river flooding can have a significant impact on touristic activities. Although these natural processes have the potential to negatively affect humans, infrastructure and activities and the environment (Gratton et al., 2015), a comprehensive understanding of their behavior is still poor in the Romanian Carpathians (Voiculescu & Ardelean, 2012). It is, therefore, a high demand to improve knowledge of the spatio-temporal occurrence of past events because this might lead to

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hazard prevention and mitigation at a regional and local scale (Copien et al., 2008).

Little information exists regarding the frequency, magnitude, and timing of these mountain-slope hazards due to the lack of archive data on past occurrences in the Romanian Carpathians (Voiculescu et al., 2016). Nevertheless, the occurrence and characteristics of past geomorphic processes on forested slopes can be deciphered using a tree-ring based approach. This method proved to be one of the most accurate and reliable dating approaches, providing annual and, in some cases, intra-annual resolution on geomorphic activity over the past centuries (Stoffel et al., 2006b). Moreover, dendrochronology allows the differentiation between geomorphic processes, mainly based on the position of growth disturbances within the annual tree ring (Stoffel et al., 2005). In various mountainous regions all over the world, studies have been carried out to reconstruct debris flows (Bollschweiler et al., 2007, Tichavsky et al., 2017), rockfall (Perret et al., 2004, Mainieri et al., 2019), snow avalanches (Corona et al., 2010, Favillier et al., 2017) and flash floods (Casteller et al., 2015).

Previous studies in the Romanian Carpathians revealed that the aforementioned geomorphic processes could sometimes reach catastrophic levels in the Făgăraș Mountains (Voiculescu & Ardelean, 2012), where many touristic hiking routes are exposed to rockfall, debris flows or snow avalanches. On the northern slope of the Făgăraș Mountains, Sâmbăta Valley is one of the most exposed and intensely frequented by tourists due to its high accessibility and spectacular relief. Despite that snow avalanches and rockfall frequently impact the trekking and the climbing routes in the Sâmbăta Valley, no previous study assessed the reconstruction of spatiotemporal patterns of these processes. Therefore, the aims of the present study are (i) to reconstruct major events on a forested snow avalanche path using dendrochronology and (ii) to analyze rockfall activity on a forested slope, based both on a tree-ring approach and visual scar counting.

Study area

The Sâmbăta Valley (45°37'N, 24°47'E) is located on the northern slope of the Făgăraș Mountains, the highest mountain range in Romania (Figure 2). Stretching around 11 km from south to north, between the main ridge and the Sâmbăta de Sus Tourist Complex, situated at the foot of the Făgăraș Mountains, Sâmbătă is a typical Carpathian north-facing glacial valley. Geology is dominated by schists, gneisses and crystalline limestones lithology belonging to the Supragetic nappe. The elevation ranges between 670 m and 2470 m (Gălășescu Peak). During the most extended glacial advance (22 ka BP), a valley glacier 4.5 km long reached down to 1150 m within this valley. During the Lateglacial, several readvances were documented in the Southern Carpathians (Ruszkiczay-Rüdiger et al., 2016). The Pleistocene glaciers sculpted the landscape and created glacial cirques and valleys. The dominant present-day processes are snow avalanches, rockfall, debris flows, gully erosion and solifluction.

The predominant air mass circulation in this region is from west to east. The mean annual precipitation at the nearby Bâlea Lake weather station (2038 m, 45°36'17''N, 24°37'01''E, period 1979-2020) is 1365 mm. The highest rainfalls are in the warm seasons (e.g., May-August), when heavy rainstorms are most frequent, whereas snowfall is characteristic between November and April. Above 2000 m, the ground is covered by snow for around 200-250 days/year. The mean annual air temperature at the Bâlea Lake weather station is 0.8 °C but increases to 4.6 °C at 1406 m (at Păltiniș weather station). A general overview of the annual meteorological patterns is depicted in Figure 1.

The treeline stands around 1800, but the hillslopes are predominantly non-forested above 1500 m due to intense geomorphic and pastoral activity. Only below

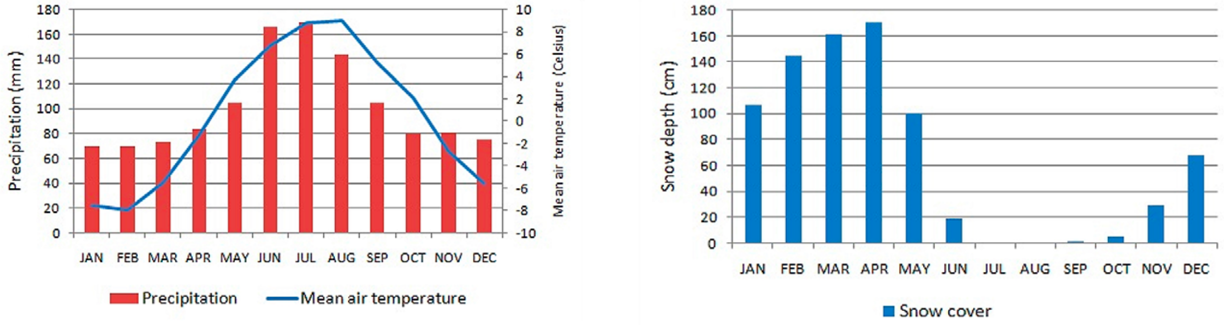


Figure 1. Temperature, precipitation and snow cover at Bâlea Lake Weather Station (1979-2020)

