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Review

Towards ecologically functional riparian zones: A meta-analysis to develop guidelines for protecting ecosystem functions and biodiversity in agricultural landscapes

Lovisa Lind[a,b,*], Eliza Maher Hasselquist[a], Hjalmar Laudon[a]

[a] *Department of Forest Ecology and Management, Swedish University of Agricultural Sciences, 901 83, Umeå, Sweden*
[b] *Department of Environmental and Life Sciences, Karlstad University, 656 37, Karlstad, Sweden*

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ABSTRACT

Riparian zones contribute with biodiversity and ecosystem functions of fundamental importance for regulating flow and nutrient transport in waterways. However, agricultural land-use and physical changes made to improve crop productivity and yield have resulted in modified hydrology and displaced natural vegetation. The modification to the hydrology and natural vegetation have affected the biodiversity and many ecosystem functions provided by riparian zones. Here we review the literature to provide state-of-the-art recommendations for riparian zones in agricultural landscapes. We analysed all available publications since 1984 that have quantified services provided by riparian zones and use this information to recommend minimum buffer widths. We also analysed publications that gave buffer width recommendations to sustain different groups of organisms. We found that drainage size matters for nutrient and sediment removal, but also that a 3 m wide buffer zone acts as a basic nutrient filter. However, to maintain a high floral diversity, a 24 m buffer zone is required, while a 144 m buffer is needed to preserve bird diversity. Based on the analysis, we developed the concept of "Ecologically Functional Riparian Zones" (ERZ) and provide a step-by-step framework that managers can use to balance agricultural needs and environmental protection of waterways from negative impacts. By applying ERZ in already existing agricultural areas, we can better meet small targets and move towards the long-term goal of achieving a more functional land management and better environmental status of waterways.

1. Introduction

The riparian zone forms a natural buffer between the surrounding land and waterways, and thus, the protection and management of near stream areas have important implications for water quality and biodiversity (Renouf and Harding, 2015). Riparian zones are the interface between the aquatic and the terrestrial ecosystems that connect and help regulate the ecological functions of both systems (Gregory et al., 1991; Naiman and Décamps, 1997). Since humans started intensive farming, society has made large-scale changes to the hydrology of streams and rivers to create conditions for cultivation, often at the expense of both riparian zones and their downstream waterbodies. Wetlands have been drained, lakes have been lowered and rivers straightened with the aim of increasing the agricultural land available and its efficiency. For example, in Sweden alone, a total of 600 000 ha of marshes and bogs have been drained and, 2500 lakes have been lowered, of which 25% were completely drained, for agricultural purposes (Jakobsson, 2013). Alterations of the landscape hydrology have led to changes in the natural water and nutrient balance that has contributed to loss of important riparian habitat and downstream eutrophication (Kiffney et al., 2003; Lam et al., 2011).

Agriculture is one of the largest sources of nitrogen (N) and phosphorus (P) to rivers and lakes (Carpenter et al., 1998; Hanifzadeh et al., 2017), and it only takes a few percent cover of agricultural land in an otherwise forested landscape to increase the nutrient leakage (Sponseller et al., 2014). However, the loss of nutrients is also correlated with variations in discharge (Mander et al., 2000). Sufficient drainage is important to sustain high productivity in agricultural land, and tile drainage (underground pipes) is still the most common method of achieving this (Gökkaya et al., 2017). Through the underground pipes, water is transported from the soil profile to main conduits and further on to wells, streams or open ditches. The pipes can also be installed in systematic networks, i.e. tile drainage systems. A study of the Shatto Watershed district in Indiana, USA, showed that 79% of the

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* Corresponding author. Department of Environmental and Life Sciences, Karlstad University, Karlstad,656 37, Sweden.
E-mail address: lovisa.lind@kau.se (L. Lind).

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agricultural land in the district was tile drained (Gökkaya et al., 2017). This practice has comes at a cost to the environment as tile drainage systems reduce the retention time of water in the soil, thereby creating a shortcut for nutrients into streams and rivers, which also affects the quality of drinking water resources (Tiemeyer et al., 2006; Hanifzadeh et al., 2017). Grazing in the riparian zone can also lead to lower water quality, soil erosion, unstable soils, and drier, warmer conditions in the riparian zone (Hughes et al., 2016; Belsky et al., 1999). One of the transport routes of pollutants to water bodies is through surface runoff. Runoff is usually limited to specific locations (e.g. erosion prone soils, tractor tracks, and areas around the drainage wells) and to storm events (Frey et al., 2009). Soil properties also influence the risk of overland flow and stable clay soils have higher risk of surface runoff than structurally weak and silty soils (Nolan et al., 2008). Areas with tile drainage systems, a high groundwater level, and/or dense soils with high clay content therefore offers fast transport routes for pollutants into neighboring waters (Lewan et al., 2009).

