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Review

Regeneration of *Salicaceae* riparian forests in the Northern Hemisphere: A new framework and management tool

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A B S T R A C T

Human activities on floodplains have severely disrupted the regeneration of foundation riparian shrub and tree species of the *Salicaceae* family (*Populus* and *Salix* spp.) throughout the Northern Hemisphere. Restoration ecologists initially tackled this problem from a terrestrial perspective that emphasized planting. More recently, floodplain restoration activities have embraced an aquatic perspective, inspired by the expanding practice of managing river flows to improve river health (environmental flows). However, riparian *Salicaceae* species occupy floodplain and riparian areas, which lie at the interface of *both* terrestrial and aquatic ecosystems along watercourses. Thus, their regeneration depends on a complex interaction of hydrologic and geomorphic processes that have shaped key life-cycle requirements for seedling establishment. Ultimately, restoration needs to integrate these concepts to succeed. However, while regeneration of *Salicaceae* is now reasonably well-understood, the literature reporting restoration actions on *Salicaceae* regeneration is sparse, and a specific theoretical framework is still missing. Here, we have reviewed 105 peer-reviewed published experiences in restoration of *Salicaceae* forests, including 91 projects in 10 world regions, to construct a decision tree to inform restoration planning through explicit links between the well-studied biophysical requirements of *Salicaceae* regeneration and 17 specific restoration actions, the most popular being planting (in 55% of the projects), land contouring (30%), removal of competing vegetation (30%), site selection (26%), and irrigation (24%). We also identified research gaps related to *Salicaceae* forest restoration and discuss alternative, innovative and feasible approaches that incorporate the human component.

Contents

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1. Introduction

In the Northern Hemisphere, most riparian forests have been historically dominated by foundation species in two genera of the *Salicaceae* family: *Populus* (cottonwoods/poplars) and *Salix* (willows). *Salicaceae*-dominated riparian forests ("*Salicaceae* forests" hereafter) provide important ecosystem services such as habitat for diverse wildlife, organic matter and shade for aquatic life, and an environment for human recreation and aesthetic enjoyment (Naiman et al., 2005). Riparian *Salicaceae* are pioneer species that depend on the hydrologic regime of rivers and associated geomorphic adjustments to complete their life cycle (Karrenberg et al., 2002). Recruitment of new individuals or stands ("regeneration" hereafter) in particular may result from various fluvial processes (Scott et al., 1996, 1997; Gom and Rood, 1999; Cooper et al., 2003), but the conditions for seedling establishment are naturally so restrictive that decades may pass without effective large-scale regeneration (Mahoney and Rood, 1998; Stromberg, 1998). As a result, *Salicaceae* forests are commonly composed of mosaics of relatively even-aged cohorts that established in different years (Johnson et al., 1976). In some regions *Salicaceae* species are highly dominant (e.g., Southwestern U.S.: Stromberg, 1993; Mediterranean and Central Europe: González et al., 2010; Klimo and Hager, 2001), whereas in others they may be a component of a more diverse mix of woody and herbaceous taxa (e.g., Scandinavia, Nilsson et al., 2015; Southern U.S., Simmons et al., 2012; northwestern U.S., Naiman et al., 1998).

Salicaceae forests globally are impacted in various ways by human activities (e.g., Rood and Mahoney, 1990; Rood et al., 1995; Johnson, 1992, 1994; 1998; Shafroth et al., 2002; Dufour et al., 2007; Stromberg et al., 2007a; González et al., 2010; Dixon et al., 2012; Scott et al., 2013; Garófano-Gómez et al., 2013, González del Tánago et al., 2016; and many others). The most common dysfunction of *Salicaceae* forests is the severe decrease of fluvial disturbance-dependent regeneration. In virtually all human-impacted rivers, hydrogeomorphic processes are simplified and homogenized, causing regeneration to be limited to a less diverse set of smaller size geomorphically-active landforms, such as abandoned channels, channel margins, alluvial bars and instream areas, compared to unregulated, free-flowing rivers. The problem of reduced regeneration may be overlooked in some rivers because recruitment may continue for years after geomorphic dynamism has ceased, as vegetation colonizes bare areas (e.g., former channels) that experienced a reduction in flooding disturbance (Johnson, 1994, 1998; Shafroth et al., 2002; Stromberg et al., 2010; Stella et al., 2011; Coble and Kolb, 2013). Meanwhile, however, remnant *Salicaceae* forests in the disconnected floodplain experience a sharp decline in regeneration, while established populations age and are replaced by later successional vegetation. The latter includes shade-tolerant trees in wet regions and grasslands and shrublands of drought-tolerant taxa in dry regions, frequently including exotic species (Friedman et al., 1995; Glaeser and Wulf, 2009; González et al., 2010; Merritt and Cooper, 2000; Dixon et al., 2012; Garófano-Gómez et al., 2013; Martínez-Fernández et al., 2017a).

There are hundreds of field- (e.g., Mahoney and Rood, 1998; Johnson, 2000), mesocosm- (e.g., Stella et al., 2010; Guilloy et al., 2011) and modeling-based (e.g., Dixon and Turner, 2006; Harper et al., 2011; Benjankar et al., 2014) studies on the biophysical requirements of riparian *Salicaceae* regeneration, particularly for *Populus* spp.; extensive work on how regeneration has been impacted by human activities (e.g., Cooper et al., 1999; Shafroth et al., 2002); and recommendations for minimizing those impacts (e.g., Hughes and Rood, 2003; González et al., 2010). However, the scientific literature reporting results of management actions to promote *Salicaceae* regeneration is less abundant and particularly scattered: traditionally, restoration of *Salicaceae* regeneration has focused on plantings, influenced by a terrestrial approach from forestry, with uncertain results (Briggs et al., 1994; Stromberg, 2001). Inspired by key advances in river ecology (*River Continuum*, Vannote et al., 1980; *Flood Pulse*, Junk et al., 1989; *Natural Flow Regime*; Poff et al., 1997), controlled releases from dams were applied during the 1990s and provided optimism for effectively restoring *Salicaceae* regeneration, extensively and at a low cost (Shafroth et al., 1998; Hill and Platts, 1998; Rood et al., 2003, 2005). Although legitimate and effective, very few projects reported using