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Challenges in applying scientific evidence to width recommendations for riparian management in agricultural Australia
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Summary

Intact riparian zones maintain aquatic-terrestrial ecosystem function and ultimately, waterway health. Effective riparian management is a major step towards improving the condition of waterways and usually involves the creation of a ‘buffer’ by fencing off the stream and planting vegetation. Determination of buffer widths often reflects logistical constraints (e.g. private land ownership, existing infrastructure) of riparian and adjacent areas, rather than relying on rigorous science. We used published information to support riparian width recommendations for waterways in agricultural Victoria, Australia. We focused on different ecological management objectives (e.g. nutrient reduction or erosion control) and scrutinised the applicability of data across different environmental contexts (e.g. adjacent land use or geomorphology). Not surprisingly, the evidence supported variable ‘effective’ riparian widths, depending on the objective and environmental context. We used this information to develop a framework for determining riparian buffer widths to meet a variety of ecological objectives in south-east Australia. Widths for reducing nutrient inputs to waterways were most strongly supported with quantitative evidence, and varied between 20 and 38 m depending on environmental context. The environmental context was inconsistently reported, making it difficult to recommend appropriate widths, under different land use and physiographic scenarios. The evidence to guide width determination generally had high levels of uncertainty. Despite the considerable amount of published riparian research, there was insufficient evidence to demonstrate that implemented widths achieved ecological objectives. We emphasise the need for managers to clearly articulate the objectives of proposed riparian management and carefully consider the environmental context. Monitoring ecological responses associated with different riparian buffer widths is essential to support future management decisions.

Introduction

Riparian zones exert important influences on the waterways they adjoin by mediating the bi-directional flow of matter and energy between the water body and surrounding uplands (Naiman *et al.* 2005). Globally, riparian zones are generally in poor condition (Sweeney & Newbold 2014) due to widespread modification of catchments through clearing of vegetation for agriculture, horticulture, grazing of livestock, forestry and urbanisation (Norris *et al.* 2001; Lake 2005; Burger *et al.* 2010). Riparian management is usually viewed as a practicable and cost-effective means of protecting waterways and enhancing ecological values in degraded landscapes. Governments and land managers spend millions of dollars on managing riparian zones on the assumption that intact riparian zones will alleviate or reverse the impacts of past and present disturbances (Hassett *et al*. 2005; Price *et al.* 2009).

Riparian management in agricultural systems involves fencing to exclude livestock, controlling weeds and planting of (usually) native vegetation (Correll 2005; Price *et al*. 2009; Buckley *et al*. 2012). The choice of where and how much riparian area to manage is usually constrained by associated costs, property boundaries, and the willingness of landholders to retire, donate, or lose productive land. The 'ideal' form of riparian management should target both banks, and ensure that the length and width of the area managed is sufficient to meet multiple restoration objectives (Weller *et al.* 1998; Mayer *et al.* 2007; Lake *et al.* 2007). As riparian land is usually divided longitudinally by property boundaries, affecting the practicability of continuous management along a waterway, width is generally the focus for determining the size of the management area (Lee *et al*. 2004).

We previously developed minimum width recommendations for riparian zones in Victoria (Hansen *et al.* 2010). Here, we investigate the evidence base riparian management, in order to emphasise broader principles and lessons for restoration. We focus on agricultural lands in south-eastern Australia, which are often highly degraded and therefore, the target for restoration. This review was not intended to be a meta-analysis to quantify effective riparian zone widths (which has been done elsewhere: e.g. Mayer *et al.* 2007; Sweeney & Newbold 2014), but rather to identify the state of knowledge about riparian zone widths required to restore streams to meet different ecological objectives in different environmental contexts. The approach we adopted was to focus on ecological management objectives, not social or economic objectives. The rationale we used could equally apply urban or mining geographic locations. We outline research and monitoring priorities for Australian riparian systems, as well as opportunities to improve the science and practice of riparian restoration.

Review method

We reviewed riparian literature on width requirements for initiating or augmenting riparian zone function. Peer-reviewed and "grey" references up to 2014 were located using the keywords riparian, "riparian zone", width, buffer and "vegetated filters" singly or combined, in search engines such as Scopus and Google Scholar. Studies containing primary width data were categorised according to riparian ecological function(s) (hereafter referred to as response(s)) and environmental context (see Supplementary Material online). Environmental contexts are modifying variables which influence riparian functions and include site-specific characteristics like vegetation type (e.g. forest versus grassland), vegetation extent (e.g. at the property scale), soil type, flow characteristics (surface versus subsurface), or slope of the riparian zone. Other environmental contexts include landscape characteristics such as physiographic features, stream order or adjacent land use.

Six broad responses were identified:

(1) improved connectivity of riparian habitat (e.g. contiguity of vegetation);

(2) reduction of nutrient, contaminant and sediment to waterways (includes erosion control);

(3) moderation of stream temperatures through riparian shading;

(4) provision of habitat and/or input of resources for aquatic fauna (e.g. wood, leaves, insects);

(5) lateral extent, or maintenance of riparian vegetation diversity;

(6) terrestrial (riparian) habitat for fauna (invertebrates, birds, reptiles, amphibians and mammals).

Empirical data from single studies that represented different responses and / or environmental contexts were defined as separate cases. For example, nitrate removal of 50% from subsurface flows was achieved through herbaceous riparian zones averaging 13.8 m in width compared to 38 m through forested riparian zones (with different soil types) in Canada (Vidon & Hill 2004). This study was split into two cases, representing the different contextual variables that influenced riparian response.

