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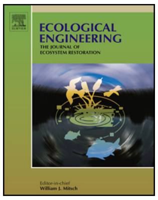

Tall herb sites as a guide for planning, maintenance and engineering of riparian continuous forest cover

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ABSTRACT

Continuous cover riparian forests host significant plant and animal species richness, a range of habitats, and natural processes of importance for both terrestrial and aquatic ecosystems. Riparian forest is thus a green infrastructure for biodiversity conservation. However, a long history of landscape alteration now calls for maintenance and restoration by ecological engineering. This study evaluates management guidelines advocating constant vs. variable width of riparian forest protected zones in managed landscapes. In naturally dynamic forests, stands with gap-phase dynamic along streams often provide a network of habitats with a high degree of continuity in tree canopy cover and dead wood for biodiversity conservation and delivery of ecosystem services including water purification. Based on the observation that tall herb sites indicate a potential for temporally continuous forest cover, we tested three null hypotheses. Tall herb sites (1) are equally common in the riparian zone and in the surrounding forest landscape; (2) have the same width on both sides of a stream; and (3) their widths are independent of the width of the adjacent stream. We described the ground vegetation in transects along and perpendicular to streams, and in the surrounding landscape, in six 3rd stream order catchment located in Sweden, Lithuania and the Komi Republic of Russia. The results showed that tall herb sites were 21–27 times more common along streams compared to in the rest of the landscape, the width of tall herb sites varied considerably along streams, and it was independent of the width of the adjacent stream. This study suggests that rather than fixed-width guidelines for riparian set-asides, to support cost-efficient maintenance of riparian forest, local site conditions should be used as guide for planning, maintenance and engineering of riparian ecotones. Because tall herb forest sites were historically cleared for agricultural purposes, the potential natural amount of riparian forest is severely underestimated.

1. Introduction

Despite comprehensive policy, research as well as common endorsement and effort by land owners and managers, it is obvious that the EU still falls short of achieving its biodiversity conservation targets (European Commission, 2015). European forest policy processes defining sustainable forest management accommodate biodiversity conservation concerns (European Commission, 2013a); and there is a general pledge to secure the supply of a diversity of ecosystem services (European Commission, 2014). However, assessment in both forestry and agricultural systems indicates that greater efforts are still needed to conserve and enhance biodiversity as base for delivery of ecosystem services (European Commission, 2015). Similarly, from a catchment perspective, good status of many waters in Europe also still remains to be achieved (European Commission, 2012). To secure ecosystem benefits that are limited in supply, strategically planned networks of representative natural and semi-natural can be designed and managed to deliver a wide range of ecosystem services; the term green infrastructure captures this (European Commission, 2013b).

Biodiversity conservation in landscapes managed for forestry and agriculture is crucial because (1) only protected areas will not protect biodiversity; (2) securing benefits from ecosystems ultimately relies on vital services provided by biodiversity; and (3) biodiversity enhances ecosystems' capacity to recover from external pressures or management mistakes (e.g., Fischer et al., 2006). To improve policy implementation, it is crucial that evidence-based knowledge is developed about the functionality of ecosystems as green infrastructure (European Commission, 2013b) that supplies ecosystem services (e.g., Burkhard et al., 2012).

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A concrete issue is the role of considerations to biodiversity in land management, such as how to design aquatic-terrestrial ecotones in forest and agricultural landscapes. Riparian ecotones are particularly important for the maintenance of biodiversity and delivery of ecosystem services (e.g., Naiman et al., 1993; Kuusemets et al., 2001; Grygoruk and Acreman, 2015). Riparian forests are an essential contributor to the precipitation and evapotranspiration cycles, by drawing in moist air from elsewhere, and improving water availability at various scales (Makarieva et al., 2014; Makarieva and Gorshkov, 2013; Ellison et al., 2011; Sheil and Murdiyarso, 2009). The interface between the terrestrial and the aquatic environment contributes to the maintenance of compositional, structural and functional elements of biodiversity (Noss, 1990) in both terrestrial and aquatic forest ecosystems (Wiens, 2002; Williams et al., 2003; Sweeney and Czapka, 2004). Naturally dynamic riparian forest ecotones provide suitable conditions for a wide range of vascular plants (Nilsson, 1983), substrate for lichens requiring a moist local climate (Sjöberg and Ericson, 1992), species dependent on naturally dynamic forest (Stighäll et al., 2011), and often a more diverse tree species composition in the adjacent terrestrial system. Riparian forest ecotones also supply streams with woody debris (Bergquist, 1999), leaf litter (Cummins et al., 1989) and regulate nutrient uptakes into the aquatic food chain (Lowrance et al., 1984; Gregory et al., 1991; Osborne and Kovacic, 1993; Mander et al., 1995; Tabacchi et al., 1998). Finally, in the aquatic system riparian forests buffer against flow peaks during snow melt and autumn rains, erosion, leakage of organic matter and nutrients (Lowrance et al., 1984; Gregory et al., 1991; Schlosser, 1991; Osborne and Kovacic, 1993; Mander et al., 1995; Tabacchi et al., 1998; Bergquist, 1999; Kuusemets et al., 2001).

