Unveiling the avalanche activity in the Upper Goms Valley (Switzerland) over the past 400 years using tree-ring records

Sébastien Guillet[1]; Markus Stoffel[1]; Christophe Corona[2]

ABSTRACT

Knowing the spatial extent of past high magnitude snow-avalanches on poorly documented forested slopes is essential for land planners as it may help to define with better accuracy avalanche hazards maps. Dendrogeomorphology has proven to be an efficient method to reconstruct spatio-temporal activity of snow avalanches on forested slopes for which limited historical avalanche records are available. Based on tree-ring records, we reconstructed avalanche activity over the past 400 years for two slopes located above the village of Oberwald in the Upper Goms Valley (Valais, Switzerland). This high resolution chronology is, to date, one of the longest records ever elaborated for the Swiss Alps. 566 trees presenting growth disturbances related to avalanche activity have been sampled and analyzed. Analyses of tree-ring growth disturbances allowed identification of 38 events and the mapping of their spatial extent for the period 1600-2014. 12 snow-avalanches traveled through the slopes and stopped at or very close to the valley bottom in 1689, 1720, 1793, 1813, 1880, 1937, 1951, 1999, and 2003.

KEYWORDS

snow-avalanches; tree-rings; dendrogeomorphology; forested slopes

INTRODUCTION

Snow avalanches are a major natural hazard in the Swiss Alps. Every year, they affect transport infrastructure and may endanger settlements and threaten human life. Over the last century, urban sprawl in mountains areas of Switzerland in combination with growing demands for mobility and recreational activities have increased avalanche risk significantly. In a society with ever increasing avalanche risk and safety expectations, risk acceptance of modern societies has been equally decreasing over recent decades. Substantial efforts have therefore been deployed over the last decades to build databases listing past avalanche events and providing accurate information regarding their magnitude, spatial extent and return period. However, for most of the Swiss Alps historical records of past avalanche activity are sparse and scarce before the 20th century. Past avalanche activity is especially poorly

1 Dendrolab.ch, Institute of Geological Sciences, University of Berne, SWITZERLAND, sebastien,guillet@dendrolab.ch

2 Geolab, Université Blaise Pascal, 4 rue Ledru F-63057 Clermont-Ferrand, FRANCE

documented in the Upper Goms valley (canton of Valais) where no long chronologies of snow avalanches currently exist.
Dendrogeomorphology is the science using information contained in tree rings to reconstruct the activity of past natural hazards in time and space. On forested slopes, this approach has proven successful to compensate for the scarcity of written sources (Corona et al., 2012). Over the past 40 years, several dendrogeomorphic studies have indeed demonstrated that trees impacted by mass movements, such as avalanches, landslides, rockfall or debris flows, record the event in the form of growth disturbances (Stoffel and Bollschweiler, 2008). Since trees form one increment ring per year in temperate climates it is possible to date the occurrence of the geomorphic process with an annual resolution.

Trees growing in the upper Goms valley are particularly suitable for dendrogeomorphic analyses. Indeed the upper Goms valley holds some of the oldest forest stands of Switzerland, thus offering a unique opportunity and first-hand information to document past avalanche activity over several centuries. In 2013 the Canton of Valais mandated the dendrolab.ch to perform an important study with the goal of reconstructing spatio-temporal avalanche activity on several slopes located on the south-facing side of the Goms Valley (Oberwald, Geschinen, Münster). Here we present the results of the dendrogeomorphic study for two avalanche paths located above the village of Oberwald.

METHODS

Study site: The Oberwald avalanche paths (46°32’N, 8°20’E) are located on the south-facing slope of the upper part of the Goms Valley in the Swiss Central Alps (Canton of Valais, Switzerland, Figure 1A-D). According to the nearby weather station of Ulrichen (46°5’N, 8°31’E, 1346 m asl), annual temperature is 3.3°C for the period 1981-2010 and annual precipitation amounts to 1212 mm. Winter temperature (DJF) is -6.6°C while winter precipitation amounts to 300 mm. Between November and April precipitation falls primarily as snow and average annual snowfall reaches 578 cm for the period 1999–2010 (MeteoSwiss, 2014). At the study site, snow avalanches are commonly triggered from several non-forested release zones located between 1680 and 2200 m asl. The forested slope located underneath the starting zones is mainly composed of European larch (Larix decidua) and Norway spruce (Picea abies) and can be subdivided into two units.