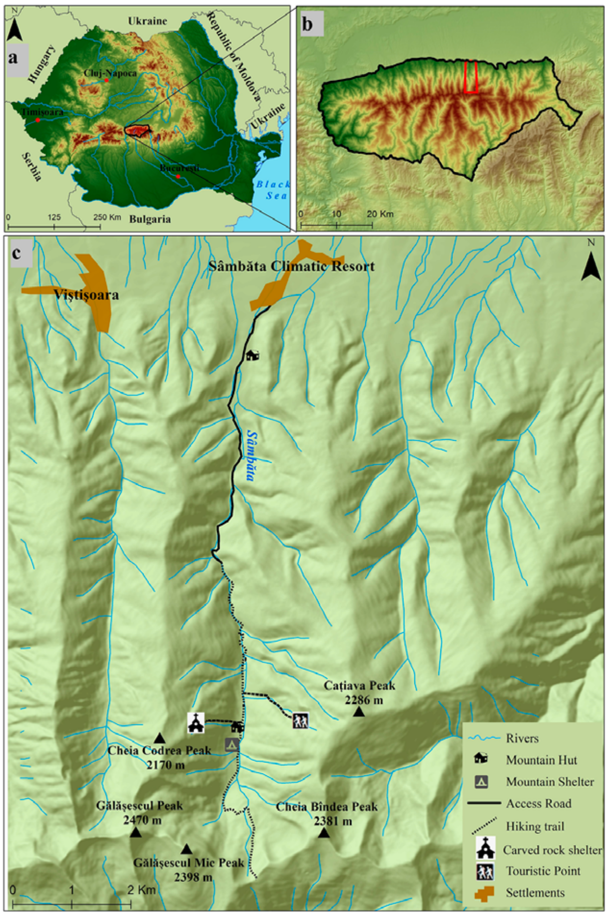


Figure 2. Location of the a. Făgăraș Mountains in Romania; b. The Sâmbăta Valley within the Făgăraș Mountains; and c. Map of Sâmbăta Valley

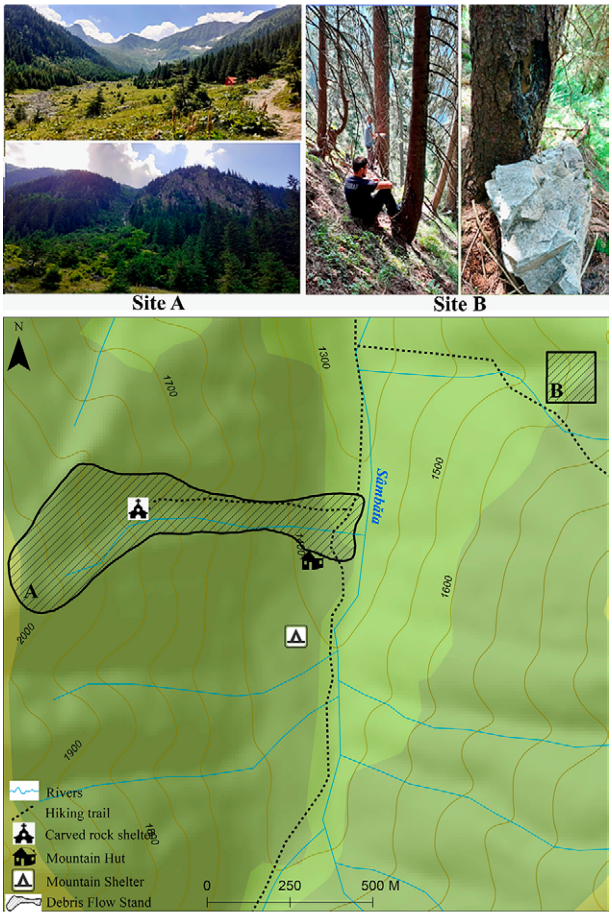


Figure 3. Location of the two analyzed sites in the Sâmbăta Valley (site A - snow avalanches, site B - rockfall)

1500 m, a dense *Picea abies* forest covers the hillslopes. Above the treeline, alpine and subalpine herbs and shrubs carpet the hillslopes. Reduced surfaces within this valley are covered with unconsolidated scree deposits or correspond to highly inclined, intensely fractured bedrock. These nearly vertical and highly sensitive to weathering outcrops constitute the primary sediment sources for rockfall and debris-flow events and the material scoured from the channels during heavy rainfalls.

The trails in the Sâmbăta Valley are one of the most popular in the Făgăraș Mountains and, due to the breathtaking landscape, attract high numbers of visitors, especially during the summer. At 1350 m, the Valea Sâmbetei chalet is located on a sizable depositional fan created by the Codrea torrent on the western slope of the valley. The chalet was a hunting house at the beginning of the last century, but in the 1930s it became a tourist lodge. From the chalet, a steep trail ascends to 1600 m to a carved rock shelter where one of the most beloved theologians in the Romanian Orthodoxy settled his praying site around the middle of the XXth century. Pilgrims from all over Romania visit this sacred place, although the trail is highly exposed to snow avalanches, rockfall and debris flow. On the eastern slope of the valley, another trail starts in the vicinity of the Valea Sâmbetei. It ascends to Piatra Caprei Peak, this path being highly endangered by rockfall as well.

The dendrogeomorphological approach was conducted on two different sites (Figure 3). The first site is the avalanche path following the Codrea creek in the vicinity of the Sâmbăta Valley chalet. Between the confluence of this creek with Sâmbăta valley and the source area, the path spans a vertical range of about 800 m. The upper basin hillslopes have a high gradient, with a mean slope angle of 39°. Between the apex of the fan and the confluence with the Sâmbăta Valley, the mean inclination of the slope decreases to 33°. The majority of the trees growing on the torrential cone show morphological evidence of former snow avalanche activity. The second site is located at the foot of a rockfall producing wall known as Piatra Caprei, around 1700 m. Most of the trees at the base of this rock wall show clear signs of disturbances (mainly impact scars) as a result of intense rockfall activity. Trekking trails cross both sites, but there is no sign warning of snow avalanche/rockfall danger.