Managing riparian forest ecotones for continuous provision of this multitude of ecosystem services is a complex task (Bergquist, 1999; Nyberg and Eriksson, 2001; Wiens, 2002). Restoring riparian vegetation as part of green infrastructures of agriculture-dominated landscapes is even more demanding. Moreover, ecological objectives in management and planning must compete with economic interests. By default, the majority or land owners and managers are interested in economic gains. Due to long landscape histories, the riparian ecotone is a natural vegetation type that has changed very much following historic clearing of forest for agriculture and development of intensive forest management through modification of streams to improve draining and for wood transportation (e.g., Carlgren, 1886; Lundberg, 1914; Bergquist, 1999). The recently reported low current loss of riparian forest in Europe (Clericia et al., 2014) underestimates this problem by just focusing on contemporary changes, and not the historic loss of forests and woodlands, which is commonly much higher on more productive ecosystems where continuous cover forests is the natural potential vegetation (e.g., Angelstam and Andersson, 2001). Therefore, there is a paucity of data from naturally dynamic reference areas, which would allow an objective determination of an appropriate structure and form of the aquatic-terrestrial ecotone (but see Lazdinis and Angelstam, 2005; Angelstam et al., 2011b). This makes it difficult to find guidance for conservation, management, restoration and re-creation of compositional, structural and functional elements of biodiversity (e.g., Angelstam and Andersson, 2001).

The ways of managing forests in riparian ecotones has been a topic for scientific research and political debate for a long time in many countries (e.g., Malanson, 1993; Greminger, 2003; Murphy et al., 2008; Kuglerová et al., 2014a; Laudon et al., 2016). Commonly, the guidelines have focused on preserving fixed-width corridors (see Macdonald et al., 2004; Lazdinis and Angelstam, 2005; Kuglerová et al., 2014a). However, some recent studies have demonstrated that the use of variable-width buffer zones with different management interventions would allow more cost-efficient trade-offs between biodiversity conservation and wood production benefits of managed forests (Murphy et al., 2008; Laudon et al., 2016; Kuglerová et al., 2014a).

To support planning, management and ecological engineering evidence-based knowledge is required from a wide range of contexts. In naturally dynamic forests, continuous cover forest stands with gap-phase dynamic on productive tall herb sites are often found along streams (Yaroshenko et al., 2001; Jasinski and Angelstam, 2002). Tall herb vegetation (see species list in Hägglund and Lundmark, 1984) is thus a good indicator when selecting sites for conservation of riparian forest by management, restoration and re-creation (Nilsson, 1983; Curry and Slater, 1986; Nilsson et al., 1988, 1989; Learner et al., 1990; Gregory et al., 1991; Satterlund and Adams, 1992; Malanson, 1993; Karazija and Vaičiūnas, 1994; Spackman and Hughes, 1995; Fries et al., 1997; Angelstam, 1998). Knowledge about how to handle riparian forest and vegetation is also relevant in a diversity of other benefits (e.g., Kuusemets et al., 2001; Richardson et al., 2007).

In this study we use ground vegetation plant communities to identify and analyze the occurrence and width of sites which are suitable to be maintained by conservation, management, restoration and re-creation as riparian continuous cover forests for biodiversity conservation and subsequent ecosystem services. In order to mirror some of the range of biophysical factors, management regulations and practices on the European continent, we conducted this study in three landscapes with different biophysical conditions and socio-economic contexts representing Sweden, Lithuania and the Komi Republic in Russia. Due to different ideological and socio-economic conditions these three countries have experienced different forest management regimes. In Lithuania and Komi Republic – both former Soviet Union territories – already before the breakup of the Soviet state after 1991, forest management guidelines had prescribed conservation of riparian forests for many decades (see Lazdinis and Angelstam, 2005), and they still remain to a large extent. By contrast, in Sweden riparian ecotone management has become an issue mainly only during the last two decades (Rosén et al., 1996; Bergquist, 1999; Nyberg and Eriksson, 2001; Kuglerová et al., 2014a).

