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Development of an eco-geomorphic modeling framework to evaluate riparian ecosystem response to flow-regime changes

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ABSTRACT

Tools that provide decision makers with an understanding of ecosystem response to changes in streamflow attributes are necessary to balance human and ecosystem water needs. Flow response curves provide one such approach for informing management based on modeled relationships between environmental control (e.g., flood magnitude) and response (e.g., plant recruitment) variables, although unidirectional relationships may fail to capture the complex interactions between ecological and physical processes in riparian ecosystems. We take advantage of the linkage between plant functional traits important for (a) determining a plant's response to environmental conditions and (b) for predicting its impact on the flow of water and transport of sediment, to build a predictive model of riparian ecosystem dynamics. By using plant functional groups (i.e., guilds), our model accounts for process linkages among streamflow properties, physical processes, and plant community response. The model relies on a series of flow response curves built and tested with data collected along semiarid, canyon-bound rivers in Colorado. We built 2D hydrodynamic models and updated them with a flexible vegetation module to represent plant-hydraulic interactions for three study reaches. Plant guild distributions are well described by the model while predictions of the occurrence and direction of topographic change are less deterministic. Our work is among the first to develop response curves for both physical and ecological processes in the same framework. The shape of the resulting curves indicate that the functioning of riparian ecosystems is driven by nonlinear relationships and that clear, identifiable thresholds exist. As such, changes to the flow regime will have a differential impact on physical and ecological processes, depending on the nature of the shift. We discuss the strength and limitations of our model and make suggestions about its applicability to river management.

1. Introduction

Identifying ecosystem responses to the introduction or removal of a stressor or changes in available resources is critical for the effective management of natural systems (Ormerod et al., 2010), and tools to isolate important factors and translate scientific understanding into an ecosystem context can aid decision making (Schaeffer et al., 1988). Response curves link the response of an ecosystem property to environmental control variables in a single relationship (Potvin et al., 1990) and provide an important tool to bridge the gap between science and management (Wohl et al., 2015). Relationships built from empirical data are used to assess how a response variable reacts to a change in the control variable (e.g., Fig. 1). Characteristics of the response curve inform us on the functioning of ecosystems (Scheffer et al., 2001). For example, nonlinearities and inflection points may indicate thresholds that signify system sensitivity and resilience (Fig. 1).

Response curves are particularly useful in aquatic and riparian ecosystems (e.g., Bovee et al., 1998). In such settings, flow is the dominant driver of ecological and physical processes (Merritt et al., 2010), resulting in functional relationships between flow and ecosystem response. Control-response relationships have been used to predict changes in ecosystem properties as a result of deliberate (e.g., water development) or unintentional (e.g., climate change) shifts in flow attributes (King and Brown, 2010; Lytle et al., 2017). For example, flow response curves for individual fish species predicted the impact of flow depletions on fish assemblage structure in Michigan (Zorn et al., 2012). On the Bill Williams River, Arizona, flow response curves characterizing seedling survival, beaver dam integrity, and the dynamics of benthic macroinvertebrate groups have been tested for use in environmental flow decisions (Shafroth et al., 2010).

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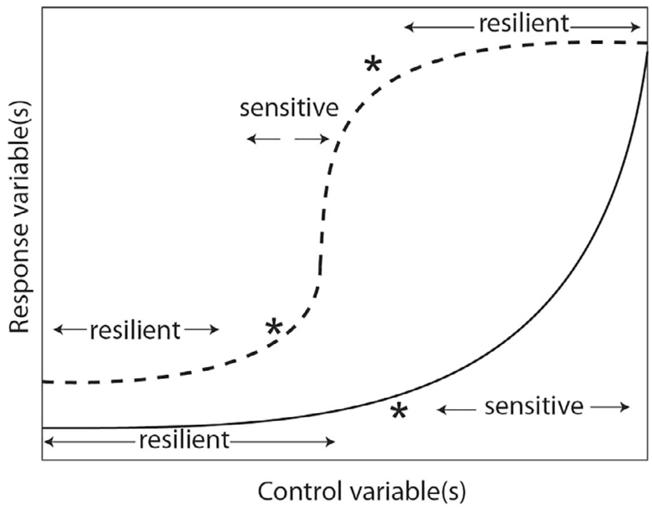

Fig. 1. Hypothetical response curves, the shape of which lends insight into ecosystem function. Both curves depicted here exhibit nonlinearities and inflection points. Asterisks identify conceptual thresholds that separate regions of the curve for which the response variable is resilient to changes in the control variable (i.e., with a change in the control variable, little change in the response variable occurs) from regions for which the response variable is sensitive to change (i.e., with a change in the control variable, a large change in the response variable occurs). Multiple thresholds may exist (e.g., dashed line) representing multiple regions of resilience and sensitivity.

Because of the process linkages and feedbacks between physical and ecological processes in aquatic and riparian ecosystems (Reinhardt et al., 2010), the complex response of these systems to changes in flow regimes are difficult to capture using response curves. Germination of riparian plants not only relies on flood peak timing and the rate of stage decline (Rood et al., 1998) but also the availability of unshaded, freshly deposited sediment (Scott et al., 1996). In turn, the recruitment of plant communities alters the physical processes that create suitable plant habitat (Corenblit et al., 2007). Moreover, the strength and direction of feedbacks between hydrogeomorphic processes and ecosystems vary temporally, for example with time since large floods and degree of maturity of riparian vegetation (Corenblit et al., 2007).

