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The role of windstorm exposure and yellow cedar decline on landslide susceptibility in southeast Alaskan temperate rainforests

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ABSTRACT

Interactions between ecological disturbances have the potential to alter other disturbances and their associated regimes, such as the likelihood, severity, and extent of events. The influence of exposure to wind and yellow cedar decline on the landslide regime of Alaskan temperate rainforests was explored using presence-only modeling techniques. The wind regime was found to be a significant influence on the spatial distribution of landslide events. This effect was mediated by slope, with little interactive effects at low angles and stronger influences on steeper slopes. Mechanistically, the interaction appears to be mediated by root strength, which is an important factor in stability of high-angle slopes. Yellow cedar decline, despite increasing landslide susceptibility in fine-scale studies, was not significant—although a stronger relationship may develop with time. Overall, inclusion of other disturbances in the modeling framework resulted in a significant spatial refinement when predicting landslide susceptibility. This results from the varying importance of individual disturbance drivers across the landscape, of which only a subset are exposed to potential disturbance interactions. This spatial effect is an important consideration when characterizing landscape-scale disturbance regimes and their interactions with other disturbances.

1. Introduction

Natural disturbances such as windthrow, fires, landslides, and insect outbreaks play a large role in forest ecosystem structure and functioning (White, 1979; Turner, 2010; Edburg et al., 2012). These events regulate broad landscape-scale processes such as biomass dynamics (Kashian et al., 2006), nutrient cycling (McLauchlan et al., 2014), and species diversity. Although individual disturbances and their associated regimes have been important study topics for several decades, interactions between multiple disturbances are also of crucial interest in the field of landscape ecology because of their potential to create nonlinear and often unexpected synergistic outcomes (Paine et al., 1998; Turner, 2010), such as altered disturbance likelihoods (Kulakowski et al., 2003), severities (Kulakowski and Veblen, 2007), and recovery trajectories (Buma and Wessman, 2011). Disturbance interactions can also shape the spatial characteristics of regional disturbance regimes. For example, Veblen et al. (1994) focused on the coarse-scale spatial patterning of multiple events (fire, avalanche, and insect mortality) via forest history reconstructions. Among the disturbance regime interactions they describe, avalanches play a fundamental role in limiting fire size, thus altering the spatial patterning (location and extent) of the fire regime in those landscapes. A better understanding of those disturbances/interactions is necessary given the expected changes to disturbance regimes in the future (Dale et al., 2001) and the potential for rapid changes associated with changing disturbance regimes (Paine et al., 1998; Buma et al., 2013).

Detailed investigations of disturbance interactions are typically achieved at fine scales, usually on single events or small groups of events (e.g., fire and wind: Buma and Wessman, 2011; landslides and yellow cedar decline: Johnson and Wilcock, 2002). These mechanistic studies of interaction processes are vital, yet scaling from single events to regional disturbance regimes remains difficult owing to a variety of contingent factors, spatial autocorrelation, and other confounding factors that make mechanistic relationships unclear at coarse scales (Wiens and Parker, 1995; Parker and Wiens, 2005). Interaction mechanisms important at fine scales are not always certain to be significant at coarser scales of analysis (their generality) or if the effects are constant across landscapes (their homogeneity); these linkages remain a challenge temporally (Buma, 2014) and spatially (Johnson and Cochrane, 2003; Turner, 2010).

Perhumid rainforests provide an excellent opportunity for studying the interaction of disturbance regimes because of their relative simplicity (in terms of disturbances). The primary, large natural disturbances are wind, avalanches, and landslides (Alaback, 1991; Veblen and Alaback, 1996) and have been well-examined in intensive, plot-scale

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studies. Climatic variability is low (Alaback, 1991), anthropogenic presence minimal, and forest tree species diversity low and relatively consistent (DellaSala et al., 2011), reducing variance across the landscape. Therefore, the interaction between disturbance regimes at landscape scales is more easily isolated relative to the influence of species composition or climate.

Wind is a major forest disturbance globally (Walter, 1984; Mitchell, 2013); in the perhumid rainforests of the Pacific Northwest coast of North America, wind is the principal forest disturbance (Nowaki and Kramer, 1998; Alaback et al., 2013). At one estimate, wind was responsible for ~25% of all observed mortality in monitored stands over a 7-year period in the region (southeast Alaska; Hutchinson and LaBau, 1975), and it has been estimated that 15–33% of productive forest in southeast Alaska is exposed to major wind disturbances (Alaback et al., 2013). The wind disturbance regime is dominated by winter season, southerly storms (southeast to southwest; Harris, 1999). These disturbances span a range of intensities and extents, from large, 100+ ha events to small, <1 ha patches (Nowaki and Kramer, 1998). Landscapes subject to this wind disturbance regime are often younger, denser, and more productive than more protected locations (Kramer et al., 2001; Alaback et al., 2013) and provide important habitat for species such as black bear, *Ursus americanus* (DeGayner et al., 2005).

Landslides are also important high severity events, which occur at a variety of scales from large, rare events to small, but chronic slide locations (Veblen and Alaback, 1996), principally related to topography (Swanston, 1997). Generally, slide events in temperate rainforests of Alaska are of the debris-avalanche–debris-flow sequence type (Varnes, 1978; Sidle et al., 1985; Hungr et al., 2001). These landslides result from altered surface loading, increased soil water levels, removal of mechanical support (e.g., tree roots), or a combination of those factors (Terzaghi, 1943; Swanston, 1974; Sidle, 1992). In southeast Alaska these failures typically are rapid in shallow soils (<2 m.) and on high angle (>30°) slopes (Johnson et al., 2000); slow moving, deep seated earthflows are very rare because of the general steep slopes, shallow soils, and heavy rainfall (D. Landwehr, USFS, *personal communication*, 2014). Landslides typically occur in depressions in hillslopes, where soil and moisture accumulate and subsequently fail cyclically on a 300–500+ year return interval (Montgomery and Deitrich, 1994; Swanston, 1997).

