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A tree-ring reconstruction of geomorphologic disturbances in cliff forests in the Tatra Mts.

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Abstract: Geomorphological events are very important disturbance factors for cliff forests and forests located on steep mountain slopes. In this study we present dendrochronological reconstruction of two types of disturbances which affect subalpine forest growing in such extreme habitats in Roztoka Valley in the Tatra Mountains: landslide and rockfalls. We determine the years of death of trees found in landslide area on Czuba Roztocka which indicate the year of 1997 as the time of this event, probably related to heavy midsummer rainfall in this year. Scars on trees growing at the base of Orle Ściany cliff allowed determining the rockfall events. We found that scars, even in neighbour trees were formed in different years between 1940 and 2004. It means that they were formed rather by separate stones which fell from the cliff sporadically then a large scale fall of debris at the same time. This may suggest that rockfalls in cliffs of Orle Ściany were limited to single rocks which fell successively when erosion process separated them from the bedrock. Dendrochronology seems to be an effective method which enables long term reconstruction of gemorphological processes in the High Tatras.

Key words: cliff forest, dednrochronology, landslide, Norway spruce (*Picea abies*), rockfall

Introduction

Forests located on steep slopes and cliffs are often affected by disturbances of geomorphologic character. Debris flow, landslides and rockfalls are common processes in the high mountains region (Bollschweiler et al. 2007, Bollschweiler et al. 2008, Stoffel et al. 2005). Mountain forests located in subalpine zone in the Carpathians Mountains are under strong influence of different types of disturbances. Strong winds and bark beetle infestations are among the most important disturbance factors, which shape forest structure in large spatial scale. Cliffs are extreme habitats which differ from the typical subalpine forest. In such conditions, disturbances like windthrows and biotic factors are less important for the growth of the forest. Trees are exposed for lean and slide due to gravitation as well as poor edaphic conditions (Larson et al. 2005). Cliffs are often colonized by different species than forests located in gentle slopes. In the High Tatra Mountains such extreme habitats are dominated by stone pine (*Pinus cembra*), while Norway spruce (*Picea abies*) is a dominant species in a "typical" subalpine forest within the same altitudinal range. Due to stronger root system, stone pine occurs in habitats which cannot be colonized by spruce: rocky shelves, fissures, boulders. Also, cliffs are distinguished by larger amount of bushy birch (*Betula carpatica*) and rowan (*Sorbus aucuparia*) occurring in small niches which cannot be colonized by larger trees.

Knowledge of geomorphologic disturbances seems to be a very important issue in terms of assessment of hazards and risks. Documentation and reconstruction of geomorphologic processes may increase our understanding of these phenomena.

In this study we present examples of local reconstruction of landslide and rockfall events conducted with dendrochronological method. The aim of this study was to verify the potential of dendrochronology for dating these geomorphological processes in the High Tatra Mountains.

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Methods

The study was conducted in Roztoka Valley in the High Tatras. The climate is moderately wet and cool with the average precipitation reaching 1800 mm/year and average annual temperature between 2–4^{0}C (Hess 1996). Skeletal acid podzol formed on the granite bedrock is the most common type of soil (Komornicki & Skiba 1996). In steep slopes and cliffs soils are of initial character. Bottom of the valley is grown by subalpine spruce forest with dominant Norway spruce (*Picea abies*) and admixture of rowan (*Sorbus aucuparia*) and birch (*Betula carpatica*). In steep slopes and cliffs stone pine (*Pinus cembra*) and single individuals of European larch (*Larix decidua*) occur.

We located a landslide on the north-eastern slopes of Czuba Roztocka. The width of the landslide was 15–20 m and its length was ca. 120 m (Fig. 1, 2). The top of the landslide was located at the elevation of 1,250 m a.s.l. In the same region, at the base of Orle Ściany cliff we located scarred spruce trees, and the scars resulted from rockfalls from the cliff (Fig. 3, 4). We found three groups of trees bearing scars and three groups of dead trees which fell from the cliff. Groups were located in distance of 30–50 meters from each other. We assumed that they indicated separate rockfalls, so they were numbered with consecutive Roman numbers (Table 1).

Fig. 2. Dead trees, which are present in the landslide, enable to cross-date the time when the event occurred

Cores from dead trees in the landslide and scarred trees were collected. For the construction of local chronology we used cores from the 30 spruces growing nearby in the subalpine zone. Reference trees belonged to the dominant layer and were free

Fig. 1. Landslide located on the slopes of Czuba Roztocka in Roztoka Valley

Fig. 3. A scar on the living spruce growing at the base of Orle Ściany resulted from the rockfall. Cross-dating of scar enables to determine when the rockfall occurred

Table 1. The results of cross-dating of samples. Landslide was dated with the year of death of spruce trees. The year of formation of scar as well as the year of death of trees which fell from the cliff was used to date rockfalls

