Testing the potential of the dwarf shrub Dryas octopetala L. for dating in dendrogeomorphology

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Dendrochronology has been applied around the world over decades to reconstruct historical geomorphological events and climatic conditions. Traditionally, this research has been conducted using trees (conifers as well as broad-leaved trees) but, in the last few decades, several shrub and dwarf shrub species have also been shown to be useful for dendrochronological purposes. This study assesses the potential of mountain avens (Dryas octopetala L.) to provide accurately dated information about past debris-flow events. The study site, the Markt-Graben debris-fan, is located in South Tyrol (Italy). 119 shrubs from three debris-flow tracks were analyzed. The longest radius of each sample was measured and cross-dated to build two chronologies for each debris-flow track, one for each levee. Correlations between these chronologies and precipitation and temperature data from five climate stations located in the proximity of the study site were calculated. The cross-dating procedure was complex, but a strict grouping of the samples, based on the specific levees of the tracks, enabled the construction of mean chronologies for each of the individual slopes. Although the development of a mean chronology for the study area was unsuccessful, the cross-dated ages of the single shrubs allowed us to reconstruct debris-flow events by utilizing the minimum age method. The low climate correlations suggest that micro site conditions strongly influence the growth of this dwarf shrub. Although the results of this study suggest that Dryas octopetala may provide useful dendroecological information, additional information about its growth dynamics is required before this potential can be fully realized.

1. Introduction

Dendrogeomorphological studies have traditionally used trees, particularly conifers, to gain information about growth conditions and to date possible disturbance events in the past (Shroder, 1980; Stoffel and Böllschweiler, 2009; Gärtner and Heinrich, 2013; Bräuning et al., 2016). By assessing how tree growth changes over time, it is possible to draw conclusions about past climatic and environmental conditions (e.g. Au and Tardif, 2007) and to date and quantify geomorphological events such as debris flows (e.g. Baumann and Kaiser, 1999; Stoffel et al., 2005; Szymczak et al., 2010; Pop et al., 2019), rock falls (e.g. Trappmann et al., 2013; Stoffel, 2006), and landslides (e.g. Gers et al., 2001; Burkhalter et al., 2019). Although a number of studies have extended their focus to deciduous trees (e.g. Arbelay et al., 2010; Burkhalter et al., 2019), few have focused on event reconstructions using shrubs and dwarf shrubs (e.g., Bar et al., 2006, 2007; Gärtner-Roer et al., 2013; Owczarek et al., 2013). In recent years, shrubs have steadily gained in importance in many fields of environmental research (Myers-Smith et al., 2015), such as the influence of changing climate on ecosystems (e.g. Buchwal et al., 2013; Prevéy et al., 2017; Hallinger et al., 2010) and the dating of geomorphological depositions (e.g. Owczarek et al., 2013). Analysis of the distribution, form, size, and growth of shrubs has resulted in new proxy data that has enabled a deeper understanding of how climate change affects arctic and high mountain areas. These regions are known to be very sensitive to rising temperatures and other consequences of climate change (Lim et al., 2020; Drake et al., 2019). With respect to rising temperatures, the latest report by the Intergovernmental Panel on Climate Change (IPCC) details the potential impacts of climate change, including an increase in the intensity of rainfall, the degradation of permafrost, and the retreat of glaciers in high mountain areas (IPCC, 2018). These changes have further implications for the occurrence of mass movements such as debris flows (Decaulne and Sæmundsson, 2007; Pavlova et al., 2014). Debris flows represent a significant hazard in high mountains, which can be influenced by changing climatic conditions.
These flows are triggered by an interplay of various factors, such as a higher influx of water due to extended snow melting or intense and recurrent rainfalls (Costa, 1984; Bacchini and Zannoni, 2003; Stoffel and Huggel, 2012; Owczarek et al., 2013; Mostbauer et al., 2018; Prenner et al., 2018). Arbellay et al. (2010) emphasized the importance of studying past events to improve our ability to predict future debris flows. Bollschweiler and Stoffel (2010) suggested that a deeper understanding of past and present events is required before meaningful extrapolations to the future can be made. To date, such events have been almost exclusively studied using trees; the only exception is a study by Owczarek et al. (2013) using shrubs to reconstruct past debris flow events.

Mountain avens (*Dryas octopetala* L.) is a widely distributed dwarf shrub that grows on calcareous soils in the Arctic, subarctic, and mountain regions, including the Alps, Pyrenees, Apennines, Caucasus, and Rocky Mountains (Elkington, 1971). Mountain avens has been studied in relation to climate change (e.g. Press et al., 1998; Piper et al., 2011) and its impact on plant phenology (e.g. Hoye et al., 2007; Nybackken et al., 2009; Gillispie et al., 2016). It has also been used to study its competitive behaviour in ecosystems (Kalandrud and Totland, 2008) and in relation to ectomycorrhiza (e.g., Ryberg et al., 2009). While this dwarf shrub is frequently seen as an important part of the Arctic or high mountain vegetation, no study to date has attempted to use its annual rings for event dating. This study aims to fill this gap by assessing the potential of *Dryas octopetala* for dendrogeomorphological research.

The main research questions to be answered by this study are: (i) is it possible to cross-date the annual rings of mountain avens to construct a reliable chronology, (ii) does the age distribution of the shrubs correlate with the vegetation cover density, and (iii) does the age of the oldest plant correspond with the minimum time since the last erosive event happened? To this end, this study examined *Dryas octopetala* growing in three adjacent debris-flow tracks in the “Marlt-Graben”, an active debris flow fan located near Suldlen, Italy.