The first unit (OB1) is a vast area (68 ha) extending from the Jostbach torrent to the Rätischbach torrent. The canton of Valais has defined 6 main avalanche tracks within this slope (Figure 1C). OB1 is characterized by a double segmentation. Between 1900 and 1680 m, the slope profile is characterized by gentle slopes (15° on average). Below 1680 m, slope angles increase significantly and exceed 20°. We therefore assume that new avalanches can be triggered from these locations. This hypothesis is further supported by several rows of avalanche barriers put in place by cantonal authorities in this portion of the slope to stabilize snowpack and to prevent the release of avalanches.

The second unit (OB2) extends from the Rätischbach torrent to the Restaurant Rhonequelle (61 ha). Three main avalanche paths have been defined by the Canton of Valais for this sector (Figure 1C). In 1951, due to the damages caused to three houses after the release of an avalanche, a deflecting barrier was built in the runout zone of the three avalanches paths to protect the village. The Oberwald avalanche tracks do not only pose a direct threat to the village of Oberwald, they also menace the Matterhorn-Gotthard Bahn (MGB) railway line connecting Brig (Canton of Valais) to Andermatt (Canton of Uri).

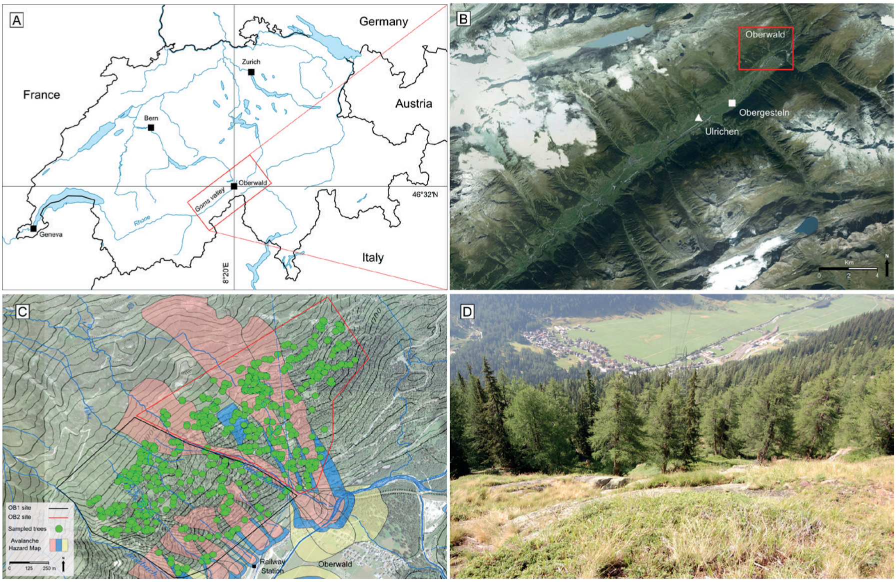

Figure 1: Location of the study site in (A) Switzerland and (B) in the Goms Valley. (C) Spatial distribution of the sampled trees. The black and red squares respectively refer to the spatial extent of the sites OB1 and OB2. The colored areas represent the hazard map defined by the canton of Valais. Red indicates an area that is exposed to considerable danger with frequent avalanches (average return period of 30 years or less). In the blue colored area, avalanches are less frequent (more than 30 year average return period) and accompanied by only small compression forces of less than 30 kN/m^2. The danger in the yellow area is low. Yellow is typically used to designate the runout zone of powder avalanches. (D) Photograph illustrating the investigated avalanche paths.

Sampling strategy: A total of 566 trees (1140 increment cores, 10 cross sections) have been sampled during the summers of 2013 and 2014 (Figure 1C). A minimum of two cores were extracted per tree, one perpendicular to the slope and one in the downslope direction. GPS coordinates were recorded for each tree with 5 m precision. Trees presenting obvious evidence of snow avalanches, such as decapitation, tilting and injury, were preferentially targeted. Following the recent recommendations made by Stoffel et al. (2013) and Stoffel and Corona (2014), we selected old trees in order to extend the reconstruction of past avalanche events as far as possible but also considered younger trees to take account of the loss in sensitivity of older trees to record damage (Šilhán and Stoffel, 2015). Trees located close to sectors with intense forest management activities (logging) were not sampled to avoid the inclusion of growth disturbances not related with avalanche activity in the final avalanche reconstruction.