	Sample number	Year of the last ring formation (tree death)	Year of scar formation (in living tree)
Landslide	25	1997	
	26	1997	
	27	1997	
	29	1997	
	30	1997	
	31	1993	
	32	1998	
	33	1998	
	35	1992	
Rockfall I	36	1990	
	37	2001	
	38	2006	
	39	2006	
	40	2006	
Rockfall II	51		1951
	52		1972
	53		1969
	55		2001
Rockfall III	56		1940
	58		2001
	60		1989
	61		1991
Rockfall IV	63	2006	
	64	2006	
	65	1987	
Rockfall V	66		2004
Rockfall VI	69	2007	
	70	2007	
	71	2007	
	72	2007	

from visual signs of the past damages (e.g. broken top or large branches, scars, rot). All cores were glued to wooden sticks, dried and polished. Then, the cores were scanned and the ring widths were measured with WinDendro software. The quality of measurements of the reference trees were verified with COFECHA (Holmes 1983, Baillie & Pilcher 1973). This program calculates correlations among tree-ring series in segments and this procedure enables the verification of the correctness of dating and the detection of possible mistakes e.g. missing rings. After indexation these ring-series were used for the construction of local chronology.

Fig. 4. Scar is formed when a heavy object hits the tree stem. As a result, the portion of cambium is damaged. Scar is formed during subsequent years, when the wound is overgrown by tissue

The samples of dead trees and cores from scares were matched against the local chronology to determine the calendar years of disturbance events (Fig. 5). Standard parameters used in dendrochronology: GLK and t-value were used to cross-date the undated samples (Schweingruber 1989). Additionally, we used pointer years to confirm the results of our dating (Schweingruber et al. 1990). The best pointer years for the 20th century were: 1912 (pale ring), 1913 (narrow ring), 1933 (narrow late wood) 1980 (narrow ring). For the dating of the landslide we used the calendar year of the death (last formed ring) (Dynesius & Jonnson 1991) of trees, which presumably uprooted due to this event. Rockfalls were dated in two ways. As in the case of landslide, we determined years of death of trees which fell from the cliff, most often they slid with rocky debris to the base of the cliff. Scares which were found in stems of living trees growing at the cliff base were treated as other indica-

