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Dendrogeomorphic reconstruction of the seasonal timing and rainfall threshold for debris slide occurrence in eastern Canada

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ABSTRACT

Debris slide occurrence on treed slopes of northeastern North America is still poorly documented, despite their abundance and their potential to change mountainous landscapes in short periods of time. To provide new information on their spatiotemporal dynamics, a study was undertaken in debris slide paths in the Wildlife Reserve of Port-Cartier-Sept-Iles, on the Québec North-Shore region of eastern Canada. Tree-ring dating of growth anomalies (impact scars and reaction wood) in nine debris slides allowed the identification of four debris slide events that occurred in 2003, 2006, 2008, and 2010. By comparison to other hillslope processes such as snow avalanches and debris flows, debris slides produce a very strong tree-ring signal. Therefore they do not require a large sample size considering also that they do not occur twice at the same place. The position of growth anomalies within individual tree rings allowed to determine the timing of the debris slide events: injuries located within a ring correspond to debris slides occurring during the growing season, whereas injuries located between the end of a ring and the beginning of the following ring were caused by debris slides occurring during the dormant season. The meteorological data indicate that a daily precipitation of 70 mm appears usually sufficient for the occurrence of debris slides.

1. Introduction

Hillslope processes such as snow avalanches, debris flows and landslides have been well documented in the northeastern North America (Crawford, 1968; Clark, 1987; Filion et al., 1991; Wahl et al., 2007; Quinn et al., 2010; Hétu et al., 2015; Germain, 2016; Martin and Germain, 2017). Debris slides have, however, so far received very little attention as studies on the subject remain very descriptive and provide little information on their spatiotemporal occurrence, except through a few direct observations (Bogucki, 1976; Hull and Scott, 1982; Neary and Swift, 1987). According to Dionne and Filion (1984), debris slides or skin slides result from water saturation of a mass of debris in the upper part of a steep slope, which after the rupture of cohesive forces suddenly slides down the slope, removing the vegetation cover and mineral soil. The description of debris slides by Hutchinson (1988) is similar to the observations of skin slides (*glissements pelliculaires*; Dionne and Filion, 1984) reported in Québec, i.e., a fast to very fast motion of a very shallow layer of material compared to the total length of the slide, usually triggered by a major rainfall event. Triggering of such mass movement is often caused by the increase of the interstitial pressure during heavy rainfall, which reduces shear stress in the surficial loose deposits (Corominas, 1996). Hutchinson (1988) and Cruden and Varnes (1996) classified this type of mass movement in the category of translational landslides affecting, essentially, unconsolidated surface materials. They usually occur along a pre-existing discontinuity such as the contact between the bedrock and surficial deposits (Cruden and Varnes, 1996).

A few studies dealing with debris slides over rocky slopes were conducted in northeastern North America. In the province of Québec (Canada), these slides have been reported by Dionne (1978) in the James Bay region, Dionne and Filion (1984) on the North-Shore region of the St. Lawrence River, and Dubois and Robitaille (1989); Simard and Lajeunesse (2015), and Baillargeon (2013) in the Québec City and Charlevoix regions. The Anglo-Saxon terminology is more variable, sometimes referring to skin flows, debris flows, avalanche debris or debris slides (Kull and Magilligan, 1994). These slides have been described as avalanche debris in the Blue Ridge Mountains (Virginia, USA; Woodruff, 1971), debris slides in the Adirondacks (New York, USA;

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Bogucki, 1976), debris flows in the White Mountains (New Hampshire, USA; Wieczorek et al., 2004) and thin-skinned debris flows in the Cape Breton Highlands (Nova Scotia, Canada; Wahl et al., 2007). Almost thirty years ago, Kochel (1987) reported differences in terminology, particularly about rapid hillslope processes involving poorly sorted mixtures of clastic debris, organic matter and water. Also considering that these mass movements may evolve, for example from a translational landslide upslope to a debris flow downslope (Wahl et al., 2007), it is then not surprising to find considerable discrepancy among authors. However, it seems that these hillslope processes occur mainly during intense liquid precipitation (Bogucki, 1976; Hull and Scott, 1982; Neary and Swift, 1987). On the other hand, even considering the abundance of debris slides paths in the northeastern Appalachian Mountains (Hack and Goodlett, 1960) and the Québec North-Shore region (Dionne and Filion, 1984), very little attention has been paid to this process of denudation in treed mountainous environments except for a few recent papers (Wahl et al., 2007; Simard and Lajeunesse, 2015). Therefore, there is no precise information on their occurrence and their link with significant rainfalls except for the extreme 3-day precipitation event of July 1996 on the North-Shore region of the St. Lawrence River (Québec, Charlevoix and Saguenay regions), which triggered hundreds of clay landslides and debris slides particularly in U-shaped valleys (Demers et al., 1999; Baillargeon, 2013).

This research, which was carried out in one of the wettest regions of the province of Québec, Canada, aims to: 1) document the biophysical setting of debris slides; 2) establish a chronology of debris slides using a dendrogeomorphic approach with intra-annual resolution; and 3) identify the probable minimum threshold of rainfall to induce debris slides.