Laboratory analyses: All samples were prepared following standard dendrochronological procedures (Bräker, 2002). Cores were mounted on wooden sticks and then polished with sandpaper. Tree rings were counted and analyzed using a LINTAB-5 positioning table connected to a Leica stereomicroscope. Individual tree-ring series were cross-dated using two local reference chronologies (Büntgen et al., 2006, Schweingruber, 1974) so as to correct our series for possibly missing rings. In a second step, all cores were visually inspected under a binocular to identify growth disturbances (GD) induced by snow avalanches. Typically the reactions most commonly observed in tree rings following an avalanche event are: (1) an abrupt growth suppression (GS) following apex loss or the break-off of branches, (2) the formation of compression wood (CW) after tilting of the trunk, (3) the production of callus tissue (CT) and tangential rows of traumatic resin ducts (TRD) after an impact . We assigned a score to each GD following the recommendations made by Kogelnig-Mayer et al. (2011) to distinguish between weak (intensity class 1), medium (intensity class 2), and strong (intensity class 3) reactions and clear evidence of injuries (intensity class 4).

Reconstruction of avalanche events: After the identification and the dating of the ***GD***, we developed the avalanche reconstruction using the weighted index factor (***Wit***) developed by Kogelnig-Mayer et al. (2011). The Wit gives a weight to each ***GD*** based on its intensity. It is expressed as follows:

$$Wit = \left[\left(\sum_{i=1}^{n} GDI4 * 7\right) + \left(\sum_{i=1}^{n} GDI3 * 5\right) + \left(\sum_{i=1}^{n} GDI2 * 3\right) + \left(\sum_{i=1}^{n} GDI1 * 1\right)\right] * \frac{\sum_{i=1}^{n} R_t}{\sum_{i=1}^{n} A_t}$$

where ***GDI*** (1 to 4)= Sum of trees showing clear evidence of injury (intensity class 4), strong reactions (intensity class 3), medium signals (intensity class 2), weak signals (intensity class 1), respectively.

R_t = Total amount of trees reacting in year t.

A_t = Number of sampled trees being alive (sample size) in year t.

All the years with ***Wit*** ≥1 were considered as avalanche events. In addition, and in order to be sure that the thresholds chosen were not too restrictive, we also carefully examined all years with a 0.8≥ ***Wit*** ≤1. The inclusion of avalanche events in the database did not only rely on the Wit index, but was also based on the spatial distribution of impacted trees. When the spatial pattern of affected trees is not meaningful (in terms of avalanche trajectory), we rejected events even if the ***Wit*** ≥ 1 criteria was clearly fulfilled.

In a last methodological step, we attempted to assess the detection of past events and to separate signal from noise. Noise is defined here as all growth disturbances that cannot be related to avalanche activity but to insect outbreaks. In the Goms valley and more widely in the Alps, larch trees have been documented to suffer from larch budmoth (Zeiraphera diniana Gn.) outbreaks such that tree growth remains suppressed for several years (Esper et al., 2007). Since growth suppression is also typical in trees with decapitation, a careful analysis of the nature of the damage and the distribution of affected trees needs to be performed. We used several databases recording larch budmoth outbreaks in the Swiss Alps and in the Goms valley in particular to this end (Weber et al., 1997; Baltenschweiler and Ruby, 1999; Esper et al., 2007). All the years with a ***Wit*** ≥ 0.8, matching with documented larch budmoth year and presenting 80% of GS but almost no evidence of TRD, CW, or injuries were thus considered as dubious and removed from the final tree-ring based avalanche reconstruction.

RESULTS

Age structure of the stand: The average age of trees sampled at OB1 amounts to 217 years (SD: 105 yrs) with the oldest individual dating back to AD 1429 and the youngest tree reaching sampling height in AD 1987. A total of 51 (16) trees were at least 300 (400) yrs old. At OB2, the mean age of sampled trees is 196 yrs (SD: 120 yrs). A total of 54 (10) trees were at least 300 (500) years old. The oldest trees sampled at OB2 date back to 1495, 1478, 1464, 1452, 1449, 1434, and 1429, respectively. The youngest tree dates back to 1998. For both sites, the distribution of the oldest larches suggests that there was no event of sufficient magnitude to destroy larger parts of the forest stands for at least 300 years.

Reconstruction of snow avalanche events: Analysis of the 566 trees revealed 2590 GD. Abrupt growth suppressions and TRD represent the most frequently observed source of evidence of past events with 1270 (49%) and 1170 (45%) occurrences in the tree-ring series. By contrast, compression wood and injuries were by far less frequently observed on the increment cores with respectively 94 (3%) and 55 (2%) observations.

