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Snow avalanche activity in the Țarcu Mountains, Southern Carpathians. Comparative analysis based on tree ring studies

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Abstract

Snow avalanches are a major natural hazard threatening human life and infrastructure in mountainous areas. They have a sudden onset and involve the rapid transport of large masses of snow and ice down on steep slopes. Thus, it is essential for risk management activities to understand avalanche activity, frequency and triggers. In this study, the dendrogeomorphic method was used to analyse an avalanche path in the Țarcu Mountains (the Southern Carpathians) in order to reconstruct the spatio-temporal activity of past snow avalanches. The reconstruction was based on the dating of growth disturbances caused by the mechanical impact of snow avalanches on trees. A total of 186 increment cores were analysed, resulting in the identification of 374 growth disturbances, including traumatic resin ducts, reaction wood, growth suppression and scars. In a chronology spanning 101 years in *Picea abies*, 13 events with I_t between 10-20% and 6 events with I_t between 20-40% were reconstructed over the period 1965-2021. The frequency of snow avalanche events was calculated, resulting in an average of 17.7 years. The climatic parameters were analysed for the event years exhibiting the strongest signal. The occurrence of avalanches was associated with warmer weather and rainy days. Event year 2010 is evidenced by a tragic incident in which two individuals lost their lives in the vicinity of the Țarcu weather station. Eleven events are synchronous with those analysed in other avalanche paths, while the event year 2005 is synchronous in nine other avalanche paths.

Keywords: *deondrogeomorphology, snow avalanches, the Southern Carpathians, Picea abies*

Introduction

Snow avalanches are a major natural hazard that occur on a large scale in mountainous areas where topo-climatic conditions favour their formation, posing a threat to human life and infrastructure (Chiroiu et al., 2024; Schweizer et al., 2003, 2021). Depending on the length and steepness of the slope, the moving masses of snow increase their volume, weight and destructive force downstream (Voiculescu, 2002, 2009). The necessity for an understanding of the evolution in time and space of extreme natural phenomena such as avalanches has arisen due to the increase in human casualties and property damage in recent decades. Avalanches occupy a central position among these phenomena, being the most destructive (Voiculescu, 2002).

Avalanche activity in high, isolated areas is not monitored or recorded in historical archives. However, environmental archives such as tree rings can provide important information on the frequency and magnitude of past avalanches. The dendrogeomorphological method has the advantage of annual dating of these phenomena, the possibility of calculating the spatiotemporal distribution and frequency of major events, leading to improved risk maps (Casteller et al., 2007; Corona et al. 2010, 2012; Decaulne et al., 2012; Germain et al, 2005, 2009: Schaerer, 1972; Rayback, 1998; Reardon et al., 2008; Voiculescu and Onaca, 2013, 2014; Šilhán and Tichavský, 2017). In the context of current tourism planning policies, which extend tourism activities and infrastructure to the slopes of the Carpathians (Pop et al., 2016; Voiculescu and Popescu, 2011; Voiculescu et al., 2023) it is essential to gain a deeper understanding of areas frequently affected by snow avalanches in order to prevent tourists and infrastructure from being exposed to the snow avalanche hazard.

Dendrogeomorphological studies have been conducted since the 1970s by Potter (1969), Schaerer (1972), Ives et al. (1976) and Carrara (1979). Dendrogeomorphological studies have received considerable attention in recent decades, and studies analysing avalanche activity have been carried out in various mountainous regions: in Canada (Boucher et al., 2003; Butler and Malanson, 1985; Butler et al., 2010; Germain et al., 2005, 2009; Reardon et al., 2008), in Chile and Argentina (Casteller et al. 2008, 2018), in Ohu Mountain, Japan (Kajimoto et al., 2004), in the Hymalayas (Laxton and Smith, 2009), in the Pyrenees (Muntán et al. (2004, 2009), in the Swiss Alps (Casteller et al., 2007; Favillier et al., 2017, 2018, 2023; Stoffel et al., 2006), or in the French Alps by Corona et al. (2010, 2012b), Mainieri et al. (2019, 2020) and Schläppy et al. (2013, 2014, 2016), in Iceland, Norway (Decaulne et al., 2012, 2014), Ukraine (Decaulne et al., 2023) or Turkey (Köse et al. (2010). In Romania, dendrogeomorphic studies on snow avalanches were conducted in the Bucegi Mountains (Voiculescu and Onaca, 2012, 2014), the Făgăraș Mountains (Voiculescu et al., 2011, 2013, 2016; Chiroiu et al., 2015, 2016, 2022, 2024), the Parâng Mountains (Decaulne et al., 2015; Germain et al., 2022; Meseșan et al., 2014, 2017, 2018; Pop et al., 2016; Todea et al., 2020), and the Piatra Craiului Mountains (Pop et al., 2017, 2018). Analyses of tree-ring-based snow avalanche activity were conducted in the Eastern Carpathians in the Maramureș Mountains by Pop et al. (2020) and in the Rodna Mountains by Gavrilă et al. (2022).

In Romania, several tree-ring-based studies have been conducted to provide insights into major historical snow avalanche years along forested paths in the Carpathians. A recent publication by Chiroiu et al. (2024) indicates that certain event years are synchronous in all mountain ranges. In this context, and given the lack of research in the western part of the region, the aim of this study was to improve the knowledge of the frequency and spatial distribution of past avalanche activity and to fill a gap in the knowledge of avalanche activity in the western extremity of the Southern Carpathians. The objectives of this study were *i)* to reconstruct the past activity of snow avalanches in the Țarcu Mountains, *ii)* to analyse the climatic triggers for major avalanche events and *iii)* to highlight the synchronicity of major events with those reconstructed in other mountain areas of the Southern Carpathians.

Study area

The study area is located in the Țarcu Mountains, in the vicinity of the Prislop peak. The area is situated in the northwestern sector of the Southern Carpathians (Fig.1).