2. Study area

The Marlt-Graben is a debris-flow fan situated in the Suldlen Valley, South Tyrol (Italy), in the Rhaetian Alps which is located on the northeast slope of the Ortler (3905 m a.s.l.), the highest mountain in the Eastern Alps (Fig. 1). The origin of this valley has been strongly influenced by glaciers, which can still be found today in the higher parts of the surrounding mountains. The debris fan is connected to large moraines of the retreated “Marlt-Ferner” glacier (Kepper, 1938) and consists mostly of calcareous moraine material that originates from the dolomite banks of the upper part of the Ortler (Stötter et al., 2003). The fan is partially vegetated; the dominant plant species are *Pinus mugo* Turra s.l. (mountain pine), *Calluna vulgaris* (L.) Hull (heather), *Salix appendiculate* Vill (willow), and *Dryas octopetala* L. (mountain avens).

Due to its position at the north-eastern flank of the Ortler, the debris-flow fan is influenced by snow avalanches (Zischg et al., 2005). Nevertheless, a detailed morphological inspection of the site indicated that these avalanches do not influence the flow tracks that we analysed.

The study site (46° 32.07′ N/10° 33.97′ E) consists of a section of three adjacent debris-flow tracks (R1, R2, and R3) at the western border of the fan. The tracks differ in extent of vegetation cover, shape, disruptive elements, and expected age. The levees of the outermost track (R3) have the least vegetation cover. A small stream flows down the middle of the track, and the amount of grasses and willows increases near the water. The middle track was designated R1 (Fig. 2) and split into two zones (Zone A upstream and zone B downstream; see Fig. 2). The third track was labelled R2 and is expected to be the oldest of the three on account of its denser vegetation cover and cut-off path.

Mean monthly air temperature at the study site ranges from -4.4 °C in three adjacent debris-flow tracks in the “Marlt-Graben”, an active debris flow fan located near Suldlen, Italy.

![Fig. 1. View to the study area on the east facing slope to the Ortler massif. The main channel of the Marlt-Graben debris-flow track, which is bordered by the moraines of the Marlt-Ferner Glacier. The white lines are indicating the spread of the single debris flow tracks originating from the main track between the moraines. The white rectangular is indicating the position of the study site (compare Fig. 2).](image-url)
January to 11.8 °C in July. Mean annual total precipitation is 750 mm. The mean monthly values reach their maximum in July (99.4 mm) and August (105.7 mm); from December to February, the mean monthly values range between 25 and 29 mm (University of Bolzano 2017 a, b).

3. Material and methods

One of the most widespread plant species within the debris-flow tracks of the Marlt-Graben is *Dryas octopetala*, a small, perennial, evergreen dwarf shrub that forms large colonies. *D. octopetala* has an adventitious root system originating from a central root, and numerous prostrate, weakly rooting branches that form dense mats through secondary branching in the upper soil layer. As a result, *D. octopetala* looks like a pillow of many small-toothed leaves and reaches a maximum height of 5 cm. This pioneer species prefers calcareous and shallow soils (Skrede et al., 2006). Its stem and branches show very irregular annual growth and the ring structure is semi-ring porous (Schweingruber et al., 2011).

The sampling of *Dryas octopetala* individuals was done during two field campaigns, one at the beginning of July and the other at the end of August 2016. The sampling strategy within all three tracks followed the same criteria: living (green) shrubs were selected randomly along the same levees of the tracks. No preference was given to larger stems to guarantee a wide spectrum of individuals for analysis and because we knew from pilot samplings that big stems do not always have the highest number of growth rings.

Samples were collected from both sides of each of the three tracks (R1, R2, and R3). At least 30 plants were selected from both sides of each track, for a total of 190 shrub samples. Each plant was carefully excuated until the stem was visible. The stem was then wrapped with a tape, labelled, and its position documented, particularly the distance to the bottom of the track. The main stems and the upper part of the roots were cut from the rest of the shrub and transported to the lab.

3.1. Sample preparation and image analyses

A disc of about 3 cm thickness was cut from each shrub at the root/shoot intersection, the part where the roots unite to a single, although short stem for further analysis. This part of the plant was found to show the highest number of countable rings in the preparation phase of the study (unpublished). Micro sections of these samples were prepared following the standards described by Gärtner and Schweingruber (2013) and Bár et al. (2006) using a WSL Lab microtome (Gärtner et al., 2015). Before cutting, the samples were immersed in water for at least 3 min to soften the structure and to avoid a breakage of the cell walls while cutting. The best sections were achieved by cutting sections of 10–15 μm thickness using common NT cutter blades in a blade holder. Due to decay and/or intense compartmentalization, the samples were brittle and challenging to cut evenly. To overcome this challenge, the samples were stabilized by adding 95 % ethanol and cornstarch to the sample surface (Schneider and Gärtner, 2013). Furthermore, if the sample was partially twisted, an additional thin section was cut from the longest radius. Nevertheless, some of the samples were fragmented near the pith or incomplete. As a result, only 119 plants of the 190 sampled *Dryas octopetala* could be analyzed further. To guarantee accurate analyses, 3–5 high-quality micro sections were cut from each sample. After cutting, the samples were treated with sodium hypochlorite (bleach) to remove the brownish phenoles of the compartmentalized areas. After flushing the sections with water, they were stained using a 1:1 mixture of Safranin and Astrablue, staining the lignified parts red (Safranin) and the non-lignified parts blue (Astrablue). After staining, the sections were carefully dehydrated stepwise using different ethanol concentrations (75 %, 96 %, and dehydrated ethanol). The colored samples were then flushed with xylene and embedded in Canada balsam. Finally, the samples were placed in an oven at 60 °C for at least 24 h (Gärtner and Schweingruber, 2013) to guarantee an equal distribution of the balsam in all cells of the section. The resulting micro slides were photographed under a microscope equipped with a CANON EOS 70D at 100x magnification. The resulting images were stitched with PT-Gui (New House Internet Services BV, Rotterdam, NL) to create one composite image for each sample.