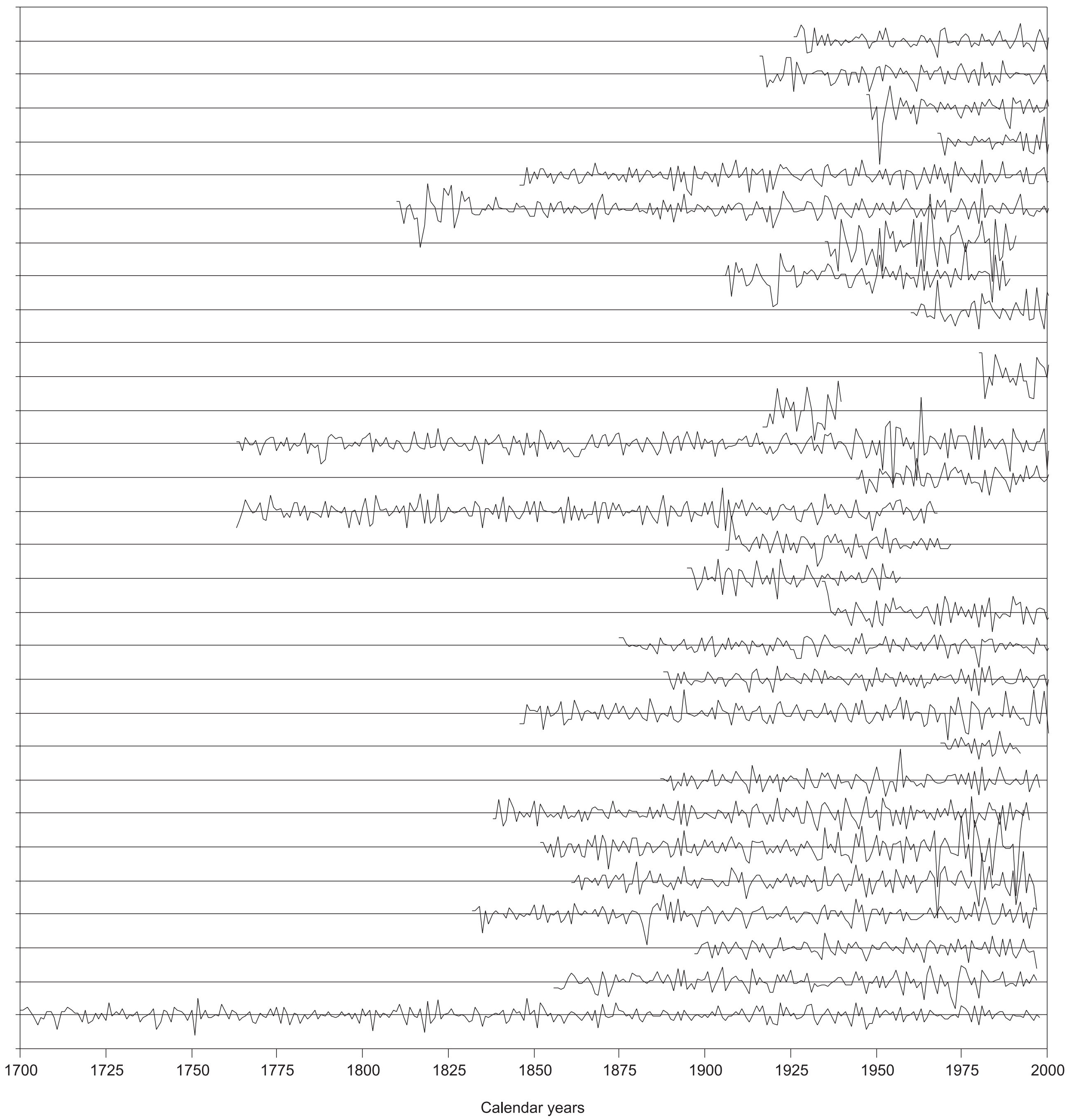

Fig. 5. The cross-dating procedure. Tree-ring series of samples are fitted against the local chronology. Calendar year of the formation of the last ring indicate the time of tree death or formation of the scar. Presented tree-ring series have been indexed

tors of rock fall (Stoffel & Perret 2006, Perret et al. 2006). We put attention whether scars came from the hit of rocks or they resulted from the fall of neighbour trees. We were able to date 21 samples from rock falls and 9 samples from the landslide.

Results and discussion

Most spruces found on the landslide died in 1997. Two trees died earlier – in 1992 and in 1993. Two other spruces died in 1998. This indicates that most likely the landslide was formed in 1997 (Table 1). Two trees which survived were probably seriously injured and died one year later. Because most of the trees which died in 1997 had fully developed latewood, the landslide occurred at the end of vegetation period. This event probably resulted from intensive rainfall in July 1997. During this month the precipitation measured in Zakopane was over 360 mm and belonged to the highest for July in the 20th century. This year, in summer, in the whole southern Poland a heavy flood was observed due to enormous summer rainfall.

Cross-dating of rock falls showed different temporal pattern of these events (Table 1). Scars caused by rocks falling from the cliff came from different years. The oldest scar was formed in 1940 (rockfall III) and the last fully formed scar was formed in 2004 (rockfall V). Scars on neighbour trees were formed in different years. It means that they were formed rather by separate stones which fell from the cliff of Orle Ściany sporadically, than a large scale fall of debris in one time. This may suggest that rockfalls in cliffs of Orle Ściany were limited to single stones which fell when erosion process separates them from the bedrock, at least in the time scale of several last decades. It is not ruled out that large portion of cliff may be separated and fall, but such disturbance would likely smash trees growing at the base of the cliff. However, we were not able to identify old stumps or logs which could be potentially a result of such severe event. Most likely during last decades, there was no such massive rock falls in the cliffs of Orle Ściany.

Similar, uneven temporal pattern of rockfall activity was observed in e. g. limestone cliffs in the Swiss Prealps (Perret et al. 2006), where distribution of rockfall changed with time and increased over the last century. It was also found that higher temperatures in the Swiss Prealps resulted in the increase of rockfall activity while seasonal precipitation seemed to be of no importance. Relatively small number of samples in our study did not allow relating years of rockfalls with climatic data, however, the same regularity can be expected in cliff of Orle Ściany. By sampling cores in visible scars in fact, we were able to detect only relatively fresh rockfalls. Spruce stems could contain older, totally overgrown scars invisible by now, which could be sampled only with cross-sections. As the study was conducted in strict reserve, such method of sampling was not possible. This constituted another methodological limitation in this study.

Dead trees found at the base of cliff showed similar pattern of their mortality. Trees growing in the cliff are exposed to harsh conditions which impede regular growth and stem development. Along with growth of the tree the stem elongates and increases its mass. But very often the space for stem, crown and roots is limited, when tree is growing on a small rocky shelf or in fissure. With the increase of the size of tree the probability of its fall also increases due to shift of the centre of mass or ground erosion (Larsson et al. 2005). Very often the potential niches for tree establishment in the cliff are colonized by a group of trees. When one of them falls it may often draw other individuals from such a group. At the same time falling trees induce fall of rocky debris and stones. This was visible in our study. Most of trees lying at the base of cliff died in similar time (Table 1). It is worth to note that these trees died in present time – most of them after 2000. Because decay process of spruce logs is relatively slow, it is not an effect of limitation of dendrochronological dating, because also older logs could be successfully cross-dated. We were not able to find dead trees which fell from the cliff in a more recent period. It is difficult to interpret this with a small number of samples.

Conclusion

Tree-ring analysis enables a precise cross-dating of events of geomorphologic character in cliffs and steep slopes in the Tatra Mountains. Rockfalls and landslides might be placed in time with yearly resolution using dendrochronological methods. Geomorphologic events may be indicated by the death of trees and by wounds and scars formed on living trees which result from geomorphologic processes. Changes in growth pattern e.g. releases, depressions and anatomical features e.g. resin ducts, compression wood can also be successfully used for the detection of changes in environment including those related with geomorphology.

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