Material and methods

Terrain analysis and geomorphic mapping

Initial examination of satellite imagery, aerial photographs and topographic maps of the study area were followed by a geomorphic survey undertaken in the field. Finally, a digital elevation model for the Sâmbăta Valley, including the two investigated sites, was constructed from digitized elevation contours of the 1:25000 topographic maps using ArcGIS. The contour lines were interpolated into a raster grid surface using Topo to Raster tool. The forest cover and the delineation of the two sites were assessed based on aerial photographs and satellite imagery.

Sampling design

The present analysis is based on two sampling campaigns that took place in 2014 (60 trees at site A) and 2021 (20 trees at site A and 50 trees at site B.) Hence, to reconstruct the occurrence of geomorphic processes in the study area, a total number of 130 *Picea abies* trees have been sampled using Pressler increment borers (ø 5.15 mm, max. length 40 cm). Selected trees generally exhibit clear evidence of geomorphic disturbance (Stoffel and Bollschweiler, 2009), such as impact scars, broken trunks, tilted and bent stems, flagged branches, uprooting and apex loss. For site A, sampling was carried out along the lateral limits of the avalanche path (see Figure 11), generally along the transportation zone and, where available, inside the path and in the run-out zone. At site B, more severely damaged trees and individuals with a higher number of visible impact scars were selected for the present analysis.

Sampling procedures were adapted to the type and location of visible anomalies in tree morphology, as suggested by Stoffel and Bollschweiler (2009), considering that growth reactions are usually better developed in the proximity of the impact (Stoffel and Corona, 2014). Between two and five increment cores were extracted per tree, with an increasing number of samples for trees with multiple visible scars. Finally, additional information was collected for each tree: exact position (using a differential GPS Trimble GeoExplorer XH6000), stem diameter at sampling height, type and description of growth anomaly, number and height of scars, specific terrain features and surrounding vegetation.

Sample analysis

All collected samples were air-dried, mounted and finely sanded (with grit from 100 to 800) following standard dendrochronological procedures described by Bräker (2002). Using marker years from a local reference chronology (Chiroiu et al., 2015), samples were visually crossdated, and for each tree-ring the exact year of formation was assessed. Tree-rings were then measured using a LINTAB-5 positioning table, connected to a Leica stereo-microscope and TSAP-Win Professional 4.64 software (Rinn, 2013).

The reconstruction of past occurrences of geomorphic processes requires the identification and precise dating of growth disturbances (referred hereafter as GD). In the present study, the following GD were used (Stoffel and Bollschweiler, 2009): (i) onset of compression wood, (ii) first year with abrupt growth suppression and (iii) abrupt growth release, (iv) onset of callus tissue formation, and (v) first year with tangential rows of traumatic resin ducts - referred hereafter as TRD - (Stoffel, 2008). According to Stoffel et al. (2006b), TRD and callus tissue found just at the beginning of the growth ring (i.e. early earlywood) were associated to snow avalanches (for site A), while TRD and callus tissue found later within the annual ring (middle and late earlywood and latewood) were considered being inflicted by other processes (rockfall and debris flows). TRD were only considered the result of geomorphic events if they formed compact, continuous and tangential rows.

Subsequently, we assessed the intensity of each identified GD (weak, intermediate and strong) and based on the classification system proposed by Stoffel and Corona (2014), we defined five intensity classes. The methodological steps adressed in the present study, from sample collection to results is depicted in Figure 4.

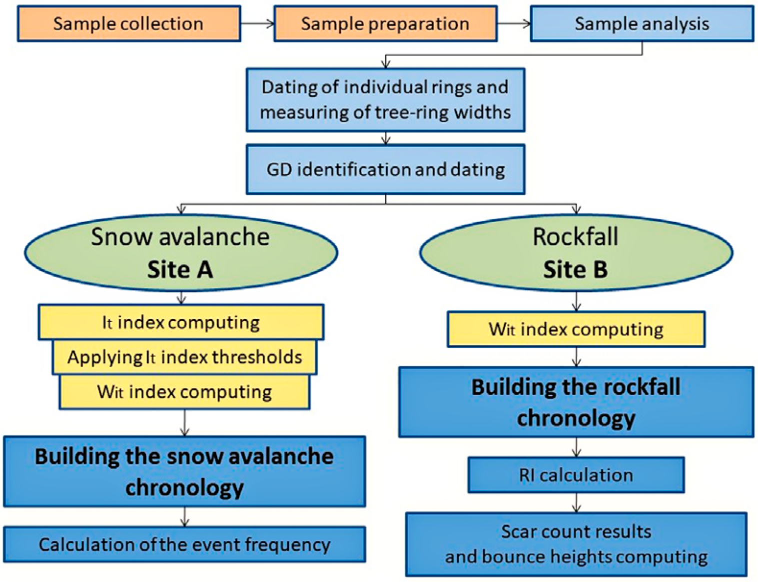


Figure 4. Methodological steps used for each of the investigates sites

Snow avalanche reconstruction and frequency

The snow avalanche reconstruction for site A is based on the total number of GDs and the semi-quantitative Shroder I_t index (Shroder, 1980). The I_t index is defined as the ratio between trees showing growth responses and all sampled trees being alive in that year, following the formula:

$$I_t = \frac{\sum_{i=1}^{n} Rt}{\sum_{i=1}^{n} At} \cdot 100$$

- where Rt = responding trees in year t; and At = sampled trees alive in year t.

Snow avalanche event years were assessed by applying sample depth adapted thresholds for GD and It, as suggested by Stoffel et al. (2013). In the present study, we used the following thresholds for avalanche filtering: $GD \geq 3$ and $I_t \geq 15$ (no. of available trees ≤ 20), $GD \geq 5$ and $I_t \geq 10$ (no. of available trees between 21 and 50) and $GD \geq 7$ and $I_t \geq 7$ (more than 50 trees available).