Where primary width data applied to nutrient or sediment reduction, the width necessary to reduce ≥ 75% of non-point pollutants to streams was used (value derived from nitrogen attenuation: Mayer *et al.* 2007). Where comparisons were made between different widths (e.g. organic matter inputs from clearcuts versus buffers of 10 m and 30 m: Kiffney & Richardson 2010) or between a control and treatment (e.g. effects on aquatic invertebrates of forested buffers versus clearcuts [Davies & Nelson 1994] or pasture [Lorian & Kennedy 2009]), the minimum width for a significant difference was used. Several studies used a modelling approach, validated by field data, to determine a width at which a change or effect occurs (e.g. distance at which coarse wood from riparian tree fall originates: van Sickle & Gregory 1990). Widths were either reported as is (e.g. a 100 m buffer reduces logging impacts on lotic macroinvertebrates; Growns & Davis 1991) or as the average of a width range (e.g. 250-300 m to reduce disturbance impacts on breeding Blue Herons *Ardea herodias*; Vos *et al*. 1985).

We described primary width data using summary statistics (median, 25th and 10th percentiles), representing individual identifiable cases, to establish a width range for each response. We distinguished wetlands (includes off-stream water bodies and lowland floodplains) from other settings for a single response, improving water quality.

Where dominant land use adjacent to waterways was specified, widths for each response were further summarised by land use intensity, categorised using Australian literature on fertiliser application and stocking rates (see Appendix 1 for details). Studies on reducing non-point pollution to waterways and providing habitat for terrestrial fauna were numerous enough to distinguish widths under low, moderate and high intensity land uses. Some of these had insufficient information to clearly differentiate low from moderate, or moderate from high land use. Patterns in widths for different responses with soil type, buffer vegetation type, stream size, geomorphology were also explored.

Width guidelines for management of Victorian riparian systems

We focused on riparian systems in agricultural Victoria (temperate climate) to determine the applicability of width data to a specific region and across a variety of land use types (e.g. cropping, irrigated pasture, market gardens). Median values for each relevant riparian response were applied to four key management objectives, considered important for determining minimum widths in Victoria:

(A) improving water quality (controlling erosion and reducing nutrient and contaminant inputs to streams) – response 2;

(B) increasing shading and moderating stream temperatures – response 3;

(C) providing food and other resource inputs to the aquatic environment – response 4;

(D) improving terrestrial biodiversity (flora and fauna) – responses 5 & 6.

Using the median values for each response, a matrix of provisional width recommendations was produced for each of the four management objectives for common environmental contexts (excluding urban and nature reserve settings). These were (1) low intensity land use, (2) moderate intensity land use, (3) high intensity land use, (4) low order, steep catchments (partially or completely cleared), and (5) lowland floodplain / wetland systems (Appendix 1). The width recommendation for a single management objective was set by the median value of the corresponding riparian response, and was increased by an amount corresponding to the 25th percentile for each increase in land use intensity. This adjustment reflected the need for wider riparian zones to mitigate greater impacts and disturbances originating from the catchment (see Castelle *et al*. 1994). It also incorporated variable width riparian zones, which often have a large range and may be more appropriate than fixed widths (Wissmar *et al.* 2004; Mac Nally *et al.* 2008; Anderson & Poage 2014).

Most quantitative riparian research originated from other regions and countries and may not be directly applicable to Victoria. We assigned three levels of scientific certainty (confidence) to data from the literature:

high - there are many overseas studies (typically >>50), several equivalent studies have been conducted in temperate Australia in different contexts, and / or general principles should be largely transferable to Victorian systems;

moderate - there are some overseas studies (typically <30) , there is limited evidence from temperate Australian systems (usually several studies done in similar contexts) and / or general principles may have limited application to Victorian systems; and

low - there are some overseas studies (typically <30), , there is little or no data from Australian studies and / or general principles are unlikely to apply in Victorian systems.

These levels were used to describe the level of confidence (in terms of the availability and relevance of scientific evidence) of each width recommendation.

In some contexts (e.g. low order streams) there was inadequate information to distinguish between different responses. This greatly increased the uncertainty of width recommendation. We used general theoretical knowledge about changes in stream function with order and size to determine width recommendations in these cases, and the certainty levels described above to highlight our confidence in the transferability of this information.

Results and discussion

Summary of evidence from riparian width studies

Information pertaining to riparian widths existed for a wide range of riparian management objectives, but most empirical evidence was skewed toward improving water quality. This predominantly originated from North America and Europe (Table 1), with some different ecological processes to Australia (particularly terrestrial processes), increasing the uncertainty of applying this data to Victorian systems.

There were over 600 relevant references, with 162 containing suitable primary width data (representing 188 response and/or context cases). Over 40% of the primary width data studies related to the reduction of sediment, nutrient and contaminant input to waterways (i.e. improving water quality). These had the lowest median widths (and percentiles) of all responses (20.0 m, range: 2-107 m) (Table 1). Of these, 61 nutrient and sediment reduction studies explicitly stated whether widths related to surface (median=16.5, n=26) and / or subsurface (median=20.0, n=35) flows. Evidence for improving terrestrial faunal biodiversity was the next most numerous (Table 1), dominated by studies on Northern Hemisphere birds and then mammals. There was less evidence for other specific responses indicating that current implemented widths may be underestimated for a range of ecological objectives. Our recommendations of 20-38 m for reducing nutrient inputs to streams and controlling erosion reflected widths documented elsewhere (Abernethy & Rutherfurd 1999; Sweeney & Newbold 2014)but larger widths were required for other responses (Lee *et al.* 2004; Table 2).