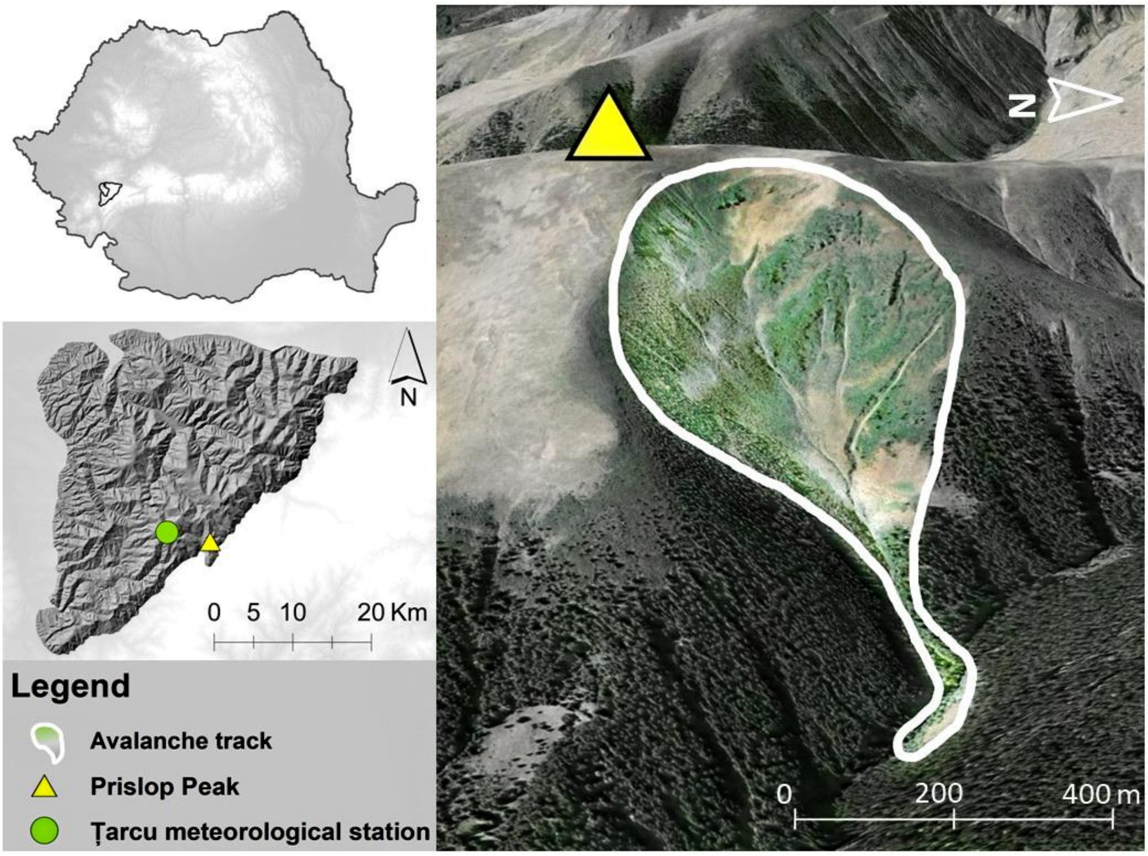

Figure 1: Location of the Țarcu Mountains and the analyzed avalanche path

From a geological perspective, the Țarcu Mountains are composed of granites, with crystalline schists and sedimentary rocks (including sandstones, tuffs, and conglomerates) surrounding them (Niculescu, 1966; Niculescu and Călin, 1990). The hard crystalline schists and gneisses comprise Țarcu Peak and Prislop Peak (Niculescu and Călin, 1990). Due to their position and altitude, the Țarcu Mountains have a dam role in the way of the air masses that enter both from the north and northwest, as well as from the south and southeast (Feher et al., 2021; Niculescu and Călin, 1990). The average annual air temperature is 0° C at the Țarcu Peak Weather station. From 1700-1800 m altitude the climate becomes harsher. The average annual temperature is below 2 °C (the average temperature of January drops below - 6 °C, and that of July is 11-12°C). In relation to the forest area, the temperatures are therefore lower, reaching their lowest values in February. The frost lasts approximately six months per year. In the alpine area of the Țarcu Mountains, over 50% of the total annual precipitation is in the form of solid precipitation, such as snow or frost. The duration of the snow layer is extended from the foot of the massif, with an average duration of approximately 150 days per year. The Țarcu Mountains exhibit a Dfb type climate, as defined by the Koeppen-Geiger climate classification (Kotek et al., 2006). This classification indicates a snowy climate with humid, warm summers and dry winters. However, the seasonal snow cover classes defined by Sturm et al (1995) suggest that the climate is alpine.

The avalanche path (PRI coded), is located on the eastern slope of the Prislop Peak. The highest point of the starting zone is situated at an altitude of 1950 m.a.s.l., while the run-out zone is located on the valley floor at 1500 m.a.s.l. Figure 2 illustrates the avalanche path and the location of the sampled trees.

Figure 2: The PRI avalanche path *(left)* and the position of the sampled trees *(right)*

The avalanche path has a general eastern orientation, and the slope surface delineated as a component of this path exhibits orientations towards the northeast and east-southeast. The slope orientation and slope values for the PRI path are presented in Figure 3. The slope values are between 15° and 45°, indicating that the area is conducive to the formation of avalanches. The steepest surfaces (> 35°) are specific to the upper part of the slope, as well as a discontinuity that is evident between 1700 and 1800 m. The lowest slope values are specific to the deposition area at the base of the path, where the slope decreases even below 10°.

The vegetation cover is found in typical altitudinal belts. Above an altitude of 2000 m a.s.l., the landscape is characterised by alpine meadows and bare rock surfaces. The slopes below the treeline, situated at an altitude of 1800-1850 m.a.s.l., are populated by the *Pinus mugo* and *Juniperus communis* species. The treeline is composed of Norway spruce (*Picea abies*) trees, which extend down to approximately 1500 m.a.s.l. Mixed forests composed of European beech (*Fagus sylvatica*) and Norway spruce appear at this altitude. The presence of typical snow avalanche disturbance paths within the forest cover indicates that major avalanches typically originate in the alpine or subalpine zones and subsequently develop downslope, resulting in the damage of the coniferous forest below.

The forest cover is composed of *Picea abies*, while within the transport zone of the avalanche path, pioneer species such as *Alnus viridis*, commonly known as green alder, can be found. The majority of trees that have colonised the path and its margins display evidence of typical damage caused by snow avalanches, including *J*-shaped stems, tilted and broken stems, impact scars, uprooting and apex loss.

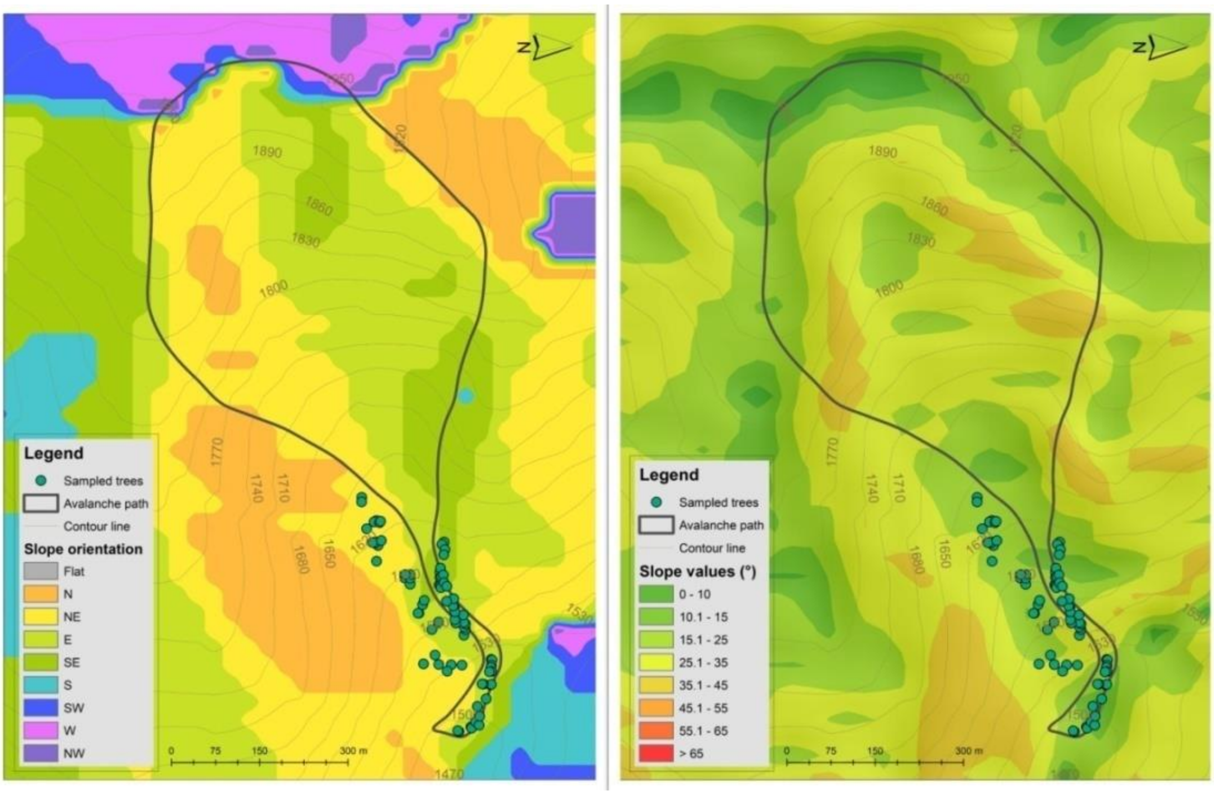

Figure 3: Slope orientation (*left*) and slope values of the analyzed path (*right*)