The strength of the dendrogeomorphic signal is evaluated using the semi-quantitative intensity weighted index (W_{it}) proposed by Kogelnig-Mayer et al. (2011) and based on the five intensity classes mentioned above:

$$W_{it} = \left[\left(\sum_{i=1}^{n} GDt5 \cdot 5\right) + \left(\sum_{i=1}^{n} GDt4 \cdot 4\right) + \left(\sum_{i=1}^{n} GDt3 \cdot 3\right) + \left(\sum_{i=1}^{n} GDt2 \cdot 2\right) + \left(\sum_{i=1}^{n} GDt1 \cdot 1\right)\right] \cdot \frac{\sum_{i=1}^{n} Rt}{\sum_{i=1}^{n} At}$$

- where $GDtn$ = GD assigned to the Intensity n Class (n=1 to 5); Rt = responding trees in year t; At = trees alive in year t.

Snow avalanche frequency is expressed as a return period and is calculated as a ratio between the length of the chronology and the number of reconstructed events (Casteller et al., 2011). Considering that the sample depth increases as we advance towards the present, tree-ring based avalanche reconstructions yield a better resolution for more recent periods. However, the limited number of trees available for older periods will influence the quality of the reconstructed frequency (Corona et al., 2010). Therefore, in this paper we calculate the return period for two different time intervals: 1950-2020 (70 years) and 1980-2020 (40 years). We expect that the results for the 40 years will best reflect the present frequency for major snow avalanche events in the study area.

Rockfall analysis

The occurrence of rockfall at site B was analyzed by GD dating and counting of visible scars on the sampled trees (Trappman & Stoffel, 2013, Mainieri et al., 2019). In addition, to evaluate the bouncing heights of downslope moving rock fragments, the average height of visible scars was noted (Schneuwly et al., 2008).

The GD based rockfall reconstruction accounts for the total number of responses per year to detect years or periods with more intense process activity. To assess the strength of the dendrogeomorphic signal, we calculated the W_{it} index for each year. The recurrence interval (RI) was calculated for each tree, representing the average number of years passing between two GDs on a single tree (Stoffel et al., 2005). The RI is

Table 1. Reccurence interval classes

RI classes	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
Number of years between 2 events	No GD	RI<10	10<RI<20	20<RI<30	30<RI<40	RI>50

calculated as a ratio between the tree's age and the number of events detected. To visualize differences of rockfall intensity along the slope, trees were assigned to different RI classes (Table 1).

Following bark and cambial injury, a tree will react by forming callus tissue which will gradually overgrow and heal the wound. The process requires several years, mainly depending on the scar size, the age and health of a tree. Thus, recent as well as older scars remain visible on the stem. In the scar count approach, we followed recommendations by Trappmann and Stoffel (2013). Unusually long, vertical scars and scars found on the downslope part of the tree were excluded from the count.

Results

Tree ages and growth disturbances

The trees analyzed in the present study reveal a mean number of 64 annual rings, with a minimum of 11 and a maximum of 289 years. Due to the sampling height and because, in most cases, the tree's pith was not reached, the age values are relative and do not reflect the absolute ages of sampled trees. Nevertheless, there is a clear difference in tree ages between the forest stands growing at the two sites. At site A, the average age of the stand is 35 years, with the oldest individual counting 86 tree rings, while at site B, trees are much older, with a mean number of 110 annual tree-rings and most of the trees exceeding 100 years.

The samples analyzed in this study allowed the identification of 711 GDs related to snow avalanches and rockfall. The different types of responses are shown in Figure 5. A number of 280 GDs were associated with snow avalanche disturbance, whilst 431 GDs were most probably inflicted by rockfall and debris flows.

Because avalanches mainly tilt trees in their downslope movement, compression wood was the most frequent response found at site A (39.5%). On the other hand, rockfall impacts damage tree stems, inducing wounds, thus promptly activating anatomical reactions in the form of callus tissue and TRD. Accordingly, at site B, almost half of the GD was in the form of TRD.

Snow avalanche reconstruction and frequency

Based on the number of GD and the semi-quantitative I_t index, we were able to reconstruct a total number of 13 major snow avalanche events at site A, the reconstructed chronology covering the period 1950 – 2021. As shown in Figure 6, the years with major events reconstructed are the following: 1976, 1988, 1992, 1995, 1996, 1997, 2005, 2006, 2007, 2008, 2012, 2016 and 2019. In addition, event years 1992 and 1995 with GD values falling close beneath the GD threshold were included in the chronology due to the spatial cluster-

Investigated site	Total number of GD	Reaction wood		Growth supression		Growth release		TRD		Callus tissue	
		No.	%	No.	%	No.	%	No.	%	No.	%
Site A	339	134	39.5	79	23.3	3	0.9	109	32.2	14	4.1
Site B	372	86	23.1	55	14.8	14	3.8	184	49.5	33	8.9