The slope stability model (simplified version of the infinite slope model, expressed in Eq. (1) as the Factor of Safety (FS); Swanston, 1997) is appropriate for the wide, shallow slides of the debris-avalanche –debris-flow sequence and is often used to describe the interaction of predisposing components acting normal and parallel to potential slip surfaces (Wu and Sidle, 1995; Swanston, 1997).

$$FS = \frac{C + R + (\sigma - u)\ \tan\ \theta}{(Ws)Z + Wt + a} \tag{1}$$

The FS model describes the ratio between forces resisting and forces promoting hillslope failure. Forces resisting failure include soil cohesion (C), root cohesion (R), and internal angle of soil friction ( ), as modified by normal stress (σ) and reduced with increasing pore pressure (u). Stability is reduced with increases in the loading parameters including soil depth (Z), weights of soil (W_s) and vegetation (W_t), and the downward force of wind acting on trees (a). As formulated and typically used, the FS model is deterministic (e.g., stable or instable), but it is used here as a conceptual model of factors promoting or resisting instability in a generalized landscape.

Conceptually, forest disturbance may alter the landslide regime by changing those factors governing hillslope stability via disrupting existing forest structural properties (Swanston, 1974; Wu et al., 1979; Johnson et al., 2000; Ammann et al., 2009; Pawlik, 2013). Tree roots can anchor into bedrock cracks and fractures (providing local stability) as well as network across hillslopes (providing additional strength laterally; Swanston, 1974). Removal of that root structure via tree mortality and subsequent decay result in weakened soil structures and the potential increased landslides (decreasing R). Wind may also affect slides by providing an additional downward force on standing trees attached to the soil (Wu et al., 1979).

Another emerging disturbance in the region is yellow cedar decline, the mass mortality of Alaskan yellow cedar (*Callitropsis nootkatensis*). Yellow cedar decline (YCD) has been linked to low snowpack and saturated soils, as cedar fine roots accumulate near the soil surface and are then susceptible to freezing mortality during cold events if not insulated by snow (Hennon et al., 2012). Similar to wind, YCD has the potential to modify the drivers of landslide initiation. Yellow cedar decline is associated with landslides via a reduction in root strength in shallow soils (<0.7 m), affecting R or changes in soil pore pressures in deeper soils (Johnson and Wilcock, 2002).

Generally, weight of the soil, vegetation, and slope have more influence than root strength (R; Swanston, 1997). Interactions between wind, YCD, and landslides are likely significant whenever factors promoting instability (high soil depths, steep slopes) are higher than frictional forces promoting stability, and soil cohesion and root strength are compensating. So the interaction effect is likely to be important primarily on steeper slopes, where a reduction in R or an increase in a would result in a significant change in slope stability. If that is the case, a spatial relationship should exist between slide occurrence and those factors which alter the FS equation.

The purpose of this study is to (i) determine if significant relationships exist between exposure to wind disturbance, the emerging disturbance of YCD, and landslide susceptibility at large spatial scales; and (ii) test if incorporating that interaction into susceptibility models improves model accuracy.

2. Study area and methods

The perhumid rainforest of the Pacific Northwest coast stretches >1000 km from British Columbia, Canada, to southeastern Alaska, USA (DellaSala et al., 2011). Kuiu Island in the Tongass National Forest (Fig. 1) was selected as the study area for two reasons. First, landslides have been mapped for the entire island (USFS, 2011), and second, a wind disturbance model was developed and tested on the island (Kramer et al., 2001; further details below). Kuiu is a large island (~2000 km^2) with a maximum elevation of 1039 m (Fig. 1). The island consists of steep terrain along the high-elevation crest with large, relatively low-lying, flat areas along the northeast portions. Precipitation, generally increasing with elevation, ranges from ~1500 to >5000 mm annually (SNAP, 2013; www.snap.uaf.edu). The dominant tree species are Sitka spruce (*Picea sitchensis*) and western and mountain hemlock (*Tsuga heterophylla* and *T. mertensiana*, respectively), with Alaskan yellow cedar and western redcedar (*Thuja plicata*) in lower concentrations. Shore pine (*Pinus contorta* var. *contorta*) is present in low-productivity bog sites. The geology consists primarily of plutonic mountains (26% of island area, 52% forested, 10% hydric bogs and wetlands), sedimentary hills (33% of island, 85% forested, 20% hydric), limestone ridges (6% of island, 83% forested, 18% hydric), and greywacke lowlands (61% of island, 59% forested, 49% hydric), as mapped by Kramer et al. (2001).

Landslides of the debris-avalanche–debris-flow type on Kuiu were mapped as part of a regional USFS mapping effort (USFS, 2011; Fig. 1, Table 1). Landslides were hand digitized from current imagery and dated if possible; failure type, vegetation cover, and other salient variables were estimated. Because this study focused on linkages between landslides, YCD, and wind in natural conditions, all landslides that were related to roads, logging activities, or occurring in nonvegetated areas (e.g., rockslides) were eliminated prior to analysis. Inside each slide, the highest elevation point was extracted and used as that slide's initiation point; the lowest as the end point. These restrictions left a total of 295 mapped landslides (Fig. 1, Table 1). All processing was conducted in R (R Core Team, 2013).