Material and methods

Field sampling strategy

The fieldwork was conducted during the summer of 2021. A total of 100 Norway Spruces were selected based on visual signs of snow avalanche impact, including tilted stems, broken trunks, scars, and uprooted trees (Alestalo, 1971; Stoffel et al., 2010) (Fig. 4).

Figure 4: Disturbed sampled trees in the PRI path

A strategy of systematic sampling of all affected trees, distributed randomly within the paths, was selected to ensure comprehensive documentation of past SA occurrences across different areas within the path. It is hypothesised that trees located along the path have experienced a greater number of avalanches in the past than those from the runout area. Consequently, they are expected to provide more detailed information regarding both the low and high frequency of avalanche activity (Johnson, 1987). Furthermore, different age classes were considered, as older trees can provide valuable information on earlier events, while younger individuals are more sensitive to avalanches occurring closer to the present day (Luckman, 2010). Two cores were extracted from each tree using a Pressler borer (diameter 0.5 cm, length 40 cm). One core was taken from the direction of the slope, and the other was taken perpendicular to it. Moreover, 20 unaffected trees were sampled near the study area but outside the affected area, to create a reference chronology. This chronology demonstrates the typical climate-driven growth variation of trees in the area, as evidenced by Cook and Kairiukstis (1990) and Schweingruber (1996). Aditional information about each tree was also recorded, including the height from which the sample was taken, the circumference of the trees, the type of disturbance. Finally, the spatial coordinates of each tree were recorded with a GPS Garmin 66sr for mapping the selected area.

Sample preparation and analysis

The increment cores were air dried and sanded with abrasive paper of different granulation (60 to 400), using a sanding belt machine, in order to improve the visibility of individual tree-rings. Every sample was then scanned at a resolution of 1200 dpi and tree rings were counted, dated and measured using CooRecorder (Larsson, 2013). Undisturbed samples were crossdated using CDendro (Larsson, 2013) and a reference chronology spanning the interval 1920 – 2020 was constructed. The reference chronology was then used to (*i*) crossdate the samples extracted from affected trees and to (*ii*) accurately distinguish between growth anomalies induced by snow avalanche events and the local stand growth conditions (Stoffel et al., 2006). Subsequently, samples exhibiting signs of disturbance were visually analyzed to identify and date specific snow avalanche-induced growth disturbances (referred to GDs hereafter). Reaction wood (RW) in response to stem tilting (Timell, 1986), growth suppression (GS) in response to stem breakage, uprooting, or apex loss (Kogelnig-Mayer et al., 2013), growth release (GR) as a consequence of eliminated competitors, formation of callus tissue (CT) in response to cambial damage (Stoffel and Corona, 2014) and formation of tangential rows of traumatic resin ducts (TRD) - Stoffel et al. 2006; Schneuwly et al., 2009). The intensity of each GDs was evaluated as weak, intermediate or strong in order to include them in one of the five intensity classes defined by Stoffel and Corona (2014), as follows:

- intensity 1: weak TRDs;
- intensity 2: weak RW, strong GR;
- intensity 3: moderate RW, moderate GS;
- intensity 4: moderate TRDs, strong RW, strong GS;
- intensity 5: SC, strong TRDs.

Event reconstruction and frequency analysis

Major snow avalanche events were reconstructed using Shroder's semi-quantitative I_t index (Shroder, 1980), which represents the ratio of the number of trees affected in a given year to the total number of trees available for analysis in that year. I_t is expressed as a percentage and calculated according to the following formula:

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

where R = responding trees to an event in year *t* and A = number of trees alive in year *t*

In the last decade, many tree-ring based approaches have focused on improving the methodology, aiming to optimize the signal-noise ratio in dendrogeomorphic reconstructions (Kogelnig-Mayer et al., 2011, Corona et al., 2012, Stoffel et al., 2013, Favillier et al., 2017, Peitzsch et al., 2021). Therefore, the present study relies on the state-of-the-art standards for identification of snow avalanche events, by using flexible GD and I_t thresholds, which vary depending on the sample size available for each year of the reconstructed period. As the sample size becomes larger, the GD threshold increases, while the I_t threshold gets lower:

- for sample size lower than 10 trees: reconstruction not reliable.
- for sample size of 10-20 trees: event if GD ≥ 3 and $I_t \geq$ 15%.
- for sample size of 21-50 trees: event if GD ≥ 5 and $I_t \geq$ 10%.
- for sample size higher than 50 trees: event if GD ≥ 7 and $I_t \geq$ 7%.

Subsequently, based on the five GD intensity classes we computed the weighted index factor W_{it} (Kogelnig-Mayer, 2011), which takes into account with a single value, the number of responding trees and the intensity of each reaction. In this approach, in order to minimize the noise that could be added to the reconstruction, we exclude the GD assigned to intensity class 1, because weak TRD could appear as a response to various exogenous factors. The W_{it} index is calculated using the following formula:

$$W_{it} = \frac{\left[\left(\sum_{i=1}^{n} T_i * 7\right) + \left(\sum_{i=1}^{n} T_s * 5\right) + \left(\sum_{i=1}^{n} T_m * 3\right) + \left(\sum_{i=1}^{n} T_w * 1\right)\right]}{\sum_{i=1}^{n} A_t}$$

where, Ti – sum of intensity class 5 GDs; Ts – sum of intensity class 4 GDs; Tm – sum of intensity class 3 GDs; Tw – sum of intensity class 2 GDs, and A - the total number of trees alive in year t.

According to Favillier et al. (2017) the use of the W_{it} index assigns different levels of confidence to snow avalanche events reconstructed by the above described It index approach. In this respect, we applied the following suggested W_{it} thresholds:

- low confidence: $W_{it} < 0.2$
- medium confidence: $0.3 > W_{it} \geq 0.2$
- high confidence: $W_{it} \geq 0.3$

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., 2018). 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. The limited number of trees available for older periods will influence the quality of the reconstructed frequency (Corona et al., 2010).

In this study, the 1920-1970 interval is characterised by a small sample size (max. 15 trees) and no event was reliably reconstructed. Therefore, the return period was only calculated for the last 50 years (1970 - 2020). Considering that the sample size reaches its maximum after the year 2000 (83 trees), the return period for the last 20 years was also calculated, which probably best reflects the current frequency of avalanches in the analysed path.