At OB1, analysis allowed reconstruction of 14 snow avalanche events for the period 1689–2014, namely in 1982, 1948, 1945, 1937, 1935, 1925, 1906, 1894, 1880, 1870, 1842, 1800, 1793, and 1689. The years with the largest amount of responses and/or the highest Wit values were 1793 (Wit=4.7), 1880 (Wit=3.3), 1842 (Wit=2.2), 1906 (Wit=2.19), and 1689 (Wit=1.97), (Figure 2A-B). As a result of the limited number of samples reaching back beyond 1670 (<30 trees), we were not able to determine snow avalanches and their spatial extent prior to the mid-17th century, despite the fact that several trees point to avalanche events in the 15th and 16th centuries. In addition, and as a result of the somewhat smaller Wit, 1995 (Wit=0.86) and 1990 (Wit=0.86) could not be determined as avalanche years with the same level of confidence, so that they were recorded in the series as possible events.

At OB2, we identified a total of 18 snow avalanches between AD 1605 and 2014, namely in 2003, 1999, 1975, 1966, 1945, 1937, 1919, 1912, 1882, 1880, 1846, 1813, 1803, 1793, 1692, 1650, 1641, and 1605. The largest number of disturbances and/or the highest Wit values were recorded in 2003 (Wit=5.3), 1999 (Wit=3.3), 1937 (Wit=8.7), 1882 (Wit=3.2), 1880 (Wit=12), 1813 (Wit=2.7), and 1641 (Wit=2.7). Again, four snow avalanches could not be determined as event years with the same level of confidence and were therefore recorded as possible events (1961, 1885, 1734 and 1681), (Figure 2C-D).

Based on the criteria introduced earlier and the fact that they match with periods of known larch budmoth outbreak activity, the years 1581, 1599, 1909, 1910, 1953, 1954, 1955 and 1981 were disregarded in the snow avalanche reconstruction. In addition, we also decided to reject 1986 from the OB1 avalanche reconstruction as the spatial distribution of the trees impacted during this year exhibited a pattern which is unlikely to stem from an avalanche.

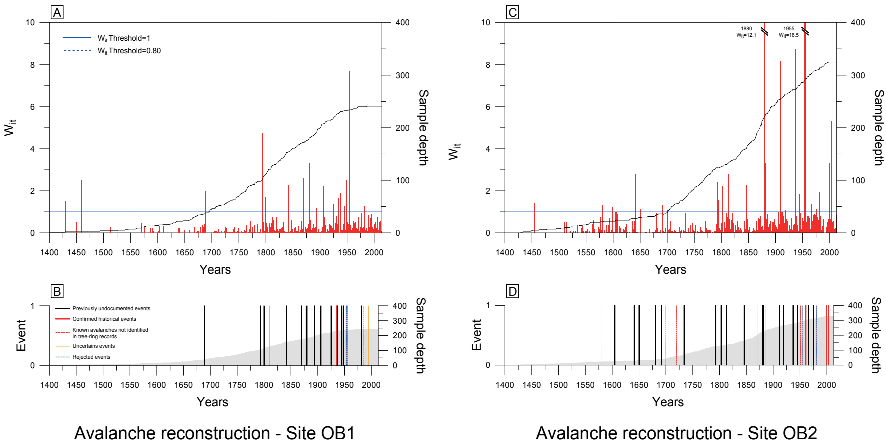

Figure 2: Event-response histograms showing avalanche induced growth responses from sampled trees at OB1 and OB2: (A) Preliminary avalanche chronology obtained at OB1 using the Weighted Index method (Wit). After additional analysis (see methods), 3 years (1954, 1955 and 1986) were removed from the final tree-ring based avalanche reconstruction. (B) Final avalanche chronology covering the period 1605-2014 at OB1. (C) Preliminary avalanche chronology obtained at OB2 using the Wit method. After additional analyses, 7 years (1581, 1599, 1909, 1910, 1954, 1955 and 1981) were removed from the final tree-ring based avalanche reconstruction. (D) Final avalanche chronology covering the period 1689-2014 at OB2.

Spatial extent of avalanches events: The spatial distribution of trees affected by the same event was used to determine the minimum lateral spread and the minimum runout elevation of reconstructed avalanches. At OB1, the mean runout elevation is calculated at 1625 m asl. Runout elevation varies between 1755 m asl in 1880 and 1450 m asl in 1935 (1370 m asl in 1951 if we include historical records; SLF 1952). Large avalanches stopped next to or at the valley bottom in at least 5 cases over the last 400 years, namely in 1689, 1793, 1894, 1937, and 1951. Two other events (1935, 1948) reached the valley floor but were released from the middle part of the slope. We also reconstructed 9 events which stopped in the upper portions of the slope (and at elevations above 1680 m asl), namely in 1800, 1810, 1870, 1880, 1906, 1925, 1945, 1990 and 1995.