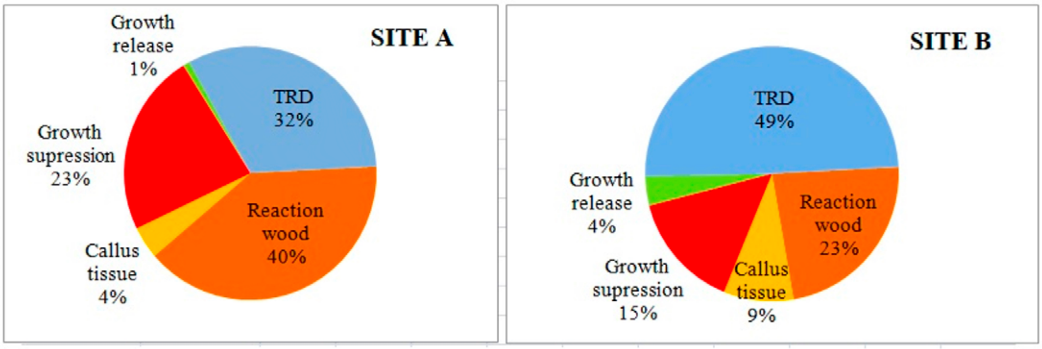


Figure 5. Distribution of GD types at the two investigated sites

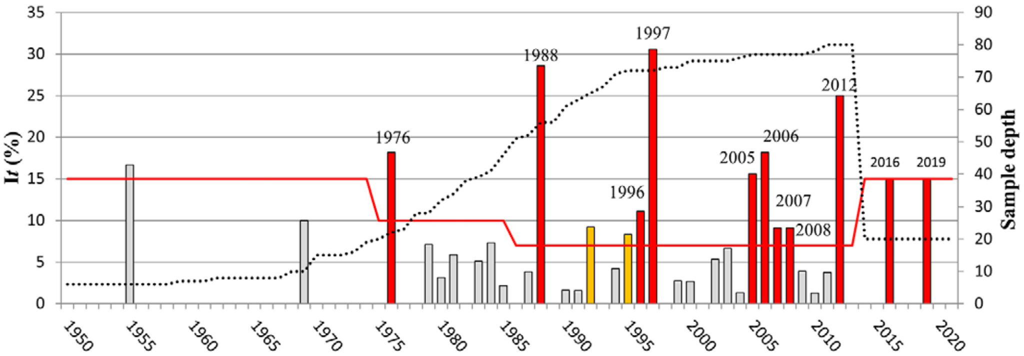


Figure 6. Histograms showing the snow avalanche chronology for site A based on the I_t index (bars – I_t values; red line – I_t threshold; dotted line – sample depth)

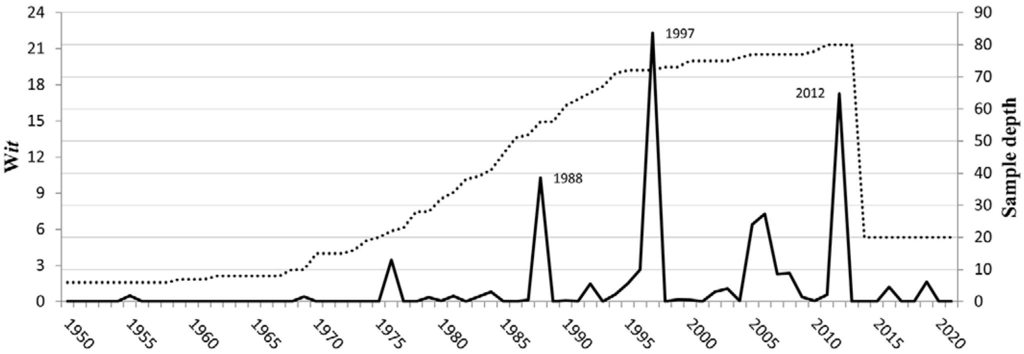


Figure 7. Histogram showing the dendrochronological signal strength for site A based on the reaction intensity (W_{it} index)

ing of strong reactions (Schneuwly-Bollschweiler et al., 2012).

The dendrochronological signal strength based on the semi-quantitative Wit index (Figure 7) is consistent with the reconstructed event chronology. Moreover, it highlights the years 1988, 1997 and 2012 as characterized by strong and long-lasting reactions, pointing to the magnitude of the events. On the other hand, moderate values of the W_{it} index (1.5 – 3) were obtained for event years 1992, 1993, 2007, 2008, 2016 and 2019.

The frequency of major events, expressed as an average return period, is 5.3 years for the whole extent of the chronology (1950-2021) and 3.3 years for the interval 1980-2021. We can also observe clustering of events in two periods (1995-1997 and 2005-2008), with avalanches occurring every year.

Rockfall analysis

The identification and dating of rockfall induced growth disturbances allowed the reconstruction of 224 events. The century-long reconstructed chronology (Figure 8) spans from 1900 to 2020 and points to several years of intense rockfall activity (GD>5): 1952, 1955, 2003, 2007, 2010, 2012 and 2019. Eight trees exhibited GDs in 1944, all in the form of weak to moderate reaction wood. This finding rather suggests the influence of another disturbing factor, such as intense

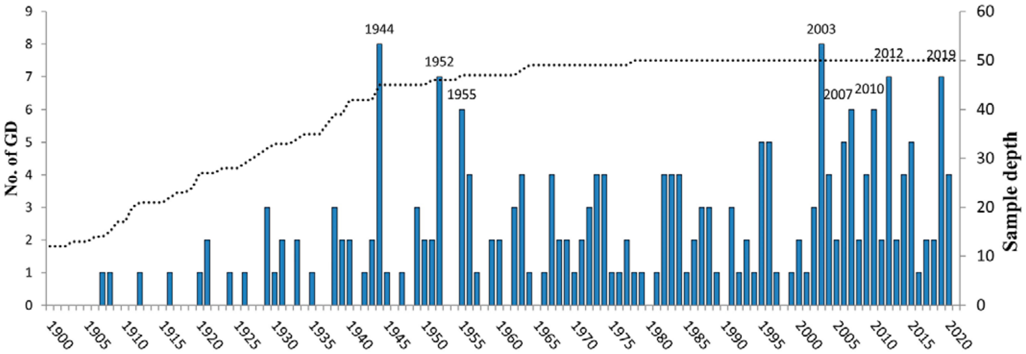


Figure 8. Histogram showing the total number of growth disturbances per year at site B

