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Review

Review on environmental alterations propagating from aquatic to terrestrial ecosystems

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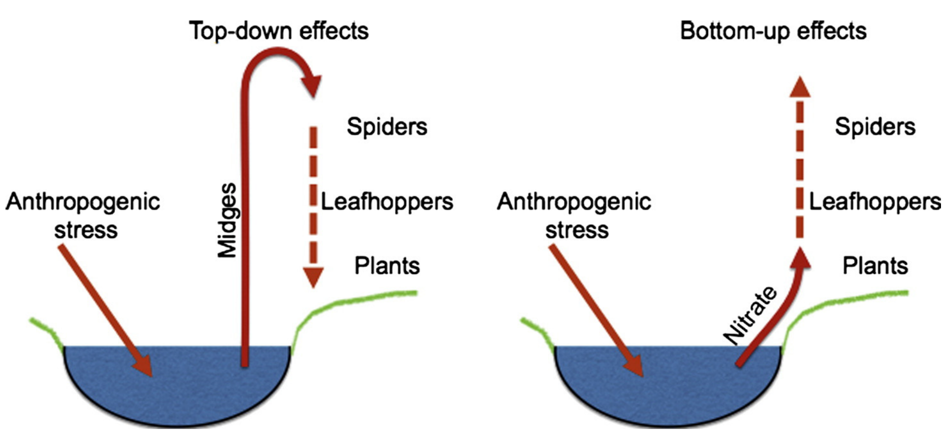
HIGHLIGHTS

- We reviewed alterations propagating from aquatic to terrestrial ecosystems
- Implications of anthropogenic alterations in this coupling are described
- Bottom-up effects via soil quality can cascade via plants to herbivores
- Top-down responses can cascade from predatory spiders via herbivores to plants
- A scientific framework combining abiotic and biotic aspects is proposed

GRAPHICAL ABSTRACT



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ABSTRACT

Terrestrial inputs into freshwater ecosystems are a classical field of environmental science. Resource fluxes (subsidy) from aquatic to terrestrial systems have been less studied, although they are of high ecological relevance particularly for the receiving ecosystem. These fluxes may, however, be impacted by anthropogenically driven alterations modifying structure and functioning of aquatic ecosystems. In this context, we reviewed the peer-reviewed literature for studies addressing the subsidy of terrestrial by aquatic ecosystems with special emphasis on the role that anthropogenic alterations play in this water–land coupling. Our analysis revealed a continuously increasing interest in the coupling of aquatic to terrestrial ecosystems between 1990 and 2014 (total: 661 studies), while the research domains focusing on abiotic (502 studies) and biotic (159 studies) processes are strongly separated. Approximately 35% (abiotic) and 25% (biotic) of the studies focused on the propagation of anthropogenic alterations from the aquatic to the terrestrial system. Among these studies, hydromorphological and hydrological alterations were predominantly assessed, whereas water pollution and invasive species were less frequently investigated. Less than 5% of these studies considered indirect effects in the terrestrial system e.g. via food web responses, as a result of anthropogenic alterations in aquatic ecosystems. Nonetheless, these very few publications indicate far-reaching consequences in the receiving terrestrial ecosystem. For example, bottom-up mediated responses via soil quality can cascade over plant communities up to the

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level of herbivorous arthropods, while top-down mediated responses via predatory spiders can cascade down to herbivorous arthropods and even plants. Overall, the current state of knowledge calls for an integrated assessment on how these interactions within terrestrial ecosystems are affected by propagation of aquatic ecosystem alterations. To fill these gaps, we propose a scientific framework, which considers abiotic and biotic aspects based on an interdisciplinary approach.

Contents

1. Introduction

Freshwater ecosystems and their hydrological dynamics are important "hot spots" and "hot moments" (defined as patches or short periods of time exhibiting disproportionally high reaction rates relative to their surrounding or longer periods of time, respectively, McClain et al., 2003) of biogeochemical processes and biodiversity supporting fundamental ecosystem functions at the landscape ecosystem scale (Costanza et al., 1997; Williamson et al., 2008). These functions ultimately translate into ecosystem services (e.g., the provision of clean drinking water), which refer to the benefits society receives as a result of ecosystem productivity (cp., Kumar, 2010). Thereby, running waters are, despite their relatively low share (0.1% for streams and rivers) of continental area, of particular importance but also depend substantially on their catchments through fluxes of resources including water, organic matter, nutrients and pollutants (Paetzold et al., 2008; Richardson and Sato, 2015; Schulz, 2004; Schwarzenbach et al., 2006). In this context, existing concepts mainly focus on the terrestrial input into freshwater ecosystems and the consequences for aquatic life. For example, the ecological role of terrestrial-derived organic carbon has attracted considerable attention in both lentic (e.g. Pace et al., 2004) and lotic systems (e.g., Wallace and Eggert, 1997). For lotic systems, the importance of terrestrial-derived organic material and the associated alterations in the benthic community along the flow gradient have been conceptualized in the "River Continuum Concept" (Vannote et al., 1980). This concept considers rivers as a receiving system of terrestrial resources with no or only limited recognition of their role as a resource donator. The "Flood Pulse Concept" initially developed by Junk et al. (1989) provided a first step towards the conceptual consideration of feedbacks from aquatic to terrestrial ecosystems (see also Tockner et al., 2000). Such spatial linkages between aquatic and terrestrial ecosystems may have, however, not sufficiently been assessed to fully understand their biogeochemical and ecological consequences (e.g., Baxter et al., 2005; Richardson and Sato, 2015). A complete characterization of a system such as the aquatic–terrestrial ecotone (i.e. floodplain and riparian habitats) requires a framework that covers the interaction of (I) spatially variable food webs and (II) transport and biogeochemical conversion of resources, which has been suggested by the concept of meta-ecosystems (Loreau et al., 2003). For instance, models linking finite and irregular spatial meta-ecosystem structures that are connected through spatial flows of materials and organisms indicate that high fluxes may destabilize local ecosystem dynamics (Gounand et al., 2014; Marleau et al., 2014).

In this context, the potential importance of anthropogenic alteration in aquatic ecosystems for the biogeochemical and ecological linkages to the surrounding terrestrial ecosystems was reviewed considering two pathways fundamental for the coupling of freshwaters and riparian ecosystems (Baxter et al., 2005; Bendix, 1997; Richardson and Sato, 2015): (I) via flood or drought events (water, nutrients, particles, toxicants), while floods are substantially more relevant for the water-to-land subsidy — this linkage is hereafter considered as abiotic coupling, and (II) via emergence of merolimnic aquatic insects, hereafter considered as biotic coupling. Both pathways provide resource pulses (Yang et al., 2008) from the aquatic to the terrestrial ecosystem with a strong potential for effects in the recipient system (Leroux and Loreau, 2012). In this context, we first link the current knowledge of the abiotic and the biotic