Generally, the environmental context of waterways was inconsistently reported, making it difficult to draw inferences about appropriate widths under different land use and physiographic scenarios. Low intensity land uses were most readily distinguishable from other environmental contexts (75 studies), and reported widths averaged across these studies were lower than for moderate or high intensity land uses (Table 3). Differentiating between moderate and high intensity land uses was often more difficult due to ambiguous land use information. Thus, widths did not differ substantially between these intensity levels (Table 3). We concluded that the available evidence supported the premise that increasing land use intensity required greater riparian widths (see also Castelle *et al*. 1994; Mayer *et al*. 2007).

Recommended riparian widths varied with environmental contexts, often unpredictably. Forested buffer widths required for improving water quality were larger than grassy buffer widths (Figure 1); forested and wetland buffer widths were largest when providing terrestrial habitat for fauna like breeding amphibians and birds (e.g. Hennings & Edge 2003; Semlitsch & Bodie 2003). Relationships between between soil type and buffer effectiveness were difficult to discern, with 35 different soil types reported across 60 studies. Geomorphic context (i.e. stream order) was specified across different nutrient and sediment reduction studies: headwater / 1st-2nd order streams had median widths of 20.0 m (n=18) but higher order waterways (3rd order and above) were 78.3 m (n=4). This seemed counter-intuitive as we might expect the opposite pattern on the basis of catchment topography and surface flow runoff rates (Nakamura & Yamada 2005; Kang & Lin 2009). It demonstrated that there is relatively fewer data from high-order waterways.

The importance of environmental contexts and objectives of riparian management in width setting

Appropriateness of width recommendation depended strongly on the management objective (reflecting the desired buffer function: Castelle *et al*. 1992). A grassy riparian buffer designed to intercept sediment (Blanco-Canqui *et al*. 2004) will be inadequate for supporting stream-dwelling invertebrates (Lorion & Kennedy 2009). Similarly, a 10-30 m forested riparian strip may provide adequate woody inputs to sustain aquatic biota (McDade *et al*. 1990, Thompson *et al*. 2009; Bahuguna *et al*. 2010), but may fail to maintain amphibian and reptile populations (Semlitsch & Bodie 2003; Ficetola *et al*. 2008). Furthermore, biophysical gaps along its length may compromise the opportunity for terrestrial fauna to migrate into suitable habitat patches (Knopf & Samson 1994).

To manage for multiple objectives, quantification of the objective(s) with the greatest relevant width is required (see for example Castelle *et al*. 1994; Nakamura & Yamada 2005; Sweeney & Newbold 2014) to set the minimum width. This can reduce the impacts of the most intensive land use practice on the waterway. For example, soil and/or vegetation type may reduce the role of the riparian zone in reducing nutrient input to streams (e.g. where groundwater flows bypass the retentive influence of riparian vegetation: Kuglerová *et al.* 2014). Managing for multiple objectives necessitates guidance on the most appropriate width - we used our review to outline how this may be achieved. Adopting a general approach of “more is better” will allow for landscapes where vegetation widths, and thus riparian widths, are longitudinally variable (i.e. where the topography is variable: Bren 1998; Polyakov *et al.* 2005; Mac Nally *et al.* 2008).

Where was the evidence lacking?

Identifying riparian zone widths for floodplains and wetlands, and low order, steep catchments, was more challenging given the scarcity of consistent evidence. Stream order and river size were specified for many studies, but general patterns were difficult to discern. Furthermore, supporting data for low and high order streams for any given objective were highly variable. The riparian zone will typically be large, relative to the channel width in headwater streams, then narrows in the gorge / valley section, and increases in lowland areas where the rivers are relatively wide and the hydrological and geomorphic complexity of floodplains produces patches of riparian vegetation around channels, billabongs and other off-stream waterbodies (Ward *et al.* 2002). In lowland waterways, the riparian zone reflects the lateral extent of hydrological influence. For example, the floodplain vegetation community in the lower Murray River may extend up to 12 km from the river (Roberts 2004). To maintain floodplain function, widths must encapsulate the connection to floodplain components (Opperman *et al.* 2010) and could be derived from conservative floodplain mapping (e.g. 1 in 30 year flood level: Peake *et al.* 2011).

Most evidence comes from the Northern Hemisphere and while general physical processes are likely to be similar on most continents, some critical biotic processes are not comparable. Extrapolating nutrient and sediment interception studies to Victoria is justifiable, given nitrogen removal and sediment transport are broadly transferable (Drewry *et al.* 2006). Some dominant sources and forms of nutrients like phosphorus do however exhibit some differences; N and P exports are usually lower in Australia (Harris 2001). Stream shading and inputs of riparian material to aquatic environments relate to generally similar physical processes (e.g. continuity of riparian canopy cover: Rutherford *et al.* 2004; or height of vegetation and valley slope dictate stream shading in low order waterways: DeWalle 2008). However, some critical aspects of riparian resource provisioning to streams (riparian subsidies) differ, depending on the ecology of riparian vegetation species and regional climate patterns (Francis & Sheldon 2002; Gawne *et al.* 2007). Northern hemisphere data relating riparian terrestrial biodiversity to buffer widths are unlikely to apply to many temperate Australian riparian systems due to the more unpredictable climate, and the idiosyncratic patterns in species abundance and distribution that often typify Australian fauna (Kingsford 2000; Woinarski *et al.* 2000). Our width recommendations for achieving terrestrial objectives had relatively high levels of uncertainty, illustrating the limitations of extrapolating research from other regions.

