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The changing ability of Norway spruce (*P. abies*) to record hydro-geomorphic processes based on the age and diameter of the tree stem – A dendrogeomorphic approach

Radek Tichavský *, Karel Šilhán

Department of Physical Geography and Geoecology, Faculty of Science, University of Ostrava, Chittussiho 10, 710 00 Ostrava, Czech Republic

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ABSTRACT

Dendrogeomorphic reconstructions of debris flows and related hydro-geomorphic processes (i.e. debris floods and flash floods) are widely used in territories with incomplete chronologies and potential future hazards. In recent years, the tree-ring analysis of disturbed trees affected by dangerous geomorphic processes has developed into a discipline with sophisticated methodical approaches and with annual up to monthly accuracy of dating. Field sampling strategies are based on various ranges of sample depth (i.e., different amounts of sampled trees of different age structures). The age and diameter of trees influence the ability of trees to respond to geomorphic processes; therefore, we investigate age-dependent and diameter-dependent tree sensitivity. Our study, for the first time, addresses the sensitivity to hydro-geomorphic processes in detail. We tested 462 individuals of Norway spruce (*Picea abies* (L.) Karst.) – a very common species used in the dendrogeomorphic reconstructions – in the apical part of the medium-high-mountains where there is widespread occurrence of debris flows and debris floods. The tree sensitivity analysis was performed based on the position of growth disturbances within the increment cores of trees (original age and original diameter of the tree before the tree was affected). *P. abies* shows very high tree sensitivity in the first two decades of the tree lifespan. With increasing age and diameter, trees are less sensitive recorders of debris flows/floods. Moreover, the intensity of growth disturbances significantly decreases with tree age. Mature trees (51–120 years) record the geomorphic events mainly through abrupt growth changes (suppression and release) and tangential rows of traumatic resin ducts. In contrast, scars, the onset of reaction wood and traumatic resin ducts are dominant growth disturbances in young, thin trees (11–30 years; diameter 0–15 cm). Different occurrences of particular growth disturbances as well as the different age- and diameter-dependent sensitivities emphasize the need for the inclusion of new variable that will take into account the amount of sensitive trees for each year. After that, adequate mixture of sampled tree (i.e. mixture of age classes), which is necessary for the completeness of debris flow/flood chronologies, could be balanced regarding their sensitivity.

1. Introduction

Hydro-geomorphic processes (such as debris flows, debris floods and flash floods) participate in the development of hillslope-channel system and affect the riparian vegetation through the transport and accumulation of sediments and large woody debris (Stoffel and Wilford, 2012). Dating of geomorphic processes using dendrogeomorphic methods (Alestalo, 1971) has become a common part of contemporary natural hazard research (Shroder, 1978; Braam et al., 1987; Butler et al., 1987; Schweingruber, 1996; Strunk, 1997; Stoffel and Bollschweiler, 2008; Stoffel et al., 2010a,b; Gärtner and Heinrich, 2013). Debris flows and debris floods belong among the most dangerous mass movement processes and have caused fatalities and loss of property all over the world, so the knowledge about their frequencies, spatial variabilities and magnitudes is a common theme of geomorphic research (Strunk, 1989; Jakob and Hungr, 2005). With ongoing climate change, which is reflected in the changing of the triggering conditions (Stoffel and Graf, 2015), compilations of accurate past debris flow/flood chronologies and comparison of the climatic data are required to better understand the contemporary development of hillslope-channel coupling (Jomelli et al., 2007; Scuderi et al., 2008; Stoffel and Wilford, 2012; Lane, 2013).

The past activity of such processes, revealed by dendrogeomorphic methods, can be dated with annual or seasonal precision according to the position of growth disturbances (GDs) within the tree-ring series. Five basic GDs are known as the response to the hydro-geomorphic processes (mainly debris flows): (1) wounding of trees (scars) after direct impact of moving material, which destroys the bark and cambium (Lundström et al., 2008); (2) occurrence of the traumatic resin duct formation – TRD – in several coniferous species as a response to the

* Corresponding author.
E-mail address: radek.tichavsky@osu.cz (R. Tichavský).