Both tile drainage and drainage ditches reduce the retention time of water in the soil, but it is still possible to manage the riparian zones to achieve some level of riparian protection. In fact, this is required according to a number of local, national and international agreements. Preventing further eutrophication and degradation of marine and freshwater ecosystems is included in, for example, the Baltic Action Plan 8 (Ejhed et al., 2014), the EU Water Framework Directive (European Commission, 2000) and the Clean Water Act (33 U.S.C. §1251 et seq. (1972)). Few countries have national regulations of buffer widths, for example Germany and Switzerland (5 m wide), but most are still lacking such regulations and therefore provide little practical guidance that can force practitioners to implement riparian buffers.

Buffer zones or riparian zones are commonly thought to be effective filters for nutrients and even provide habitat for organisms in highly fragmented landscapes, but the effectiveness of these zones may depend on a variety of factors. Buffer zones have been used to reduce the leakage of N, P, and pesticides, provide flood protection and habitat for animals and plants, increase ecological connectivity, reduce erosion problems and create recreational areas (Arora et al., 1996; Décamps et al., 2004; Mankin et al., 2007). However, the relative effectiveness of these buffer zones depends on topography, vegetation and soil types, climate, the extent of the nutrient load, and probably most importantly, their width (Hill, 1996; Hefting et al., 2005; Mander et al., 2005; Dosskey et al., 2010; Lam et al., 2011). Riparian vegetation influences stream water quality in many ways both directly and indirectly (Dosskey et al., 2010). Designed correctly, buffer zones can provide an important step towards more functional land management with a specific aim to protect waterways (Schulte et al., 2015). The required width of a riparian buffer zone depends on the goal society is trying to achieve and can therefore vary from one to 500 m in practice, depending on the context of the site. For example, areas with steep slopes require wider buffers than flat areas, and buffer width may also be restricted by the surrounding infrastructure. Previously, many separate studies have been conducted on buffer zone width and the subsequent performance of the riparian zone. Such effects have also been reviewed by for example Mayer et al. (2007) on nutrient removal and Zhang et al. (2010) on vegetated buffers and nonpoint source pollution. However, no study so far has systematically analysed the scientific literature to determine the optimal buffer width or type of protection needed to achieve various ecosystem functions together with biodiversity goals.

In agricultural areas, however, it will likely be difficult to achieve a buffer width that provides optimal conditions for all ecosystem functions and biodiversity, and manage the demands for intensified agricultural practices at the same time. Thus, our goal was to review and analyse the literature to determine optimal widths for riparian buffers, and the type of protection needed to fulfil different levels of required (or needed) functions and, thus, help set multi-step goals towards obtaining, what we call "Ecologically Functional Riparian Zones (ERZ)". As decision makers usually lack the resources needed to make site-specific decisions regarding the function and design of riparian zones in agricultural landscapes, we provide a framework for working towards achieving these goals by implementing small steps on the way to ERZ. Specifically, we asked the following questions: 1) Is there an optimal width for riparian buffer zones in agricultural landscapes that achieves different types of ecosystem functions, such as filtering nutrients and sediments, shading to buffer water temperature, organic material, in-stream wood, and biodiversity? (2) When buffer zones cannot be wide enough due to landscape constraints inherent to cultivated areas, are there ways we can increase the efficiency of the buffer? (3) Does the ability of riparian zones to reduce different types of negative impacts on water quality depend on stream size, soil type, vegetation cover, or slope of the near stream area? Moreover, we suggest applying the new concept of ERZ in the agricultural landscape and suggest ways to improve the quality of the riparian zone to benefit various ecosystem functions and biodiversity goals in a 'step-by-step ERZ framework'. For each step, new functions of the riparian zone are introduced as the width increases.

2. Methods

To answer if there are optimal widths to achieve different ecosystem functions or biodiversity goals, we first analysed results and recommendations in 52 published peer-reviewed studies, from years 1984 and onwards (first year of study we encountered that provide sufficient information) (Appendix A1). Secondly, we reviewed the literature to outline the specific functions and characteristics that need to be considered when designing effective riparian buffers. The ecosystem functions or biodiversity we were able to find sufficient information for were filtering of sediments, P, or N, buffering of temperature, and provision of habitat to enhance diversity and abundance of birds, fish, insects, vascular plants, and amphibians and small mammals (number of studies presented in Fig. 1). Criteria for inclusion of the studies were that they (1) were original research (not review papers) that included quantitative recommendations or results regarding buffer widths, and if applicable, (2) resulted in successful removal of nutrients/sediments at ≥ 75% efficiency. The studies included different countries, physical and geographic settings, and biomes spanning tropical to boreal to get a generalized overview of the effects of buffer width. We found literature regarding riparian buffers by using the search engines Google Scholar and Web of Science, and references within these papers (search time-span June 2016–2018). Specifically, we searched for 'riparian buffer,' 'vegetated filter strip,' 'riparian zone,' 'filter strips,' and 'buffer strips' as synonyms. Because of the relatively low number of available studies on recommended buffer widths needed to support small mammals and amphibians, we grouped them. When sufficient information was provided (i.e. site specifics or drainage area information, Appendix A1), we also extracted the drainage area (a proxy for stream size) used for field studies and compared the drainage area with the recommended buffer widths. We averaged the drainage area if multiple streams were used in a given study.