Comparative analysis of tree-ring based snow avalanche reconstructions in the Southern Carpathians

Several dendrogeomorphological studies have been carried out with the aim of reconstructing past avalanche events in the Southern Carpathians. The events identified in each path were collated in order to observe synchronous events with those reconstructed in the present study. In order to ensure consistency with the methodology used in the aforementioned previous studies, the comparative analysis presented here uses the reconstruction with fixed It thresholds (Fig. 10 in the Discussions section). The most commonly used thresholds were 10%-20% and 20%-40%. Consequently, all reconstructed events were divided into these two classes.

Results

Tree-age structure and growth disturbances

For various reasons (i.e. degraded samples, unreadable samples, failed cross-dating) only 83 of the total 100 sampled trees were included in the present analysis. As shown in Figure 5, most of the trees analysed (84%) had less than 50 annual rings, indicating the young age of the sample population.

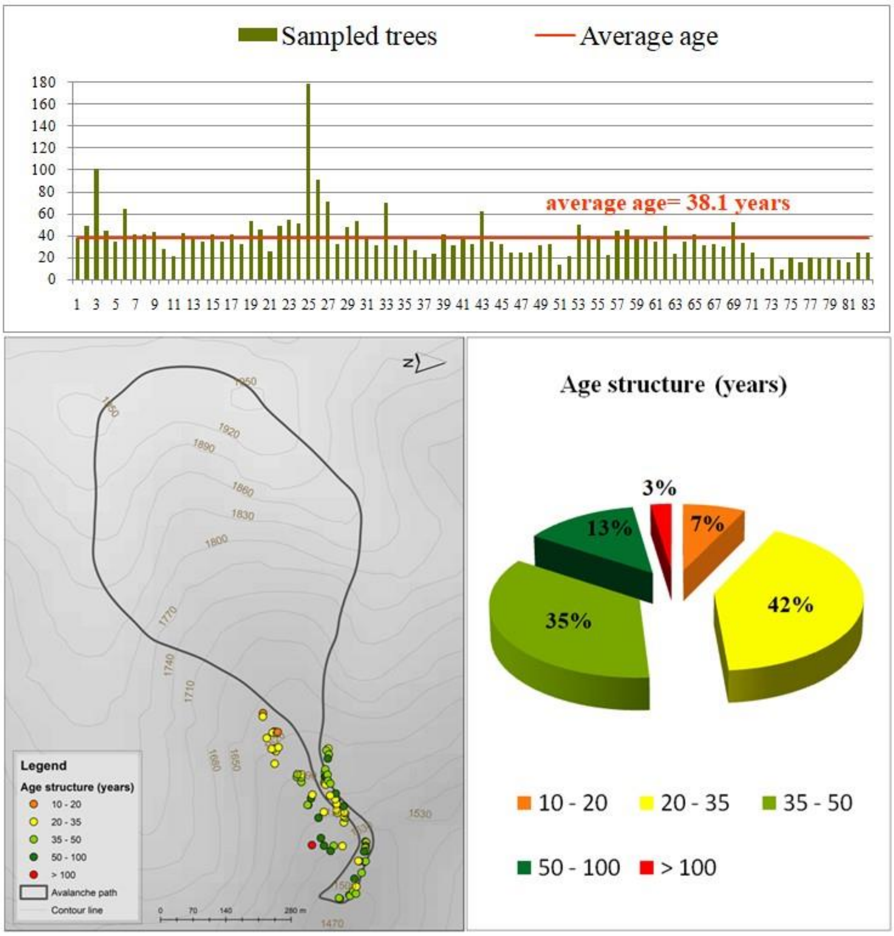

Figure 5: Relative age of individual trees (above); spatial distribution (left) and percentage (right) of different age classes

The average age of the sampled trees is 38.1 years. The youngest tree analysed formed 9 annual rings, while the oldest tree had a total of 179 annual rings. The youngest trees are situated in the upper part of the path and within the avalanche path, while older trees are typically found outside the path (Fig. 5).

A number of 370 GDs were identified in 166 crement cores. The identified GDs were reaction wood (RW), growth suppression (GS), traumatic resin ducts (TRD) and growth release (GR) (Table 1). Most of the reactions were GS (38.1 %), followed by TRD (30.5 %) and RW (27 %).

Table 1: Total number of GDs by type and intensity

GD type	**Intensity class**					**TOTAL**	**%**
	1	2	3	4	5		
RW	-	25	33	42	-	100	27.0 %
GS	-	27	70	44	-	141	38.1 %
GR	-	15	1	-	-	16	4.3 %
TRD	-	-	-	80	33	113	30.5 %
TOTAL	0	67	104	166	33	370	
%	0.0 %	18.1 %	28.1 %	44.9 %	8.9 %		

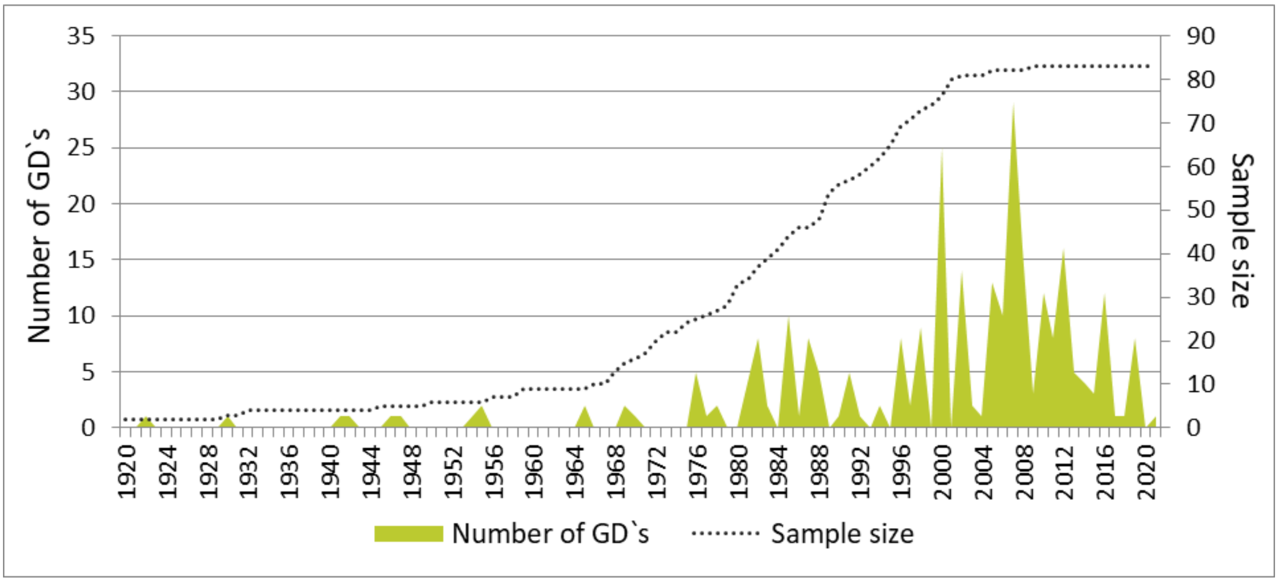

Figure 6: Total number of growth disturbances and sample size for PRI path

A small number of GR (4.3 %) were also dated. Almost half of the GDs were classified as intensity class 4 and almost 1/3 were moderate reactions (intensity 3). This indicates a strong impact of avalanches on normal tree growth, but the relatively young age of the sampled trees could be the reason for this high amount of above average reaction intensity.

The total number of GDs identified for each year of the reconstructed chronology (1920-2020) is shown in Figure 6. Throughout the analysed interval, the highest number of GDs was found in 2000 (n= 25), 2007 (n= 29) and 2012 (n= 16).