Management considerations

Our review demonstrated that greater widths were required to achieve objectives when adjacent land use intensity was high, or when the objective of management was improving terrestrial biodiversity (particularly fauna). This becomes problematic when intense land use practices occur on small properties, reducing the amount of riparian land that can economically be protected or targeted for management. Large widths recommendations may be impractical in these landscape settings. As the evidence originated predominantly from North American landscapes, the applicability of these data to south-eastern Australia may be limited. In order for practitioners to determine trade-offs between ecological and economic considerations, they require information on “functional effectiveness” of different widths under different land uses. This evidence is still broadly lacking, despite the considerable investment in riparian management. Decisions about appropriate riparian widths should be guided by strategic prioritisation of target areas within catchments (e.g. headwaters) that maximise ecological benefits (Parkyn *et al*. 2005; Craig *et al*. 2008; Stranko *et al*. 2012). For example, if we apply the evidence summarised here to a streamside property used for dairying in the lower Hunter River, New South Wales, a riparian zone width of 40 m may achieve ≥75% reduction of nitrogen inputs to the river and reduce stream bank erosion, contributing to improved downstream water quality. However, the same investment in riparian set-aside in the upper reaches of the Hunter catchment may provide additional improvements to stream nutrient processing (Lowe & Likens 2005), aquatic biodiversity (Chessman *et al.* 1997) and bird diversity (Bennett *et al.* 2014).

Riparian width decisions should be underpinned by three important considerations: (1) clear definitions of the ecological objectives of management, (2) incorporation of the spatio-temporal context of the restoration effort into management, and (3) documentation of the success (or failure) of management, to inform future programs.

Over the last two decades of riparian management, the failure to adequately document successes or failures has hindered riparian restoration science (Reich *et al.* 2011; Morandi *et al.* 2014). Compared to investment in restoration implementation, investment in monitoring has been minimal. The collection of monitoring data, for a suite of key indicators, linked to clearly stated goals, should be integral to any restoration programme (Palmer *et al.* 1997). Without these data, practitioners will continue to find it difficult to transfer the evidence from riparian research.

Research and monitoring priorities

We have focused on width recommendations, but for riparian management to be fully effective, interactive effects of other variables need to be understood. These are hydrology, climate, invasive species management, and longitudinal continuity of the riparian zone. Hydrology and climate strongly influence riparian function (Ward *et al*. 2002) and the effectiveness of the riparian zone as a buffer from disturbance, or as habitat for biota, may be different in non-perennial systems (Bond & Cottingham 2008).

Invasive species are widespread in riparian zones and weed control is usually required to reduce their impact on native vegetation survival and recruitment. Weed invasion into riparian zones may be pronounced when widths are small (Ferris *et al.* 2012). However, the extent to which invasive species positively or negatively interfere with management is not well understood, usually due to poor understanding of target ecological processes.

Evidence is accumulating that restoring longitudinal continuity of riparian zones should be a priority for management (e.g. Parkyn *et al*., 2005). Continuous riparian zones are important as even small gaps can allow disturbance impacts originating from the catchment to compromise the efficacy of downstream management (Weller *et al*. 1998). However, knowledge about the relationship between width and length remains poor in relation to objectives, e.g. riparian habitat as faunal conduits versus breeding areas, nutrient interception in upland versus lowland systems.

We found that the environmental context was inconsistently reported across many riparian studies, making it difficult to infer appropriate widths under different land use and physiographic scenarios. Exploration of gradients across different environmental contexts (e.g. lowland floodplains or low-order streams subject to high intensity adjacent land uses), to test hypotheses about effective riparian widths, would address this knowledge gap (e.g. riparian widths required to support woodland bird breeding under different adjacent agricultural practices.

Conclusions

In devising guidelines for riparian land managers, we found that the effectiveness of managed riparian zones in achieving their stated ecological objective was often unquantified, probably because restoration may take years or even decades of monitoring to detect. By focusing on riparian zones in agricultural Victoria, we demonstrated that evidence to support management guidelines is difficult to apply beyond the study area, despite the generality of some responses and their biophysical processes. Furthermore, any attempt to develop such recommendations becomes plagued with uncertainty resulting from high variability in riparian ecological responses, as well as a lack of information about the effect of environmental context. This requires flexibility in widths applied, which may rely on a combination of flood level mapping and adoption of the general principle that, the greater the land use intensity, the wider the riparian zone required to buffer against catchment modifications and disturbances. Thus, where land use changes are proposed, riparian zones need to be adjusted to account for forecasted increases in disturbance impacts. Our understanding of the sources of variation in ecological responses to riparian management would be greatly improved if the appropriate and acknowledged ‘contextual’ information was gathered and documented.

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References

Abernethy B. and Rutherfurd I. D. (1999) Guidelines for stabilising streambanks with riparian vegetation. Technical Report 99/10. Cooperative Research Centre for Catchment Hydrology. University of Melbourne, Parkville.

Anderson P. D. and Poage N. J. (2014) The Density Management and Riparian Buffer Study: A large-scale silviculture experiment informing riparian management in the Pacific Northwest, USA. *Forestry Ecology and Management* **316**, 90-99.

Barling R. and Moore I. D. (1994) Role of buffer strips in management of waterway pollution: a review. *Environmental Management* **18**, 543-558.

Bahuguna D., Mitchell S. J. and Miquelajauregui Y. (2010) Windthrow and recruitment of large woody debris in riparian stands. *Forestry Ecology and Management* **259**, 2048-2055.

Bennett A. F., Nimmo D. G. and Radford J. Q. (2014) Riparian vegetation has disproportionate benefits for landscape-scale conservation of woodland birds in highly modified environments. *Journal of Applied Ecology* **51**, 514-523.

Blanco-Canqui H., Gantzer C. J., Anderson S. H., Alberts E. E. and Thompson A. L. (2004) Grass barrier and vegetative filter strip effectiveness in reducing runoff, sediment, nitrogen, and phosphorus loss. *Soil Science Society of America Journal* **68**, 1670-1678.