All statistics were performed in R version 3.4.1 (2017-06-30). The data on drainage area and buffer width was log-transformed to fit the assumption of normality and analysed by fitting a linear regression. Vegetation type, country, soil texture, and buffer width were tested to determine which best explained the removal efficiency of N, P and sediments using linear mixed models (package nlme: Pinheiro et al., 2018); the study was included as the random effect. Selection of the best model to predict removal efficiency was based on the lowest Akaike information criterion (AIC). Vegetation type, country were thereby removed from the model. AIC estimates the quality of each model and the less information a model loses the higher the quality of that model (Crawley, 2005).

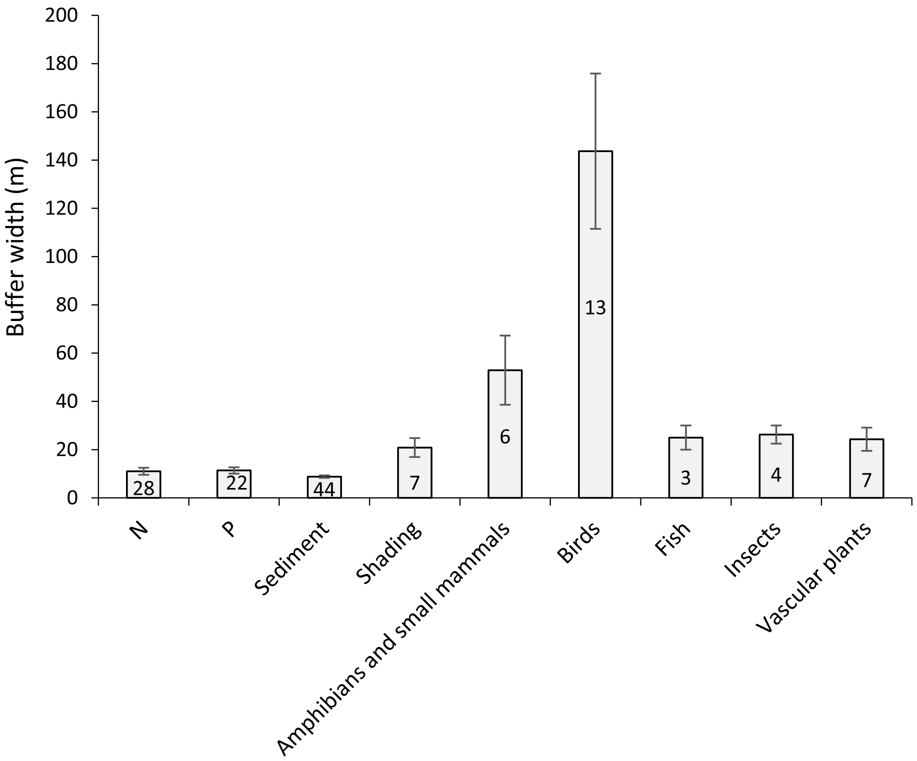

Fig. 1. The width of the riparian zone needed to fulfil different ecosystem services for reduction in nitrogen (N), phosphorus (P) and sediment inputs (≥75% removal efficiency), shading, and protecting/promoting biodiversity and plants and animals. The figure is based on quantitatively derived width recommendations from 134 data points from 43 peer-reviewed studies. Number of data points for each ecosystem function are indicated in the different bars. Data are means ± 1 SE.

3. Results

3.1. Buffer width

By analysing data from scientific publications we showed that the average buffer width needed for ≥75% removal efficiency (range: 75–100% removal efficiency) of sediment trapping and nutrient uptake is between 9 and 11 m (Fig. 1). More specifically, for sediment trapping (trapping efficiency 77–100%), the buffer width ranged between 3.3 and 18 m with an average of 8.8 m. For N (trapping efficiency 75–100%), the average buffer width needed was 11 m, and ranged from 0.7 to 30 m. For P (trapping efficiency 75–98%), the recommended buffer width ranged between 4 and 18 m with an average of 11 m. We also found that to generate stable water temperature (shading), an average of 21 m (range: 5–30 m) of forested riparian buffer was needed (Fig. 1). To maintain floral diversity, an average of 24 m (range: 10–40 m) of forested riparian buffer was typically needed; while to preserve birds, the forested riparian buffer width needed to be, on average, 144 m (range: 40–500 m) (Fig. 1). For amphibians and small mammals combined, an average of 53 m of forested riparian buffer was needed for protecting this group of organisms (ranged: 20–100 m), while fish and insects required about 25 m of forested riparian buffer (ranged: 15–30 m, and 15–33 m) (Fig. 1). We also found a low but significant relationship between the removal efficiency and the buffer width for sediment, P and N (all: $P < 0.001$, Fig. 2).

