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Research paper

Testing dendrogeomorphic approaches and thresholds to reconstruct snow avalanche activity in the Făgăraş Mountains (Romanian Carpathians)

Patrick Chiroiu [a,*], Markus Stoffel [b,c], Alexandru Onaca [a], Petru Urdea [a]

[a] Department of Geography, West University of Timişoara, Str. V. Pârvan nr.4, 300223 Timişoara, Romania
[b] Dendrolab.ch, Institute of Geological Sciences, University of Berne, Baltzerstrasse 1+3, CH-3012 Berne, Switzerland
[c] Institute for Environmental Sciences, University of Geneva, 7 route de Drize, CH-1227 Carouge-Geneva, Switzerland

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ABSTRACT

Snow avalanches are a widespread natural phenomenon in steep mountain environments, where they modulate landscapes and frequently disturb forest stands. Such disturbances in trees have been used since the 1970s to retrospectively date avalanches, study their extent and reach, as well as to document their triggers. Although virtually every dendrogeomorphic paper is still based on the concepts established by Shroder (1978), important methodological improvements have been achieved in the field ever since and more particularly over the last decade. This study therefore reports on recent methodological progress and employs three different approaches (i.e. *Shroder* index value and *Kogelnig-Mayer* weighted index value) and different sets of signals in trees (i.e. inclusion of tangential rows of traumatic resin ducts as evidence of past avalanching) to record snow avalanche activity. Using 238 increment cores from 105 *Picea abies* (L.) Karst trees which colonize a snow avalanche path in the Romanian Carpathians, we illustrate possibilities and limitations of the different approaches for the period covered by the chronologies (1852–2013). In addition, we sampled 30 undisturbed *P. abies* trees from a forest stand north of the avalanche path, where no geomorphic disturbance was identified, so as to build a reference tree-ring chronology. The three avalanche chronologies constructed with the disturbed trees allow identification of past process activity, but results differ quite considerably in terms of avalanche frequency, number of reconstructed events and their temporal distribution. Depending on the approach used, 15 to 20 snow avalanches can be reconstructed, with the best results being obtained in the dataset including tangential rows of traumatic resin ducts. The addition of this anatomical feature, formed after mechanical impact enlarges the number of growth disturbances by 43.5%, and can thus explain the increase of reconstructed avalanches by one-third as compared to the results of the chronology using the "conventional" *Shroder* approach.

1. Introduction

Snow avalanches are among the most frequent slope processes in mountain environments (Luckman, 1977; Eckerstorfer et al., 2013). When occurring in populated areas, they represent a major threat to human lives and property, calling for hazard mitigation and risk management measures, including their artificial release (Weir, 2002). By contrast, in isolated regions, avalanches are exclusively driven by natural triggers and develop typical spatio-temporal patterns, thereby offering ideal conditions to study the process under natural conditions.

In forested avalanche paths, trees have been demonstrated to be precise recorders of past geomorphic activity, thus the occurrence and characteristics of past events can be deciphered using dendrogeomorphology (Alestalo, 1971; Shroder, 1978). Dendrogeomorphic techniques are based on the fact that trees will provide evidence of past disturbance in their growth ring record (process-event-response; Shroder, 1978). Tree-ring studies have been applied widely for the reconstruction of avalanche chronologies (Casteller et al., 2011; Corona et al., 2012a), to assess their frequency (Reardon et al., 2008) and magnitude (Butler and

* Corresponding author.
E-mail address: p.chiroiu@gmail.com (P. Chiroiu).

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Malanson, 1985; Dubé et al., 2004; Schläppy et al., 2014), as well as the spatial extent of past events (Stoffel et al., 2006; Corona et al., 2010). At the same time, tree-ring based reconstructions of snow avalanches have also served the study of relationships between snow avalanches and climate variables (Germain et al., 2009; Muntan et al., 2009; Schläppy et al., in press). Although virtually every dendrogeomorphic paper is still based on the seminal papers and techniques established by Shroder (1978, 1980), important methodological improvements have been achieved in the field ever since and more particularly over the last decade (Reardon et al., 2008; Germain et al., 2009; Kogelnig-Mayer et al., 2011; Corona et al., 2012b; Schläppy et al., 2013). Recently, the lack of agreement among researchers upon minimum sample size and minimum responding trees (discussed by Butler and Sawyer, 2008), as well as the assessment of different response intensity classes (Germain et al., 2009; Casteller et al., 2011; Kogelnig-Mayer et al., 2011), have urged the need for setting clear guidelines and standards in dendrogeomorphic applications. In this respect, the questions of optimal sample depths, minimum numbers of responding trees and index value thresholds have been tested statistically and new standards have been suggested (Corona et al., 2012b, 2014; Stoffel et al., 2013). Likewise, Kogelnig-Mayer et al. (2011) have developed a response intensity weighted index, whereas Stoffel and Corona (2014) have proposed a standard method for all geomorphic processes to classify growth reactions in trees according to their intensity. Improvements have also been made regarding the identification of new growth disturbances in tree-rings (in addition to those widely utilized since the 1970s, such as injuries, reaction wood, abrupt growth changes). This is the case for tangential rows of traumatic resin ducts (Stoffel, 2008), which provide accurate information on the timing of events and offer the possibility of differentiating between several geomorphic processes occurring at the same study site (Stoffel et al., 2006; Stoffel and Hitz, 2008; Szymczak et al., 2010).

Despite the continuous improvements made in dendrogeomorphic techniques, the Shroder approach (referred hereafter as ‘conventional approach’) still represents the backbone of every tree-ring study (Butler and Stoffel, 2013). The latest standards developed in the field, however, aim at increasing the confidence of dendrogeomorphic results and at optimizing cost and benefit in fieldwork and laboratory analyses. One might thus ask the question what the differences are between results of ‘modern’ as compared to ‘conventional’ approaches.

