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Effects of the invasive plant *Lupinus polyphyllus* on vertical accretion of fine sediment and nutrient availability in bars of the gravel-bed Paloma river☆

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ABSTRACT

Floodplain vegetation is fundamental in fluvial systems, controlling river corridor geomorphology and ecology through a series of hydraulic, sedimentological, and biological processes. Changes caused by introduced plant species can thus result in shifts in river regime, succession trajectories and nutrient availability, affecting native biodiversity. The exotic bigleaf or marsh lupine *Lupinus polyphyllus*, introduced in Patagonia in the last decades, is aggressively invading fluvial corridors. It fills unoccupied ecological niches in southern Chilean rivers, due to its capacity for nitrogen fixation, its perennial habit, and high shoot density and leaf surface area.

We investigated the effects of *L. polyphyllus* on vertical accretion of fine sediment, and soil carbon and nitrogen content, on gravel bars of the Paloma river, Chilean Patagonia, where lupine is believed to have been introduced in 1994. We sampled plot pairs with and without lupine, with each pair located at the same elevation above river stage, and plots distributed over the reach scale. We measured the thickness of the fine soil horizon, grain size distribution, and soil carbon and nitrogen content. We also compared aerial photographs to evaluate changes in spatial coverage of lupine along the study reach.

Presence of lupine was strongly correlated with a thicker layer of finer sediment, in turn characterized by higher organic carbon, carbon to nitrogen ratio, and inorganic carbon content. Contrary to our expectations, we did not find any significant differences in total nitrogen. Aerial photographs did not reveal important differences in coverage between 2007 and 2010, but plant density appears to have increased between the two dates, and invaded gravel bars also appear to be more stable. Lupine dominance of otherwise sparsely vegetated gravel bars in Patagonian rivers appears to have greatest consequences on bar physical structure (increased rates of accretion of fines) and secondary repercussions on soil quality (increase in recalcitrant organic matter), with potential transient effects on nutrient availability (possible increased soil metabolism, followed by carbon mineralization and loss of lupine nitrogen subsidy).

Introduction

Vegetation is one of the most important controls on geomorphological processes and landforms (Kirkby 1995). Riparian plants affect fluvial landforms through changes in water budgets, soil moisture, resistance to flow, nutrient availability, sediment deposition, bank strength and erosion, channel and floodplain evolution, etc. (Simon et al. 2004). As a rule, river landscapes have been considered to be controlled mostly by hydrogeomorphic processes, the interaction between the flow and sediment regimes. This idea was first challenged by Hickin (1984), who emphasized the effects of vegetation on flow resistance and bar sedimentation, among others. More recently, Gurnell and Petts (2002) and Gurnell et al. (2012) show that vegetation actually plays an active role, particularly in the case of wandering gravel-bed rivers. For example, Tal et al. (2004) confirm the role of riparian vegetation as a primary control on channel form, in the case of multi-thread gravel-bed rivers. Indeed, Paola (2011) argues that the emergence of terrestrial vegetation corresponds in geological time with dramatic global changes in river morphology. Not only does riparian vegetation directly affect many hydrogeomorphic processes, its development depends in turn on those same processes, through positive feedback loops (Gregory et al. 1991; Richards et al. 2002; Francis 2006; Corenblit et al. 2007, 2009; Schnauder and Moggridge 2009).

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Primary succession is among the oldest (Cowles 1911) but still evolving concepts in the field of ecology (Connell and Slatyer 1977); in summary, it states that pioneering species establish on bare substrates and then facilitate the colonization by woody species through pedogenesis or other modifications to the micro environment.

The colonization of gravel bars in wandering or braided river systems is a good example of primary succession. Floodplain succession in gravel-bed rivers begins in the active part of the river corridor, the parafluvial zone (sensu Stanford et al. 2005), when plants colonize recently created, bare gravel bars (Braatne et al. 1996; Karrenberg et al. 2002). The initial colonization of gravel bars by pioneering vegetation is a fundamental process underlying floodplain formation and habitat dynamics in alluvial rivers (Gregory et al. 1991; Décamps 1996; Bennett and Simon 2004; Stanford et al. 2005). When covered with vegetation, bars become hydraulically rougher and trap more fine sediment during floods, thus growing by vertical accretion (Hickin 1984; Gurnell and Petts 2002). In a positive feedback loop, deeper and finer soils, located at higher elevations provide a better environment for plant growth, because the frequency of flooding and scouring disturbances is reduced, while water-holding capacity increases (Décamps 1996; Gurnell and Petts 2002; Francis 2006; Corenblit et al. 2007). In time, bare gravel bars become the new floodplain surface, allowing for succession to proceed.

One of the key limiting factors in plant succession on fluvial gravel bars is the restricted availability of soil nutrients, especially nitrogen (Adair and Binkley 2002; Morris and Stanford 2011). Therefore, key characteristics that determine plant succession and soil development in riparian zones include the presence of plants with adaptations to withstand at least temporary nitrogen limitation or else with the capacity for nitrogen fixation, or systems that receive nitrogen subsidies such as from salmon carcasses (Morris and Stanford 2011).