Ring-width measurements of the samples were measured from the images using WinDendro software (Regent Instruments Inc. Québec, QC, Canada). A measuring track was determined, beginning from the pith and following the xylem rays. As the annual rings of *Dryas octopetala* are semi-ring-porous, the first row of vessels in the earlywood helped define the ring boundaries (Fig. 3). In addition, the micro sections were checked for additional rings present elsewhere in the micro section (i.e., not in the measured pathway). These partially missing rings (PMR) were marked as missing rings in the resulting raw chronology (Schweingruber et al., 2011; Buchwal et al., 2013).
3.2. Test of serial sectioning

To learn more about the growth patterns of mountain avens, serial sectioning was tested for several plants. As an example, taken from by taking samples every ten centimeters \((N = 12)\) from the roots, the stem and the branches. It happened frequently, that samples taken were too bridle to be sectioned successfully. For the example presented, these were only two of the root samples.

To end up with meaningful data, 32 radii were measured for each thin-section. After crossdating the 32 radii, a section chronology was established. The chronologies of all sections were then crossdated for the plant. The difference in measured age between and within the samples, the number of PMR (partially missing rings) and missing outer rings (FR) was assessed (Table 1).

The thin sections showed variations in growth depending on their location within the plants (Table 1). The highest number of rings was measured in the stem sample. Towards the branches and the roots, the number of rings generally decreased. This decline appears faster in the branches than in the roots.

The age divergence of the 32 different radii measured varied depending on their position within the sample and their length. The longest radii had the least PMR and FR. The farther away from the longest radius the more (mostly the outer) rings turn into partially missing rings. The number of PMR is extremely variable and in some radii very high. While the longest radii have generally a low percentage of PMR (2.86–13.79 %), radii that were measured farther away from the longest radii showed a higher percentage of PMR (up to 54.17 %).

The test showed that: 1. The 32 radii showed a high level of similarity and it was simple to confront them with each other. The chronologies

Table 1

| Plant part | Cut- | Age longest radius | Age youngest radius | PMR min | PMR max |
|------------|-----|--------------------|---------------------|--------|--------|
| I          | 36  | 33                 | 4                   | 17     |
| II         | 37  | 35                 | 0                   | 12     |
| III        | 43  | 37                 | 2                   | 10     |
| IV         | 40  | 23                 | 0                   | 4      |
| V          | 50  | 38                 | 1                   | 15     |
| VI         | 53  | 38                 | 10                  | 25     |
| VII        | 33  | 17                 | 1                   | 10     |
| VIII       | 28  | 14                 | 0                   | 10     |
| IX         | 15  | 1                  | 0                   | 14     |
| X          | 5   | 1                  | 0                   | 4      |

Fig. 3. Micro sections taken from two samples of Dryas octopetala. A: Micro section of a stem showing two lobes and the respective positions of radii for measurement. B: Micro section of a (typical) eccentric stem of Dryas octopetala indicating the path of ring-width measurement done using WinDenro software. A1: Detailed view of the semiring porous structure of the rings. A2: Blue lines indicating the ring boundaries (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).
had the most suitable fit when orientated around their common pith.

2. The longest radii manifested the highest number of measurable rings and the least number of PMR as well as FR. Furthermore, the amount of PMR and FR increase with the distance from the longest radius of the sample.

3. While the 32 measured chronologies could be clearly cross-dated, a comparison of their mean curves showed a high heterogeneity of growth patterns within the plant.

Based on these observations and considering the very small length of the *Dryas octopetala* stem (approx. 2–5 cm), it was decided to measure just the longest radius (or the longest radii for lobed samples) and to do a visual check for wedging rings to define PMR. Due to the high heterogeneity of growth patterns within the plant and to avoid creating an excessively constructed plant chronology a limit of probable missing rings (to be inserted during the cross-dating process) would have to be defined, which is out of scope of this study.

### 3.3. Cross-dating

The chronologies for the right (R) and left (L) leveé of each track consist of 18–22 shrubs each (R1-L: 22; R1-L: 20; R2-L: 19; R2-L: 20; R3-L: 20; R3-L: 18). Cross-dating was first applied to the samples of the single levees. The resulting mean chronologies of the single levees where then cross-dated in a second step.

In detail, all measured radii were initially sorted according to their length, visually compared and then cross-dated using the software TSAP-Win starting with the longest radii. However due to the heterogeneity in the growth patterns of the single radii, a high amount of missing rings had to be added (sometimes >50 %) to end up with comparable growth patterns. For this, the resulting chronologies appeared constructed.