The present study, undertaken on an avalanche path located in a remote area of the Romanian Carpathians, wants to address these research questions by comparing the results of the ‘conventional’ approach towards the outcomes obtained by using the latest developments in the field of dendrogeomorphology. At the same time, a secondary and implicit objective of this paper is the reconstruction of spatio-temporal patterns of snow avalanches that occur on the investigated path.

2. Study site

The avalanche path (45°36′59″N, 24°36′25″E) investigated here is located on an east-facing slope in the Arpaş Valley, Făgăraş Mountains (Southern Carpathians). The Făgăraş Mountains are the highest part of the Romanian Carpathians with 8 peaks over 2500 m asl and clear evidence of Quaternary glaciations and contemporary periglacial processes. The Arpaş Valley is a north-south oriented valley located in the central part of the Făgăraş Mountains (see Fig. 1 for details), and largely void of human activities. Specific landforms, deposits and vegetation features witness the recent activity of geomorphic slope processes such as snow avalanches, debris flows and rockfall. The geological setting consists of easily weathered foliated crystalline schists (phillites and micaschists), gneisses and amphibolitic schists, as well as limestone intrusions.

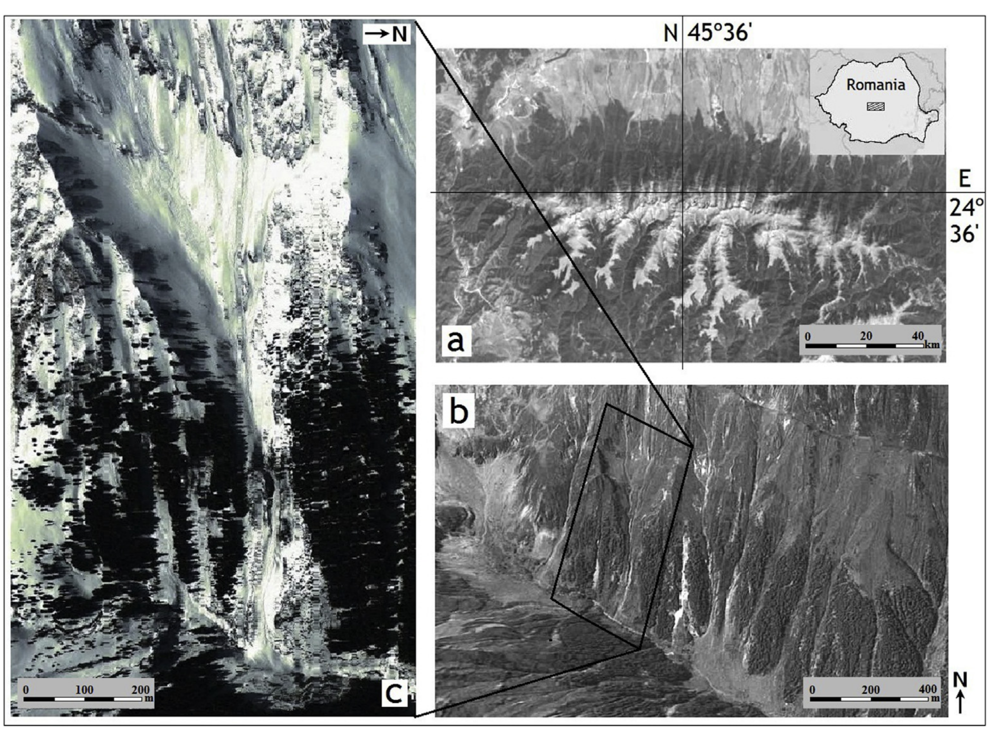


Fig. 1. Location of the study area: (a) Făgăraş Mountains (Southern Carpathians, Romania) (b) Arpaş Valley (c) MP Avalanche Path (source: Google Earth, 2012).

According to the climatic data from the nearby Bâlea meteorological station (45°36′17″N, 24°37′01″E, 2038 m asl, period 1979–2007), mean annual temperature is 0.4 °C and the average number of winter days (max. temp. ≤ 0 °C) is 119.5. Snowfall is possible during the whole year but significant amounts of snow, a prerequisite for snow avalanche occurrence, appear mainly between November and April. The mean number of days with snow cover is 221, whereas the mean annual precipitation is 1220 mm year^{-1}. Wind direction is predominantly W–E, i.e. perpendicular to crest orientation, which favors the formation of cornices.

Alpine and sub-alpine herbs and shrubs carpet the slopes between the highest altitudes (above 2200 m asl) and the forest treeline, found at approximately 1800 m asl. A dense *Picea abies* forest covers the steep slopes down to 1200 m asl, where deciduous trees (mainly Common beech; *Fagus sylvatica* L.) become predominant. On both sides of the valley, the forests exhibit characteristic avalanche disturbance patterns (Rixen et al., 2007), with nearly parallel couloirs resulting from the repeated occurrence of snow avalanches. Within the avalanche paths, vegetation consists of three typical transverse zones as described by Ives et al. (1976): (i) an inner zone with herbs and shrubs incl. *Sorbus aucuparia* and *Rubus idaeus*, (ii) an intermediate zone colonized by flexible pioneer species of deciduous trees -mainly *Alnus viridis*- and (iii) an outer zone where various damaged trees (conifers mixed with deciduous trees, both young and mature) border the undamaged, established spruce forest.

