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Riparian buffers in tropical agriculture: scientific support, effectiveness, and directions for policy

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Abstract

1. There is a weak evidence-base supporting the effective management of riparian ecosystems within tropical agriculture. Policies to protect riparian buffers - strips of non-cultivated land alongside waterways – are vague and vary greatly between countries.
2. From a rapid evidence appraisal we find that riparian buffers are beneficial for hydrology, water quality, biodiversity and some ecosystem functions in tropical landscapes. However, effects on connectivity, carbon storage, and emissions reduction remain understudied. Riparian functions are mediated by buffer width and habitat quality, but explicit threshold recommendations are rare.
3. *Policy implications.* A one-size-fits-all width criterion, commonly applied, will be insufficient to provide all riparian functions in all circumstances. Context-specific guidelines for allocating, restoring, and managing riparian buffers are necessary to minimise continued degradation of biodiversity and ecosystem functioning in tropical agriculture.

Keywords

river, riparian reserve, riparian corridor, environmental policy, ecosystem function, water quality, biodiversity, conservation set-aside

1. Introduction

Conservation set-asides are an important strategy to maintain biodiversity and ecosystem functions in tropical agricultural landscapes. Protected riparian areas, known as buffers, strips, margins, zones, or reserves, are a typical set-aside strategy. They comprise natural non-converted habitat, actively restored natural habitat, or unmanaged areas (Barclay et al. 2017).

Globally, most research on riparian buffers concerns hydrology, water quality and quantity (Tabacchi et al. 2000, Allan 2004, Mayer et al. 2007). More recently, there has been a growing interest in provisions for biodiversity, landscape connectivity, and ecosystem services such as pollination, pest control, carbon storage, and emissions reduction (e.g. Marczak et al. 2010). However, the scientific evidence for these alleged benefits is often lacking and unavailable to policymakers and practitioners.

With the emergence of sustainability standards, and increased transparency in agribusiness and producer governments, there is a window of opportunity to inform policies in tropical countries. Strengthened protection of riparian buffers is attracting industry interest, particularly via crop certification schemes, such as the Roundtable on Sustainable Palm Oil (RSPO); Fair Trade International, and Rainforest Alliance. As producers embrace demands for sustainability, it is timely to evaluate current riparian policies and the scientific evidence-base available to inform them.

Riparian policies typically prescribe a minimum width for protection (Table S1). However, much of the research on the ecological impact of buffer width is from North America and Europe (Figure 1). Policies are absent or poorly defined in many tropical countries, particularly the emerging agricultural markets of Central Africa (Table S1). Where policies do exist in tropical countries, they can be vague, highly variable between and within countries, and often loosely based on information from other locations.

2. Assessing the tropical evidence-base

To assess the research and recommendations available for riparian buffers in tropical agriculture, we undertook a rapid evidence appraisal of the scientific literature (see Appendix S1 in Supporting Information). The search returned 847 publications. After including papers we knew had been missed by the search, there were 265 studies that considered the impacts of tropical agriculture on riparian zones and waterways, of which 107 explicitly focussed on the effects of riparian buffers. Most of these 107 studies were from Brazil (31%), Malaysia (14%), and Costa Rica (11%) (Figure S1). Fifty percent of the 107 studies considered terrestrial ecology, biodiversity, and function; 30% hydrology and/or water quality; 18% covered freshwater ecosystems; 15% terrestrial connectivity; 11% agricultural ecosystem services; and 4% carbon storage and emissions (some publications covered multiple themes). Below we summarise the current state of knowledge, drawing on examples from the 107 studies. Very few gave specific recommendations for buffer design or management, but where they did we report them.

2.1. Hydrology and water quality

Riparian areas regulate rainfall and run-off into freshwaters, filter sediments and pollutants, stabilise riverbanks, maintain shading and low water temperatures, and provide inputs of terrestrial organic matter such as wood, leaves, seeds, and insects (Tabacchi et al. 2000, Allan 2004). Protecting non-cultivated riparian buffers also mitigates flooding, sedimentation, and nutrient run-off in farmland (Tabacchi et al. 2000, Mayer et al. 2007).