Based on the evidence that tall herb sites indicate a potential for conservation, management, restoration and re-creation of continuous cover forests highly valuable for biodiversity conservation (e.g., Kuuluvainen, 1994; Angelstam, 1998; Jasinski and Angelstam, 2002), we test three null hypotheses. Herb sites: (1) are equally common in the riparian zone and in the surrounding forests; (2) have the same width on both sides of the stream at the same location and do not vary along a stream; and (3) their width is directly related to the stream width.

2. Methods

2.1. Study areas

A total of six sets of transects were replicated in two catchments each in south-central Sweden, southern Lithuania and the Komi Republic of Russia. The selected study areas represent similar types of forest landscapes with mixed pine (*Pinus sylvestris*) and spruce (*Picea abies*) stands with small proportions of birches (*Betula* spp.) and aspen (*Populus tremula*). The biophysical conditions at the stand level scale in the six sets of transects in catchments of the three countries all provide opportunity for the same range of ground vegetation types linked to edaphic, hydrological and climatic conditions. This is clearly indicated by the close similarity of ground vegetation classification systems in Sweden (Arnborg, 1990), Lithuania (Karazija, 1988) and Russia (Sukachev, 1928; Sukachev and Dylis, 1964).

Land forms and topography in Sweden are strongly related to the underlying ancient Fennoscandian shield of Pre-Cambrian bedrock, overlaid with glacial till and glacio-fluvial deposits (Anonymous, 1965). An additional variable to be taken into consideration while designing representative studies in this country is whether or not the land is located below or above the Marine Limit, a major biophysical factor affecting biodiversity in central Sweden (Fransson, 1965). Below the Marine Limit, fluvial and marine deposits of clay and silt are found, while above it, the terrain usually consists of coarse glacial till. In central Sweden the study was replicated twice, using the catchments Sandån near northeast of Ramsberg (stream order 3; ca. 40 km^2; 59°50′ N, 15°20′ E) and Hedtjärn/Malingen in Grangärde (stream order 3; ca. 50 km^2; 60°20′ N, 14°50′ E). These two catchments were located below and above the Marine Limit, respectively. The growing season is around 240 days in the south and 150 days in the north. Within our study areas in south-central Sweden the annual precipitation is 600–800 mm and the average annual temperature is 4–5 °C (Atlas över Sverige, 1953).

The East European plain is the world's most extensive extra-tropical plain and is dominated by sandy and loamy sediments, which occupy half of the European continent (Atlas Komi, ASSR, 1964; Alayev et al., 1990). The annual precipitation decreases to the east and southeast, from about 800 mm in the taiga-forest zone to 500 mm in the steppe (Tochenov, 1984). In Lithuania, sampling was made in two catchments in the Dzūkija region; the Ūla/Išrūginis (stream order 3; ca. 70 km^2) northeast of Marcinkonys and Skroblus (stream order 3; ca. 60 km^2) north of Margionys (both 54°05′ N, 24° 20–30′ E). Within our study areas in southern Lithuania the annual precipitation is 624 mm, the average temperature for January is −5,4 °C, the lowest −40 °C; the average July temperature is +17,7 °C, with the highest being +37 °C. Dry sandy soils dominate. The two catchments lie on average 100 m above the sea level. The study area is abundant with rivers, rivulets and lakes. Many rivers are fed by the spring waters. In the Komi Republic in Russia, the sampling was made in two catchments near Syktyvkar, both of them tributaries to Vychegda. These were El' (stream order 3; ca. 40 km^2) north of Prioziorny (both 61°50′N, 51°45′ E) and Bolshoy Achim (stream order 3; ca. 30 km^2) south of Lyali (both 62°15′N, 51°35′E). The Komi Republic is situated to the west of the Ural Mountains, in the north-east of the East European Plain. Forests cover over 70% of the territory. Winters in the study areas are long and cold (mean January temperature is −17 °C), and the summers, while short, are quite warm (mean July temperature is 13 °C).