3.2. Buffer efficiency

In order to determine if there are other besides buffer width that can be used to increase the efficiency of the buffers, we further analysed the data of sediment and nutrient removal from grass and forested areas with different slopes and soil properties. We found that riparian buffer width for all ecosystem functions and biodiversity data combined (all data with available drainage area information, $n = 43$) was correlated with drainage area in the reviewed studies ($r^2 = 0.18$, $P = 0.008$). The relationship of drainage area with recommended buffer width for sediments and nutrients was significant ($r^2 = 0.345$, $P = 0.010$, Fig. 3a), but had no relationship with water temperature (shading) ($r^2 = 0.112$, $P = 0.582$, Fig. 3b), diversity of vascular plants ($r^2 = 0.0004$, $P = 0.965$, Fig. 3c), or birds ($r^2 = 0.095$, $P = 0.458$, Fig. 3d) (Appendix A1). We were unable to find a sufficient number of studies that provided drainage area data for the other taxa.

When analysed separately, we found no relationship between slope (%) and removal efficiency for P or sediments (all: $P > 0.05$), but when we combined all data for sediments and nutrients (P and N) we found that the removal efficiency decreased with increasing slope ($P = 0.006$). We also found a significant relationship between slope (%) and removal efficiency of N ($r^2 = 0.246$, $P = 0.002$), with less N being removed with increasing slope (Fig. 4). The type of vegetation (grass and herbs or woody vegetation) did not affect removal efficiency in the buffer zone for sediment, nutrients (P and N) when data were analysed separately nor when combined (all: $P > 0.05$). However, we did find a relationship between removal efficiency of sediments and soil texture ($P = 0.009$, Fig. 5), but this relationship did not exist for N nor P ($P > 0.05$). Specifically, we found a higher removal efficiency of sediments when riparian buffers were located in silt loam soil than in silt or sandy loam soils ($P = 0.019$ and $P = 0.030$, respectively).

4. Discussion

4.1. Implementing Ecologically Functional Riparian Zones

Many studies have shown the importance of riparian zones (e.g. Gregory et al., 1991; Naiman and Décamps, 1997; Pusey and Arthington, 2003). Designing riparian buffers in human modified landscapes in order to adapt properly to each site to achieve both good water quality and high biodiversity is of great importance. We have found that the optimal width for riparian buffer zones in agricultural landscapes depends on the type of ecosystem function one is trying to achieve. For example, reducing sediments and nutrients only requires a narrow riparian zone (3–10 m), while the protection of many organisms requires wider riparian zones (> 30 m). Furthermore, we identified different characteristics of the riparian zone that can influence the efficiency of buffers. Additionally, based on our literature search and

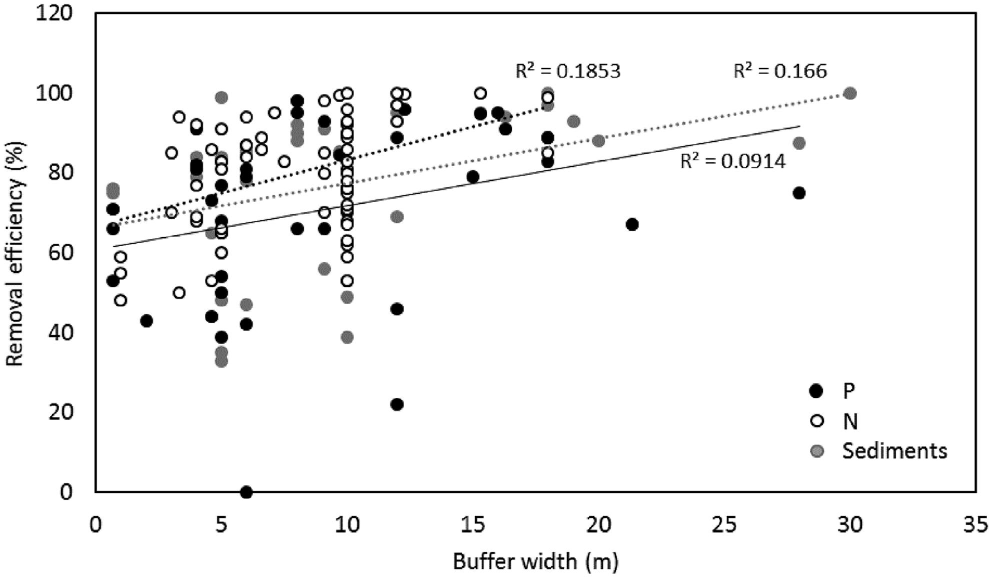

Fig. 2. The relationship between buffer width (m) and removal efficiency (%) of phosphorous (P), nitrogen (N), and sediments (all: $P < 0.001$). All data included regardless of removal efficiency.

analysis we develop the concept of “Ecologically Functional Riparian Zones” (ERZ; Fig. 6). The ERZ has the goal of providing as many primary ecosystem functions as possible including: (1) reducing nutrients and sediments through acting as a filter, (2) providing or capturing organic material which functions as an important source of energy and habitat for instream organisms, (3) stabilizing the banks of the waterway through the establishment of trees, shrubs and understory vegetation, (4) providing or capturing instream wood that is habitat for instream organisms in itself, but also through increases flow heterogeneity, and (5) shading to moderate temperature extremes in the waterway. Because riparian zones in agricultural areas are largely cultivated and the riparian zone can rarely be of optimal width, we also present the ERZ in a ‘step-by-step ERZ framework’ to support the real-world implementation of riparian buffer zones in agricultural landscapes (Fig. 6). The framework is step-wise because these different functions build on each other; if you achieve, for example, stable banks