On the east-facing slope of the Arpaş Valley, 11 primary avalanche paths and several secondary corridors shape the forest cover. With starting zones above the treeline, avalanches cross the forested zone, reach the valley bottom and - in some cases - run up the opposite slope. Among these avalanche paths, the “Major Path” (MP) was considered the most appropriate for the purpose of this study, as the magnitude of snow avalanches occurring here is by far the largest. Extending over a surface of 17 ha, the investigated path ranges from 1920 to 1350 m asl. The starting zone is found just beneath the mountain crest, which favors the triggering of snow avalanches by cornice failure. The general mean slope angle is 27°, whereas the mean inclination of the starting zone is 33°, fitting well into the 25°–45° range defined as ideal for snow avalanche release (McClung and Shearer, 2006). The track and the run-out zone record a gradual slope angle decrease as one descends towards the valley floor. Around 1550 m asl, a sudden slope angle increase (up to 70°) over a distance of 100 m in longitudinal direction is observed, a feature which runs along the entire slope. The presence of this steep threshold, witness of glacial erosion, generates an acceleration of the downslope moving material (snow, ice, rocky and woody debris).

The avalanche footprint suggests that the largest snow avalanches cross the valley bottom and climb up to 150 m on the opposite slope. In the extreme run-out zone, trees are leaning upslope as a result of avalanche impact. In the same respect, within the avalanche path and along the lateral limits, all characteristic anomalies in tree morphology associated to avalanche disturbance are present: tilted trunks (Fig. 2a), impact scars (Fig. 2b), broken trunks and apex loss linked with candelabra growth (Fig. 2c), flagged branches and uprooted trees.

3. Material and methods

3.1. Geomorphic mapping

The spatial boundaries of the avalanche path were delineated on satellite imagery and topographic maps. In this phase, we also excluded areas where geomorphic processes other than snow avalanches or anthropogenic factors could have generated tree-ring anomalies. A digital elevation model was then created by processing information contained in the 1:25,000 topographic map. The starting, transportation, and run-out zones were assessed and morphometric parameters (elevation, aspect, inclination and curvature) were computed for the slope.

3.2. Sampling design

To identify anatomical reactions induced by avalanche impacts, a total of 105 *P. abies* trees have been selected in the field based on their location and visible anomalies in tree morphology (Stoffel and Bollschweiler, 2008). Samples consisted entirely of increment cores ($n = 238$) extracted with Pressler increment borers (ø 5.15 mm, length max. 40 cm).

Fig. 2. Anomalies in tree morphology following avalanche impact on the MP Path include (a) tilted trees, (b) impact scars and (c) broken trunks and/or apex loss.

Younger trees and those with visible growth anomalies, such as impact scars, tend to provide information on more recent events, and likewise, older or apparently not affected trees will be excellent witnesses of events farther back in time (Stoffel et al., 2013; Stoffel and Corona, 2014). We therefore decided for a balanced sampling strategy which included younger as well as older trees. In the same respect, we selected both trees with obvious evidence of avalanche impact (i.e. tilted trees, scars, broken stems and apex loss, flagged branches) and trees that seemed undisturbed by past events. Sampling was carried out on longitudinal transects along the lateral limits of the upper, mid, and lower track, within the avalanche path, and in the run-out zone, as shown in Fig. 3.

At least two cores were extracted per tree, one in the direction of the avalanche flow, if possible crossing the stem, and the second perpendicular to the slope. Sampling height and technique were chosen according to the location and type of visible anomalies in tree morphology: in the case of tilted trees sampling was carried out at the point with the maximum bending angle, from bark to bark (Braam et al., 1987; Lopez-Saez et al., 2012), while trees showing impact scars were sampled from the overgrowing scar tissue (Stoffel and Bollschweiler, 2008; Schneuwly and Stoffel, 2008; Trappmann and Stoffel, 2013).

In order to develop a reference chronology, 30 undisturbed *P. abies* trees were sampled from a forest stand north of the avalanche path, where no geomorphic disturbance was identified. Two cores were collected from each tree, both perpendicular to the slope and at breast height.

For each sampled tree we recorded additional information consisting of: type, description and photography of the visible growth anomaly, sampling height, stem diameter at sampling height, exact location of the sampled tree (using a Trimble Geo-Explorer 6300DGPS), and data on neighboring trees.

3.3. Tree-ring analysis

All samples were prepared following standard dendrochronological procedures (Bräker, 2002), which consisted in air-drying, mounting and sanding of increment cores (with grit from 150 to 800). Tree rings were then counted and tree-ring widths were measured using a LINTAB-5 positioning table, connected to a Leica stereo-microscope and TSAP-Win Professional 4.64 software (Rinn, 2013). To build a reference chronology, the tree-ring width series of undisturbed trees were visually crossdated and the crossdating results checked with inter-correlation analysis using the program COFECHA (Holmes, 1983). All samples collected from the trees colonizing the study area were then visually crossdated with the reference curve to distinguish between responses induced by snow avalanches and the general growth pattern depending on non-geomorphic, site characteristic factors.

Snow avalanches can tilt, injure and uproot trees and as well break their trunks or the upslope growing branches (Stoffel and Bollschweiler, 2009). Reconstructing past events implies the identification and precise dating of anatomical growth responses. In this study, event years associated with avalanche occurrence were identified through the dating of the following growth disturbances(GD): (i) onset of compression wood (Timell, 1986), (ii) first year with abrupt growth suppression (Kogelnig-Mayer et al., 2013) and (iii) release (Mundo et al., 2007), (iv) onset of callus tissue formation (Stoffel and Klinkmüller, 2013), and (v) formation of tangential rows of traumatic resin ducts (TRD; Stoffel et al., 2006; Schneuwly et al., 2009a, b). In case of TRD formed in consecutive years, only the first year was assigned as an event year. According to the position of TRD within the annual growth ring (Stoffel et al., 2005), and in order to avoid reactions induced by non-geomorphic agents, we only included TRD found at the beginning of the growth ring (i.e. early earlywood). GD associated with snow

