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Channel and landscape dynamics in the alluvial forest mosaic of the Carmanah River valley, British Columbia, Canada

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ABSTRACT

The highly diverse shifting-mosaic of forest patches of an alluvial forest within the Carmanah River valley on the west coast of Vancouver Island, British Columbia was studied to examine the hydrogeomorphic disturbance regime that structures it. We used a landscape-scale analysis to quantify historical channel migrations and changes in the extent of specific forest types. This GIS-based analysis using a 70-year aerial photographic record was complemented by field-based research. Thirty-eight plots containing 4509 trees were sampled for forest structure, age, and elevation above the contemporary channel. These data, including a vegetation chronosequence spanning over 500 years, were used to examine channel and landscape dynamics. Our findings support a general conceptual model that describes cycles of patch development and destruction in unconfined alluvial forests of the Pacific Coastal Ecoregion. Over the past century, Carmanah River has eroded nearly 30% of the alluvial forest in this study area, and approximately 65% over the past 500 years. At least 80% of the 2007 channel was forested area within the past 70 years. Younger landforms were disturbed more frequently than mature forest patches, which suggest that as biogeomorphic succession progresses the likelihood of future disturbance decreases. Estimated half lives of landforms ranged from 24 years for pioneer bars to over 1500 years for old growth terraces. Years of regional high magnitude floods resulted in a net loss of floodplain forest area indicating that disturbance was climate driven in this pluvial watershed, whereby rain events result in flood disturbance that converted forests to channel. These events initiate a subsequent course of vegetation succession and geomorphic development, and often result in the deposition of large wood that modifies the channel environment and contributes to channel avulsion and further hydrogeomorphic disturbance. The composition of the landscape is a reflection of the balance between the disturbance rate and successional development. We also observed a relationship between landscape composition and watershed size. Specifically, the ratio of mature to developing alluvial forests was higher in this smaller watershed compared to larger watersheds in the region. Results imply that larger flood events predicted to occur with climate change may change the disturbance regime of floodplain forests and alter landscape composition.

1. Introduction

Floodplain forests of unregulated, dynamic rivers are composed of a patchwork or mosaic of different forest ages and compositions. The diversity of these alluvial ecosystems is an effect of the interplay between biogeomorphic succession and hydrogeomorphic disturbance (Geerling et al., 2006; Latterell et al., 2006). That is, the development of individual floodplain landforms is controlled by feedbacks between physical constraints of the hydrogeomorphic disturbance regime and biological and geomorphic processes that modify the resistance of patches over time (Tabacchi et al., 2009). The resulting configuration of the landscape mosaic is a reflection of the process interactions between historical episodes of hydrologic disturbance and the successional trajectories of floodplain forests (Whited et al., 2007).

In dynamic floodplain environments, channels may regularly shift laterally due to processes such as channel migration and avulsion, and vertically due to channel incision, avulsion and sediment wedge formation (Beechie et al., 2006). Regardless of the specific geomorphic process, a shifting mosaic of forest patches is maintained by the net effect of erosion and new colonization of vegetation (Balian and Naiman, 2005; Polzin and Rood, 2006; Stolnack and Naiman, 2010; Van Pelt et al., 2006).

The distribution, extent, and disturbance regime of riparian forest patch types are of interest to problems of landscape ecology and landscape evolution, as this dynamic mosaic results in a diversity of landform types that sustain biodiversity, ecosystem functions, and geomorphological processes. For example, in the Pacific Coastal Ecoregion, mature terraces support an abundance of large mature conifers and are a primary source of large wood capable of initiating

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log jams that control river geomorphology and eventual forest disturbance (Fetherston et al., 1995; Latterell and Naiman, 2007). In contrast, recently formed floodplains are characterized by dense stands of deciduous pioneer tree species such as red alder (*Alnus rubra* Bong.), whose leaves are a primary energy source that will affect the abundance and composition of benthic invertebrate communities (Hernandez et al., 2005; Richardson et al., 2005; Wipfli and Musslewhite, 2004). Furthermore, differences in type, age, density and composition of forests may result in varying degrees of resistance to erosion during flood events and can result in differences in channel geometry (Allmendinger et al., 2005; Anderson et al., 2004; Beschta and Ripple, 2006; Bird, 1993). Thus, the dynamics of riparian patch distributions have implications for many aspects of stream ecology and geomorphology.

Several studies have proposed that across the floodplain mosaic the combined total area (aerial extent) of each riparian patch type may remain steady at large spatial and temporal scales. However, locally, over time scales of less than a century the spatial distribution and extent are bound to change as a result of many factors including upstream sediment flux, changes in the hydrologic regime, river modification or stabilization, and natural or anthropogenic climate fluctuations (Kalliola and Puhakka, 1988; Latterell et al., 2006; Naiman et al., 2010; Whited et al., 2007). Recently, much effort has been put into monitoring the current and historical conditions of landscape mosaics along large rivers in Europe and elsewhere to provide a baseline for future restoration efforts (Geerling et al., 2006; Gonzalez et al., 2010; Van Looy et al., 2008). Similar studies in more natural systems in North America have focused on large rivers to define disturbance and succession processes and resulting landscape signatures of healthy riparian mosaics (Latterell et al., 2006; Whited et al., 2007). However, few projects have examined natural conditions within smaller river systems. This research is necessary for understanding how processes of riparian landscape development transfer across river systems of varying sizes in order to define restoration goals in small and medium size rivers and for informing forest harvest practices that seek to mimic natural disturbance regimes. Furthermore, this basic research is needed to define reference conditions that may serve to gauge the effects of climate change on riparian forests (Primack, 2000; Whited et al., 2007).