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wounding of trees after direct impact (Stoffel, 2008; Gärtner and Heinrich, 2009); (3) the onset of reaction (compression in the case of coniferous trees) wood caused by the tilting of trunks after the one-sided pressure of material deposition or the undercutting of channel banks (Braam et al., 1987); (4) reduced tree ring growth (abrupt growth suppression) caused either by the burial of debris material or root exposure and damage after bank undercutting, which can both result in limited water and nutrient supply; another reason may be the decapitation of tree (Strunk, 1997); and (5) abrupt growth release after the elimination of neighbouring trees or, in special cases, after the burial of debris flow material enriched with nutrients (Schweingruber, 1996; Procter et al., 2011). During the last 15 years, the progress in dendrogeomorphology has led to an increased number of papers that addressed the spatio-temporal reconstruction of debris flows (Wilkerson and Schmid, 2003; Pelfini and Santilli, 2008; Bollschweiler et al., 2008; Arbellay et al., 2010; Šilhán and Pánek, 2010; Lopez Saez et al., 2011; Schraml et al., 2015), debris floods/hyperconcentrated flows (Mayer et al., 2010; Ouellet and Germain, 2014; Vaidean et al., 2015) and flash floods (Ruiz-Villanueva et al., 2013; Ballesteros-Cánovas et al., 2015a; Génova et al., 2015; Šilhán and Galia, 2015) as well as the combination of debris flows with the other geomorphic processes (Stoffel et al., 2006; Szymczak et al., 2010; Šilhán et al., 2012; Savi et al., 2013; Šilhán, 2015; Tichavský and Šilhán, 2015).

Dendrogeomorphic reconstructions determine only the minimum frequencies of the past events (Bollschweiler et al., 2011), and the precision of the final results depends on the chosen methodology and scientist experience (e.g., correct selection and number of sampled trees and correct laboratory interpretation of GDs). Age variability of trees affected by hydro-geomorphic processes, as well as the distribution of GDs within the trees, differs from place to place (Table 1). In many cases, the limited number of suitable trees for sampling (e.g. because of the health conditions or intense forest management) impede the completeness and accuracy of the compiled chronologies. The varied age structure of the forest, from juvenile to several hundred year old trees, provides an ideal study site for debris flow chronologies (Stoffel and Corona, 2014). However, what if the younger/thinner trees are not affected by the moving material, older trees with thicker bark resist the impact of boulders, and the trees in their prime life are not such sensitive to burial? There is a common agreement that trees, across their lifespan, have changing sensitivity and response to geomorphic processes (i.e., by different types and/or intensity of GDs), but the lack of quantitative data has prevented confirmation of such premises.

Generally, age- or stem diameter-dependent sensitivity of trees is the research question that interconnects fields of interest, including climate, biodiversity, tree physiology, forest management etc. (Table 2). Age-dependent and stem diameter-dependent tree sensitivity to hydro-geomorphic processes has not been solved in detail, although several studies have outlined possible influences (Trappmann et al., 2013; Stoffel and Corona, 2014), and the initial research has been started within the dendrogeomorphic time series of rockfalls (Šilhán et al., 2013), landslides (Šilhán and Stoffel, 2015; Šilhán, 2016) and debris flow frequencies (Šilhán et al., 2015).

This study aims to determine the tree sensitivity of Norway spruce (*Picea abies* (L.) Karst.) to hydro-geomorphic processes (debris flows or debris floods) across their lifespan (i.e., different age and diameter of tree stem) in three different levels: (i) to show the general age- and diameter-dependent sensitivity through the position of all GDs, (ii) to show the differences and similarities in the occurrence of the five basic GD types, and (iii) to show the strongest debris flow/flood events (according to the archival records) and to analyse which trees recorded these events and how the trees responded to such events.