To reduce a potentially unintentional construction of chronologies another approach was implemented (Fig. 4):

Firstly, to get an overview on the pattern of the heterogenous curves, the raw curves were arranged and sorted based on their CDI-value (Cross-Dating Index), a statistical indicator for the level of correspondence between two cross-dated curves. The CDI-value incorporates several T-values, which describe the influence of extreme values, and the “Gleichläufigkeit”, which is a dimension for matching growth trends (Rinn, 2012). The value of the CDI threshold depends strongly on number, length, and heterogeneity of the measured radii and needs to be defined for each dataset to which it is applied (Hordo et al., 2009; Ilmen et al., 2013; Malik et al., 2015). A comparison of the T- and CDI-values of the first run showed that all cross-dated samples with a CDI > 18 presented high visual similarities. Consequently, the samples were divided into two clusters, where 18 was used as the threshold value of the CDI. The curves showing a CDI > 18 were grouped as cluster 1; curves with a CDI < 18 were grouped as cluster 2 (Fig. 4).

Further analyses started with the curves of cluster 1: The curves to be cross-dated were visually compared and grouped based on their best fit, i.e., the offset of the outermost ring. Samples showing high visual similarities were arranged in small groups. If a curve had high visual similarities with curves in different groups, the curve was added to all of these subgroups. Thus, a single sample could belong to several different groups. The same procedure was then applied to the samples of cluster 2.

The cross-dating process was then applied in two steps for each leveé (Figs. 5 and 6) and began within the groups of the samples of cluster 1 beginning with the curves showing the highest CDI-value (cross-dating step 1, Fig. 4).

Two main problems occurred during the cross-dating process. First, only small sections of the curves (5–15 years) matched. Although the curves might have matched in more than one section, longer and unequivocally fitting sequences were very rare. Second, missing rings rarely had a clear insertion point, so it would have been possible to insert too many rings. To prevent the involuntarily assemblage of a compatible curve, an upper limit of 5–6 missing rings (for insertion into each curve) was set. This limit was defined by cross-dating 32 radii on several thin sections of one plant, taking into consideration that the cross-dated samples did not always end in 2015. The 32 radii of these sections showed a high similarity when shifted to their common measuring starting point (the pith). Nevertheless, 1–6 missing rings had to be added to match the other measurements. Therefore, we implemented the missing ring limit of 5–6 rings.

After the first cluster was cross-dated, the samples were either assigned to a final group or set aside for further testing. If further cross-dating failed, the curves were excluded (Fig. 4).

When the cross-dating procedure of cluster 1 was finalized, the samples of cluster 2 were cross-dated with the newly established group mean chronologies. When the samples of one group were successfully cross-dated a new group mean chronology was created. As a final step (cross-dating step 2), the mean curves of each group were cross-dated and a chronology for each debris-flow leveé was created.

Due to the heterogeneity of the track’s leveé chronologies and the high number of inserted missing rings, we did not attempt to create a full site chronology. Instead, the relationship between the growth position on a leveé and the plant age was graphically and statistically analyzed, as was the relationship between the tracks and the age distribution of *Dryas octopetala*. For the graphical analysis, samples were plotted in a scatterplot as functions of age and distance to the bottom of the debris flow track (growth position). The spread of the samples was then observed visually. The statistical analysis was achieved using the Pearson correlation test in R.

### 4. Results

#### 4.1. Cross-dating

Of the initial 190 plants only 119 could be cross-dated. On the leveé R1-L 60.6 % of the samples were crossdated and included in the track’s leveé chronology. The percentage of cross-dated samples on the other
Fig. 5. Ring-width measurements (crossdated) of the single radii are displayed for each slope (left and right) of the three debris-flow tracks. Single radii are displayed in grey; the black curves represent the mean chronologies.

Fig. 6. Mean chronologies for each of the analyzed slopes and debris-flow tracks. The continuous lines in the plot represent the left slopes. The right slopes are plotted with dashed lines. Open triangles indicating positive pointer years, filled triangles indicating negative pointer years appearing on all levees.
track’s levees were similar: 66.7%, 64.5%, 54.3%, 62.1% and 69.1% on the debris-flow track’s levees R1-R, R2-L, R2-R, R3-L and R3-R respectively. The percentage of the samples that were excluded during the crossdating process varies: 18.2% for R1-L, 24.2% for R1-R, 16.1% for R2-L, 11.4% for R2-R, 6.9% for R3-L and 24.1% for R3-R.

The number of missing rings (MR) inserted into the raw chronologies of the shrubs from R1-L ranged between 1 and 3, with only two exceptions, for which 5-6 rings were inserted. In the curves of the right slope (R1-R), up to 5 MR were inserted during the first cross-dating (cross-dating step 1, Fig. 4). The dwarf shrubs on R2-L had the highest number of MR. The sample R2-L009 had 7 MR, and 50% of all shrubs on this slope needed 4 or more rings to be inserted in order to be successfully cross-dated. On the other slopes (R2-R, R3-L and R3-R), the number of MR was seldom higher than 4. On R2-R, four shrubs had 5-6 MR; only one sample had 5 MR on R3-L. The remaining shrubs required the insertion of less than 5 MR to be successfully cross-dated.

During step 2 of the cross-dating process (Fig. 4), the means of the most similar samples were used to cross-date the remaining samples. The maximum number of MR added during this second cross-dating was 9 rings; only four samples in the track with the oldest plants (R1) required the insertion of this many MR (see chapter 4.2). The other shrubs needed 0-6 MR to build a slope chronology. Samples on the right slopes of tracks 2 and 3 required the fewest MR insertions (0-3 MR).