Snow avalanche reconstruction and frequency

A number of 18 years with I_t values exceeding both GD and It minimum thresholds were reconstructed. Prior to 1970 (as illustrated by the grey lines in Fig. 7), there was insufficient data to evaluate avalanche events due to the relatively small sample size (less than 10 trees) and the low number of identified GDs. Therefore, the chronology covers a period of 50 years (1970 - 2020) and reconstructs 18 avalanche events (the red lines) in: 1976, 1982, 1985, 1987, 1988, 1996, 1998, 2000, 2002, 2005, 2006, 2007, 2008, 2010, 2011, 2012, 2016 and 2019. In the case of 1965 and 1981, the I_t threshold is reached but not the GD threshold. Consequently, these two years have been excluded from the reconstruction. The event year 2007 recorded the highest number of affected trees (n= 29) and the highest value of the I_t index (35.4 %).

Based on the GD intensity computed with the W_{it} index, the majority of reconstructed events exhibited a high level of confidence (Fig. 8), with the exception of the years 1996, 2006 and 2010, which exhibited a moderate confidence level. Table 2 provides detailed information about I_t, W_{it} and intensity classes for each event year.

The return period (frequency-1) of snow avalanches in the analysed path is 4.2 years for the interval between 1970-2020. This indicates that a major event is most probably to occur once in 4-5 years. Nevertheless, when the last 20 years (2000–2022) are analysed separately, the return interval shrinks to 1.8 years.

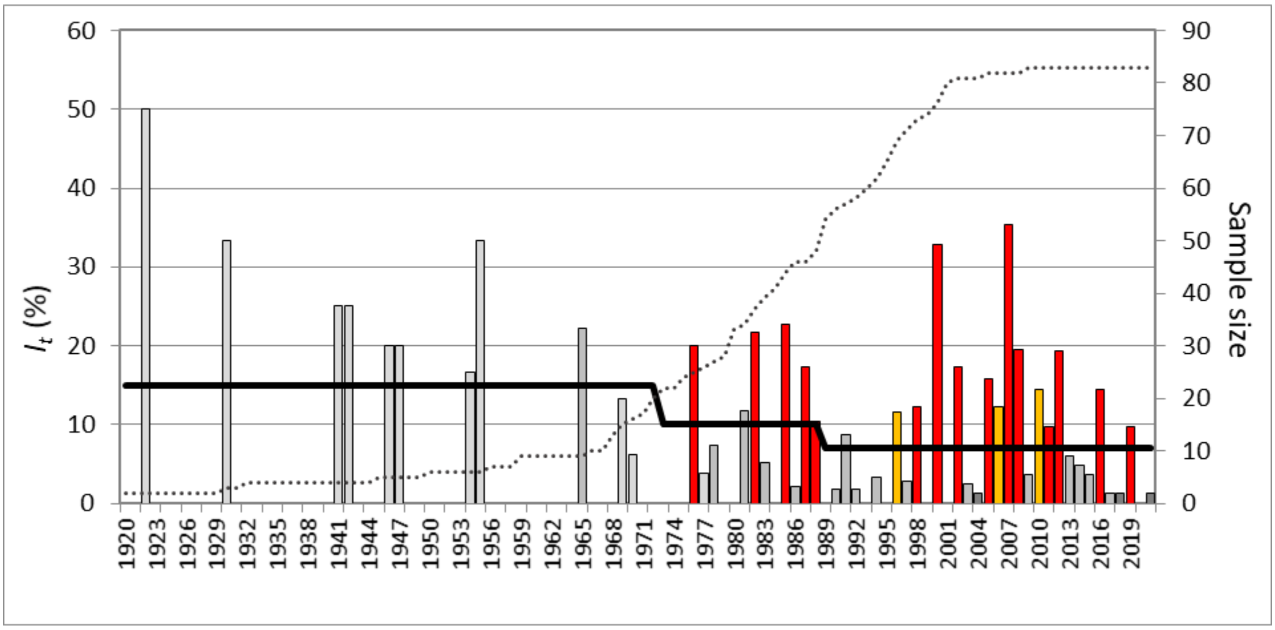

Figure 7: Identified snow avalanche events (based on the I_t index). High confidence events are marked with red, while moderate confidence events are marked with yellow. The solid line represents the I_t threshold and the dotted line shows the sample size

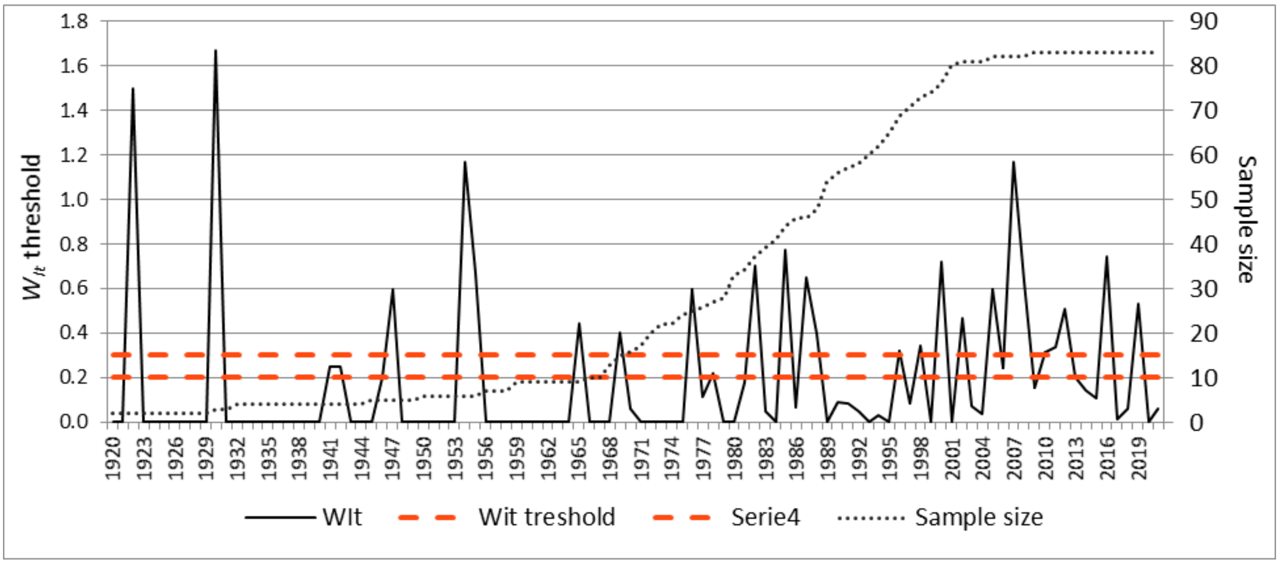

Figure 8: Confidence level (based on the Wit index)

Based on the frequency calculations, we determined the individual frequency of GD`s for each tree, the minimum value being 4.7 years, the maximum value is 89.0 and the average return period is 17.7 years. Table 3 shows that the return period in Țarcu Mountains is similar to those in other analyzed avalanche paths in the Southern Carpathians.

Figure 9a shows the avalanche return interval calculated for each tree. Overall, the map provides an overview of the areas with higher/lower frequency of reconstructed events.