Riparian vegetation is a fundamental driver of river ecosystem function (Tabacchi et al. 1998). The Shifting Habitat Mosaic of Stanford et al. (2005) explains the pattern and process of fluvial ecosystems in the case of alluvial rivers with floods. It refers to the complex, heterogeneous, and dynamic distribution of habitat patches within a floodplain, which are used by aquatic and riparian organisms. This mosaic is driven by the flow, sediment, and large woody debris (LWD) regimes, interacting with the floodplain vegetation and materials along a given reach. Plants are a primary control on the biophysical complexity of alluvial ecosystems, partly explaining their structure and functioning (Gregory et al. 1991; Malanson 1993; Naiman and Décamps 1997; Décamps 2005): they provide shade, allochthonous organic matter inputs, filtration of nutrients in shallow groundwater flows and of fine sediments in overland flows, and are a source of LWD to aquatic ecosystems; they modify the microclimate and serve as corridor for movements of both animals and plants, and also as habitat for mammals and birds.

Lupinus polyphyllus Lindl. is an invasive, perennial herbaceous plant in the Fabaceae family. It is native to western North America, but has successfully invaded rivers in many European countries (Fremstad 2010), as well as in New Zealand, Australia, and Argentina (ISSG global invasive species database, http://www.issg.org/database/species/ecology.asp?si=944&fr=1&sts=&lang=EN). Because it produces a considerable number of large seeds, has capacity for nitrogen fixation, is toxic (it produces an alkaloid that may enhance competition with other plants and reduce grazing impacts), and can reproduce vegetatively, it has a high regeneration capacity following disturbances such as scour or fire (Fernández 2007; Quiroz et al. 2009). Lupines were introduced as ornamental plants by the first European settlers to Chilean Patagonia, and *Lupinus* spp. now cover many of its river corridors and roadside areas. Although the first record for *L. polyphyllus* in the Aysén region (Central Patagonia) of Chile is relatively recent (Rodríguez et al. 2008), general observations suggest that it is already widespread and often an aggressive invader in many river basins in the region. For example, bars dominated by *L. polyphyllus* stands up to 2.0 m in height have been observed on the Palena (Palena river), Aysén (Mañihuales, Simpson, and Paloma rivers) and Baker Catchments (Murta and Baker rivers), a range spanning over 400 km, with possibly hundreds of kilometers of riparian zone invaded in three major watersheds of Chilean Patagonia. This study focuses on the colonization by *L. polyphyllus* of coarse, recently deposited gravel bars. However, the species has also been observed in a wide range of habitats in the region: vegetated wetlands bordering shallow lakes, roadsides, well-drained upland pasture on andisols, in addition to a variety of riparian habitats, from poorly drained depressions, coarse sands, low orthofluvial terraces (mixed with *Holcus*) and on bare gravel and cobble bars.

In this reach-scale investigation, we examine the effects of *L. polyphyllus* on vertical accretion of fine sediment and on nutrient availability (organic carbon and nitrogen) on gravel bars of the Rio Paloma, a wandering gravel-bed river in Chilean Patagonia. We hypothesize that the presence of *L. polyphyllus* increases bed roughness over bars, resulting in slower flow velocities and enhanced deposition of finer sediment. We expect that a subsequent increase in vertical accretion rates, together with litterfall and nitrogen fixation in dense lupine stands, will also alter nutrient availability, specifically with an increase in total soil nitrogen. The lupine invasion in Patagonia, which remains largely undocumented, may be among the most significant alterations in rivers and streams in the region, with potential changes in geomorphological regimes and soil fertility and consequent effects on primary succession, and novel feedbacks between vegetation and river geomorphology.

Methods

Study reach

The field data were collected on bars located along the Paloma river, a 5th order, wandering gravel-bed stream in Chilean Patagonia, located about 60 km south of the city of Coyhaique (Fig. 1). The study reach is about 13 km long, with an average valley slope of 0.33%. The active channel along the reach ranges in width from 80 to about 300 m. Flow regime is mixed, with runoff from over 50% of the catchment regulated by large lakes, but also with significant rainfall-driven runoff events from unregulated tributaries throughout the year, as well as predictable snowmelt floods in spring. The drainage area at the lower end of the study reach is 832 km^2, with a mean annual flow estimated at about 50 $m^3\ s^{-1}$. Lowest flows occur during the winter.

Woody riparian vegetation on forested islands is mostly composed of lenga (*Nothofagus pumilio*), ñirre (*N. antarctica*), and notro (*Embothrium coccineum*; Chilean fire bush), with some coihue (*N. dombeyi*). Recent bars are sparsely colonized by *Holcus lanatus*, also non-native and widespread in pastures in Chile, with occasional contribution by native bamboos in the genus *Chusquea*. *Holcus* is the most common associate of lupine, and is co-dominant on the orthofluvial zone, when a consistent layer of fines has already accumulated. The colonization sequence and interaction (competition or facilitation) between the two taxa is unknown. In the Paloma valley, which is inhabited by only a handful of families, it is clear that lupine was introduced in 1994, by the owner of a then recently opened fishing lodge. Indeed, its observed distribution within the valley covers from the lodge downstream.