Overall, the percentage of MR, as a result of both cross-dating processes, reached a maximum of 18.5% in a sample of R1-L. The minimum percentage of MR was 0%, which was measured in two R3-R samples.

A visual analysis of the chronologies yielded only six pointer years that all plants had in common: 2006, 2005, 1997, 1996, 1934, and 1933 (see Fig. 6). The years 1933, 1997, and 2005 show wide rings, while the years 1934, 1996, and 2006 have narrow rings. If the singular debris-flow track’s slopes are inspected separately a few other particularly wide/narrow rings stand out: The most noticeable positive pointer years were 1946, 1949, and 1956, as slope of the track R3-L show a period of increased growth between 1963 and 1925 and 1929 in the longest (R1-R) chronology. The plants on the right slope of R2 had the largest age span (69 years); the left slope had an age range more similar to that of R1-L, R1-R and R3-R. The plants growing on R3-L were the most similar in age, with a difference of only 27 years between the oldest and youngest plants. The mean values of the slopes R1 and R2 only showed a gap of 4.25 years and 5.96 years, respectively. The mean age of the slopes R3-L (49.5 years) and R3-R (42.35 years) showed a higher difference. The mean values between the tracks were different. Track R2 had the highest average plant age, whereas R3 had the lowest. The average plant age in R1 was closer to that in R2 than in R3 (Fig. 7).

### 4.3. Relationship between age and growth position

The relationship between the age of the shrubs and their position on the slope is shown in Fig. 8. The position is defined by the distance between the plant growth site and the middle part of the debris flow track. Each plot represents a track slope. No clear trend is recognizable

#### Table 2

Correlations (p-values) between the slope chronologies (left and right) for each of the channels (R1, R2, and R3).

|          | R1-L | R1-R | R2-L | R2-R | R3-L | R3-R |
|----------|------|------|------|------|------|------|
| R1-L     |      | 0.04*| 0.01*| 0.00*| 0.84 | 0.29 |
| R1-R     | 0.04*|      | 0.02*| 0.21 | 0.52 | 0.61 |
| R2-L     | 0.01*| 0.02*|      | 0.44 | 0.82 | 0.89 |
| R2-R     | 0.00*| 0.21 | 0.44 |      | 0.49 | 0.33 |
| R3-L     | 0.84 | 0.52 | 0.82 | 0.49 |      | 0.36 |
| R3-R     | 0.29 | 0.61 | 0.89 | 0.33 | 0.36 |      |

Fig. 7. Plant-age distribution along the levees (channel slopes). Left slopes are shown in light gray; right slopes are shown in dark grey. As the data do not show any outliers, the whiskers represent the minimum and maximum ages.
because the point clouds are scattered. Statistically, the relationship between the age and the position of the plants on the slopes does not show any correlation. The \( p \)-values of the Pearson correlation test are higher than 0.05, so the variables do not correlate. Nevertheless, a few patterns can be detected. The data points in R1-L, R1-R, R3-L, and R3-R appear slightly more clustered than they are in the R2-L and R2-R plots. The age intervals, in which most of the points are found, are about 50 years (40–90a) in both plots of R1. In R3, the intervals are narrower, 35–55a on the left and 30–60a on the right levee (compare Fig. 7).

The plant positions in R1-L seem to be limited at three height intervals above the track bottom (50 cm–200 cm; 300–400 cm, and 525–625 cm). R1-R, R3-L, and R3-R mostly lack samples near the center of the track. Note that the flowing stream in the center of the R3 track accounts for the lack of plants in this area.

The lower number of samples in the lower parts of the levees can also be observed in the plots of R3-L and R3-R. Nevertheless, plant cover in the upper parts of the levee plots is generally equally distributed. In R2-R, the samples show a wide age range across the slope.

The highest number of old plants were found in R2, namely between 100 and 250 cm from the middle of the track in R2-L. R2-R does not show any pattern regarding the distribution of plants of different ages.

5. Discussion

5.1. Cross-dating the dwarf shrub Dryas octopetala

The measured radii showed heterogeneous variations in ring width (Fig. 5). The measured chronologies rarely had unequivocally matching sections. Nevertheless, it was possible to cross-date the plants of each slope. The biggest challenge in this process was the insertion of MR. Since no other studies on these shrub species were found, it was not possible to assess whether this plant commonly has a high number of MR. Therefore, the difficulty lies in knowing when to stop trying to match curves.

It would be possible to develop mean chronologies for each track or even for the whole site, but the number of additional MR would result in many consecutive sequences. Nearly every second ring would be a MR, so the chronology would be largely artificial. The cross-dated radii
already resulted in an increase of age of nearly 20%.

Comparable results were found for other shrub species before. Bär et al. (2007) documented the challenges resulting from the insertion of missing rings. In their study they state to have 0–4 inserted MRs in Empetrum hermaphroditum, yet Blok et al. (2011) did not find any MR in their samples of Betula nana. Similar cross-dating problems are described by Au (2006), who dealt with Dryas integrifolia L., but no exact quantity of MR was given.

Myers-Smith et al. (2015) discussed the importance of using minimum-age dating to find the oldest plant at the site; as height and stem thickness seldom correlate with shrub age, it is rarely possible to compare ages visually. We found this to be true for Dryas octopetala, the appearance of which does not necessarily correlate with its age. The diameter of older samples, for example, was often found to be smaller than that of some younger samples, so ring counting was necessary to confirm age. The lack of any immediate indicators of age further argues for a larger sample number.