Table 2: I_t and W_{it} and intensity classes for each event year

Event year	Sample depth	Intensity classes				I_t (%)	W_{it} (%)
		2	3	4	5		
1969	15	1		1		13.3	0.8
1976	25	1	3	1		20.0	3.0
1981	34	3	1			11.8	1.2
1982	37	2	3	3		21.6	5.6
1985	44	2	4	4		22.7	7.3
1987	46	1	3	4		17.4	5.0
1996	69	2	5	1		11.6	2.7
1998	73	2	6	1		12.3	3.2
2000	76	8	8	5	1	28.9	18.8
2002	81	5	2	7		17.3	8.1
2005	82	4	6	10		24.4	16.1
2006	82	7	1	2		12.2	3.0
2007	82	7	6	15	1	35.4	35.4
2008	82	5	6	3	2	19.5	10.5
2010	83	7	3	2		14.5	4.8
2012	83	7	5	4		19.3	9.6
2016	83			11	1	14.5	7.2

Table 3: Return period calculated for mountain ranges in Southern Carpathians

Path/localization	Return period (years)
PRI/Țarcu	**17,1**
BLCS1/Făgăraş	14,9
BLCS2/Făgăraş	13
BLCS3/Făgăraş	15,4
BLCS4/Făgăraş	15,9
CARP/Bucegi	15,2
PAR/Bucegi	13,7
TAR/Bucegi	13,1

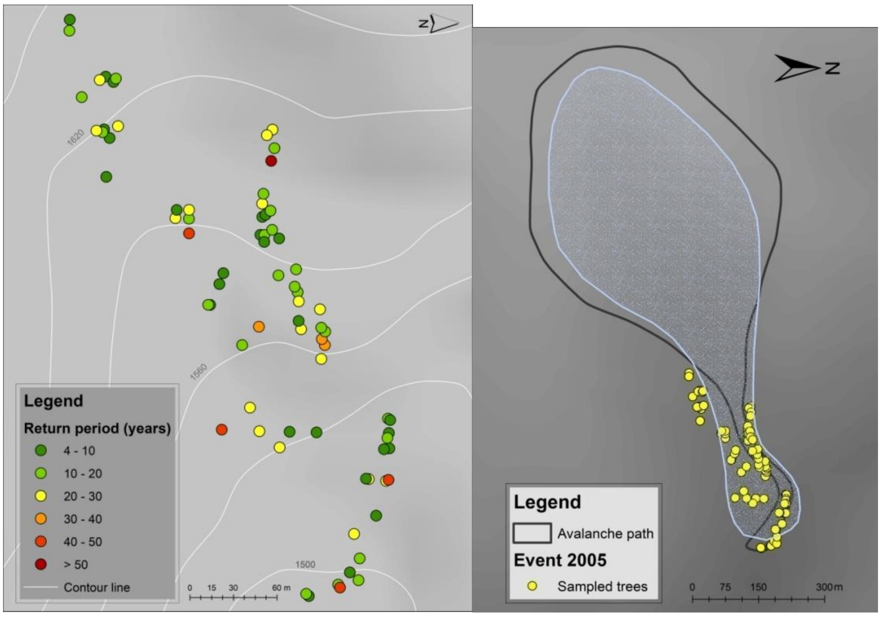

Figure 9: Return period calculated for each tree *(a)* and the spatial extent of 2005 snow avalanche event *(b)*

The avalanche return index values were used to create six distinct classes. Areas with a high frequency of events are concentrated both in the middle of the path and on its edges. However, as the edges of the path are approached, the frequency of events decreases.

One of the most significant avalanche events in recent history occurred in 2005 in all of the avalanche paths in the Southern Carpathians that were analysed (Voiculescu and Onaca, 2012, 2014; Voiculescu et al., 2013; Chiroiu et al., 2015, 2024; Pop et al., 2016; Pop et al., 2017; Todea et al., 2020). In order to gain further insight into this phenomenon, this event year was also reconstructed and analyzed in the present study area. The affected trees are distributed throughout the area, both in the central part of the path and in the marginal parts, with the greatest extent of damage occurring in the latter (Figure 9b). However, it is observed that a number of trees located in the upper-left part of the corridor do not seem to be affected by the event with an impressive spatial development. The explanation could be given by the very young age of the trees in the northern part, which may not have had an optimal sensitivity, being covered by snow when the avalanche started. Another hypothesis is related to the possibility of the existence of several main snow flows, and that the respective trees were outside their range.

Comparative analysis of tree-ring based snow avalanche reconstructions in the Southern Carpathians

Over the past decade, numerous tree-ring based studies have been conducted to analyse past occurrences of snow avalanches in mountain ranges within of the Southern Carpathians, including Bucegi, Piatra Craiului, Făgăraș, Șureanu and Parâng Mountains.

A comparative analysis of the data revealed that 14 events reconstructed for the PRI path in the Țarcu Mountains were also identified in other mountain ranges. The snow avalanches that occurred in 2005 appear to be the most spatially widespread events, with 19 avalanche paths exhibiting a major event in that year. The majority of reconstructed events in 2005 exhibited high values of the I_t index (20%–40%) and were identified in all of the investigated mountain ranges. Furthermore, the avalanches that occurred in 1987 were also reconstructed in the Făgăraș, Piatra Craiului, and in Parâng Mountains, while in 1988 there was intense snow avalanche activity in the Făgăraș and Bucegi mountains.

Discussion

Snow avalanche activity was analysed on the basis of tree-ring analysis in an avalanche path in the Țarcu Mountains, Southern Carpathians. The chronology relies on the latest methodological standards in dendrogeomorphology and reconstructed a total number of 18 events in a 50-year long series (1970-2020).

The age of the trees analysed is generally underestimated, mainly because of the sampling height, but also because of the lack of pith in many of the samples. Nevertheless, the length of the reconstruction is limited by the young age of the trees growing in the study area, with sample sizes falling below 10 trees for the period before 1970. At the same time, the age of the trees has an important influence on the calculation of the W_{it} index. For the same event, younger trees show stronger reactions than older individuals. Therefore, the values obtained for the W_{it} index could be overestimated by the young age of the trees. However, in this study the W_{it} index was only used to assess the confidence level of the detected events and does not affect the overall chronology.

Regarding the uncertainties caused by the number of trees sampled, we consider that they are reduced because in this study we used 83 trees, a representative number if we consider the recommendations of Hebertson and Jenkins (2003), who suggested a minimum threshold of sampling 20 trees. Regarding the minimum threshold of 10% considered to distinguish avalanches from other events that may be the result of different disturbances, this has been accepted in other similar studies (Decaulne et al., 2012).

Comparative analysis and the use of flexible vs. non-fexible thresholds

The I_t values for the decades 1980-1990 and 2000-2010 are higher than those for the decades 1990-2000 and 2010-2020. This may indicate a higher incidence of snow avalanches in the 1980s and the first decade of the 21st century, in comparison to the 1990s and the last decade.

From a methodological point of view, tree-ring based snow avalanche reconstructions have evolved since the first approaches in the 1970s. Indices have been developed (Shroder, 1980, Kogelnig-Mayer et al., 2011), optimal sample sizes have been proposed (Corona et al., 2010) and flexible index thresholds have been implemented (Corona et al., 2012). As mentioned in the Materials and Methods section, the present paper uses state-of-the-art standards in tree-ring based avalanche reconstructions, but this is not the case for all previous studies in the Carpathians. Therefore, for a relevant comparative analysis and to be consistent with other studies in the Southern Carpathians, we have also constructed an avalanche chronology based on non-flexible I_t thresholds of 10% and 20%, as most commonly used in previous studies in the Southern Carpathians. The resulting chronology (Fig. 10) identifies five events that exceed the 20% threshold. The subsequent years were identified as exceeding the 20% threshold: 1965, 1982, 1985, 2000 and 2007. Concurrently, 14 years exhibited I_t values between 10% and 20%.