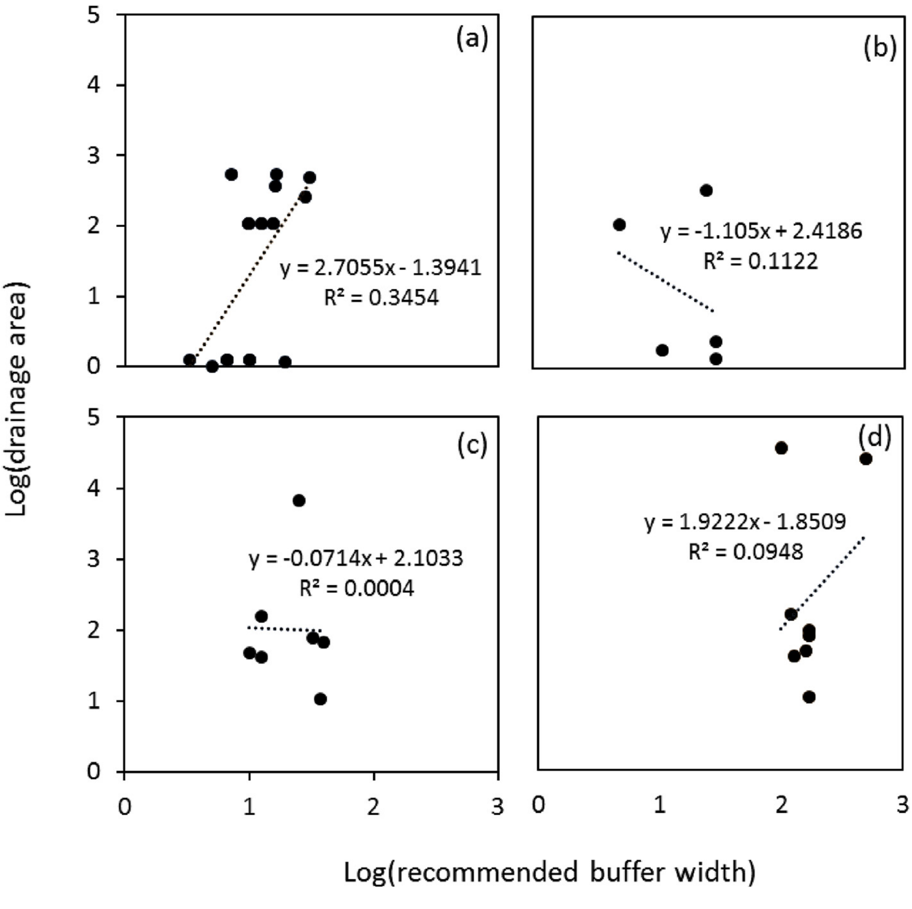

Fig. 3. Average drainage area (km^2) compared to recommended buffer width (m) for studies of (a) sediment, nitrogen, phosphorous (≥75% removal efficiency of nutrients and sediments), (b) shading, (c) vascular plants and (d) birds. Only studies of sediments and nutrients (a) showed a significant relationship ($P = 0.010$) of drainage area and recommended riparian buffer width.

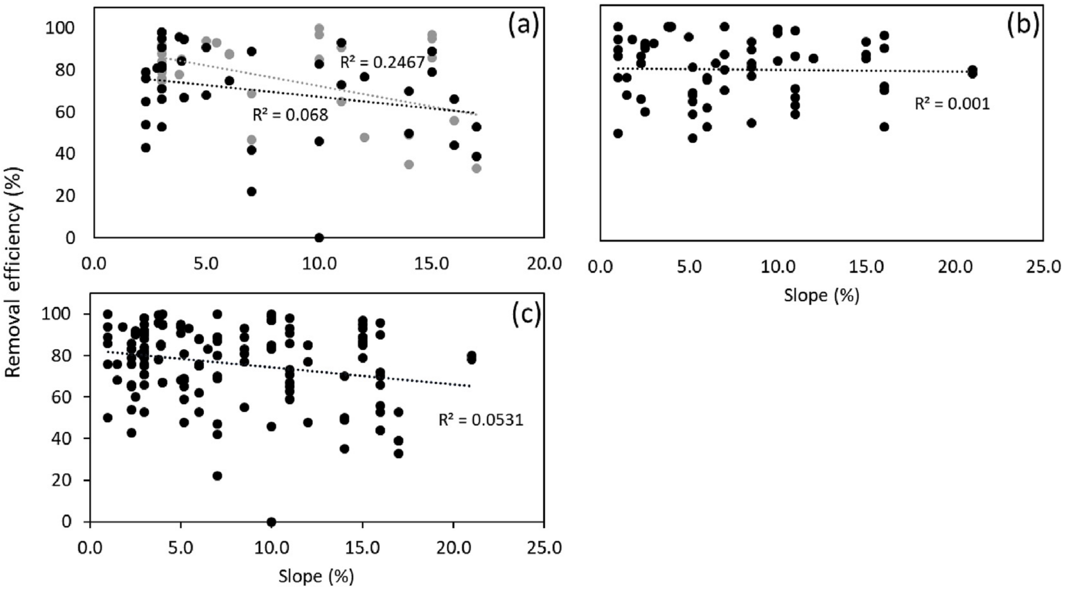

Fig. 4. Removal efficiency (%) in relation to slope of the buffer zone of; (a) N (grey dots) and P (black dots), (b) sediment, and (c) nutrients and sediment combined. Significant relationship was found between slope and the combination of nutrients and sediments (P = 0.006) and for N (P = 0.002).