Without a clearer understanding of the growth within the plant, it is challenging to complete a chronology because of the high variability of ring width around the stem and the high number of wedging and missing rings. Therefore, this study followed the guideline ‘as many as needed and as few as possible’ during the cross-dating process.

5.2. Cross-dating challenges

Ring-width measurement was challenging due to the very irregular, eccentric, and sometimes extremely narrow rings of mountain avens. The semi-ring-porous structure of the vessels provided support during the ring detection process. It further allowed us to recognize the partly missing rings (PMR), which were ‘hidden’ between the rings. However, this structure can also have a misleading effect on the identification of ring boundaries when vessel sizes vary within a ring (Au and Tardif, 2007; Bär et al., 2006; Schweingruber and Poschlod, 2005). To reduce the potential for misinterpretation, a frequent change of perspective (e.g., changes in magnification) was applied.

Owczarek (2010) and Myers-Smith et al. (2015) both noted that the maximum number of rings is generally found between the roots and the branches. This observation was also made for the Dryas octopetala when twelve sections of one plant were analyzed. Consequently, the position from which a thin section was taken can further influence the cross-dating process. Schweingruber and Poschlod (2005) described the perfect location as the transition zone between the shoot and the root collar, or the so-called root/shoot intersection; this is the position from which the shrubs were sampled in this study. If the position where the thin section was taken would not correspond to the described position, the age is underestimated. However, there is no possibility of recognizing where this position is located based on the appearance of a stem. Thus, there is a high probability that the thin sections do not reflect the maximum age of the plants. Although it is not known how strong the ring variation within the stem-root collar is, it is possible that this ring-difference between the various slides influenced the number of missing rings and thus the cross-dating results. The number of MR and PMR might vary depending on where the thin section sample was taken.

Owczarek (2010) resolved this problem by taking 4–7 thin sections from all points along the branches, stem, and roots of the studied shrub, as well as by measuring along multiple radii. The same serial-sectioning approach was suggested by Myers-Smith et al. (2015). A similar procedure as Owczarek (2010) implemented with one plant. The comparison of the measured radii showed a very high growth heterogeneity not only within a section but also between the different sections through the dwarf shrub. While we assessed the minimal-dating potential of the Dryas octopetala, we refrained to perform a more specific serial sectioning. For a more accurate dating and for potential climate reconstructions, however, a more precise study of the inner plant ring and growth variation is needed.

5.3. Spatial distribution of Dryas octopetala

Although no slope patterns could be assessed by analyzing the plant age distribution, the age-distribution between the track slopes seems relevant to determine the frequency of different debris-flow events. The oldest shrubs define the minimum time since the last event occurred at this location. As noted in Section 3.1, the mean ages show a clear trend: the slopes of track R2 are the oldest (undisturbed for the longest time) followed by the slopes of R1 and R3. No clear trend could be determined from the samples of one specific slope. Dryas octopetala plants grow randomly over the vertical extent of the slopes of the tracks. It can therefore be assumed that no larger event has occurred within the individual tracks since the plants colonized the slopes.

5.4. Reconstruction of debris-flow events using Dryas octopetala

The oldest plant in the track defines the minimum amount of time that has passed since the last debris-flow event (Owczarek et al., 2013). The oldest plant at our study site was found on the left slope of R2, which we assumed to be the oldest on account of its denser vegetation cover. Before cross-dating, the oldest plant in R2 had 105 rings; after cross-dating, it had 116 rings. Therefore, the oldest debris-flow event at our study site occurred at least 116 years before the sampling. This finding coincides with the results of other studies showing that with the end of the little ice age many alpine areas showed an increase or at least a change of geomorphic process activity at the turn of the 19th and 20th century (Cury et al., 2006; Stoffel et al., 2005). This age is remarkable, as the oldest Dryas octopetala plant ever documented had 108 rings (Büntgen et al., 2015; Schweingruber and Poschlod, 2005).

In the central track (R1), the oldest Dryas octopetala sample had 90 rings; in track R3, the oldest sample a maximum age of 70 years. This dating allowed for the determination of a chronology of three events. At the end of the 19th century, a debris flow occurred, creating track R2. During the middle of the 1920s, a second debris flow probably broke through track R2. About 20 years later, a final debris-flow shaped the track R3 and, breaking through the right ridge of R1, created a connection between the two adjacent tracks. Since we do not know anything about the plant succession of Dryas octopetala (Muller, 1952) in this area, it remains unclear whether track R3 was created by the same event as R1 or whether it resulted from a later event.

As shown in the site description, the vegetation density increases in the sampling area from track R3 to R2. This order corresponds with the determined age-order of the tracks. As noted by Stoffel and Bollschweiler (2008), the dating approach remains an approximation of the event date due to the unknown time period between the event and the reestablishment of plants.

6. Conclusion

The analysis of dwarf shrubs is challenging due to the irregular, extremely narrow, and partially missing structure of the rings. In addition, the sample preparation process is relatively time-consuming. However, Dryas octopetala is a pioneer plant that is commonly found on calcareous ground in formerly glaciated areas or areas shaped by strong slope processes in mountain and the Arctic. It therefore has a high potential for dendrogeomorphological and dendroecological studies. Although missing rings occur frequently in the analysis of Dryas octopetala, we were able to establish chronologies.