Bond N., and Cottingham P. (2008) Ecology and hydrology of temporary streams: implications for sustainable water management. eWater Technical Report. eWater Cooperative Research Centre, Canberra, 35p.

Bren L. J. (1998) The geometry of a constant buffer-loading design method for humid watersheds. *Forest Ecology and Management* **110**, 113–125.

Buckley C., Hynes S. and Mechan S. (2012) Supply of an ecosystem service—Farmers' willingness to adopt riparian buffer zones in agricultural catchments. *Environmental Science and Policy* **24**, 101-109.

Burger B., Reich R. and Cavagnaro T. (2010) Trajectories of change: riparian vegetation and soil conditions following livestock removal and replanting. *Austral Ecology* **35**, 980-987.

Castelle A. J., Conolly C., Cooke S., Emers M., Erickson T., Metz E. D., Meyer S., Mauermann S. and Witter M. (1992) *Wetland buffers: use and effectiveness*. Adolfson Associates, Inc., Shorelands and Coastal Zone Management Program, Washington Department of Ecology: Olympia. Pub. No. 92-10.

Castelle A. J., Johnson A. W. and Conolly C. (1994) Wetland and steam buffer size requirements - a review. *Journal of Environmental Quality* **23**, 878-882.

Chessman B. C., Growns J. E. and Kotlash A. R. (1997) Objective derivation of macroinvertebrate family sensitivity grade numbers for the SIGNAL biotic index: application to the Hunter River system, New South Wales. *Marine and Freshwater Research* **48**, 159-172.

Correll D. L. (2005) Principles of planning and establishment of buffer zones. *Ecological Engineering* **24**, 433-439.

Craig L. S., Palmer M. A., Richardson D. C., Filoso S., Bernhardt E. S., Bledsoe B. P., Doyle M. W., Groffman P. M., Hassett B. A., Kaushal S. S., Mayer P. M., Smith S. M. and Wilcock P. R. (2008) Stream restoration strategies for reducing river nitrogen loads. *Frontiers in Ecology and the Environment* **6**, 529-538.

Davies P. E. and Nelson M. (1994) Relationships between riparian buffer widths and the effects of logging on stream habitat, invertebrate community composition and fish abundance. *Australian Journal of Marine and Freshwater Research* **45,** 1289-1305.

DeWalle D. R. (2008) Guidelines for Riparian Vegetative Shade Restoration Based Upon a Theoretical Shaded-Stream Model. *Journal of the American Water Resources Association* **44,** 1373-1387.

Drewry J. J., Newham L. T. H., Greene R. S. B., Jakeman A. J. and Croke B.F.W. (2006) A review of nitrogen and phosphorus export to waterways: context for catchment modelling. *Marine and Freshwater Research* **57,** 757-774.

Ferris G., D'Amico V. and Williams C. K. (2012) Determining effective riparian buffer width for nonnative plant exclusion and habitat enhancement. *International Journal of Ecology* **2012**. doi:10.1155/2012/170931

Ficetola G. F., Padoa-Schioppa E. and De Bernardi F. (2008) Influence of landscape elements in riparian buffers on the conservation of semiaquatic amphibians. *Conservation Biology* **23**, 114-123.

Francis C. and Sheldon F. (2002) River Red Gum (*Eucalyptus camaldulensis* Dehnh.) organic matter as a carbon source in the lower Darling River, Australia. *Hydrobiologia* **481**, 113-124.

Gawne B., Merrick C., Williams D. G., Rees G., Oliver R., Bowen P. M., Treadwell S., Beattie G., Ellis I., Frankenberg J. and Lorenz, Z. (2007) Patterns of Primary and Heterotrophic Productivity in an Arid Lowland River. *River Research and Applications* **23,** 1070-1087.

Growns I. O. and Davis J. A. (1991) Comparison of the macroinvertebrate communities in streams in logged and undisturbed catchments 8 years after harvesting. *Australian Journal of Marine and Freshwater Research* **42,** 689-706.

Hansen B. D., Reich P., Lake P. S. and Cavagnaro T. (2010) Minimum width requirements for riparian zones to protect flowing waters and to conserve biodiversity: a review and recommendations. Unpublished report to Department of Sustainability and Environment, School of Biological Sciences, Monash University.

Harris G. P. (2001) Biogeochemistry of nitrogen and phosphorus in Australian catchments, rivers and estuaries: effects of land use and flow regulation and comparisons with global patterns. *Marine and Freshwater Research* **52,** 139-149.

Hassett B., Palmer M., Bernhardt E., Smith S., Carr J. and Hart D. (2005) Restoring watersheds project by project: trends in Chesapeake Bay tributary restoration. *Frontiers in Ecology and Environment* **3,** 259–267.

Hennings L. A. and Edge W. D. (2003) Riparian bird community structure in Portland, Oregon: Habitat, urbanization, and spatial scale patterns. *Condor* **105,** 288-302.

Jansen A. and Robertson A. I. (2001) Relationships between livestock management and the ecological condition of riparian habitats along an Australian floodplain river. *Journal of Applied Ecology* **38**, 63-75.

Johnston W. H., Garden D. L., Rančić A., Koen T. B., Dassanayake K. B., Langford C. M., Ellis N. J. S., Rab M. A., Tuteja N. K., Mitchell M., Wadsworth J., Dight D., Holbrook K., LeLievre K. and McGeoch S. M. (2003) The impact of pasture development and grazing on water-yielding catchments in the Murray-Darling Basin in south-eastern Australia. *Australian Journal of Experimental Agriculture* **43**, 817-841.