At OB2, the mean runout elevation is 1625 m asl, varying between 1840 m asl in 1690 and 1460 m asl in 2003 (1370 m in 1720 if we include historical records). Since 1580, at least 7 snow avalanches developed sufficient energy to reach the valley floor, namely in 1720, 1793, 1813, 1880, 1937, 1951, and 2003. According to our reconstruction, 15 events were, by contrast, restricted the upper part of the slope and would have stopped at elevations > 1680 m asl, namely in 1605, 1641, 1650, 1681, 1692, 1734, 1803, 1880, 1882, 1885, 1912, 1919, 1945, 1966, and 1975.

Temporal and spatial accuracy of the reconstruction: In this study, a total of 38 avalanche events were reconstructed for the period 1600-2014 based on a dendrogeomorphic approach. To assess the temporal and spatial reliability of our reconstruction, we compared our results with local records of past avalanches. We observe that 4 out of the 5 documented snow avalanches that occurred on the avalanche forested slopes of Oberwald could be reconstructed with dendrogeomorphic techniques. The most recent avalanche which occurred in 2003 at OB2 and destroyed about 500 m³ of forest, is successfully recorded in our reconstruction. Its spatial extent is also very well captured by tree rings, as can been seen from visual comparison between two aerial photographs taken in 1999 and 2003 (Figure 3A-C). The events of 1999 (OB2), 1961 (OB2) and 1935 (OB1), known from archival records, were also successfully identified. Only one event occurring during the winter 1920-1921 could not be identified. The success rate is slightly higher than for tree-ring reconstructions of avalanches performed in the Oisans massif in France (Corona et al., 2010) and in the Mont-Blanc massif at Chamonix (Corona et al., 2012).

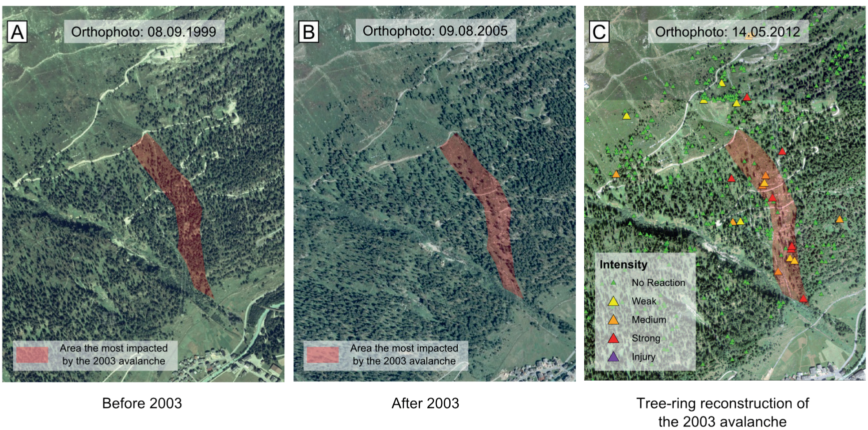

Figure 3: (A, B) Diachronic evolution of the forested slope of Oberwald (OB2) between 1999 and 2005. (C), Tree-ring-based reconstruction of the 2003 avalanche event.

Three other large avalanches were documented in Oberwald (one event in 1720, and two in 1951). However none of them occurred on the forested slopes of OB1 and OB2. The avalanches occurred and stayed within the incised paths of the Jostbach and the Rätischbach torrents. Dendrogeomorphic techniques have more limitations when it comes to reconstruct avalanche activity in these deeply incised paths, as avalanches tend to break, uproot and remove trees, leaving no datable evidence of past avalanche events. As a consequence, most of the vegetation found in these paths consists of young broadleaved trees, often in the form of large shrubs such as Alnus viridis or Betula pendula Roth. While these specimens can be used to assess the most recent past, they will not yield any information on more ancient snow avalanches. For this reason, we could not find evidence for the 1720 and 1951 avalanches which reportedly occurred in the Jostbach and Rätischbach torrents.