The position on the plant from which thin sections are made, the relevance of PMR, and the irregular structure of the rings complicate the dating process. The unknown inner structure of the dwarf shrub, the growth behavior of mountain avens, and the factors influencing ring development need to be analyzed further. This can be achieved by applying serial sectioning to the plant (Kolišchuk, 1990). Further and more accurate studies of the local growth (with a sampling distance <10 cm) within the stem, the roots and the branches might help improve the
cross-dating process and the formation of a full chronology. **Drys octopetala** can be used to obtain the minimum age of debris-flow events, and to determine their sequence. This work suggests that more samples might improve the results, as many plants have a compartmentalized area or are partly twisted. Despite the usefulness of measuring and cross-dating samples, we expect further studies of **Drys octopetala** to reveal more about their inner ring structure and usefulness for dendrochronological research.

**Declaration of Competing Interest**

The authors report no declarations of interest.

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**References**

Arbelay, E., Bollschweiler, M., Stoffel, M., 2010. Dendrogeomorphic reconstruction of past debris-flow activity using injured broad-leaved trees. Earth Surf. Process. Landf. 35, 399–406.

Au, R., 2006. Dendroecology of the Dwarf Shrub Dryas integrifolia Near Churchill, Manitoba. Doctoral dissertation. Department of Biology, University of Winnipeg. Au, R., Tartif, J.C., 2007. Allometric relationships and dendroecology of the dwarf shrub Dryas integrifolia near Churchill, subarctic Manitoba. Can. J. Bot. 85, 585–597.

Baccini, M., Zannoni, A., 2003. Relations between rainfall and triggering of debris-flow: case study of Cancri (Dolomites, Northeastern Italy). Nat. Hazards Earth Syst. Sci. 3, 71–79.

Bir, A., Braunung, A., Löffler, J., 2006. Dendrochronology of dwarf shrubs in the high mountains of Norway—a methodological approach. Dendrochronologia 24, 17–27.

Bir, A., Braunung, A., Löffler, J., 2007. Ring width chronologies of the alpine dwarf shrub Empetrum hermaphroditum from the Norwegian mountains. IAWA J. 28, 325–338.

Baumann, F., Kaiser, K.F., 1999. The multetta debris fan, eastern Swiss Alps: a 500-year geochronology. Zeitschrift für Alpinologie 29, 1–28. Bacchini, M., Zannoni, A., 2003. Relations between rainfall and triggering of debris-flow: case study of Cancri (Dolomites, Northeastern Italy). Nat. Hazards Earth Syst. Sci. 3, 71–79.

Birrer, H., Heinrich, I., 2013. Dendrogeomorphic assessment and sediment transfer of natural and mining-induced debris-flow activity in Cancia (Dolomites, Northeastern Italy). Nat. Hazards Earth Syst. Sci. 3, 312–327.

Blok, D., Sass-Klaassen, U., Schaepman-Strub, G., Heijmans, M.M.P.D., Sauren, P., Hallinger, M., Manthey, M., Wilmking, M., 2010. Establishing a missing link: warm summers and winter snow cover promote shrub expansion into alpine tundra in Scandinavia. New Phytol. 186, 890–899.

Bordt, M., Metslaid, S., Kiviste, A., 2009. Response of Scots pine (Pinus sylvestris L.) radial growth to climate factors in Estonia. Balt. For. 15, 195–205.

Boleslawski, M., Sæmundsson, Th., 2007. Spatial and temporal diversity for debris-flow and plant–pollinator interactions in response to delayed snow melt and simulated warming. Environ. Res. Lett. 11, 1–12.

Kepler, U., 1938. Zur Geologie der Ortlergruppe und zur Stratigraphie der Ortlertzone. Gebiete zwischen Sulden und dem Endalp, Zürich: Buchdruckerei Fluntern.

Kolisch, V.G., 1990. Dendroclimatological study of prostrate woody plants in the Alps. In: Cook, E.R., Kairiukstis, L.A. (Eds.), Methods of Dendrochronology: Applications in the Environmental Sciences. Kluwer Academic Publishers, Dordrecht, pp. 51–55.

Kothenbeutel, K., Tölland, O., 2018. Impacts of future climate change (2030–2059) on debris flow hazard: A case study in the Upper Minijiang River basin, China. J. Sci. 15 (8), 1836–1850.

Lim, M., Strzelecki, M.C., Kasprzak, M., Swida, Z.M., Webster, C., Woodward, J., 2020. Arctic rock coast responses under a changing climate. Remote Sens. Environ. 236, 111500.

Malik, I., Wintuba, M., Opala, M., Frank, M., Woskowicz-Szabik, B., Manycz, G., Tyrol, C., 2015. Historical water-powered ferrous metallurgy reconstructed from treering and laccustrine deposits (Mala Panew basin, southern Poland). Geochronometria 42, 79–91.

Montbaurer, K., Kaitna, R., Prenner, D., Harchowitz, M., 2018. The temporally varying roles of rainfall, snowmelt and soil moisture for debris flow initiation in a snow-dominated system. Hydrolog. Earth Syst. Sci. 22, 3493–3513.

Muller, C.H., 1952. Plant succession in arctic heath and tundra in northern Scandinavia. Bull. Torrey Bot. Club 296–309.