In comparison to the initial reconstruction, the chronology includes additional events (1965, 1969 and 1981) that were initially excluded due to insufficient sample size and limited number of GDs. On the other hand, the fixed 10% threshold approach underestimates avalanches in 2011 and 2019. In the study by Voiculescu and Onaca (2014), avalanches exceeding the 20% threshold were considered major events. Therefore, considering both the flexible and the fixed thresholds, it can be assumed that there are at least four event years with high-magnitude avalanches in the studied path: 1982, 1985, 2000 and 2007.

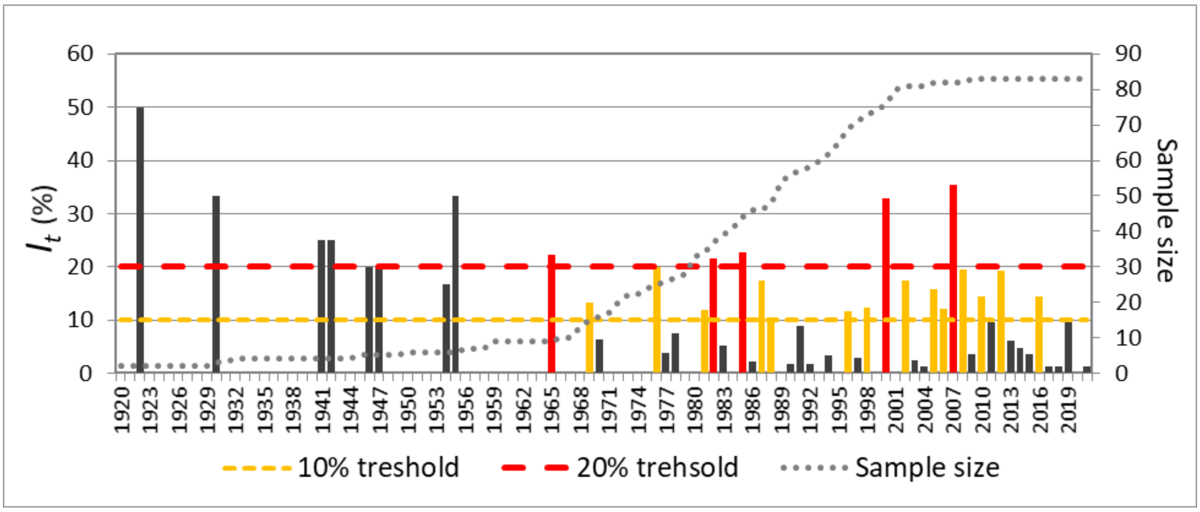

Figure 10: The reconstructed events based on fixed thresholds: above 10% - yellow bars and above 20% - red bars

The return period values are higher than those obtained by Corona et al. (2010) in the French Alps (2.5-12 years), smaller than those obtained by Corona et al. (2007) in the Swiss Alps (slightly over 20 years) and similar to those obtained by Decaulne et al. (2012) in Northern Iceland (15-20 years). The spatial extent reconstruction of the 2005 event ($I_t > 30\%$) exhibits a remarkable extension, comparable to those observed in other study cases in the Southern Carpathians.

Synchronous events in the Southern Carpathians

The tree-ring based literature on snow avalanche reconstructions in the Southern Carpathians is still spatially unbalanced, as all previous studies have focused on the central and eastern parts of this mountain range. We therefore decided to conduct our study in the westernmost part of the Southern Carpathians and compare our results with those obtained in other locations. The comparative analysis revealed synchronous events in the different mountain ranges, suggesting a common behaviour induced by climatic controls.

With regard to the synchronicity of avalanches, there is a common regime of their manifestation in the Southern Carpathians. A limited number of studies analysing several avalanche paths simultaneously can be found in the dendrogeomorphological literature (Muntán et al., 2009; Germain et al., 2009). Consequently, there are few references to avalanche synchronicity extracted by dendrogeomorphological techniques. However, the study of Chiroiu et al. (2024) addresses this gap in knowledge for the Southern Carpathians.

A total of 33 avalanche paths have been analysed in the Southern Carpathians. The study of our avalanche path and its comparison with other paths in the Southern Carpathians revealed 11 synchronous events in: 1985, 1987, 1988, 1998, 2000, 2005, 2006, 2007, 2008, 2010, 2016. The event year 2005 is synchronous with 19 other paths. The event years 1988 and 2005 in our chronology were also identified in all valleys in the Făgăraș Mountains analysed by Chiroiu et al. (2024), as well as in the Parâng Mountains (Meseșan et al., 2018) and the Bucegi Mountains (Voiculescu and Onaca, 2014). The event year 2007, which exhibits the highest I_t values in our chronology, is synchronous with those obtained by Pop et al. (2018, 2017a) in the Șureanu and Parâng Mountains. Additionally, the year 2000 is identified as an event year in the Parâng Mountains (Meseșan et al., 2018), the Șureanu Mountains (Pop et al., 2017a) and the Piatra Craiului Mountains (Pop et al., 2018). This synchronicity suggests their natural onset as a result of reaching certain critical thresholds of meteorological parameters.

Climatic triggers in event years

The analysis of climatic aspects and the identification of possible triggers is a key element in understanding the snow avalanche regime in a given area. The microstructural properties of the snow layer depend on the variation of climatic parameters such as precipitation, temperature and wind speed during a cold season. However, avalanche activity is usually controlled by short-term variations (24-72 hours) of these parameters (Eckerstorfer and Christiansen, 2011). The annual duration and thickness of snow cover is currently changing due to the effects of global warming (Vaughan et al., 2013). In mountainous areas, this warming also corresponds to changes in avalanche activity (Eckert et al, 2013, 2024).

The chronology of avalanches in the Carpathians indicates that there have been frequent years with large avalanches in the last 50 years, but there are still uncertainties about the climatic controls. In order to describe the climatic conditions in the winter of 2004-2005, we use daily precipitation, temperature and snow cover data from the meteorological station Țarcu Peak, located at 2180 m a.s.l..

In order to capture the climatic conditions in the study area during the winter season of 2009-2010, as well as those of the event years with the highest I_t values (2000, 2005 and 2007), meteorological data from the Țarcu Peak meteorological station, situated at an altitude of 2180 m a.s.l., were analyzed. Figure 11 illustrates the daily precipitation, temperature and snow thickness values recorded between December 2009 and April 2010. The data is presented in the following format: P (precipitation), T (temperatures) and S (snow thickness).