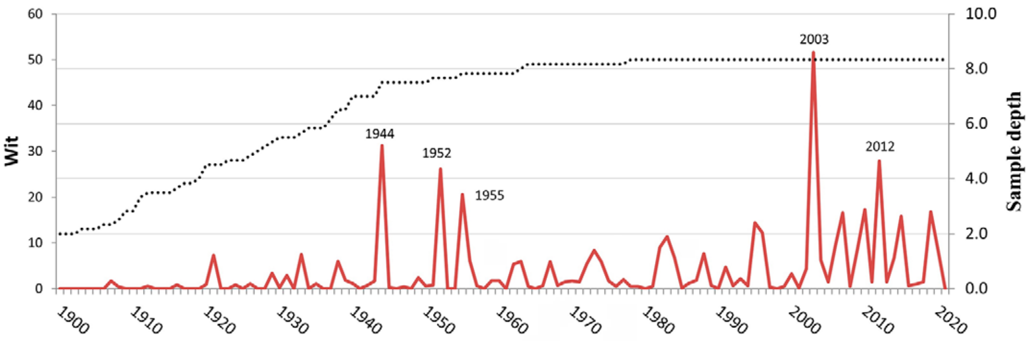


Figure 9. Histogram showing the semi-quantitative W_{it} index at site B

creep activity. We thereby exclude the year from the final rockfall reconstruction.

The chronology also indicates periods with a higher number of responses, such as 1972-1974, 1982-1984 and 1995-1996, with an increased dendrochronological signal as well (see Figure 9). The last 20 years of the chronology concentrate 35% of the identified GD, with virtually every year recording an event. Due to decreasing sample depth, the first 50 years of the chronology (1900-1950) showed a lower number of detected events (19%). The W_{it} index highlights the years 1952, 1955, 2003 and 2012 with a strong dendrochronological signal.

The recurrence interval calculated for each tree resulted in an average period of 27.4 years between two impacts on the same tree. In this regard, the RI varies between 6.4 and 105 years, while nine of the selected trees showed no GD in the tree-ring sequence. The spatial distribution of trees associated with different recurrence interval classes is depicted in Figure 10A, showing a decreasing of the RI as we move downslope and further away from the rockfall source area.

The visual counting of impact scars allowed us to identify a total number of 140 scars. Five of the 50 analyzed trees did not present any observable evidence of past rockfall impact, while the mean value of visible scars per tree for the rest of the 45 trees is 3.1. Results for each tree are illustrated in Figure 10B. The heights of the visible scars vary between 13 cm and 257 cm, with an average value of 67.8 cm. Around half of the scars (49.3%) are located between 20 and 60 cm, while another 23,5% lie between 60 and 100 cm. We only found two scars higher than 200 cm on the selected trees.

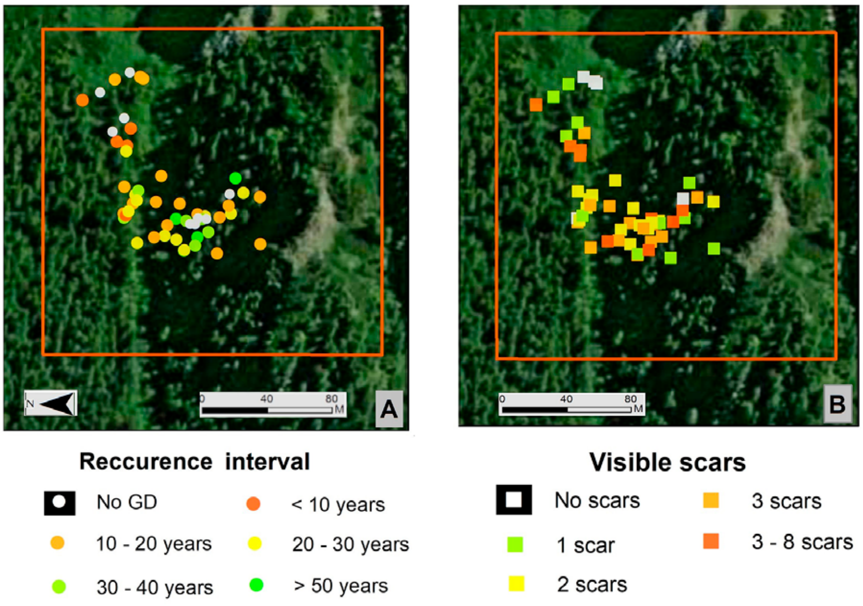


Figure 10. Recurrence interval classes for each tree - dendrogeomorphic approach (A) and visible scars counting approach (B)

Discussion

Snow avalanche reconstruction

The robustness of the snow avalanche chronology decreases in time, being biased by sample depth. Even if the I_t index is specially designed to lower the influence of sample size, the chronology clearly shows a rise in event frequency as the sample size increases. Because 75% of the analyzed trees at site A reached sampling height after 1975, a sample size of only 20 trees hinders efficient event detection in the first 25-year segment of the chronology. Another specific limitation of the dendrochronological approach states that major events tend to blur responses in the upcoming years (Stoffel & Bollschweiler, 2009). This could be the case for the 1976, 1988 and 1997 events, as each of them were followed by „avalanche-free" periods of 8 up to 12 years. In this sense, the 2005-2008 interval, with yearly reconstructed events, could point to the lower magnitude of the snow avalanches. Therefore, the avalanche frequency calculated for site A should be regarded as a minimum frequency. Most probably, snow flows and minor avalanches occur every winter, and the present reconstruction only highlights the major events.

During the last decade, several tree-ring-based snow avalanche reconstructions (Table 2) have been undertaken in the Southern Carpathians (Voiculescu & Onaca, 2012; 2014; Meseșan et al., 2014; 2017; 2018; Pop et al., 2015; 2017a; 2017b; Chiroiu et al. 2015; 2015; Voiculescu et al., 2016; Todea et al., 2020). Some of the event years reconstructed in the present paper were also found in other mountain ranges, such as the 1997 avalanche (in Parâng, Șureanu, and Piatra Craiului Mountains) and the 2005 avalanche (Parâng, Șureanu and Făgăraș Mountains). This suggests a common meteo-climatic trigger which could also be connected to the general athmospheric circulation.