2.2. Transects to study the distribution of ground vegetation

In naturally dynamic boreal and hemiboreal forests continuous cover gap phase dynamic prevails on wet rich sites (Angelstam, 1998; Jasinski and Angelstam, 2002; Axelsson et al., 2007) where ground water levels are high, such as commonly along low order streams (Jansson et al., 2007; Kuglerová et al., 2014b). Riparian zones often include distinct forest vegetation types (Malanson, 1993). As some vascular plant species are closely associated with the presence of areas with readily available soil moisture and nutrients (e.g., Kuglerová et al., 2015), they can be used as indicators of the width of the potential riparian wet forest at a particular location (Nilsson, 1983; Curry and Slater, 1986; Nilsson et al., 1988, 1989; Learner et al., 1990; Gregory et al., 1991; Satterlund and Adams, 1992; Malanson, 1993; Karazija and Vaičiūnas, 1994; Spackman and Hughes, 1995). This pattern is a widespread base for forest site type classification and forest management planning (e.g., Arnborg, 1990 Karazija, 1988).

To describe the site type, field layer descriptions according to Hägglund and Lundmark (1984) were made. The list of vascular plant indicator species for the different site types provided by Hägglund and Lundmark (1984) is very similar to the species listed for forest site type classification in Lithuania and Russia. The following site types in the wet/nutrient-rich to dry/nutrient-poor gradient were used in this study: TH – Tall herbs; LH – Low herbs; WF – Without field layer vegetation cover or moss species; BG – Broadleaf grass; NG – Narrowleaf grass; CE – *Carex* species and *Equisetum sylvaticum*; BL – Blueberry *Vaccinium myrtillus*; CO – Cowberry *Empetrum nigrum*; CA – Heather *Calluna vulgaris*; LI – Lichens.

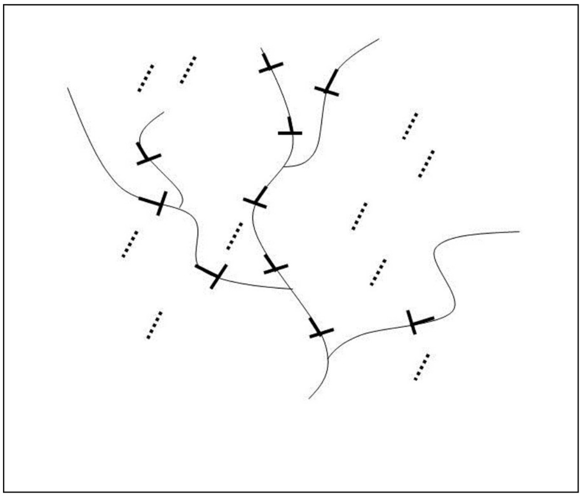

Fig. 1. Schematic illustration of how ten replicates of three types 100-m long transects with 20 quadratic 5 × 5 m plots in each were placed in each of the six catchments studied. Transect were located (1) along streams of stream order 1–3 according to Strahler (1957); (2) perpendicular to the stream and centered at the stream at the beginning of each 100-m interval; (3) random transects in the surrounding landscape. Each catchment thus included at total of 600 individual 5 × 5 m sample plots.

To survey the distribution of different forest site types in each of the six small catchments, three types of 100-m long transects with 20 quadratic 5 × 5 m plots in each were made (Fig. 1). These were: (1) along streams of stream order 1–3 according to Strahler (1957), the width of which was measured to the nearest dm at each sampling plot; (2) perpendicular to the stream and centered at the stream at the beginning of each 100-m interval made along the streams; (3) random transects in the surrounding landscape. The total number of 5 × 5 m plots in each catchment was thus 600.

3. Results

3.1. Site type distribution in riparian and random transects

First, we compared the distribution of different site types according to Hägglund and Lundmark (1984) using plot descriptions made in the random and two types of riparian zone transects. In order to better control for possible impacts on results of differences in forest management approaches over the years (long tradition in protection of riparian forests in Lithuania and Komi Republic, and intensive forest management practices in Sweden), and different biophysical contexts, in data analysis and presentation we have clustered Lithuania and Komi Republic study sites into one East European "plain" category; whereas study sites in Sweden are presented as Fennoscandia "shield" category. In shield landscapes, the pattern of site type distribution in random transects was dominated by mesic site types (55%), with herb types (i.e. TH and LH) constituting around 9% of total vegetation cover (Fig. 2, left). In contrast, on the plain, the distribution was bimodal with only 15% mesic site types and a high proportion of both herb (20%) and lichen sites (22%). These distributions were clearly different ($p = 0.0001$, $\chi^2 = 337$).