Kang S. and Lin H. (2009) General soil-landscape distribution patterns in buffer zones of different order streams. *Geoderma* **151**, 233-240.

Kiffney P. M. and Richardson J. S. (2010) Organic matter inputs into headwater streams of southwestern British Columbia as a function of riparian reserves and time since harvesting. *Forest Ecology and Management* **260**, 1931-1942.

Kingsford R. T. (2000) Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. *Austral Ecology* **25**, 109-127.

Knopf F. L. and Samson F. B. (1994) Scale perspectives on avian diversity in Western riparian ecosystems. *Conservation Biology* **8,** 668-676.

Kuglerová L., Ågren A., Jansson R. and Laudon H. (2014) Towards optimizing riparian buffer zones: Ecological and biogeochemical implications for forest management. *Forest Ecology and Management* **334**, 74-84.

Lake P. S. (2005) Perturbation, restoration and seeking ecological sustainability in Australian flowing waters. *Hydrobiologia* **552,** 109-120.

Lake P. S., Bond N. and Reich P. (2007) Linking ecological theory with stream restoration. *Freshwater Biology* **52**, 597-615.

Lee P., Smyth C. and Boutin S. (2004) Quantitative review of riparian buffer width guidelines from Canada and the United States. *Journal of Environmental Management* **70,** 165-180.

Lorion C. M. and Kennedy B. P. (2008) Relationships between deforestation, riparian forest buffers and benthic macroinvertebrates in neotropical headwater streams. *Freshwater Biology* **54**, 165-180.

Lowe W. H. and Likens G.E. (2005) Moving headwater streams to the head of the class. *Bioscience* **55**, 196-197.

Mac Nally R., Molyneaux G., Thomson J. R., Lake P. S. and Read J. (2008) Variation in widths of riparian-zone vegetation of higher-elevation streams and implications for conservation management. *Plant Ecology* **198**, 89-100.

Mayer P. M., Reynolds Jr S. K., McCutchen M. D. and Canfield T. J. (2007) Meta-analysis of nitrogen removal in riparian buffers. *Journal of Environmental Quality* **36**, 1172-1180.

McDade M. S., Swanson F. J., Mckee W. A., Franklin J. F. and Van Sickle J. (1990) Source distances for coarse woody debris entering small streams in western Oregon and Washington. *Canadian Journal of Forest Research* **20**, 326-330.

Morandi B., Piégay H., Lamouroux N. and Vaudor L. (2014) How is success or failure in river restoration projects evaluated? Feedback from French restoration projects. *Journal of Environmental Management* **137**, 178-188.

Naiman R. J., Décamps H. and McClain M. E. (2005) *Riparia. Ecology, Conservation, and Management of Streamside Communities*. Elsevier Academic Press: Burlington, Ma.

Nakamura F. and Yamada H. (2005) Effects of pasture development on the ecological functions of riparian forests in Hokkaido in northern Japan. *Ecological Engineering* **24**, 539-550.

Nash D., Riffkin P., Harris R., Blackburn A., Nicholson C. and McDonald M. (2013) Modelling gross margins and potential N exports from cropland in south-eastern Australia *Journal of Agronomy* **47**, 23-32.

Norris R. H., Prosser I. P., Young B., Liston P., Bauer N., Davies N., Dyer F., Linke S. and Thoms M. (2001) *The Assessment of River Conditions (ARC). An Audit of the Ecological Condition of Australian Rivers*, CSIRO, National Land and Water Resources Audit Office: Canberra.

Opperman J. J., Galloway G. E., Fargione J., Mount J. F., Richter B. D. and Secchi S. (2009) Sustainable Floodplains Through Large-Scale Reconnection to Rivers. *Science* **326**, 1487-1488.

Palmer M. A., Ambrose R. F. and Poff N. L. (1997) Ecological theory and community restoration ecology. *Restoration Ecology* **5**, 291-300.

Parkyn S. M., Davies-Colley R. J., Bryce Cooper A. and Stroud M. J. (2005) Predictions of stream nutrient and sediment yield changes following restoration of forested riparian buffers. *Ecological Engineering* **24**, 551-558.

Peake P., Fitzsimmons J., Frood D., Mitchell M., Withers N., White M. and Webster R. (2011) A new approach to determining environmental flow requirements: Sustaining the natural values of floodplains of the southern Murray-Darling Basin. *Ecological Management and Restoration* **12**, 128-137.

Polyakov V., Fares A. and Ryder M. H. (2005) Precision riparian buffers for the control of nonpoint source pollutant loading into surface water: A review. *Environmental Reviews* **13**, 129–144.

Price P., Lovett S. and Davies P. (2009) *A national synthesis of river restoration projects.* Waterlines report, National Water Commission: Canberra.

Radcliffe J. C. (2002) *Pesticide Use in Australia*. Australian Academy of Technological Sciences and Engineering: Parkville, Victoria.

Ralph T. J. and Hesse P. B. (2010) Downstream hydrogeomorphic changes along the Macquarie River, southeastern Australia, leading to channel breakdown and floodplain wetlands. *Geomorphology* **118**, 48-64.

Reich P., Lake P. S., Williams L. and Hale R. (2011) On improving the science and practice of riparian restoration. *Ecological Management & Restoration* **12**, 4-5.

Ridley A. M., Christy B. P., White R. E., McLean T. and Green R. (2003) North-east Victoria SGS National Experimental Site: water and nutrient losses from grazing systems on contrasting soil types and levels of input. *Australian Journal of Experimental Agriculture* **43**, 799-815.