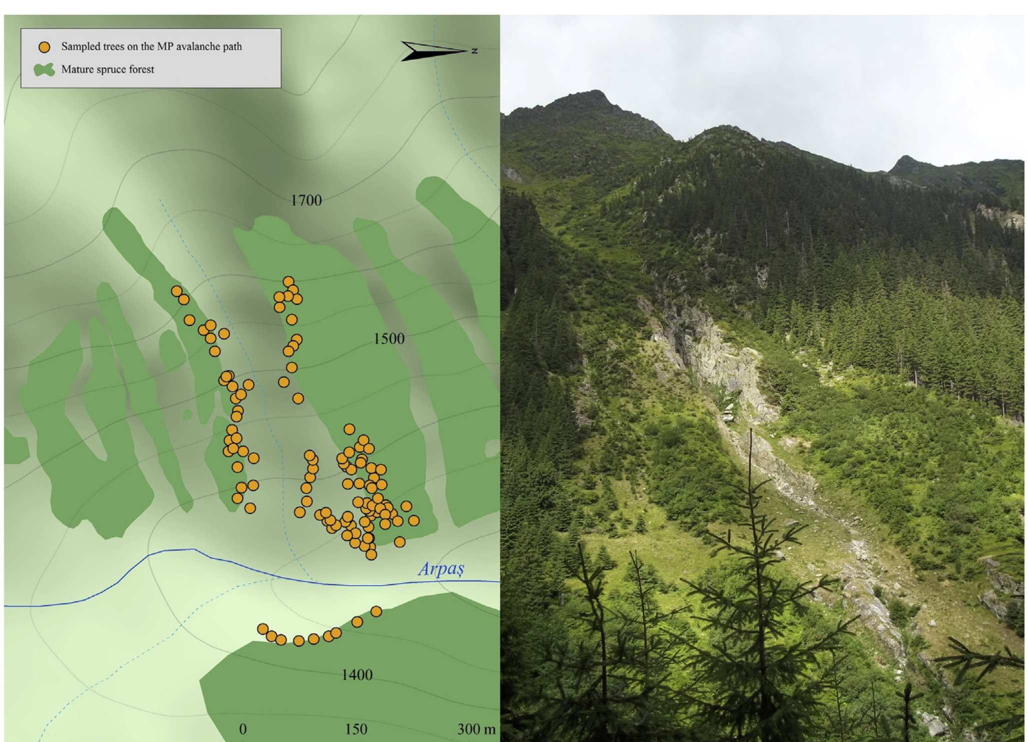


Fig. 3. Localization of sampled trees along the MP avalanche path (left); Photograph illustrating the investigated avalanche path (right).

avalanches were dated, classified and compiled in an Excel database.

3.4. Event reconstruction using the 'conventional' approach

Early studies dealing with snow avalanche disturbance by means of dendrogeomorphology (Carrara, 1979; Butler and Malanson, 1985; Johnson et al., 1985; Bryant et al., 1989) were all based on the *process-event-response* concept and the semi-quantitative interpretation of data as ascertained by Shroder (1978, 1980, 1978) established the use of a yearly index value defined as the ratio between trees showing growth responses and all sampled trees being alive in that year. This method was widely used by researchers and is still a reliable tool and support for event reconstructions. In our 'conventional' approach, an index value I_t was calculated for each year *t*, based on the following formula:

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

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

To increase the reliability of dendrogeomorphic reconstructions, a threshold is usually set to minimize noise induced by non-geomorphic agents and to maximize signals. Butler et al. (1987) were the first to question the optimal index threshold, underlining the dependence on the type of investigated geomorphic process. In snow avalanche studies, thresholds range from 10% to 40%. We selected a threshold of $I_t \geq 10\%$ for this study as this was the most commonly found value in snow avalanche literature (Dubé et al., 2004; Germain et al., 2009; Reardon et al., 2008; Corona et al., 2010; Voiculescu and Onaca, 2013, 2014). In addition, we only accepted event years where sample depth (i.e. the number of trees available for analysis) exceeded 10 trees (Dubé et al., 2004; Germain et al., 2009).

3.5. Event reconstruction using the 'modern' approach

In addition to the 'conventional' approach, the 'modern' approach includes methodological improvements, in particular the inclusion of TRD, the application of variable index and GD thresholds, the classification of GD depending on their intensity, and the use of a weighted index factor.

Certain conifer species, including *P. abies*, form TRD following geomorphic disturbance (Stoffel, 2008). In recent snow avalanche studies (Stoffel et al., 2006; Butler et al., 2010; Corona et al., 2010, 2012a, 2012b; Szymczak et al., 2010; Schläppy et al., 2013, in press), the inclusion of TRD has been found to enhance the quality and length of chronologies and to represent a valuable indicator for the indirect dating of mechanical damage.

Sampling depth and optimized GD and I_t thresholds were based on the findings of Corona et al. (2012b), Schneuwly-Bollschweiler et al. (2013), Stoffel et al. (2013), Corona et al. (2014) and Morel et al. (in press). These studies recommend the use of variable thresholds adjusted to changes in sample size. To maximize signal and reduce noise in avalanche reconstructions, we used different thresholds for sample sizes of $\leq$20 (GD $\geq$ 3 and $I_t \geq 15$), 21–50 (GD $\geq$ 5 and $I_t \geq 10$), and $\geq$51 trees (GD $\geq$ 7 and $I_t \geq 7$).