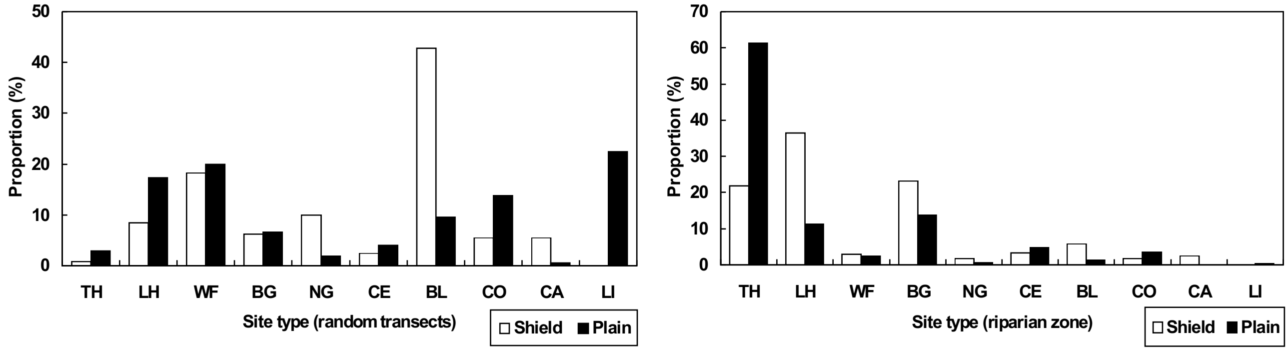

Fig. 2. Distribution of ground vegetation cover types according to Hägglund and Lundmark (1984) on the Swedish shield and the East European plain in random sites (left, n = 400 and 800, respectively) and in riparian ecotones (0–5 m from the stream) (right, n = 400 and 800, respectively). The following site types in the wet/nutrient-rich to dry/nutrient-poor gradient were used in this study: TH – Tall herbs; LH – Low herbs; WF – Without field layer vegetation cover or moss species; BG – Broadleaf grass; NG – Narrowleaf grass; CE – *Carex* species and *Equisetum sylvaticum*; BL – Blueberry *Vaccinium myrtillus*; CO – Cowberry *Empetrum nigrum*; CA – Heather *Calluna vulgaris*; LI – Lichens (for detailed species lists, see Hägglund and Lundmark, 1984).

In contrast, herb type (TH and LH) vegetation in transects along water made up 72% in Komi/Lithuania and 58% in Sweden of all vegetation types observed (Fig. 2, right). This compares to 20% and 9% in random transects located in the surrounding landscapes. Both in Komi/Lithuania (p = 0.0001, $\chi^2 = 836$) and Sweden (p = 0.0001, $\chi^2 = 540$) the site types in transects along streams were statistically richer, *i.e.* with more herb-rich sites, than in random locations in forest. For tall herb sites alone, the difference was even greater. The ratios of tall herb vegetation site types at random transects versus transects along streams were similar in Komi/Lithuania and Sweden (corresponding to a 21- and 27-fold difference, respectively; Fig. 2, right). This result allows us to reject the first of our three null hypotheses, showing that tall herb sites were not equally common in the riparian zone and in the surrounding forest landscape.

3.2. Width and symmetry of riparian ecotones

In Sweden, the mean width of the tall herb site was 3.0 ± 6.2 SD m (range 0–35 m) to the left and 1.8 ± 2.9 SD m (range 0–10) to the right. In Komi/Lithuania, the mean width of the tall herb site along perpendicular transects was 13.0 ± 15.7 SD m (range 0–50) to the left and 10.9 ± 12.2 SD m (range 0–50) to the right of the stream. However, we often found that streams were located in a terrain where the existence of a tall herb site was not possible due to local site conditions. Ravines in deep sandy soils in the plain landscapes, and steep rocky slopes or coarse-grained glacial till in shield landscapes were the two most common examples. We therefore compared the width of tall herb sites both using the whole data set, and without plots located in sections of streams that lacked tall herb sites.

In Sweden we found a positive relationship between the width of tall herb sites on the left and right sides (adj. r-square = 0.15, p = 0.007; n = 20). However, if stream sections without suitable conditions (i.e. deep sand or rocks) for tall herb sites on opposite sides were removed from the analyses, the relationship disappeared (adj. r-square = 0, p = 0.80; n = 16). Similarly, in Komi/Lithuania we found a positive relationship between the left and right sides (adj. r-square = 0.12, p = 0.017; n = 40). However, if sections without tall herb sites at all were removed, the relationship disappeared (adj. r-square = 0.049, p = 0.11, n = 34). By showing that tall herb vegetation type are likely to have different widths on opposite sides of streams at the same location, and may vary along a stream, the second null hypothesis can be rejected.