Roberts J. (2004) *Floodplain Forests and Woodlands in the southern Murray-Darling Basin.* Report JR 03/2004: Canberra, ACT.

Rutherford J. C., Marsh N. A., Davies P. M. and Bunn S.E. (2004) Effects of patchy shade on stream water temperature: how quickly do small streams heat and cool? *Marine and Freshwater Research* **55,** 737-748.

Semlitsch R. D. and Bodie J. R. (2003) Biological criteria for buffer zones around Wetlands and riparian habitats for amphibians and reptiles. *Conservation Biology* **17**, 1219-1228.

Stranko S. A., Hilderbrand R. H. and Palmer M. A. (2012) Comparing the fish and benthic macroinvertebrate diversity of restored urban streams to reference streams. *Restoration Ecology* **20**, 747-755.

Sweeney B. W. and Newbold J.D. (2014) Streamside forest buffer width needed to protect stream water quality, habitat, and organisms: a literature review. *Journal of the American Water Resources Association* **50**, 560-584.

Thompson R. M., Phillips N. R. and Townsend C. R. (2009) Biological consequences of clear-cut logging around streams - Moderating effects of management. *Forest Ecology and Management* **257**, 931–940.

Van Sickle J. V. and Gregory S. N. (1990) Modeling inputs of large woody debris to streams from falling trees. *Canadian Journal of Fisheries and Aquatic Sciences* **20,** 1593-1601.

Vidon P. G. F. and Hill A. R. (2004) Landscape controls on nitrate removal in stream riparian zones. *Water Resources Research* **40**, W03201.

Vos D. K., Ryder R. A. and Graul W. D. (1985) Response of breeding Great Blue Herons to human disturbance in northcentral Colorado. *Colonial Waterbirds* **8**, 13-22.

Ward J. V., Tockner K., Arscott D. B. and Claret C. (2002) Riverine landscape diversity. *Freshwater Biology* **47,** 517-539.

Weller D. E., Jordan T. E. and Correll D. L. (1998) Heuristic models for material discharge from landscapes with riparian buffers. *Ecological Applications* **8**, 1156-1169.

Wissmar R. C., Beer W.N. and Timm R.K. (2004) Spatially explicit estimates of erosion-risk indices and variable riparian buffer widths in watersheds. *Aquatic Sciences* **66**, 446-455.

Woinarski J. C. Z., Brock C., Armstrong M., Hempel C., Cheal D. and Brennan K. (2000) Bird Distribution in Riparian Vegetation in the Extensive Natural Landscape of Australia's Tropical Savanna: A Broad-scale Survey and Analysis of a Distributional Data Base. *Journal of Biogeography* **27**, 843-868.

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Table 1. Summary statistics for riparian width-related studies classified according to ecological function (or response) and geographic region. 25th and 10th percentiles are provided for comparison. No. cases = total number of width/response/context combinations across all studies. Nth Am. = North American, Eur. = Europe (and United Knigdom), AUS=Australasian. All widths are in metres.

Ecological function	Median width	25th perc.	10th perc.	Width range	No. cases	Nth Am.	Eur.	AUS	Other
Improving water quality	20.0	9.4	5.8	2-107	77	49	17	9	2
Improving water quality - wetlands	28.8	7.0	-	1-2250	4	2	1	1	0
Riparian inputs for aquatic fauna	30.0	20.0	11.4	10-100	21	14	1	6	0
Stream shading	27.5	18.1	10.3	10-83	11	11	0	1	0
Riparian vegetation	35.0	11.6	10.0	10-330	20†	9	2	8	1
Riparian habitat for fauna	78.5	30.0	15.0	5-900	53†	44	4	3	2
Connectivity for fauna	100.0	93.3	-	91-183	4	4	0	0	0
Total number of cases					188	136	25	28	5

† these responses share four cases where reported widths related to both riparian flora and fauna. Thus, total number of cases is four less than sum over all rows.

Table 2. Minimum width recommendations for riparian management in Victoria, developed on the basis of existing primary width data. The level of confidence for each recommendation (high, moderate and low) is written below the width. All widths are in metres.

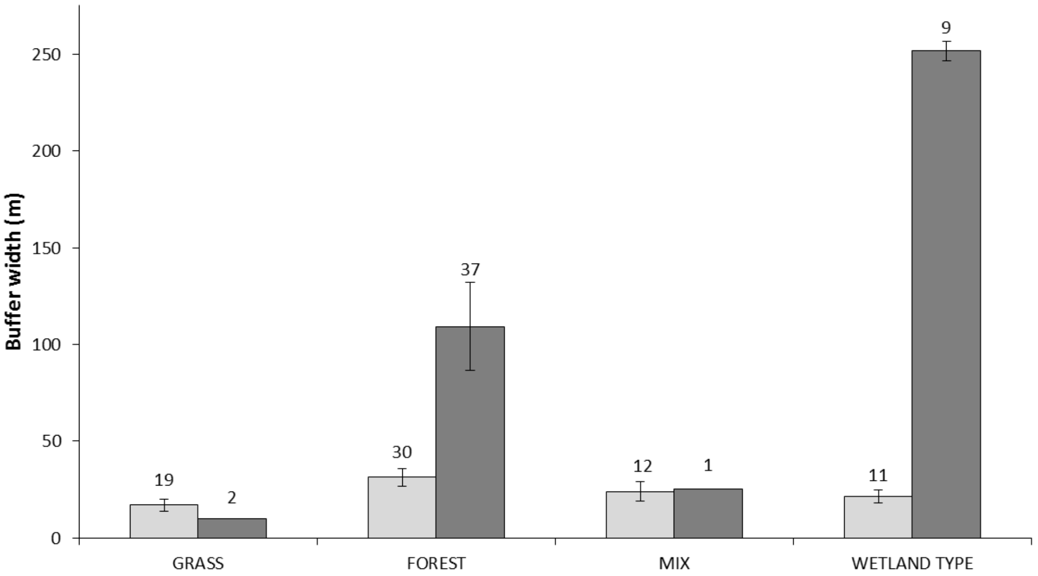
Environmental context / Management Objective	Land Use Intensity Low	Land Use Intensity Moderate	Land Use Intensity High	Lowland floodplain /wetland systems	Steep catchments/ low order streams
Improve water quality	20 **high**	29 **high**	38 **high**	29 *moderate*	38 *moderate*
Moderate stream temperatures	28 *moderate*	46 *moderate*	64 *moderate*	28 † *moderate*	28 *moderate*
Provide food and resources	30 *moderate*	50 *moderate*	70 *moderate*	30 † *moderate*	30 *moderate*
Improve terrestrial biodiversity	50 low	80 low	110 low	110 † low	50 low