Following the identification and dating of GD, we then assigned the intensity of each reaction and distinguished between weak, intermediate, and strong signals according to the classification proposed by Stoffel and Corona (2014). Following Kogelnig-Mayer et al. (2011) we then calculated a weighted index factor W_{it} to substantiate the dating of snow avalanches, by taking into account with a single value, the number of responding trees and the intensity of the reactions. To assess avalanche years we set a threshold of $W_{it} \geq 2$.

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

where GD*tn* = GD assigned to the Intensity *n* Class (*n* = 1–5); Rt = responding trees in year *t*; At = trees alive in year *t*.

Results using the "modern" approaches are presented here with two different reconstructions: (i) the semi-quantitative 'modern' GD-I_t and (ii) the semi-quantitative W_{it}.

3.6. Calculation of avalanche frequency

Snow avalanche frequency is generally expressed as *return period* or *avalanche interval* (AI_t). Some authors infer this value by averaging event intervals of individual sampled trees (Reardon et al., 2008; Corona et al., 2010), while others extract it by dividing the length of the chronology with the number of reconstructed events (Casteller et al., 2011). In this paper, the second method is being used to assess snow avalanche frequency for specific time intervals of the past.

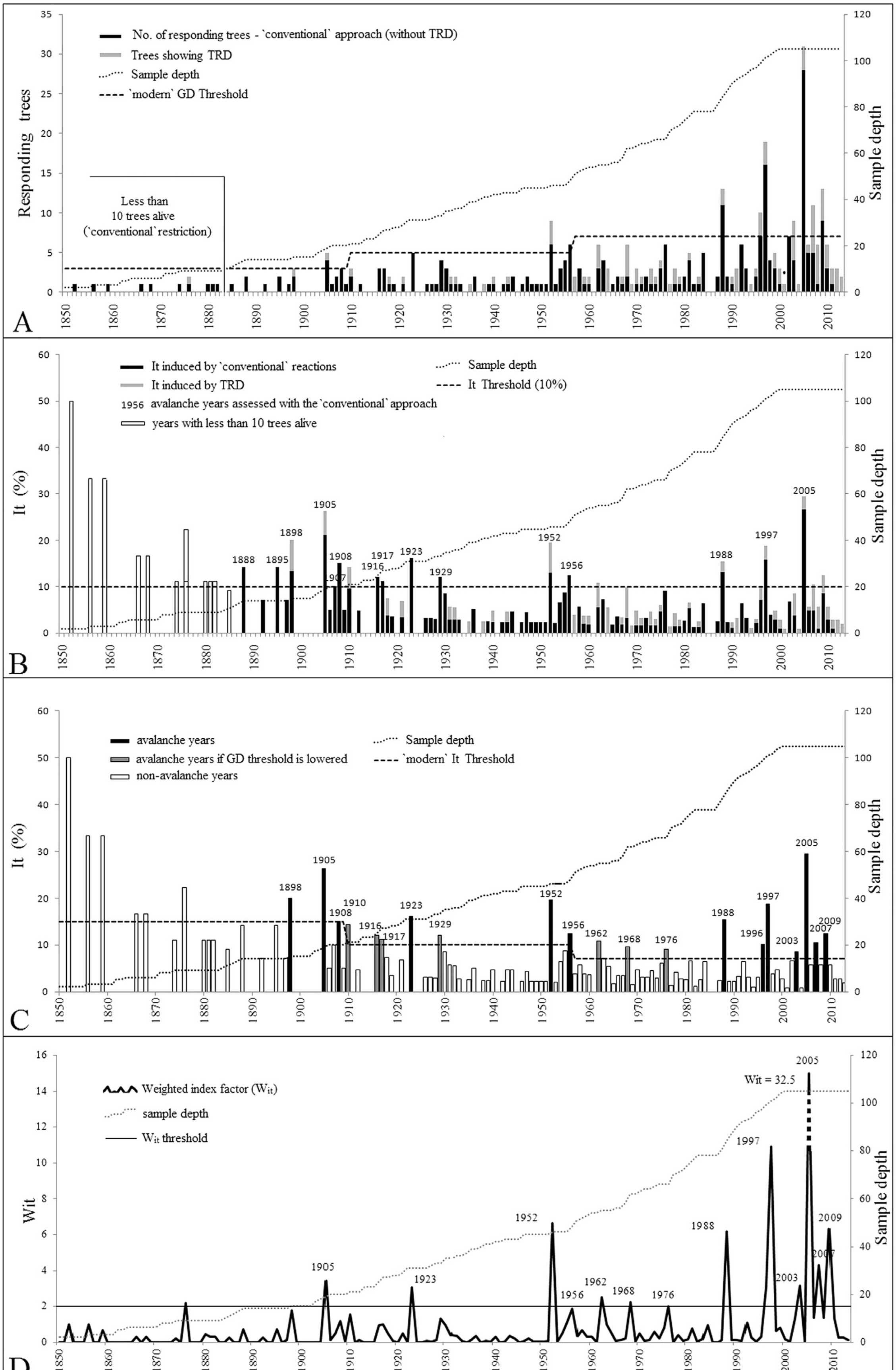
4. Results

4.1. Anomalies in tree morphology and wood anatomy

Analyses of 238 increment cores allowed identification of 534 GD of various types and intensities (Table 1). The most common response to past avalanche activity was in the form of compression wood (36.9%) following tree tilting, TRD formation (30.3%) resulting from mechanical impact and growth suppression (27.9%) following elimination of photosynthetic material (e.g., branches, crown), whereas growth releases (3.6%), an indicator of elimination of neighbors, and wound-healing callus tissue (1.3%) appeared much less frequently. The chronology covers the period A.D.1852–2013. Sample depth surpassed 10 trees in A.D.1884, but responses remain sparse before A.D.1900, steadily increasing numbers of reactions

Table 1
Number, type and intensity class for dated growth disturbances at MP Path. CW = compression wood; CT = callus tissue; GS = growth suppression; GR = growth release; TRD = tangential rows of traumatic resin ducts. Total amounts (on rows and columns) are written with Bold.