Table 1
Widths of streams at 5-m intervals along 100-m transects replicated 10 times in each of the eight study areas.

Regions studied	Mean (m)	Std. Dev. (m)	Sample size
Sweden	3.6	3.7	400
Komi	3.3	2.5	400
Lithuania	8.9	7.7	400

3.3. Effects of stream size on tall herb site width

On average streams in Sweden were 3.6 ± 3.8 SD m wide (range 0.1–20 m) and in Komi/Lithuania 6.1 ± 6.3 SD m wide (range 0.5–25 m) wide (Table 1). For the stream width and the perpendicular width of tall herb vegetation sites on both sides of the stream, correlation analyses for both in Komi/Lithuania and Sweden was completed. The results indicated no correlation between the width of the tall herb site and stream width on any side of the stream in neither shield (left: $r^2 = 0.064$, p = 0.11, n = 20; right: $r^2 = 0.01$, p = 0.51, n = 20) nor the plain (left: $r^2 = 0.049$, p = 0.17, n = 40; right: $r^2 = 0.055$, p = 0.14, n = 40) study areas. This finding allows us to reject the third of our null hypotheses by demonstrating that the width of tall herb sites is not directly related to the stream width.

4. Discussion

4.1. Setting aside the riparian forests, and how wide is enough?

Our study shows that tall herb vegetation, which may be considered as a proxy that can guide biodiversity restoration by restoring and re-creating continuous cover forests, was 27–21 times more common along streams than in random transects in the surrounding forest landscape. The results also show that the width of herb vegetation sites was not related to stream width. This implies that small streams are as important for biodiversity conservation management as large streams in terms of providing sites for ecological restoration of riparian ecotones with continuous forest cover. Moreover, we show that the width of rich vegetation sites varies considerably along streams, having different widths on opposite sides of the stream at the same location. Consequently, our results support the idea of applying variable-width conservation buffers in riparian corridor management, in particular along small- and medium-sized streams.

The issue of fixed-width or variable-with management rules for riparian vegetation have been in focus for decades. Riparian forests provide functions of supplying the stream with dead wood, buffering the release of humus and nutrients (Degerman et al., 2004), and it has been suggested that the width of riparian buffers ought to be related both to the up-slope effect and the forest age distribution in the local catchment (Bergquist, 1999). Others have proposed that riparian forests along streams should be sufficiently wide to effectively perform the functions of both controlling water and nutrient flows from upland to stream, and facilitating the movement of and providing habitat for upland forest interior animals and plants along the stream system (see Forman and Godron, 1986). To accomplish all these objectives, riparian forests should cover the floodplain, both banks, and an area of upland – at least on one side – that is wider than an edge effect, for example one that could destroy the humid local climate (Forman and Godron, 1986). Statements have been made that a sufficient width is important for the interaction of the riparian zones as a whole with both the surrounding matrix and with the stream. In this way, the width will affect the heterogeneity of the riparian element, i.e. the number and kinds of terraces that develop within the riparian zone (Malanson, 1993).

It is obvious that management of riparian ecotones for different conservation purposes in various climatic zones may contain specific features. For example, for Southern Appalachian streams Jones et al. (1999) suggested that continuous disturbance of riparian forests restricted to a kilometer or less along the stream may constitute a relatively minor disturbance to some fish assemblages; however, clearing in excess of 1–3 km will have substantial effects on fish assemblages. An assessment of the minimum stream ecotone width for biological conservation along mid-order streams in Vermont, USA found that widths of at least 30 m above high water mark were necessary to capture >90% of the vascular plant species. However, ecotone widths of 150 and 175 m were necessary to include 90 and 95% of the bird species (Spackman and Hughes, 1995). The study of two watersheds in Central Pennsylvania, indicated that naturally vegetated riparian ecotones >125 m were needed to support the full complement of bird communities that approached reference conditions (Croonquist and Brooks, 1993). Still, protecting at least 25 m of riparian habitat provided both dispersal and breeding opportunities for avian communities. The same study also pointed out that impoverished bird community can exist in the vicinity of the riparian bank immediately adjacent to the water with <10 m of natural vegetation; however, sensitive species will not occur unless an undisturbed ecotone >25 m in width on each bank is present. Similarly, Stauffer and Best (1980) studied habitat selection by birds of riparian communities in Iowa and found that bird species richness increased with an increasing width of the wooded riparian habitats, and a similar trend was evident for herbaceous study plots. The same authors reported that of the 17 species, only 7 were found breeding in relatively narrow (<20 m wide) riparian ecotones, three additional species were recorded only in wide habitat strips; thus, 13 species bred only in relatively wide patches of riparian habitat (Stauffer and Best, 1980). Delong and Brusven (1991) in their study on classification and spatial mapping of riparian habitats with applications toward management of streams impacted by non-point source pollution used riparian zone width of 0–10 m. Osborne and Kovacic (1993) summarized that in North America vegetative buffer strips of widths between 10 and 30 m have been shown to maintain effectively stream temperatures. According to the same authors, the field studies on the width of vegetated buffer strips that removed a substantial portion of sediments in overland flow from a variety of disturbances in geographic locations indicated range of vegetative buffer strips between 9 and 45 m (Osborne and Kovacic, 1993). Rudolph and Dickson (1990) found that streamside zone width significantly influenced the abundance of amphibians and reptiles within the streamside zones. They recommended retaining streamside zones with mature trees at least 30 m in width and preferably wider when forest stands are harvested.