2. Materials and methods

2.1. Study site characteristics

We study the apical parts of the Hrubý Jeseník Mts., (Eastern Sudetes; Central Europe; Fig. 1A) with the presence of several fossil and active debris flow paths that couple with high-gradient streams to form a hillslope-channel coupling system with the occurrence of debris flows and debris floods (Migoń, 2008; Tichavský and Šilhán, 2015). Colluvial weathered material (represented mainly by gneisses and mica schists fractions of different sizes from several cm up to 2 m boulders) is transported from the steep slopes (20–50°) to the high-gradient channels and marginal parts of the valleys where the debris flow lobes, levees and mounds are formed and which are often reactivated during the short duration, high magnitude precipitation (>70 mm/day). Such suitable conditions for debris flow/flood occurrence are predominantly in the Keprnická highlands (part of the Hrubý Jeseník Mts.; Fig. 1B, C) where a minimum of eleven debris flow events since 1770 have been confirmed from the archival records (e.g., 1880, 1921, 1951,

Table 1
Overview of past dendrogeomorphic reconstruction of debris flows (D flow) and debris floods (D flood) using *Picea abies* (as a single reconstructed species or as a prevailing species mixed with the other species) and distribution of observed GD (sca = scars, trd = traumatic resin ducts, rea = reaction wood, spr = abrupt growth suppression, rls = abrupt growth release).

Author	Type of process	Location	No. of trees[a]	Age structure (years)	Types of GD % (sca-trd-rea-spr-rls)
Strunk (1997)	D flow	Alps (FRA)	400 (?)	Not specified	Not specified
Wilkerson and Schmid (2003)	D flow	Montana (USA)	53 (?)	Not specified	Not specified
Stoffel et al. (2005)	D flow	Valais (SUI)	1102 (?)	40–510	Not specified
Stoffel et al. (2006)	D flow	Valais (SUI)	251 (?)	13–346	7-61-22-20[b]
Stoffel and Beniston (2006)	D flow	Valais (SUI)	1102 (?)	Not specified	6-44-32-9-9
Bollschweiler et al. (2007)	D flow	Valais (SUI)	401 (?)	19–215	3-51-27-19[b]
Bollschweiler and Stoffel (2007)	D flow	Valais (SUI)	278 (73)	37–325	1-78-5-11-5
Bollschweiler et al. (2008)	D flow	Valais (SUI)	71 (?)	42–356	3-50-19-11-17
Bollschweiler and Stoffel (2010)	D flow	Valais (SUI)	210 (?)	16–334	11-74-9-3-3
Mayer et al. (2010)	D flow	Alps (AUT)	227 (224)	13–280	1-35-6-28-30
Sorg et al. (2010)	D flow	Valais (SUI)	28 (2)	40–130	9-37-20-21-13
Stoffel et al. (2010b)	D flow	Valais (SUI)	252 (?)	27–304	2-71-16-9-2
Szymczak et al. (2010)	D flow	Valais (SUI)	61 (57)	4–95[c]	8-35-19-24-14
Bollschweiler et al. (2011)	D flow	Valais (SUI)	44 (44)	15–154[c]	2-75-3-9-11
Kogelnig-Mayer et al. (2011)	D flood	Alps (AUT)	372 (?)	17–188	6-80-3-9-2
Procter et al. (2011)	D flow	Voralberg (AUT)	442 (164)	25–451	5-19-<1-76[b,d]
Schraml et al. (2015)	D flow	Gesause (AUT)	384 (?)	12–131	0-20-4-43-33
Tichavský and Šilhán (2015)	D flow, D flood	Eastern Sudetes (CZE)	397 (390)	9–169	13-17-14-29-27
Vaidean et al. (2015)	D flood	Carphatians (ROM)	20 (20)	39–70	trd and rea (not specified)

[a] Amount of all sampled trees; Amount of *P. abies* samples in the brackets (if known).
[b] Abrupt growth suppression and release were calculated together.
[c] Age structure for both coniferous and deciduous trees, GD distribution only for coniferous.
[d] GD structure influenced by *Pinus mugo* (not possible to count TRD).