on the waterway by planting or preserving vegetation, then you will also have provided the function of filtering, organic matter and shading. In order to provide better water quality and biodiversity, we propose that the ERZ could serve as a goal in the agricultural landscape where it is better to compromise and take steps towards an ERZ then to not take any actions at all (Fig. 6).

4.2. Buffer design and EFZ

When applying the 'step-by-step ERZ framework', one has to consider that several interests have to coexist in agricultural areas. Generally, there is no one optimal buffer zone design, and planning should be adapted to local conditions, including topography, flow regime and species composition of the landscape as well as the specific impacts of the agriculture, such as nutrients or sedimentation. However, our meta-analysis suggests some general aspects on how riparian buffers should be implemented to achieve one or several goals. For example, riparian zones should be at least 11–15 m wide to contribute to good water quality in terms of nutrient and sediment removal efficiency ≥75% (Fig. 2), which is in line with other reviews specific to sediment removal (Liu et al., 2008; Mayer et al., 2007; Yuan et al., 2009). Our results also suggest that there are differences in sediment removal depending on soil texture. Sandy textured soils have high infiltration rates and hence deliver very little overland runoff to riparian buffers compared to finer soils which have higher overland flows, that is not included in most measurements (see e.g. Dosskey et al., 2006). We did, however, not find a relationship between soil texture and removal efficiency of nutrients, even though it could be expected to follow the same patterns as the water holding efficiency of the soil (Dosskey et al., 2006). Bechtold and Naiman (2006) also found N mineralization to be strongly related to fine particulate concentrations. However, in agricultural areas, the main concern is often nutrient leakage, and because we found a relationship between drainage area and buffer width for nutrients and sediments, the buffer width can be scaled up or down depending on the size of the stream. Using this approach will also decrease the amount of agricultural land that would be taken out of production due to water protection as most streams are small (Benstead and Leigh, 2012). Furthermore, we found that the slope of the riparian area is important to take into consideration when designing riparian buffer zones, and previous studies have shown that there is an interaction between vegetation type and slope in regards to its removal efficiency (Van Dijk et al., 1996; Liu et al., 2008; Yuan et al., 2009). Collectively, these studies indicate that in steeper terrain there is a need for woody vegetation, whereas in flat terrain a grass covered riparian buffer is sufficient for removal of sediments and nutrients (Lee et al., 2003; Mankin et al., 2007; Yuan et al., 2009). Once again, the buffer width can be adjusted to the upper end of each category in EFZ framework to compensate for steeper slopes (Fig. 6).

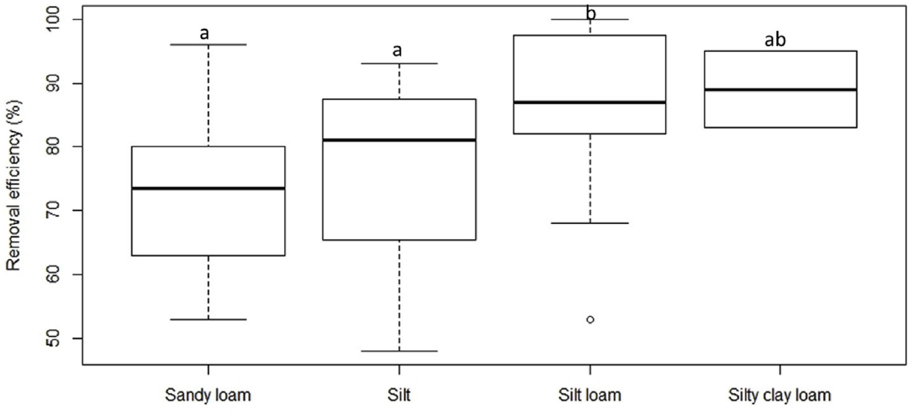

Fig. 5. Boxplots showing sediment removal efficiency (%) in relation to differences in soil textures of the buffer zone (P = 0.0093, t = 2.7, df = 46). Letters above boxes designate which soil types have different removal efficiencies; boxes that share a letter are not different from each other (P > 0.05). There was a higher removal efficiency of sediments in silt loam than in silt or sandy loam soils (P = 0.019 and P = 0.030).