4.2. *Ground vegetation as a guide for ecological engineering*

The functional characteristics of a stream ecotone, involving the flows of water, minerals, nutrients and species, along with a habitat function for many species valuable from biodiversity conservation point of view, provide the essential management planning question of how riparian buffer zone should be designed? The answer that emerges from many studies on riparian forests is that wider buffers are almost always better for maintaining biodiversity than narrow ones (Brinson and Verhoeven, 1999). However, other objectives of landscape management and realities within society often make the fixed-width zone option unacceptable by land owners, for example due to trade-offs with economic benefits such as wood production or agricultural crop production.

While the focus for long has been on the utility of riparian forests and fixed-width buffer strips, already Forman and Godron (1986) argued that variation in the width of stream ecotones among streams, and along a single stream system is very large. As a stream winds through a landscape, the riparian ecotone changes by alternating or changing width between the two sides (Forman and Godron, 1986). Croonquist and Brooks (1993) suggested that standard widths for undisturbed riparian ecotones can be determined and enforced only for specific landscape types. Similarly, Spackman and Hughes (1995) concluded that ecotone width must be evaluated on a stream by stream basis.

In the boreal forest context, Kuglerová et al. (2014a) recently argued that fixed-width buffers are not the ideal solution in the context of sustainable forest management, because they are neither economically nor ecologically optimal along the entire stream networks. Their study suggested that site-specific management, taking local hydrological conditions into consideration, would create more heterogeneous riparian buffers and maximize ecosystem services provided by riparian forests. They also proposed taking into consideration groundwater discharge hotspots as an indicator for landscape elements along streams with higher ecological significance, which may be identified using digital elevation models, if sufficiently detailed. Such discharge hotspots coincide with species-rich herb vegetation (Kuglerová et al., 2015). This would benefit biodiversity and important ecosystem services such as maintaining water quality without necessarily incurring costs from a wood production standpoint (Laudon et al., 2016). As this study shows, the site type (tall herb) that bests indicates the opportunity of restoration of continuous cover forest,which has declined seriously (e.g. Axelsson et al., 2007), occurred irregularly along streams in the Sweden, Lithuanian and Russian case studies. The widths were also variable. Fixed-width buffer zones would thus be applied also to mesic and poor sites, which are of limited value for biodiversity conservation by restoration of continuous cover forest. Variable-width zoning would enable more effective and targeted efforts towards biodiversity conservation and assurance of quality water, by being better balanced with economic interests of private land owners and managers. However, in other societal contexts with state-owned land such as in Russia, fixed-width zoning has a long history (Lazdinis and Angelstam, 2005).

Also our study thus supports the idea of variable-width buffer strips along streams on private land, and that tall herb ground vegetation is a good proxy indicator of local site conditions with potential high value for biodiversity. We propose that this indicator may be used as a complementary, finer scale, instrument in designing land restoration on agricultural lands or forest management planning in addition to, for example, sufficiently fine-grained digital elevation models identifying biogeochemical hotspots advocated by Laudon et al. (2016), or other meso-scale planning approaches based on site information in forest management plans (e.g., Naumov et al., 2016). The value for biodiversity conservation of riparian ecotones can be further improved as a green infrastructure if it also becomes a landscape scale network. If sufficiently well-connected in time and space, such riparian forest ecotone networks form both green and blue infrastructures for specialized species in both terrestrial (e.g., Angelstam et al., 2011a; Stighäll et al., 2011) and aquatic ecosystems (Degerman et al., 2004, 2013; Lasne et al., 2008; Morita and Yamamoto, 2002; Pringle, 2006; Sheer and Steel, 2006). The historic variability of woodlands and natural dynamics of forests has been proposed as source of inspiration for woodland and forest biodiversity conservation (e.g., Franklin, 1989; Remmert, 1991; Peterken, 1996; Bergeron et al., 2002; Angelstam and Kuuluvainen, 2004). Hence, a landscape perspective is needed that involves both entire biophysical catchments at multiple spatial scales (e.g., Hunter et al., 1988; Rabeni and Sowa, 2002), and social systems including land owners, planners and stewards with different profiles of benefits from ecosystems, and at multiple levels of governance (e.g., Kennedy et al., 2001; Axelsson and Angelstam, 2011; Elbakidze et al., 2015; Naumov et al., 2016).