Type of GD	Intensity Class 1	Intensity Class 2	Intensity Class 3	Intensity Class 4	Intensity Class 5	Total	%
RW	–	99	63	35	–	**197**	36.9
CT	–	–	–	–	7	**7**	1.3
Suppression	–	11	62	76	–	**149**	27.9
Release	10	9	–	–	–	**19**	3.6
TRD	31	–	–	59	72	**162**	30.3
TOTAL	**41**	**119**	**125**	**170**	**79**	**534**	100.0


A
Responding trees
Sample depth
No. of responding trees - `conventional` approach (without TRD)
Trees showing TRD
Sample depth
`modern` GD Threshold
Less than
10 trees alive
(`conventional` restriction)
B
It (%)
Sample depth
It induced by `conventional` reactions
It induced by TRD
1956 avalanche years assessed with the `conventional` approach
years with less than 10 trees alive
Sample depth
It Threshold (10%)
C
It (%)
Sample depth
avalanche years
avalanche years if GD threshold is lowered
non-avalanche years
Sample depth
`modern` It Threshold
D
Wit
Sample depth
Weighted index factor (Wit)
sample depth
Wit threshold
Wit = 32.5

can be, in contrast, found as we approach the present day. With few exceptions, at least one tree displays GD in every single year of the chronology after A.D.1925.

4.2. Event reconstruction using the' conventional' approach

The event-response histogram depicted in Fig. 4a shows all reactions recorded in the trees along the avalanche path. In the 'conventional approach' (GD = 372), TRD are not included and are thus given in grey. The 10% index value threshold used to assess avalanche events is exceeded 15 times in this case (Fig. 4b): 1888, 1895, 1898, 1905, 1907, 1908, 1916, 1917, 1923, 1929, 1952, 1956, 1988, 1997 and 2005. The reconstruction of avalanches before A.D.1952 is based on relatively few GD ($n = 2$–4), except for 1923 where 5 trees reacted simultaneously. Evidence for avalanches was particularly high in A.D.1997 ($n = 16$) and A.D.2005 ($n = 28$), suggesting the occurrence of major events. The average avalanche interval for the entire chronology is 10.7 years.

4.3. Event reconstruction using the 'modern' approach

The addition of TRD ($n = 162$) to the GD analysis raises the total number of reactions to 534. Moreover, the inclusion of TRD results in a higher number of years during which the 'conventional' 10% I_t threshold is passed (Fig. 4b), namely 20 times (compared to 15 times without TRD). In this case the oldest event occurs in 1888, and the youngest is recorded in 2009.

Using the 'modern' GD-I_t approach with all growth reactions as well as the variable thresholds for GD and I_t, a total of 13 avalanche years are determined in 1898, 1905, 1908, 1923, 1952, 1956, 1988, 1996, 1997, 2003, 2005, 2007, and 2009. Fig. 4c indicates that for another seven years (1910, 1916, 1917, 1929, 1962, 1968 and 1976) the I_t value threshold has been passed, whereas the absolute number of GD remains slightly too small for them to be considered events with the thresholds as defined above. In the case of these seven years, a spatial analysis of reacting trees could possibly help for them being included in the reconstruction. Again, most reactions are recorded during the avalanches in 1997 and 2005. The average avalanche interval for the entire chronology is 12.3 years.

The weighted index factor W_{it} adds an intensity to each GD. Strong signals of snow avalanche activity ($W_{it} \geq 2$) are easily recognizable in 13 years (the event of A.D.1876 was rejected due to the low number of responses; GD = 2): 1905, 1923, 1952, 1962, 1968, 1976, 1988, 1996, 1997, 2003, 2005, 2007 and 2009. Two more years (A.D.1898 and A.D.1956) could possibly be included in the chronology, due to the fact that both corresponding W_{it} values fall close beneath the fixed minimum (1.8 and 1.9 respectively). The individual yearly values of the qualitative index are represented in Fig. 4d. The mean avalanche interval in this case is again 12.3 years.

5. Discussion

The study we report here employs dendrogeomorphic techniques in the analysis of snow avalanche activity on a forested path located in a remote area of the Romanian Carpathians. The dendrogeomorphic signals extracted from 238 increment cores (105 *Picea abies* trees) were interpreted by applying three different avalanche reconstruction methods in order to compare the outcomes of different techniques. Within the 'modern' approach we used both semi-quantitative GD-I_t and W_{it} analyses, thereby splitting the outcomes of the 'modern' approach into two separate reconstructions. We demonstrate that different approaches and thresholds will yield different event years (and hence different avalanche intervals), but that the main avalanches causing most damage to the forest stand will emerge in all of the reconstructions.

Table 2 illustrates the different years identified in each approach with the corresponding number of GD, I_t, W_{it} and number of living trees (i.e. sample size). Based on the recent statistical testing of optimum sample size and noise reduction thresholds (Corona et al., 2012b; Schneuwly-Bollschweiler et al., 2013; Stoffel et al., 2013; Corona et al., 2014; Morel et al., in press), there is scope and reason to believe that the event reconstructions emerging from the 'modern' approach best reflect the real avalanche activity on the MP path and that they include the smallest amount of noise to the reconstruction.

