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Review

Towards optimizing riparian buffer zones: Ecological and biogeochemical implications for forest management

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ABSTRACT

Riparian forests (RFs) along streams and rivers in forested landscapes provide many ecosystem functions that are important for the biodiversity and biogeochemistry of both terrestrial and aquatic ecosystems. In riverine landscapes, many of these ecological and biogeochemical functions have been found to be maximized in riparian areas with discharge of upland-originating groundwater (GW). This ecological significance, and the fact that riparian areas with GW discharge are important sources of many chemical elements in streams and rivers, makes these places important hotspots in the landscape. The natural functioning of RFs is however threatened by poorly designed management practices, with forestry being one of the most important examples in timber producing regions. Logging operations in riparian, but also in adjoining upland forests, threaten to alter many riparian functions. This effect is accelerated in GW discharge hotspots because of their sensitive soils and the high connectivity with uphill areas. We thus argue that forestry practices should give higher consideration to riparian GW discharge areas, and we demonstrate how improved riparian buffer zone management can be incorporated into every-day forestry planning. We offer a practical tool for more optimized site-specific riparian buffer design by using model-derived high resolution maps with detailed information about wetness and soil–water flow paths within RFs. We describe how such site-specific riparian buffer management differs from fixed-width buffers, which are generally applied in today's forestry, and address some risks connected to fixed-width buffer management. We conclude that site-specific riparian management, allowing wider buffers at GW discharge areas and more narrow buffers on sites of lower ecological significance (i.e. riparian sites without GW flow paths), would benefit a variety of ecosystem services, mitigate negative effects caused by forestry and create more variable and heterogeneous riparian corridors. Finally, we show examples of how the new forestry planning can be applied.

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Abbreviations: DTW, depth to water index; GW, groundwater; RFs, riparian forests.

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1. Introduction

Riparian forests (RFs) along streams and rivers provide a variety of ecosystem services and therefore have fundamental function in most forested landscapes around the world (Gundersen et al., 2010; Luke et al., 2007; Naiman and Décamps, 1997; Swanson et al., 1982). The specificity, magnitude and importance of those services depend on particular system characteristics, such as large scale, regional properties including climate, bedrock characteristics and landscape formation history. Besides that, it is being increasingly recognized that riparian functions vary across individual catchments as well as across individual river segments (Patten, 1998). In fact, recent research has shown that small-scale heterogeneity, ranging from a few to some tens of meters, is more important in shaping riparian ecosystem functioning than previously thought (Atkins et al., 2013; Grabs et al., 2012; Kuglerová et al., 2014; Zimmer et al., 2013). Although discussed by scientists for decades (Toth, 1963; Buttle, 2002; Vidon and Hill, 2004), the heterogeneity of RFs at small spatial scales needs to be better acknowledged in landscape management.

RFs are also some of the most degraded ecosystems worldwide (Nilsson and Berggren, 2000). The most obvious threat to near-stream areas is river regulation because riparian processes are so closely linked to fluvial regimes. Indeed, river channelization and damming fundamentally change riparian dynamics (Nilsson and Berggren, 2000; Nilsson et al., 2005). In addition, perturbations and disturbances in the upland areas also threaten the functioning of RFs, with forestry being the most important example in many timber-producing countries (Bengtsson et al., 2000; Lee et al., 2004; MacDonald et al., 2014).