4.3. Benchmarks for ecological engineering

The composition, structure and function of most landscapes in Europe deviate considerably from the historic range of variability, and this makes biodiversity conservation policy difficult to implement. A general pattern across spatial scales is that sites and regions with high biological production are more altered than those with low productivity (e.g., Nilsson and Götmark, 1992; Angelstam and Andersson, 2001). As a consequence, because productive sites are indicated by species-rich tall herb plant communities (Hägglund and Lundmark, 1984) the loss of continuous cover forests linked to herb site types is underestimated (e.g., Axelsson et al., 2007). If the forest structure in managed forests is severely altered, the composition of vascular plant still reliably indicates conditions before deforestation. Hence, the vascular plant community can be used as an indicator of the potential for restoration and re-creation of riparian ecotones. Therefore the spatial location of tall herb species can be used to guide this. Typical species are *Cirsium heterophyllum*, *C. palustre*, *Urtica dioica*, *Aconitum septrionale*, *Paris quadrifolia*, *Trollius europaeus*, *Angelica sylvestris*, *Actaea spicata*, *Filipendula ulmaria*, *Matteuccia struthopteris* and *Dryopteris filix-mas* (Hägglund and Lundmark, 1984). Another example of the usefulness of tall herb vegetation as an indicator is the maintenance of buffering efficiency of riparian zones (ecotones) (e.g., Mander et al., 1995). They recommended that on such sites alder forests and/or willow bushes should be maintained as buffer strips on and adjacent to the stream banks to enhance water quality. Similarly, Kuusemets et al. (2001) studied the purification efficiency and nutrient assimilation in riparian buffers with wet meadow vegetation. A 31-m wide buffer zone removed 40% of total nitrogen and 78% of total phosphorus; the maximum biomass production was observed in tall herb vegetation.

In the absence of guiding natural ground vegetation, such as if forests have been harvested and drained or transformed to agricultural land, other indicators than field layer vegetation may be needed to determine the opportunity for restoration of riparian forest zones. Historic maps (Rose, 2012), interviews (Valinia et al., 2012), soil maps and digital elevation modelling (Kuglerová et al., 2014a) may be used successfully to define benchmarks for ecological restoration at the local site level (e.g., Baird et al., 2005). The latter approach is particularly valuable for operational use over large areas. In topographically variable boreal forest landscapes the availability of shallow groundwater is a major determinant of plant species numbers. Zinko et al. (2005) applied a topographically derived hydrologic wetness index based on a 20-m grid digital terrain model and multidirectional flow algorithms to map the availability of shallow groundwater in the landscape. This wetness index was a good tool to identify areas with high (and low) probability of having high species numbers and rarity of vascular plants, and thus species-rich tall herb sites. They concluded that their approach is useful not only for conservation management, such as designing riparian corridors and removal of ditches, but also for road construction and operational forestry. Indeed, Friberg (2015) showed that use of airborne laser (LiDAR) and digital terrain models to map shallow groundwater decreased the total driving distance on forest harvesting sites. Additionally, wet sites sensitive for damages were completely avoided.

5. Conclusions

This study shows that tall herb ground vegetation is more common in the riparian zone than in the surrounding forest landscape, that the width of ground vegetation indicating suitable conditions for continuous cover forests may differ on both sides of a stream at the same location, and varies considerably along a stream. This suggests that variable-width buffers of riparian forests should be aimed at in forest planning and in ecological restoration projects. Planning and delineation of sites for conservation, management, restoration and re-creation may be aided by surveys of ground vegetation. Finally, we found that the width of vegetation-rich sites is not directly related to the stream width. This should contribute to awareness rising on the importance of ecosystems also in proximity to headwater and lower stream orders.

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