The avalanche chronology covers 161 years, the first tree reaction being identified in 1852 and the most recent in 2013. In the 'conventional' approach, events are reconstructed independently of the GD threshold and only require a sample size above 10 trees. This allows years with a relatively low number of disturbance signals to be accepted as avalanche years (GD = 2 for 1888, 1895, 1898, 1907). The 'modern' approach, on the other hand, uses a rather restrictive GD threshold, which rejects seven event years where index values exceed the variable I_t thresholds but where the criteria of the GD threshold are not fully fulfilled (1910, 1916, 1917, 1929, 1962, 1968, and 1976). In cases where the criteria are almost met, Stoffel and Corona (2014) suggest that a careful analysis of the spatial distribution of simultaneously reacting trees with high intensity GD can justify the usage of lower GD threshold. The inclusion of avalanche years with low GD and I_t values can also be justified if strong reactions are spatially clustered (see Lopez-Saez et al., 2012 or Schneuwly-Bollschweiler et al., 2013 for statistical approaches used for cluster analyses). In the case of the seven event years with somewhat limited GD values, the analysis of spatial patterns of reacting trees may well justify their inclusion in the 'modern' GD-I_t based chronology without adding noise to the reconstruction. Consequently, the 'modern' GD-I_t approach will reconstruct a total of 20 avalanche years, i.e. one-third more events as compared to the 'conventional' approach, and yields an average avalanche interval of 8.5 years.

The same criteria were used in the 'modern' W_{it} approach to include the avalanches of 1898 and 1956 for which the W_{it} values fall closely beneath the threshold. The 'modern' W_{it} approach allows for the reconstruction of 15 events, of which all are confirmed in the 'modern' GD-I_t approach, and yields an avalanche interval of 10.7 years.

A simple event count, though, may not fully reflect similarities or fundamental differences between the three reconstructions. Comparison of the resulting semi-quantitative (I_t) chronologies (Fig. 4b and c) indicates a different event distribution along the entire period. To ease the comparison process the reconstructed period has been split into four distinct intervals (Table 3) with individual characteristics: (1) 1852–1887 (no reconstructed event due to small sample size and GD ≤ 1), (2) 1888–1929 (event years with 5 or less responding trees); (3) 1930–1951 (low dendrogeomorphic signal); (4) 1952–present (larger dendrogeomorphic signal).

Fig. 4. Event-response histograms depicting quantitative, semi-quantitative and qualitative avalanche signals: A. Absolute number of responding trees with distinction made between 'conventional' GD and TRD (given in grey). B. Avalanche chronology resulted from the 'conventional' I_t approach, showing also I_t increase following addition of TRD (given in grey). C. Avalanche chronology resulted from the 'modern' GD-I_t approach. D. Avalanche activity signal obtained by computing the reaction intensity weighted index factor ('modern' W_{it}).

Table 2
Essential parameters of reconstructed avalanche years as obtained with different approaches (The asterisk (*) points to avalanches which have been accepted based on the spatial distribution of affected trees and despite the fact that the threshold for GD and/or W_{it} was not fully met).

Event years	Reconstructed by			Growth disturbances		Avalanche Indices			Sample depth
	Conventional I_t	Modern I_t	Modern W_{it}	Conventional (no TRD)	Modern (with TRD)	Conventional I_t (%)	Modern I_t (%)	Modern W_{it}	
1888	Yes			2	2	14.3	14.3	0.7	14
1895	Yes			2	2	14.3	14.3	0.7	14
1898	Yes	Yes	Yes*	2	3	13.3	20.0	1.8	15
1905	Yes	Yes	Yes	4	5	21.1	26.3	3.4	19
1907	Yes			2	2	10.0	10.0	0.5	20
1908	Yes	Yes		3	3	15.0	15.0	1.2	20
1910		Yes*		2	3	9.5	14.3	1.6	21
1916	Yes	Yes*		3	3	12.0	12.0	1.0	25
1917	Yes	Yes*		3	3	11.1	11.1	1.0	27
1923	Yes	Yes	Yes	5	5	16.1	16.1	3.1	31
1929	Yes	Yes*		4	4	12.1	12.1	1.3	33
1952	Yes	Yes	Yes	6	9	13.0	19.6	6.7	46
1956	Yes	Yes	Yes*	6	6	12.5	12.5	1.9	48
1962		Yes*	Yes	3	6	5.5	10.9	2.5	55
1968		Yes*	Yes	2	6	3.2	9.7	2.2	62
1976		Yes*	Yes	6	6	9.1	9.1	2.0	66
1988	Yes	Yes	Yes	11	13	13.1	15.5	6.2	84
1996		Yes	Yes	7	10	7.1	10.1	3.1	99
1997	Yes	Yes	Yes	16	19	15.5	18.8	10.9	101
2003		Yes	Yes	4	9	3.8	8.6	3.2	105
2005	Yes	Yes	Yes	28	31	26.7	29.5	32.5	105
2007		Yes	Yes	5	11	4.8	10.5	4.3	105
2009		Yes	Yes	9	13	8.6	12.4	6.3	105

Table 3
Comparison of 'conventional' and 'modern' results (in terms of number of reconstructed events and avalanche intervals) in four different time-intervals and for the entire chronology.