In general, buffers with greater vegetation quality provide better hydrological benefits. Across multiple studies and tropical regions, high tree cover is associated with high levels of dissolved oxygen in rivers, and low levels of sediment (Heartsill-Scalley and Aide 2003), sand (Luke et al. 2017a), and disease-causing bacteria (Ragosta et al. 2011). In Malaysia, oil palm plantation streams with high riparian foliage cover are more shaded and cooler, and have more leaf litter (Luke et al. 2017a, Chellaiah and Yule 2018b). In mixed farmland of Nicaragua, buffers with higher leaf area index and decreased grazing intensity also have higher levels of water absorption and slower overall flow (Niemeyer et al. 2014). In contrast, the limited available evidence indicates greater forest cover may not directly result in greater nitrogen removal (Chaves et al. 2009, Connor et al. 2013).

Landscape structure at larger spatial scales may outweigh the impact of localised riparian buffers. Forest quality and anthropogenic activities at the catchment scale were found to be important in both Malaysia and Brazil, particularly where buffer widths are <100m (Luke et al. 2017a, Mello et al. 2017). Subtle changes in road layouts or forest cover across a catchment can strongly influence run-off, sedimentation, and water temperatures (Leal et al. 2016).

Riparian management policies should account for multiple scales from the riparian to catchment level. Once this is considered it is likely that protecting relatively narrow buffers (ca. 5-10 m) will help regulate hydrology in tropical farmland (Figure 1).

2.2. Freshwater biodiversity

Freshwater biodiversity is heavily affected by upstream and downstream areas as well as surrounding riparian habitat through the influence of nutrient inputs and microclimate (Pusey and Arthington 2003). Although fish communities in agricultural streams with buffers are typically more similar to those in pristine forest than those without buffers (Lorion and Kennedy 2009a, Giam et al. 2015), there are mixed effects on species richness, abundance, and biomass reported in the literature. For example, fish that use leaf litter and coarse substrate for hiding and foraging were found to be missing from oil palm rivers without buffers (Lorion and Kennedy 2009a, Giam et al. 2015). As with water quality fish diversity responds to both local stream and catchment level conditions, and may also depend on buffer widths (Tanaka et al. 2016, Leal et al. 2018).

Freshwater invertebrates are central to aquatic food webs, contribute to decomposition and therefore support healthy freshwaters (Covich et al. 1999). Macroinvertebrate composition and diversity in buffer-protected rivers is typically intermediate between that of pristine and agricultural sites, although there is notable variation between studies and crop types (Lorion and Kennedy 2009b, Cunha et al. 2015, Tanaka et al. 2016, Cunha and Juen 2017, Luke et al. 2017b, Chellaiah and Yule 2018a). Higher aquatic invertebrate diversity is associated with high levels of coarse particulate organic matter, coarse substrate, dissolved oxygen, low levels of slow-flowing ‘glide’ habitat and ammonium concentrations (Chará-Serna et al. 2015, Tanaka et al. 2016, Connolly et al. 2016). Although land-use changes are known to reduce freshwater decomposition (Torres and Ramírez 2014), there are no tropical studies examining the potential for buffers to improve them.

As with hydrological studies, freshwater research point to the benefits of retaining sufficient forest cover (e.g. >50%, Connolly et al. 2016) of sufficient quality (e.g. larger trees and greater vertical canopy structure, Tanaka et al. 2016) adjacent to rivers.

No studies gave explicit recommendations of riparian widths needed to help protect tropical freshwaters. This might be partly explained by the difficulty in distinguishing localised effectiveness of riparian buffers from confounding catchment-level effects (see Leal et al. 2018).

2.3. Terrestrial biodiversity

Vegetation within riparian buffers tends to support more terrestrial biodiversity than surrounding farmland, and can, in some cases, support comparable diversity to riparian vegetation surrounded by continuous forest (e.g. mammals, Medina et al. 2007; birds, Mitchell et al. 2018; ants, Gray et al. 2015; butterflies, Harvey et al. 2006). However, in many situations buffer biodiversity is intermediate between that found in farmland and continuous forest (e.g. mammals, Zimbres et al. 2017; anurans, Konopik et al. 2015; dung beetles, Gray et al. 2014). As can be expected from habitat degradation and fragmentation, the number of species supported is variable, with many being generalist, disturbance-, or matrix-tolerant taxa, particularly in narrow buffers (Metzger et al. 1997, Marczak et al. 2010, Keir et al. 2015). Riparian zones may also support transient populations at particular times of the year, during extreme seasons or life stages (Keuroghlian and Eaton 2008, Rodriguez-Mendoza and Pineda 2010).