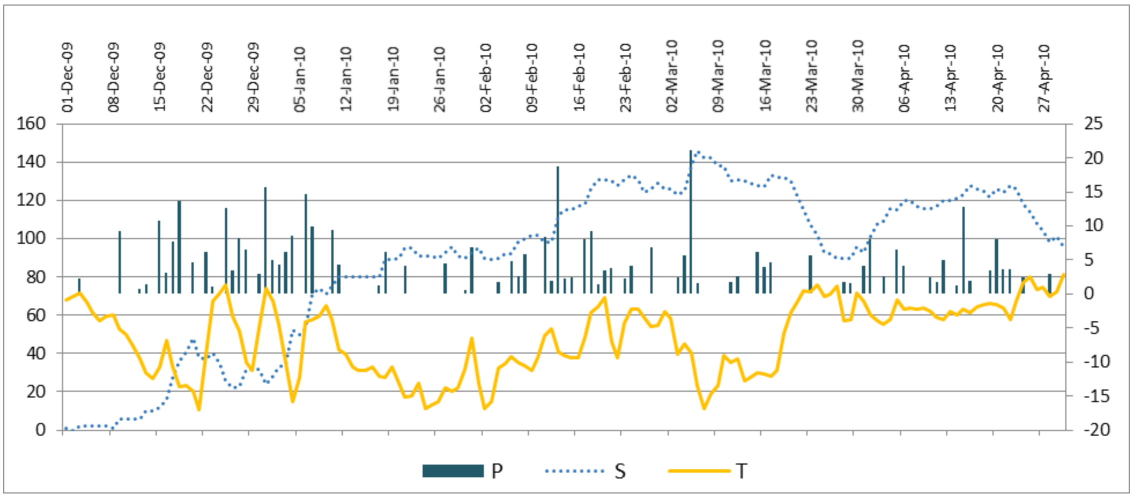

Figure 11: Daily data of precipitation, temperature and snow thickness for event year 2010 between December 2009- April 2010

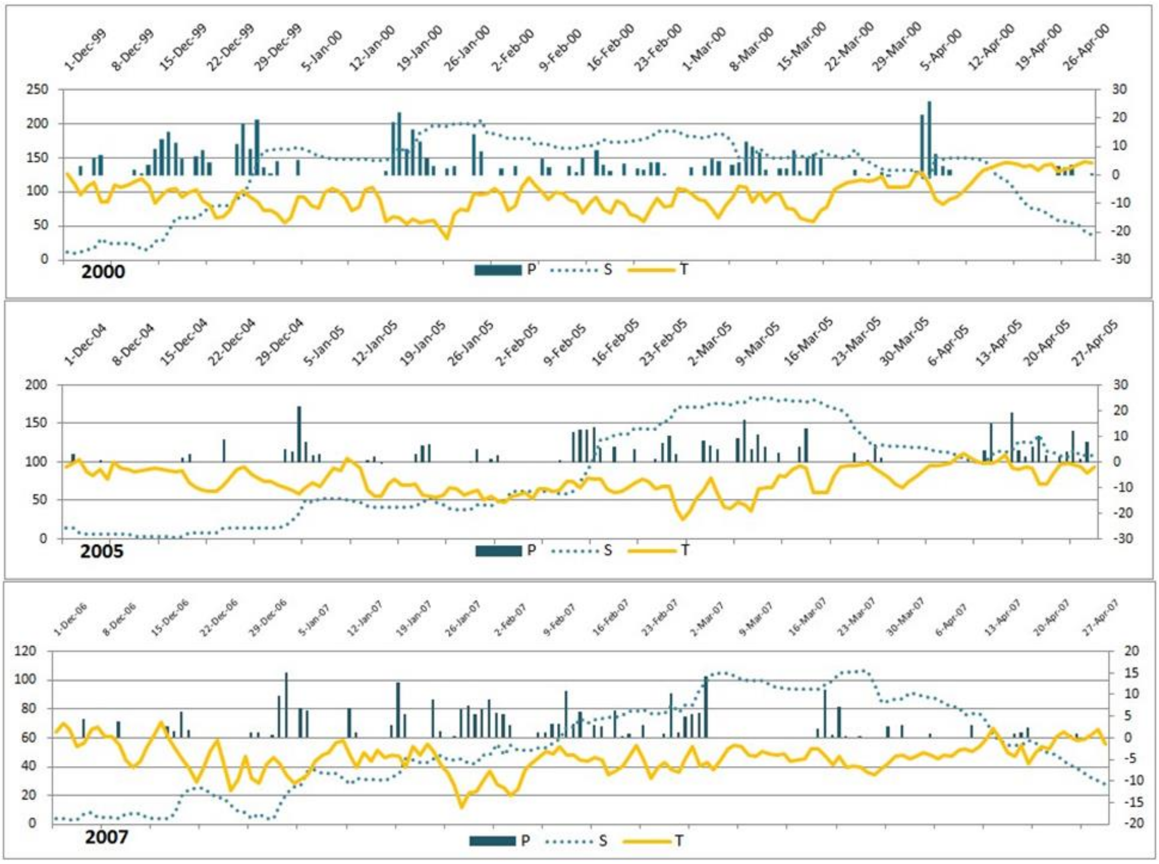

Figure 12: Daily data of precipitation, temperature and snow thickness for event years 2000, 2005 and 2007 between December- April

From mid-December onwards, precipitation was observed on a near-daily basis, with an average of 80–120 mm. The temperatures were notably high, with positive values recorded on a few days, as reported by mountain rescue personnel and other individuals. In such conditions, the probability of avalanches is considerable. The aforementioned parameters were also analyzed for the event years, presented in Figure 12.

In the 2000 event year, the month of December was characterised by a rainy period and high temperatures. Similarly, the meteorological conditions were conducive to precipitation and higher temperatures in April. In 2005, a period of precipitation and higher temperatures was observed from the middle of February to the middle of March. This was followed by a warmer period with higher precipitation in April. In February 2007, a period of high temperatures and precipitation was observed, particularly at the beginning of March, when precipitation exceeded 70 mm and temperatures were close to 0°C. The aforementioned data allows us to hypothesise that the common factor in years where snow avalanches occurred is the combination of heavy rainfall (for several days) and higher temperatures.

Conclusions

In this study, the dendrogeomorphic approach was employed for the spatiotemporal reconstruction of snow avalanche activity in a remote avalanche path situated in the Țarcu Mountains, at the western extremity of the Southern Carpathians. The analysis was based on the identification of growth disturbances in tree-rings of 83 Norway Spruces (*Picea abies*). The reconstruction is limited to a period of 50 years (1970-2020), primarily due to the relatively young age of the trees. However, it also highlights 18 years with major avalanche events. The average return period of major events is 4.2 years for the 1970-2020 interval. However, if the interval is reduced to the last 20 years, where the sample depth is at its maximum, the return period will also decrease to 1.8 years.

The lack of archival records of snow avalanches for most of the Southern Carpathians requires the analysis of proxy data such as tree rings. During the last decade several studies have been carried out in different areas, but a complete picture is still lacking. The present study aimed to fill a gap in the spatial distribution of tree-ring reconstructions in the Southern Carpathians and at the same time to compare the results of previous studies. The analysis outlined the synchronous behaviour of avalanches in different areas of the Southern Carpathians, pointing to common climatic conditions and triggers that remain to be deciphered. In 2005, large snow avalanches were widespread on all analysed mountain ranges in the Southern Carpathians. The present analysis indicates that the conditions for avalanches in the Țarcu Mountains are optimal in late April. These conditions include a constant snow cover, several days with positive temperatures, and rain-on-snow episodes, which are triggering conditions to wet spring avalanches. However, a more comprehensive climatic analysis of large synoptic conditions is necessary to fully understand the snow avalanche regime in the Southern Carpathians.

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Author contribution

Conceptualization: R.F., M.V., C.P.; methodology: R.F., M.V., C.P.; writing – original draft, R.F, M.V., C.P., A.P. All authors have read and agreed to the published version of the paper.

Conflicts of interest

The authors declare no conflict of interest.

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