CONCLUSIONS

The analyses of growth disturbances in trees growing on the forested slopes located above the village of Oberwald allowed identification of 38 events as well as the mapping of their spatial extent over the past 400 years. In total, 32 of the avalanches documented through tree-ring analyses have not been known prior to this study. At least 12 snow avalanches traveled through the slopes and stopped at or very close to the valley floor. The 1689, 1720, 1793, 1813, 1880, 1937, 1951, 1999, and 2003 events were the largest avalanches observed over the last 400 years. The tree-ring based chronology of past avalanches presented in this paper is, to date, one of the longest records ever elaborated for the Swiss Alps, and the third longest record existing at the level of the European Alps (Luzian et al., 2011, Corona et al., 2013). This study highlights how beneficial can the dendrogeomorphic approach be to land use planners, as it provides first-hand information for the assessment of runout distances and return periods of extreme avalanche events on forested slopes for which only scarce historical archives are available. This approach may help practitioners in the future to define with better accuracy avalanche hazard zones.

REFERENCES

- Baltensweiler W., Rubli D. (1999). Dispersal, an important driving force of the cyclic population dynamics of the larch-bud-moth Zeiraphera diniana Gn. Forest Snow Landscape Research 74: 1-153.
- Bräker O. U. (2002). Measuring and data processing in tree-ring research: a methodological introduction. Dendrochronologia 20: 203-216.
- Büntgen U., Esper J., Frank D., Nicolussi K., Schmidhalter M. (2005). A 1052-Year tree-ring proxy for alpine summer temperatures. Climate Dynamics 25: 41-153.
- Esper J., Büntgen U., Frank D.C., Nievergelt D., Liebhold A. (2007). 1200 years of regular outbreaks in alpine insects. Proceedings of the Royal Society B 274: 671-679.
- Corona C., Rovéra G., Lopez Saez J., Stoffel M., Perfettini P. (2010). Spatio-temporal reconstruction of snow avalanche activity using tree rings: Jean Jeanne avalanche talus, Massif de l'Oisans, France. Catena 83: 107-118.

- Corona C., Lopez Saez J., Stoffel M., Bonnefoy M., Richard D., Astrade L., Berger F. (2012). How much of the real avalanche activity can be captured with tree rings? An evaluation of classic dendrogeomorphic approaches and comparison with historical archives. Cold Regions Science and Technology 74-75: 31-42.
- Corona C., Lopez Saez J., Stoffel M., Rovéra G., Edouard J.-P., Berger F. (2013). Seven centuries of avalanche activity at Echalp (Queyras massif, southern French Alps) as inferred from tree rings. The Holocene 23: 292-304.
- Kogelnig-Mayer B., Stoffel M., Bollschweiler M., Hübl J., Rudolf-Miklau F. (2011). Possibilities and limitations of dendrogeomorphic time-series reconstructions on sites influenced by debris flows and frequent snow avalanche activity. Arctic, Antarctic, and Alpine Research 43: 619-658.
- Luzian R., Pindur P., Nicolussi K., Sailer R., Haas J.N., Zwerger P. (2011). Holozänes Lawinengeschehen und „Global Warming". Zeitschrift für Wildbach, Lawinen, Erosions und Steinschlagschutz 167: 102-117.
- MeteoSwiss (2014). http://www.meteoswiss.admin.ch/product/output/climate-data/climate-diagrams-normal-values-station-processing/ULR/climsheet_ULR_np8110_e.pdf. Accessed on 02.04.2014.
- SLF (1952). Schnee und Lawinen in den Schweizeralpen im Winter 1950/51, Winterbericht des Eidg. Instituts für Schnee und Lawinenforschung, Davos, Nr. 15, SLF Davos, 232 p.
Schweingruber F.H. (1974). Riederalp VS Aletschwald, Swit140. NOAA International Tree-Ring Databank (ITRDB).
- Šilhán K, Stoffel M. (2015). Impacts of age-dependent tree sensitivity and dating approaches on dendrogeomorphic time series of landslides. Geomorphology 236: 34-43.
- Stoffel M., Bollschweiler M. (2008). Tree-ring analysis in natural hazards research – an overview. Natural Hazards and Earth System Sciences 8: 187-202.
- Stoffel M., Butler D.R., Corona C. (2013). Mass movements and tree rings: A guide to dendrogeomorphic field sampling and dating. Geomorphology 200: 106-120.
- Stoffel M., Corona C. (2014). Dendroecological dating of geomorphic disturbance in trees. Tree-Ring Research 70: 3-20.
- Weber U. M. (1997). Dendroecological reconstruction and interpretation of larch budmoth (Zeiraphera diniana) outbreaks in two central alpine valleys of Switzerland from 1470-1990. Trees 11: 277-290.