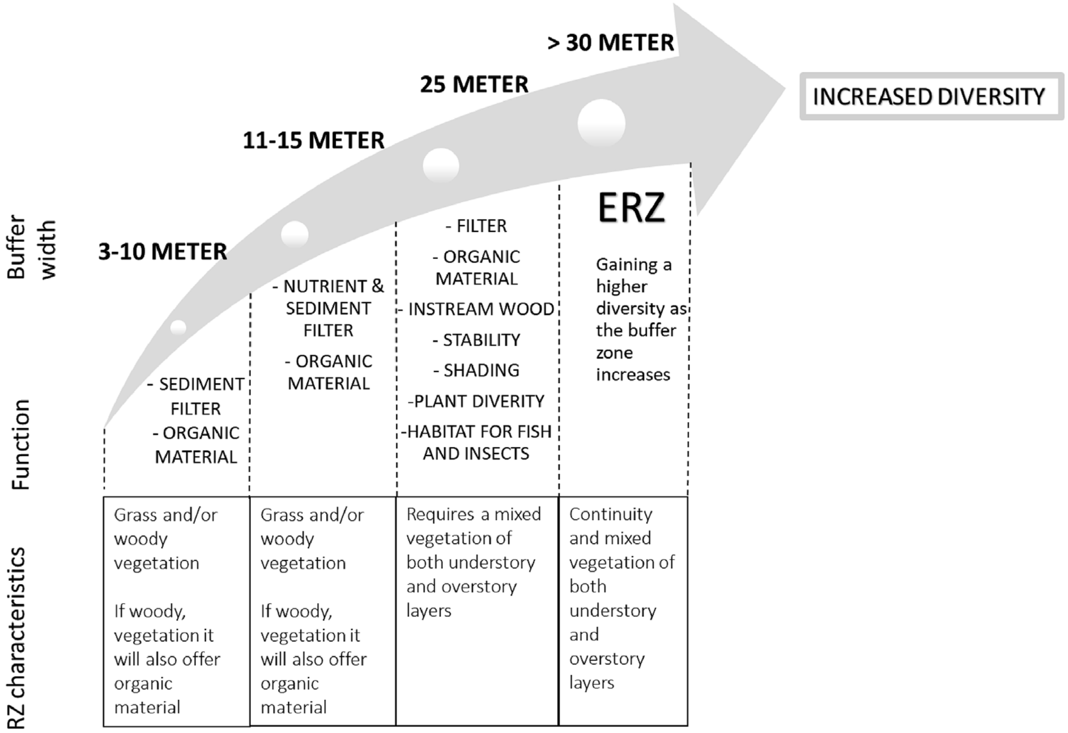

Fig. 6. The 'step-by-step ERZ framework' combines the concept of "Ecologically Functional Riparian Zones", the literature review and results from the meta-analysis. Riparian zones of 3–10 m with woody vegetation (i.e. trees and/or shrubs) will control sedimentation and increase organic material input. Riparian zones of 11–15 m with woody vegetation will have the same function as the narrower zones, but will also filter nutrients. Steeper slopes and finer soils can be compensated for by adjusting towards a wider buffer width within each category. Considerations also needs to be takes to the specific hydrological pathways. A 25 m riparian zone will also be sufficient to generate larger trees and consequently shade, influence the water temperature, and ensure bank stability. The floral and faunal diversity will increase with increasing buffer width, but if a high diversity of both plants and animals is the main goal, more than a 30 m wide zone on both sides of the waterway is needed in many cases. RZ = Riparian zones.

A vegetated riparian zone also reduces the velocity of runoff water and provides time for the water to infiltrate and percolate into the soil (Liu et al., 2008), and supports a higher microbial community diversity, which is, for example, important for decomposition of organic agrochemicals (Unger et al., 2013). Although we could not find any interaction between removal efficiency and vegetation type, we found that in all but two studies regarding organisms, that buffer vegetation was composed of forest or mixed vegetation (including trees or shrubs). However, there are other important ecosystem functions that are achieved by adding or preserving a forested riparian zone, such as shading, addition of instream wood and bank stabilization (Beechie and Sibley, 1997; Kiffney et al., 2003; Polvi et al., 2014). In general, woody vegetation has greater bank-stabilizing root properties than non-woody vegetation. Trees and shrubs have, for example, greater maximum root diameter, tensile strength, and lateral root extent (Polvi et al., 2014). A high root to area ratio increases the ability of certain species of plants to protect against erosion. Therefore, grass could function efficiently in reinforcing river bank stability in many cases. However, during wet years grass cover only can contribute to bank failures instead reinforcing bank stability (Simon and Collison, 2002). All types of vegetation will contribute with organic material, but the quality of the different sources varies. Hence, designing the plant species composition of riparian zones to include diverse functional groups, to have the desired physical properties, as well as be native to the location are important for its function and to prevent further ecosystem degradation (Blanco-Canqui et al., 2004).