2. Study area

The study area is located within the Wildlife Reserve of Port-Cartier-Sept-Iles on the North-Shore region of the St. Lawrence River, about 600 km northeast of Québec City (Fig. 1). It is part of the Canadian Shield and the landscape is characterised by a succession of deep north-south-oriented glacial valleys and low-elevated hills up to 300 m (Tremblay, 1975). The geology is dominated by crystalline gneiss and rock outcrops can be seen in several places (Franconi et al., 1975), especially in the upper part of steep slopes. Valley bottoms are lightly covered with postglacial deposits, mainly a 1- to 3-m thick ablation till consisting of blocks and angular and sub-angular pebbles of Precambrian origin (Tremblay, 1975; Dionne and Filion, 1984). The postglacial Goldthwait Sea invaded the region up to an altitude of 129 m (Tremblay, 1975). Lakes Walker and Pasteur, located at an elevation of approximately 90 m above sea level (a.s.l.) and possessing a U-shaped valley thus correspond to former fjords (Fig. 1). Therefore, the steep slopes on both sides of these valleys appear to be debris slide-prone areas.

The humid sub-polar climate is cold and wet (Proulx et al., 1987). According to data from the Sept-Iles weather station (Environment Canada, 2017), the average annual temperature is 0.8 °C with an average temperature of the coldest and warmest months of -15.3 °C (January) and + 15.2 °C (July), respectively. Total annual rainfall is 1119.9 mm with a snow fraction of about 35%. The study area is part of the boreal forest and is dominated by black spruce [*Picea mariana* (Mill.) B.S.P.] and balsam fir [*Abies balsamea* (L.) Mill.] (Robitaille and Saucier, 1998).

3. Methods

3.1. Sites selection and mapping

The North-Shore region of the St. Lawrence River has been particularly affected by debris slides in the past decades, judging by the number of visible paths on multi-date aerial photos (Dionne and Filion, 1984). In addition, the Wildlife Reserve of Port-Cartier-Sept-Iles greatly facilitates access to the sites by a network of roads, trails and lakes (Fig. 1). In this respect, sites selection was based primarily on examination of different series of aerial photos but accessibility was also considered. The mapping of landslides was performed in ArcGIS using the Topographic Database of Quebec (BDTQ) combined with Google Earth images. Satellite images were particularly useful considering that debris slides do not appear on the most recent aerial photographs (1999 and 2000). Slope inclination was measured in the field using a laser rangefinder TruePulse 200 (Laser Technology Inc.) with an accuracy of ± 30 cm for distance and ± 0.25° for slope incline.

3.2. Dendrogeomorphic analysis

Between 8 and 34 impacted trees were sampled along the trimlines and in the run-out zones of 9 debris slide sites, in July 2011 and August 2012, for a total of 148 trees corresponding to 184 cross-sectional disks (Table 1). Sampling was restricted to live conifers apparently damaged (i.e., impact scars facing upslope and tilted stems) by debris slides. The cross-sectional disks were dried and sanded (400 grit), their rings were visually cross-dated under a 40X-magnification binocular microscope. Indeed, considering the absence of other forest cover disturbances for the period studied (De Grandpré et al., 2018), the sampling of cross-sections, the absence of significant growth reduction before and after the occurrence of debris slides, dating in most cases of a single scar per tree is adequate based on visual cross-dating.

Two types of growth anomalies were considered: impact scars and reaction wood (Stoffel and Bollschweiler, 2008), although traumatic resin ducts (TRD) were observed occasionally. The choice not to use them as a marker in the same way as scars and sequences of reaction wood is simply due to their smaller number. Impact scars are formed when the flowing material impacts tree trunks, resulting in the partial destruction of the cambium layer, stopping wood formation locally (Fig. 2); only impact scars facing upslope were sampled. Reaction wood is composed of modified wood cells forming wide tree rings and is produced to allow tilted trees or branches to regain an upward position. In conifers, reaction wood is formed on the tilt side of the trees and has a typical brownish colour. Depending on the degree of tilting, reaction wood can be produced for one year or for a sequence of several years. For this study, we only considered reaction wood that was produced for at least two years in a row, and we ignored the 20 innermost rings because small-diameter tree stems are unstable and highly susceptible to stem deformation (Germain et al., 2009; Filion and Gärtner, 2010). In order to work as much as possible with the raw data, impact scar and reaction wood count data were only expressed in the form of event-response histograms for each site (Shroder, 1978). For each year t, the index I was calculated as the percentage of the number of responses (here, impact scars or reaction wood) relative to the total number of trees alive in year t:

$$I_t = \left(\sum_{i=1}^{n} \mathrm{Rt}\right) / \left(\sum_{i=1}^{n} \mathrm{Nt}\right) * 100\% \tag{1}$$

where R represents the response to an event for year t and N represents the number of trees alive in year t. Only years with a sample size ≥ 10 trees were considered in the chronologies to avoid overestimation caused by a low number of trees in the event-response calculations. The only exception is the debris slide F with a sample size of 8 trees (Table 1).

After the assessment of event years, we analysed the onset of growth anomalies (reaction wood sequences and impact scars; Table 1) within individual tree rings to determine the timing of the impact (Stoffel et al., 2005, 2006). In tree rings, wood cells produced at the beginning of the growing season (earlywood) are wider and have thinner cell walls than those produced at the end of the growing season (latewood). Ring formation completely stops during the dormant season (fall to