Rockfall analysis

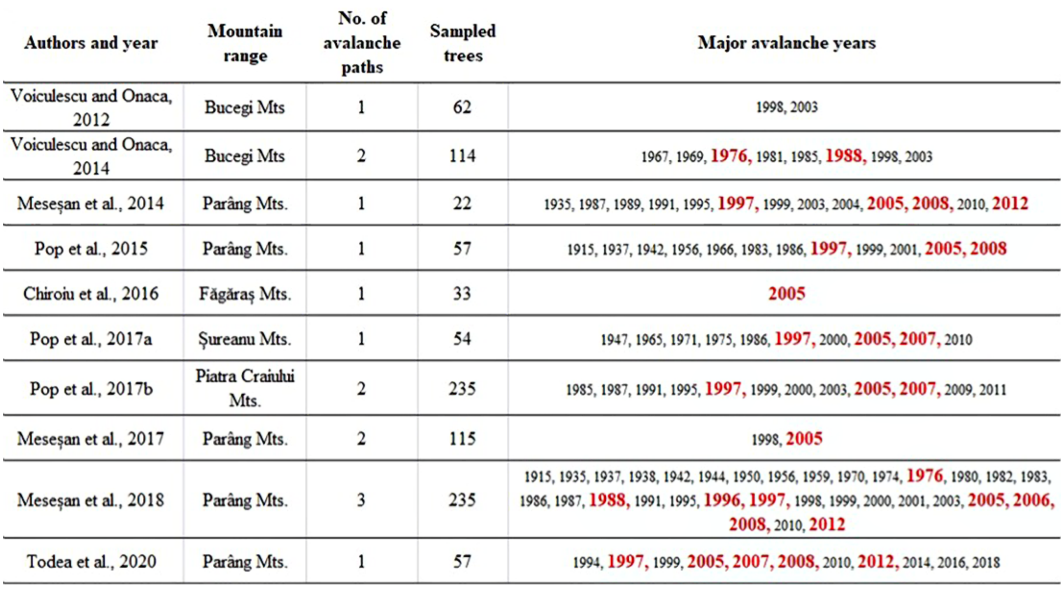
At site B, rockfall is the only geomorphological process causing growth disturbances in trees, except creep movements which mainly induce GDs in the form of reaction wood. Even if cambial damage (trunk wounds) can be inflicted by animal browsing and falling of nearby trees, we argue that the rockfall chronology is relevant for site B, at least for the peak years. Still, the actual rockfall rate is blurred by several factors: forest density, sample depth, stem diameter, hidden scars and the fact that a falling fragment generally injures more than one individual in its trajectory (Stoffel & Perret, 2006a; Stoffel et al., 2006b). While the RI is generally decreasing downslope (Figure 8A), we can also identify protected areas which show clusters of trees with no GD detected.

The scar counting approach does not yield sufficient information in our study, as the correlation between the number of visible scars and the number of reconstructed events is very low (r = 0.06). This result is mainly influenced by the bark thickness and the specific healing mechanisms of *Picea abies*, which seal the wounds faster than other tree species (Trappman & Stoffel, 2013).

Documented major events in the Sâmbăta Valley

One of the main reasons for including site A in the present analysis was the clear evidence of debris-flow

Table 2. Southern Carpathians tree-ring based snow avalanche reconstructions (avalanche years identified in the present study as well are marked with red)



Authors and year	Mountain range	No. of avalanche paths	Sampled trees	Major avalanche years
Voiculescu and Onaca, 2012	Bucegi Mts	1	62	1998, 2003
Voiculescu and Onaca, 2014	Bucegi Mts	2	114	1967, 1969, **1976,** 1981, 1985, **1988,** 1998, 2003
Meseșan et al., 2014	Parâng Mts.	1	22	1935, 1987, 1989, 1991, 1995, **1997,** 1999, 2003, 2004, **2005, 2008,** 2010, **2012**
Pop et al., 2015	Parâng Mts.	1	57	1915, 1937, 1942, 1956, 1966, 1983, 1986, **1997,** 1999, 2001, **2005, 2008**
Chiroiu et al., 2016	Făgăraș Mts.	1	33	**2005**
Pop et al., 2017a	Șureanu Mts.	1	54	1947, 1965, 1971, 1975, 1986, **1997,** 2000, **2005, 2007,** 2010
Pop et al., 2017b	Piatra Craiului Mts.	2	235	1985, 1987, 1991, 1995, **1997,** 1999, 2000, 2003, **2005, 2007,** 2009, 2011
Meseșan et al., 2017	Parâng Mts.	2	115	1998, **2005**
Meseșan et al., 2018	Parâng Mts.	3	235	1915, 1935, 1937, 1938, 1942, 1944, 1950, 1956, 1959, 1970, 1974, **1976,** 1980, 1982, 1983, 1986, 1987, **1988,** 1991, 1995, **1996, 1997,** 1998, 1999, 2000, 2001, 2003, **2005, 2006, 2008,** 2010, **2012**
Todea et al., 2020	Parâng Mts.	1	57	1994, **1997,** 1999, **2005, 2007, 2008,** 2010, **2012,** 2014, 2016, 2018

occurrence and the recorded major event which took place in 1968 (Cioacă, 1970). The process was triggered in the night between the 21st-22nd of August, after a period of heavy rainfall which had maximum values on the 20th and 21st of August. Even if the GD analysis points to some processes occurring in spring and summer (which have been excluded from the avalanche reconstruction), unfortunately, none of the selected trees showed evidence of the 1968 debris-flow event. The only print observed is found in the forest stand's age structure, colonizing site A (Figure 11). Cioacă (1970) notes that the debris flow had an unusual trajectory being deviated to the right. Age analysis shows that all of the sampled trees in the southern part of the debris fan germinated in the early ,70s or later. Destructive events can remove entire parts of forest stands, thus erasing tree-ring evidence of past processes. Regarding the results of our analysis, we argue that this could be the case for the 1968 event. Another major debris-flow event in the Sâmbăta valley occurred in August 2007 and affected the forest road, the tourist trail, a few cars and damaged electricity poles (Petre et al., 2012).