Combining all the data in our 'step-by-step ERZ framework' suggests that ERZ can be fully achieved within a 30 m wide riparian zone (Fig. 6). This is similar to Kiffney et al. (2003) who suggested that a riparian zone of 30 m should be sufficient to ensure good ecological status. We also found that 30 m would provide sufficient habitat for many plants and animals, except for birds and amphibians that need wider buffers (average of 144 and 53 m, respectively). Furthermore, we did not find that birds need increased buffer width as the discharge area increases. This is a surprising result since some bird species are more sensitive to area of habitat available than others, and for example, species living along small woodland streams will have different habitat needs than floodplain birds along large rivers (Hodges and Krementz, 1996). There was a large variation in recommendations for buffer widths for achieving good faunal diversity, but in our study they all required more than a 15 m wide riparian zone to ensure optimal conditions (Appendix A1). Our step-by-step framework combined with data for recommended buffer widths (Fig. 6) show that there is a mismatch between the riparian buffer width needed to ensure a good physical environment vs. biodiversity. Hence, we suggest that the physical environment can already be improved after adding a 5 m buffer with mixed vegetation (grasses and woody vegetation), while the diversity or organisms often requires buffer widths of > 30 m. Adding a 30 m wide riparian zone could result in a significant loss of agricultural land and is likely not possible to establish in many places. Implementation of the ERZ can therefore be done in incremental steps and adjusted according to the landscape features, with wider buffers in steep and inaccessible areas that are less productive, and narrower zones in sites with less potential for erosion (Fig. 6).

Even though we are generalising for all agricultural areas, there are some local factors, such as type of drainage, climate and stream size that may need to be considered at each site. For example, in areas with extensive tile drainage systems, the riparian buffer zone will not function as filter to the same extent because water bypasses the riparian zone through pipes (Gökkaya et al., 2017), even if a riparian zone will still support bank stability, instream wood recruitment, shading and diversity further downstream (Beechie and Sibley, 1997; Kiffney et al., 2003; Polvi et al., 2014). Therefore, additional measures should be considered to prevent sediment and nutrient leakage where drainage systems meet more natural systems. For example, tile drainage systems can drain into wetlands before entering rivers and lakes (Osborne and Kovacic, 1993) or by flowing through riparian buffers before entering the stream. Specific hydrological pathways, such as groundwater beneath riparian zones, also needs to be considered when designing a buffer zone, and our results only apply to average conditions. Authors of various publications also use different approaches/criteria for their measurements, which should also be taken into consideration when interpreting the results. Furthermore, our analysis mainly included data from North American or European countries as these areas to a larger extent are represented in the peer-review literature. Hence, the results might primarily be reflecting temperate conditions. The buffer width may also need to be adapted depending on climate, as a higher degree of shading, and thus, wider buffers may be needed in warmer climates to ensure low water temperatures and reduced evaporation. Hence, coastal and more southern areas could benefit more from having 30 m wide riparian zones, while in higher altitudes and latitudes it may be sufficient to have a 10 m wide riparian zone, when focusing on temperature (Osborne and Kovacic, 1993). Luke et al. (2018) reviewed buffer zones in the tropics and found that there are a lack of studies giving width recommendations and policies to protect riparian buffers. However, similar to our study they found that a narrow buffer of 5–10 m is important to maintain a good water quality.

Organic matter inputs and terrestrial shading will of course also vary in importance depending on the stream size (Vannote et al., 1980). At the same time, the size of the stream needs to be considered as even small ditches, headwaters and springs are important for the freshwater biodiversity and have a role in contributing to ecosystems services (Biggs et al., 2017). Small water bodies are most vulnerable to anthropogenic disturbances, cumulatively influence larger downstream reaches, and thus need to be well managed. For example, the loss of riparian trees causes a larger increase in the daily maximum water temperature in small and intermediate streams than in large streams (Quinn and Wright-Stow, 2008), therefore small streams should not be ignored when designing buffer zones. How much the temperature increases with reduced shading depends on, for example, water velocity and water depth. Hence, the water temperature changes relatively quickly in small streams and in the littoral zone of lakes in comparison to deep areas of lakes and large rivers (Davies and Nelson, 1994; Kiffney et al., 2003; Mander et al., 2005).

5. Conclusions

We present a step-by-step framework that can be used by practitioners for determining management actions for riparian buffer zones. We also show that depending on the goal for the riparian zone, the required actions will vary. By using the ‘step-by-step ERZ framework’ we can move towards more optimized riparian zones and more environmentally friendly agricultural land-use. Even though there is no optimal width for ensuring all ecosystem functions and high biodiversity, our analysis of the literature shows that a 30 m wide riparian zone ensures an ‘Ecologically Functional Riparian Zone’ with stable water temperature, a high floral diversity that delivers sufficient organic material, instream wood, and bank stability. However, an 11–15 m wide riparian zone with trees and shrubs would also contribute with organic material, filter the drainage and support the system to some extent with instream wood and bank stability. Even a 3–10 m wide riparian zone has positive effects as a filter, mainly for sediment, and will contribute with organic material essential for many instream organisms and processes. Drainage size also matters, at least for sediment and nutrient removal, hence reducing negative impacts on water quality, and we therefore suggest leaving wider buffers along larger streams. By choosing the appropriate buffer design based on site characteristics and landscape constraints, we offer a tool for practitioners to take steps toward more ecologically sound agriculture practice. When buffer width is constrained by its surroundings, allowing a natural vegetation growth will increase the riparian buffer efficiency. By implementing even relatively small steps to protect these abundant degraded agricultural waterways, there is much potential to have a cumulative large-scale positive effect on downstream freshwater, marine and terrestrial ecosystems.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2019.109391.

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