In this paper, we present an eco-geomorphic modeling framework that incorporates the interactions and feedbacks among flow, plants, and physical processes in riparian ecosystems. This modeling framework is built from a series of flow response curves, or curves for which attributes of the flow regime serve as one or more of the control variable(s). To date, response curves have been predominately used to describe changes in ecological attributes (e.g., species presence or distribution). Flow response curves also have strong potential for use in understanding controls on physical ecosystem attributes, and predicting shifts with a change in flow (Wohl et al., 2015). Our objectives in developing the eco-geomorphic modeling framework presented here are to tackle the challenge of building these relationships and, by using ecological and physical flow response curves in the same framework, to demonstrate the feasibility of applying a series of flow response curves to capture the integrative nature of riparian ecosystem response to shifts in flow attributes. Such a framework allows us to explore ecosystem functioning by identifying sensitivities and resiliencies. Additionally, with the use of relatively straightforward relationships between flows and ecosystem properties, this framework can inform decision-making about water allocation, changes in water due to climate change, and managing hydrographs for the benefit of riparian ecosystems. The example we use is for the Yampa and Green Rivers in Dinosaur National Monument, Colorado and Utah, USA where, as in many dryland river systems, climate change and upstream water use have the potential to substantially shift the flow regime in the coming decades (Yampa/White/Green Basin Implementation Plan, 2015).

To incorporate linkages between physical and ecological processes we rely on the relationship between functional plant traits important for describing how a plant will respond to abiotic stressors (ecological-response traits) and those traits important for determining how a plant alters the flow of water and transport of sediment (morphological-effect traits) (Lavorel and Garnier, 2002). Ecological-response and morphological-effect plant traits show similarities and correlations (Diehl et al., 2017a), and as a result, assemblages of species with similar combinations of traits (i.e., guilds) built from ecological response traits are likely to have a unique and consistent impact on fluvial processes. Data collected for 35 species along the Yampa and Green Rivers in Dinosaur National Monument in Colorado and Utah provide support for relationships among ecological-response and morphological-effect plant traits and fluvial processes (Diehl et al., 2017a). Using cluster analysis, Diehl et al. (2017a) identified 11 ecological-response guilds for the Yampa and Green Rivers. Morphological-effect traits were distinct (i.e., the range of values for the species within the guild) for 70% of the guild comparisons. As such, they demonstrated that ecological guilds are, in fact, morphologically unique and provided evidence that these morphologically-important groupings of plants have a distinct geomorphic signature.

The eco-geomorphic model we present here is built from three flow response curves that predict the response of plant-guild presence, total vegetation cover, and topographic response to a change in flow regime attributes. The use of flow response curves presents at least two basic challenges: quantifying the relationship between control and response variables, and identifying limitations in applying the flow response curves (Wohl et al., 2015). To address the first of these we use three years of data collected on the Yampa and Green Rivers to build statistical models that describe the relationship between flow and ecosystem properties. To identify limitations in the flow response curves, we apply the full eco-geomorphic model, based on the established relationships, to a fourth year of data. The model successfully identifies the spatial distribution of suitable plant guild habitat while having moderate success predicting the occurrence and direction of the geomorphic response to floods. We discuss insights derived from the model into the function of semiarid riparian ecosystems, as well as the model's utility in evaluating the impact of shifts to the flow regime on plant community dynamics and the evolution of landforms.

2. Yampa and Green Rivers

We work along the Yampa and Green Rivers; major tributaries to the Colorado River. Our analyses focus on three reaches, Harding Hole and Laddie Park on the lower Yampa, and Seacliff on the middle Green River, in Dinosaur National Monument (Fig. 2). These reaches are gravel-bedded and confined within bedrock canyons. The Harding Hole (slope of 0.004) and Laddie Park (slope of 0.007) reaches have incised meanders with tight bends in the bedrock, whereas the Seacliff reach (slope of 0.001) is debris-fan dominated; all reaches have mid-channel gravel bars. We focus on these gravel bars because of their susceptibility to vegetation establishment and expansion, deposition of fine-grained sediment, and changes in morphology (Manners et al., 2014; Van Steeter and Pitlick, 1998). Narrowing and simplification of the river channel has occurred within Dinosaur National Monument during the last century in large part from secondary channel aggradation (Alexander and Schmidt, 2007; Allred and Schmidt, 1999; Grams and Schmidt, 2002; Manners et al., 2014).

Riparian ecosystems in Dinosaur National Monument have been well described elsewhere (Merritt and Cooper, 2000; Uowolo et al., 2005). Species distributions represent the continuum of environmental conditions from the active channel, where early-successional species such as *Salix exigua* and *Carex emoryii* are found, up to intermediate floodplain benches with *Symphoricarpos occidentalis*, and then to upper surfaces with mature, late-successional floodplain trees and shrubs