Myers, A.C., H. Hallinger, M., Cook, D., Sass-Klaassen, U., Rayback, S.A., Weijers, S., Trant, A.J., Tape, K.D., Naito, A.T., Wipf, S., Rixen, C., Dawes, M.A., Wheeler, J.A., Buchwal, A., Baittinger, C., Macias-Fauria, M., Forbes, B.C., Levesque, E., Boulanger-Lapointe, N., Beil, I., Ravalainen, V., Wilmking, M., Forbes, B.C., 2018. Impacts of future climate change (2030–2059) for debris flow hazard: A case study in the Upper Minijiang River basin, China. J. Sci. 15 (8), 1836–1850.

Nybackken, L., Kalanderud, K., Totland, Ø., 2009. Simulated environmental change: Dendrogeomorphic effects of contrasting defoliation severity on compound concentration in three alpine plant species. Arct. Antarct. Alp. Res. 40, 709–715.

Ouwecarz, P., 2010. Dendrogeomorphological dating of geomorphic processes in the High Arctic. Landl. Anal. 14, 45–56.

Ouwecarz, P., Latocha, A., Wintuba, M., Malik, I., 2013. Reconstruction of modern debris flow activity in the arctic environment with the use of dwarf shrubs (south-western Spitsbergen) – a new dendrogeomorphological approach. Zeitschrift für Geomorphologie 57, 75–95.

Pavllova, I., Jomelli, V., Brunstein, D., Gancher, D., Martin, E., Déqué, M., 2014. Debris flow activity related to recent climate conditions in the French Alps: a regional reconstruction. Geomorphology 248–255.

Piper, S.J., Loewen, V., Gill, M., Johnstone, J.F., 2011. Plant responses to natural and experimental variations in temperature in Alpine Tundra, Southern Yukon. Canada. Sens. Environ. 236, 111500.

Piper, S.J., Loewen, V., Gill, M., Johnstone, J.F., 2011. Plant responses to natural and experimental variations in temperature in Alpine Tundra, Southern Yukon. Canada. Sens. Environ. 236, 111500.

Renger, H., Schweingruber, F.H., 2013. Microscopic Preparation Techniques for Plant Stem Analysis. Verlag Dr. Lensel, Remagen-Bonn.

Renger, H., Liciuchietti, S., Schum, B., 2015. A new needle microtome to combine wood anatomy and tree-ring ecology. IAWA J. 36, 452–459.

Romer, R., Birk, A., Heinrich, I., Gartner, H., 2013. Wood anatomical analysis of Swiss willow (Salix Helvetica) shrubs growing on creeping mountain permafrost. Dendrochronologia 31, 97–105.

Gers, E., Florin, N., Gartner, H., Glade, T., Dikau, R., Schweingruber, F.H., 2001. Application of shrubs for dendrogeomorphological analysis to reconstruct spatial and temporal landslide movement patterns. A preliminary study. Zeitschrift für Geomorphologie 125, 163–175.

Gilleip, M.A.K., Bagnessen, N., Cooper, E.J., 2016. High Arctic flowering phenology and plant–pollinator interactions in response to delayed snow melt and simulated warming. Environ. Res. Lett. 11, 1–12.

Gartner, H., Schweingruber, F.H., 2013. Microscopic Preparation Techniques for Plant Stem Analysis. Verlag Dr. Lensel, Remagen-Bonn.

Gartner, H., Liciuchietti, S., Schum, B., 2015. A new needle microtome to combine wood anatomy and tree-ring ecology. IAWA J. 36, 452–459.

Gartner, H., Schweingruber, F.H., 2013. Microscopic Preparation Techniques for Plant Stem Analysis. Verlag Dr. Lensel, Remagen-Bonn.

Gartner, H., Schweingruber, F.H., 2013. Microscopic Preparation Techniques for Plant Stem Analysis. Verlag Dr. Lensel, Remagen-Bonn.
temperature sensitivity of plant phenology at colder sites: implications for convergence across northern latitudes. Glob. Chang. Biol. 23, 2660–2671.

Rinn, F., 2012. TSAP-winTM Professional. Zeitanalyse und Präsentation für Dendrochronologie für verwandte Anwendungen. Version 4.5 für Microsoft Windows. Benutzerhandbuch. Rinntech, Heidelberg.

Ryberg, M., Larsson, E., Molau, U., 2009. Ectomycorrhizal diversity on Dryas octopetala and Salix reticulata in an alpine cliff ecosystem. Arct. Antarct. Alp. Res. 41, 506–514.

Schweingruber, F.H., Poschlod, P., 2005. Growth Rings in Herbs and Shrubs: life span, age determination and stem anatomy. Forest Snow and Landscape Research 79, 195–415.

Szymczak, S., Bollschweiler, M., Stoffel, M., Dikau, R., 2010. Debris-flow activity and snow avalanches in a steep watershed of the Valais Alps (Switzerland): dendrogeomorphic event reconstruction and identification of triggers. Geomorphology 116, 107–114.

Trappmann, D., Corona, C., Stoffel, M., 2013. Rolling stones and tree rings: a state of research on dendrogeomorphic reconstructions of rockfall. Prog. Phys. Geogr. 37, 701–716.

Zischg, A.P., Fuchs, S., Keiler, M., Stötter, J., 2005. Temporal variability of damage potential on roads as a conceptual contribution towards a short-term avalanche risk simulation. Nat. Hazards Earth Syst. Sci. 5, 235–242.