The hydrogeomorphic processes that shape the fluvial landscape in pluvial watersheds occur mostly during high-flow hydrologic conditions (floods). Floristic composition has been linked to flood return periods and studies have related changes in the riparian patchwork to climate characteristics (Primack, 2000; Whited et al., 2007). At the reach scale, it was found that areal extent of vegetation classes would change by up to 27% due to changes in hydrologic inundation under future climate scenarios (Primack, 2000). In this ecosystem, duration of flood inundation was thought to be a major control on riparian composition. Because riparian compositions were presumably adapted to a particular inundation regime, a change in the duration of annual flood inundation would cause 27% of the riparian area to be mismatched with suitable hydrologic conditions.

In a landscape scale study, Whited et al. (2007) examined the distribution and extent of floodplain habitat types along a 6 km long river corridor in relation to historical hydrologic disturbance and regional climate over a 60-year period. It was found that warming and cooling phases of the Pacific Decadal Oscillation resulted in different frequencies and magnitudes of critical overbank flows which were responsible for channel migration and floodplain forest erosion. This was reflected in the landscape as the extent of forest types changed according to the magnitude of recent hydrologic disturbance. Although short-term changes were observed, over sufficiently large temporal and spatial scales the abundance and extent of different patch types were reported to have remained in roughly constant proportions — a steady-state mosaic.

The Carmanah River floodplain mosaic is part of a pristine watershed, which has not been exposed to forest harvesting or other human activities. This river valley is representative of the natural state of hundreds of isolated ecosystems on floodplains of alluvial rivers within the temperate rainforest of the Pacific Coastal Ecoregion of North America. Our overall objective was to test and further develop a general conceptual model that describes cycles of landscape dynamics driven by hydrogeomorphic disturbance in unconfined alluvial forests of the Pacific Coastal Ecoregion within the Carmanah River valley bottom. Specific inter-related objectives were: 1) to examine patterns of lateral channel migration and avulsion and to quantify the magnitude and areal extent of hydrogeomorphic disturbance over the past centuries; 2) to analyze the areal dynamics of riparian patch types to assess differences in the frequency and extent of hydrogeomorphic disturbance across forest types; and 3) to investigate the extent to which the regional historical hydrologic record is linked to changes in landscape composition.

2. Material and methods

2.1. Site

The Carmanah River Valley is located on the west coast of Vancouver Island in the Carmanah Walbran Provincial Park of British Columbia, Canada (48° 40′ N, 124° 41′ W) (Fig. 1). The watershed covers an area of 67 km^2, mostly composed of steep forested valleys within the Coastal Western Hemlock Biogeoclimatic Zone. The most extensive alluvial floodplain area occurs well above the mouth of the stream. This area, which included our study site, is part of a hanging valley, downstream of which the river becomes dramatically steeper. The alluvial study area was a 400–800 m wide, 3 km stretch of valley-bottom forest (Fig. 2). Here, the Carmanah River is a wandering gravel-bed stream with a 40–90 m wide active channel characterized by riffles, pools and glides (Fig. 3). Downstream of the study area the river morphology becomes a cascade, step-pool, followed by a bedrock canyon system that includes a set of waterfalls before reaching the Pacific Ocean.

The climate is dominated by moisture-laden air masses from the Pacific Ocean driven by westerly winds and locally influenced by steep mountainous topography. Catchment elevation ranges from 0 to 1050 m above sea level. Orographic forcing of heavily saturated air masses results in high annual precipitation. Annual precipitation at the nearest well gauged watershed, Carnation Creek, which is ~35 km away, is 2000–5000 mm across the watershed. Three-quarters of this precipitation falls during the fall and winter seasons (October to March), though soils remain moist year round (Hartman and Scrivener, 1990). The hydrologic regime of these small Pacific coastal catchments is pluvial with snowfall occurring infrequently, and that which does fall rarely stays on the ground for extended periods (Fannin et al., 2000). At Carnation Creek, streamflow is highly responsive to precipitation intensity (Hetherington, 1988) and is related to hourly precipitation (Hetherington, 1982). We expect that Carmanah Creek has a very similar hydrologic regime to Carnation Creek.

2.2. Air photo analysis

A 70-year chronology of air photos and high-resolution satellite images from 1937, 1952, 1963, 1965, 1969, 1987, 2001, and 2007 provided an extensive dataset to examine geomorphic evolution and vegetation succession over the past century. The 2001 image had been orthorectified by the British Columbia Ministry of Environment and was used as a base for georectification of images from other flight years. Air photos were rectified in ArcGIS using recognizable individual trees, clusters of trees, and stable geomorphic features such as old landslide scars and mountain ridges as base points.

Our study area is limited to the extent of the alluvial forest that has grown on landforms which have been formed by fluvial processes. This area is referred to as the historical floodplain. Using a digital elevation model, the extent of this area was delineated using slope as an indicator of the floodplain edge — a boundary was drawn where the relatively flat