Period	Time interval	Period length (yr.)	Number of reconstructed avalanches			Avalanche interval		
			Conventional I_t	Modern GD-I_t	Modern W_{it}	Conventional I_t	Modern GD-I_t	Modern W_{it}
1	1852–1887	35	0	0	0	∞	∞	∞
2	1888–1929	41	10	8	3	4.1	5.1	13.6
3	1930–1951	21	0	0	0	∞	∞	∞
4	1952–2013	61	5	12	12	12.2	5.1	5.1
TOTAL	1852–2013	161	15	20	15	10.7	8.5	10.7

Both the 'conventional' and 'modern' approaches agree upon the weak dendrogeomorphic signal in intervals 1 and 3. At the same time, the 'conventional' method exhibits a clustering of avalanche years in the second period, with 10 events in only 41 years, thus, an avalanche interval of 4.1 years. Passing over the 21-year 'avalanche-free' period, we distinguish only 5 events in the remaining 61 years ($AI_t = 12.2$ years). While the 'conventional' chronology shows an uneven distribution of events along the entire period, the 'modern' GD-I_t approach produces more balanced results with similar frequencies ($AI_t = 5.1$) in periods with avalanche activity (2 and 4). We argue that the clustering of events ('conventional' approach) in the second period is induced by the missing GD threshold, which favors an overestimation of events when sample size is still small (from 14 trees in 1888 to 33 trees in 1929). With continuously increasing sample size as we advance to the present day, the 10% I_t threshold limits the reconstruction to 5 avalanche-years for interval 4, compared to the 12 events reconstructed for the same interval by applying variable GD-I_t thresholds.

The weighting of GD according to their intensity and the use of the W_{it} threshold confirms all the results of the 'modern' GD-I_t reconstruction corresponding to the most recent period (interval 4). Nevertheless, a clear decrease of identified avalanches is observed as one goes farther back in time, with only three events for interval 2, whereas the 'modern' GD-I_t method reconstructs 8 avalanche years for the same interval. With a relatively low dendrogeomorphic signal due to a limited number of trees alive in older periods, the rigid W_{it} threshold could hamper the identification of several major events. Therefore, we suggest the use of a variable W_{it} threshold which shall be adapted based on sample size, similar to the variability of the I_t and GD thresholds as described above.

The inclusion of TRD into the 'modern' analysis results in substantial changes in the final outcome. Firstly, from a quantitative perspective, the 162 dated TRD occurrences increase the total amount of GD by 43.5% (illustrated in Fig. 4a), leading concurrently to an average I_t index raise of 1% for the entire chronology (specific interval increases are shown in Table 4). Table 4 underlines the significant impact of TRD inclusion for the most recent period (1952–2013), for which TRD has been the main cause for the higher number of avalanche events assessed to this period. In other words,

Table 4
Analysis of the semi-quantitative index increase induced by the addition of TRD.

Time interval	Average 'Conventional' I_t index	Average 'Modern' I_t index	Average I_t increase due to TRD inclusion
1852–1887	6.0%	6.3%	0.3%
1888–1929	4.7%	5.3%	0.6%
1930–1951	2.4%	3.1%	0.7%
1952–2013	3.9%	5.6%	1.7%
TOTAL (1852–2013)	4.3%	5.3%	1.0%

if the ‘conventional’ 10% index threshold is applied, 5 more events can be reconstructed as a result of the addition of TRD in period 4 alone. Secondly, assigning an important percentage of TRD (80%, $n = 131$) to intensity classes 4 and 5 was transferred to the results of the qualitative analysis causing higher values of W_{it} in certain years. This partially explains the enhanced dendrogeomorphic signal obtained for the last decade of the chronology ($AI_t = 2.5$ years).

We also notice an exceptionally strong signal for 2005 ($W_{it} = 32.5$) and a wide spatial distribution of affected trees (with evidence found in the extreme run-out zone on the opposite slope), both suggesting the occurrence of a major event in 2005. Interestingly, other studies undertaken in the Făgăraş Mountains (Voiculescu and Ardelean, 2012), Piatra Craiului Mountains, as well as the statistics from the Mountain Rescue Service and eye-witness reports point to the widespread occurrence of snow avalanches in the winter of 2004–2005 in the Romanian Carpathians, and thus confirm the results of our study for that particular year.

Major snow avalanches have the ability to shape the outskirts of avalanche paths leaving strong dendrogeomorphic signals in impacted trees. At the same time, they can destroy large parts of the forest, blurring or removing tree-ring evidence of previous events (Carrara, 1979). This could be the case of the 1952 avalanche, a very large event in the Arpaş Valley, which can be at least partially the cause for the “avalanche-free” period of more than 20 years in the third interval (1930–1951). Moreover, the spatial distribution of trees responding to certain events shows that reactions of older, presumably major avalanches (such as 1952), tend to be preserved by a more limited number of trees, most of them found at higher elevations in the mid- and lower track, whereas individuals affected in the run-out zone seem to have been wiped out by more recent activity. In the same respect, we observe that the spatial spread of trees affected by ‘younger’ events (e.g., 1997, 2005) delivers a better accuracy with respect to the avalanche footprint.

6. Conclusions

This study not only provides one of the first snow avalanche chronologies for the Romanian Carpathians, offering the longest reconstruction (161 years) and first indications on spatio-temporal behavior of avalanches in the region, but also applies three different methodological approaches on the same set of samples to improve dating accuracy and the distinction of signal from noise in dendrogeomorphic records. The reconstruction offers a clear picture on where and to what degree ‘modern’ approaches improve dendrogeomorphic results.

We conclude that the ‘modern’ GD-I_t approach provides a better noise reduction due to sample-size-adapted thresholds. At the same time, the most significant improvements brought by the intensity weighting of reactions is the amplification of the dendrogeomorphic signal, inducing a better separation between avalanche years and non-avalanche years, or – to say it in other words – an improved separation of signal from noise. However, a sample-size-adapted W_{it} threshold may deliver better results for older periods, characterized by a smaller number of available trees, with an accordingly weaker dendrogeomorphic signal. The addition of TRD into the analysis supplements the number of events by positively affecting both semi-quantitative and qualitative indices, proving to be essential in contemporary dendrogeomorphic avalanche studies.

In another line of thoughts, further analyses of climatic data and dendrogeomorphic investigations on several additional avalanche paths in the Arpaş Valley are critically needed to complement the picture of avalanching and to enhance the understanding of avalanche triggers in the Făgăraş Mountains.

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