Forestry practices are intensifying not only due to higher demand for stem wood but also for utilization of other forest products, such as logging residuals and stumps, for biofuel (Laudon et al., 2011b). RFs are thus often exposed to logging pressure despite repeatedly raised concerns about negative effects of forest harvest on riparian and aquatic ecosystems (Bengtsson et al., 2000; Broadmeadow and Nisbet, 2004; Kreutzweiser et al., 2008). Among the most acknowledged issues in boreal and temperate regions related to forestry are species losses and alteration in species composition of riparian and aquatic habitats (Hylander et al., 2002; MacDonald et al., 2014; Marczak et al., 2010), changes in stream-water chemistry (Bishop et al., 2009; Futter et al., 2010; Löfgren et al., 2009), increased siltation (Kreutzweiser and Capell, 2001) and altered hydrology (Andréassian, 2004; Creed et al., 2008b; Schelker et al., 2013). Retained RFs can be important in mitigating such negative effects on stream ecosystems (Hickey and Doran, 2004), but the efficiency of the buffering depends on the width of remaining strips, the size of harvested upland areas and specific local conditions (Broadmeadow and Nisbet, 2004; Castelle et al., 1994). Improved strategies for how to effectively avoid and mitigate impacts of forest management on riparian ecosystem functions should thus be central for sustainable forestry management. At the same time, such methods have to balance forest production and conservation needs, with ecological benefits weighed against economic losses (Gundersen et al., 2010; Work et al., 2003).

In most of the major temperate and boreal timber-producing regions (e.g. Fennoscandia, North America, and Russia) management plans now incorporate some riparian protection (Blinn and Kilgore, 2001; Lee et al., 2004). Because it is convenient and easy to implement, fixed-width unharvested buffers (Fig. 1A and 2) have become a standard practice (Castelle et al., 1994; Richardson et al., 2012). Despite this, fixed-width buffers are not the ideal solution to forestry problems because they are neither economically nor ecologically optimal along the entire stream network. Fixed-width buffers may locally fail their conservation goals because they do not incorporate the potential importance of small-scale spatial heterogeneity of riparian processes. This implies that riparian functioning would be enhanced by varying the width and density of adjoining RFs. Sustainable catchment management would hence benefit from knowledge about how ecosystem services provided by RFs vary at small spatial scales and the driving force behind such heterogeneity. Consequently the riparian buffer management could be tailored, not only to specific catchments, but also to specific river segments if those are identified as areas of higher ecological significance.

The aim of this work is to summarize knowledge about small-scale variation in RF functioning, and use this information to guide how riparian buffers can be designed. We focus on the role of hydrological principles, namely groundwater (GW) flow pathways imposed by local topography as the underlying mechanism driving riparian heterogeneity and we further discuss the implementation of this in terms of forest management. Riparian areas with GW inputs from upland hillslopes have been found important for a variety of ecosystem processes and we describe how such areas could be effectively localized using model-derived terrain indices. Based on spatial variation in RF ecosystem functions, biodiversity and sensitivity to disturbance, we discuss alternatives for riparian buffer management. Although the principles introduced here may be widely applicable, we use examples mainly from boreal and temperate forested regions, because most riparian buffer management methods have been developed and implemented there.

2. Ecosystem functions of riparian forests

Riparian areas are generally important for biodiversity at the landscape-scale. Compared to upland forests, stream-side riparian zones often harbor substantially higher number of species of vascular plants and bryophytes (Dynesius et al., 2009; Hylander et al., 2002; Luke et al., 2007) with different species composition (Sabo et al., 2005). Several studies have suggested similar patterns for beetles, birds and other animals (Mosley et al., 2006; Nilsson, 1992; Patten, 1998; Spackman and Hughes, 1995). These patterns are mostly attributed to the riparian habitat dynamics with regular flood-related disturbance resulting in high productivity, suppressed competition, high diversity of physical conditions and flow-facilitated dispersal (Harner and Stanford 2003; Naiman and Décamps, 1997; Nilsson et al., 2010). Further, RFs are often referred to as important corridors for animal migration, especially when upland areas experience perturbations (Naiman and Décamps, 1997; Spackman and Hughes, 1995).

Even though the importance of RFs for biodiversity is high, it may be exceeded by their role in regulating stream water quality. It has been suggested that the extent and spatial arrangement of riparian areas along streams and rivers impose the first-order control over stream water quality and quantity (Hill, 1996; McDonnell, 2003; Swanson et al., 1982). RFs provide substrate for aquatic organisms in the form of leaf litter and other organic material, they control water temperature and light by shading, and riparian