† Width will relate to the lateral extent of hydrological influences, and thus, the actual minimum should reflect flood mapping (e.g. 1 in 30 year).

Table 3. Riparian buffer widths (m) for each ecological function (excluding studies with 4 cases or less), averaged across low, moderate and high land use intensity categories. Standard errors are given in parentheses. Where it was difficult to distinguish between low and moderate or moderate and high land use intensity, the lowest intensity was selected for summary.

Ecological function	Land use intensity			No. cases
	Low	Moderate	High	
Improving water quality	20.6 (2.6)	31.8 (9.4)	26.4 (3.6)	68
Inputs for aquatic fauna	38.6 (9.6)	50.0 (na)	-	10
Shading	35.6 (8.5)	-	-	9
Terrestrial biodiversity (flora & fauna combined)	62.6 (30.5)	169.4 (105.6)	130.0 (57.2)	44

Figure 1. Riparian buffer width for two key responses (improving water quality – pale bars, and terrestrial fauna habitat – dark bars), averaged across major buffer vegetation types (where stated in each study). Mixed buffer types may be any combination of grass, trees, and / or shrubs. Wetland types include floodplain and wetland forests (as stated in given studies). Values above each bar provide number of studies. Error bars are ±1 SE.



Appendix 1. Definitions of environmental contexts used in this review to reflect the majority of land uses in south-eastern Australia.

High intensity land use	Dairy (high stocking rates >10 DSE/ha/annum [1,2]) Irrigated dairy Dryland cropping (e.g. canola, wheat) Livestock grazing (stocking rates >15 DSE/ha/annum [1,2]) Swine and poultry (CAFO) Market gardens (vegetable production) High fertilizer application rates (>15kg P/Ha/yr [3] or >110kg N/Ha/yr[4,5]) Sealed roads within 30m
Moderate intensity land use	Dairy (all other stocking rates ≤ 10 DSE/ha/annum) Grazing (stocking rates 5-15 DSE/ha/annum) Other forms of dryland cropping (e.g. lucerne, clover) Orchards (including citrus) Other production crops including vines hops olives Medium-low fertilizer application rates (<15 kg P/Ha/yr or ≤110kg N/Ha/yr) Unsealed roads within 30m
Low intensity land use	Grazing (low stocking rates <5 DSE/ha/annum all stock) Pasture cropping Timber plantations Forestry operations Pesticide application (e.g. Endosulfan-containing insecticides, glyphosate, organophosphates, etc. [6])
Steep catchments / low order streams	Highly incised waterways with slopes typically exceeding 30° [7] where adjacent land is cleared or partially cleared of woody vegetation Headwater systems and low order streams (1-4)
Lowland floodplain / wetland systems	Typically higher order waterways with complex geomorphological features like anabranches, oxbow lakes and billabongs, and paleo-channels, and where the lateral extent of floodplain vegetation is large but highly variable and usually subjected to seasonal inundation [8] Chain-of-ponds or lakes or similar that are connected at any time to flowing waters (which may resemble lowland floodplains)

Sources used for defining land use intensity levels and environmental contexts:

[1] adapted from Jansen & Robertson (2001) – horses considered equivalent to bulls DSE (dry sheep equivalents) and deer equivalent to weaner calves (on the basis of relative size)

[2] adapted from Ridley *et al.* (2003)

[3] adapted from Johnston *et al.* (2003)

[4] adapted from Nash *et al.* (2013)

[5] 33rd percentile of N/NO_3-N application rates reported in water quality studies investigated in this review (range 75-389kg N/ha)

[6] refer to Radcliffe (2002) for more information on pesticide use in Australia

[7] derived from Barling & Moore (1994), plus valley slope data determined in this review (Supplementary material online)

[8] Ralph & Hesse (2010)

[BOX]

Implications for managers

- The effectiveness of managed riparian zones in achieving their stated ecological objective was often unquantified, probably because the restoration response may take years or even decades of monitoring to detect.
- Evidence to determine riparian zone widths for agricultural contexts in Victoria was frequently associated with high levels of uncertainty as many of the studies originated from the Northern Hemisphere
- The environmental context of waterways was often inconsistently reported, making it difficult to draw inferences about appropriate widths under different land use and physiographic scenarios
- The influence of hydrology, climate, invasive species management, and longitudinal continuity of the riparian zone on effective riparian zone widths should be targets for future investigation
- Generally, the greater the land use intensity, the wider the riparian zone needs to be to buffer against catchment modifications and disturbances.
- The collection of monitoring data, for a suite of key indicators and linked to clearly stated goals should be an integral part of any restoration program