In 1996 a snow avalanche affected the Mountain Rescue cabin located 160 m to the south of Valea Sâmbetei chalet (Petre et al., 2012). Moreover, in February 2012, another snow avalanche affected the kitchen of the Valea Sâmbetei chalet.

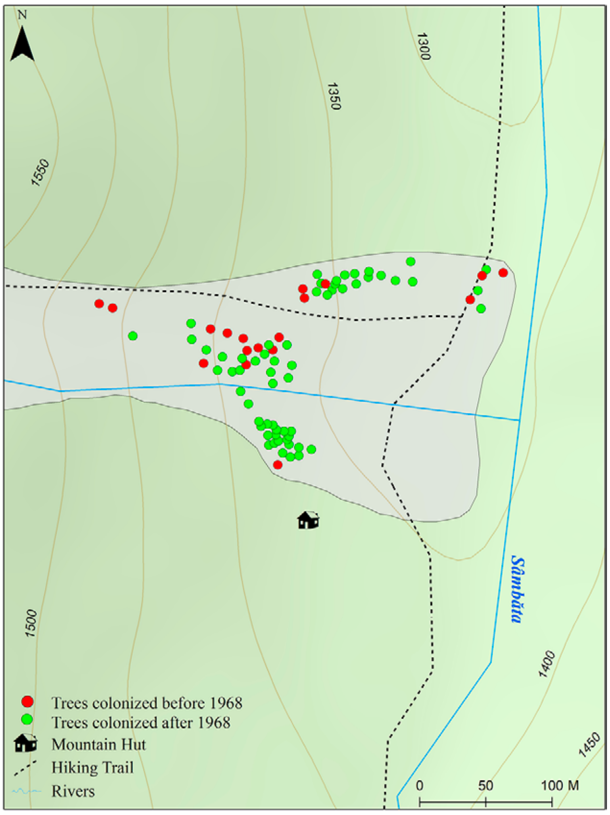


Figure 11. Succession analysis (trees established before the debris flow event in 1968 - RED, trees established after 1968 - GREEN)

Following heavy rainfall in April 2021, a giant snow avalanche occurred in the Pârâul Vârtejelor creek, which is a small tributary of Sâmbăta valley on the eastern slope. The major event has broken hundreds of trees and transported most of them into the Sâmbăta channel (Figure 12). The deposited tree trunks entirely covered a valley sector of around 200 meters at the confluence with Pârâul Vârtejelor. In mid-July 2021, a snow deposit with a thickness of 1-3 m, almost entirely covered by dead trees, was

Figure 12. Effects of the major 2021 snow avalanche event on the eastern slope of the Sâmbăta Valley: clear signs of avalanche destruction along the newly created path (a) and the several meters thick wood and debris deposit located in the run-out zone at the confluence with the Sâmbăta Valley (b)

still present in the Sâmbăta Valley at 1150 m. The avalanche also destroyed the forest road on the eastern side of the Sâmbăta Valley. In the same year, in March, the snow depth reached 2 m at 1400 m, and the Valea Sâmbetei chalet was closed for tourists due to closed trails and high risks of avalanches (https://www.monitorfg.ro/2021/03/23/cabana-valea-sambetei-acoperita-de-zapada/).

Conclusions

In the present paper, we reconstructed the activity of snow avalanches and rockfall at two sites located in the Sâmbăta Valley (Romanian Carpathians) using dendrogeomorphology. Regarding the snow avalanche reconstruction, the young age of the majority of the trees limits the timespan to 70 years. The results highlight 13 major avalanche events which occurred on the studied path in the period 1950-2020, with the highest dendrogeomorphic signal obtained for 1988, 1997 and 2012. The minimum return period of major events is 3.3 years, but most probably, weak to moderate avalanches can occur every year. This is a common limitation of the dendrogeomorphic method, due to the fact that tree-rings exhibit anatomical responses only if the respective tree is impacted by the avalanche. Therefore, it should be noted that the reconstructed frequency is valid only for major events. The rockfall reconstruction at site B highlights years with more intense process activity: 1952, 1955, 2003 and 2012. As falling rocks can leave trees unharmed in their downslope trajectory, some events are impossible to reconstruct by the tree-ring approach. On the other hand, downslope moving fragments can impact more than one tree, therefore altering the event reconstruction. Eventually, in the same respect, old and hidden scars are hard or impossible to identify and date.

Nevertheless, our study demonstrates that geomorphic hazards in the Sâmbăta Valley, a top-rated touristic destination for hikers and off-piste skiers, are remarkably active. The most recent event occurred in April 2021 on the valley's eastern slope. This giant snow avalanche created a new avalanche path by severely affecting the forest cover, indicating that if specific conditions and triggers are met, destructive and life-threatening events can also occur in areas with no signs of past disturbances. Regarding tourist exposure to geomorphic hazards, the main trail, which runs along the valley up to the Fereastra Mare saddle, is repeatedly crossed by avalanche couloirs and debris flow cones. Also, secondary trails, which climb the eastern slope (Piatra Caprei trail) and western slope (Arsenie Boca shelter), have sectors located beneath steep unconsolidated rock walls. Finally, tourists visiting the Sâmbăta Valley should be more effectively informed about the geomorphic hazards they are exposed to by installing warning signs for rockfall, snow avalanches and debris flows.

In future studies on geomorphic hazards related to snow avalanches, debris flows and rockfall, it is of utmost importance to identify and understand the complex topo-climatic factors responsible for triggering catastrophic events.

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