As habitat quality and tree species numbers are often greater in wider buffers (Metzger et al. 1997, Lees and Peres 2008), it is difficult to discern the influence of forest structure on riparian biodiversity. For birds at least, more species are recorded in riparian areas with a more even canopy profile (Lees and Peres 2008), or greater aboveground biomass (Mitchell et al. 2018). For this reason, exclusion of cattle from riparian buffers has been recommended in Brazil (Mendoza et al. 2014), which leads to vegetation regeneration (Griscom et al. 2009) and improved bird diversity (Lees and Peres 2008).

Several studies have investigated the role of isolation from forest in structuring buffer communities. Notably, buffers near to large tracts of forest support larger bat populations (Galindo-González and Sosa 2003), and more diverse dung beetle (Barlow et al. 2010) and bird assemblages (Lees and Peres 2008, Keir et al. 2015). However, the long-term viability of terrestrial biodiversity in buffers remains open to question as edge effects may cause continual habitat degradation, and the extent to which buffers act as ecological sinks is unclear (Beier and Noss 1998).

In Brazil, riparian buffers of >60m included both annually flooded and dry forest types, maintaining higher tree species diversity (Metzger et al. 1997). In pasture, widths >100m-200m for mammals, birds (Lees and Peres 2008, Zimbres et al. 2017), and dung beetles (Barlow et al. 2010) are recommended. In oil palm in Borneo, minimum riparian widths of 40-100m (either side of the river) for birds (Mitchell et al. 2018) and dung beetles (Gray et al. 2017a) are suggested (Figure 2), while in sugarcane in Queensland, widths >90m are needed to support forest specialist birds (Keir et al. 2015).

Positive associations exist between riparian buffer width and terrestrial tropical biodiversity. A buffer width of 100m each side of the bank would help support multiple animal and tree taxa regardless of agricultural land use or geographic location.

2.4. Landscape connectivity

Riparian buffers represent the essential connection between both terrestrial and aquatic ecosystems, and can potentially connect habitat patches in fragmented landscapes. For example, forest antshrikes (Gillies and St. Clair 2008), bats (Medina et al. 2007), peccaries (Keuroghlian and Eaton 2008), sloths (Garcés-Restrepo et al. 2018), and dung beetles and moths (Gray et al. 2017b) have been shown to use riparian buffers to move around agricultural-dominated landscapes. Buffers may also facilitate the spread of invasive species (Proches et al. 2005), although there are no studies that specifically address this in riparian buffers.

Only a few tropical studies have investigated the use of riparian buffers to increase landscape connectivity, with most focussing on single species. This is a key knowledge gap that is in critical need of further research to inform policy.

2.5. Greenhouse gas (GHG) balance

Depending on how they are managed, riparian buffers could exacerbate GHG emissions (i.e. loss of carbon through continued degradation and erosion or by retaining nitrogen in soil as fertiliser run-off from farmland), and/or serve as stores of carbon in otherwise impoverished farmland (Descloux et al. 2011, Kachenchart et al. 2012, Wantzen et al. 2012, Nagy et al. 2015, Brauman et al. 2015, Masese et al. 2017). Carbon stocks in buffers surrounded by soya farms were similar to intact riparian areas in Amazonia (Nagy et al. 2015). Similar trends were apparent in Borneo, although riparian carbon stocks were highly variable (Mitchell et al. 2018). Data from Brazil indicated that effective restoration of degraded riparian habitats could reverse high carbon losses associated with drainage and erosion, and result in a net increase of 70% carbon storage (Wantzen et al. 2012).

The effects of buffers on emissions is limited to a single study, which found similar N_2O emissions in riparian forest and fertilised maize farms in the dry season, but higher emissions in the buffers in the wet season. However, the buffer still provided positive benefits such as reduced nitrogen inputs to freshwater (Kachenchart et al. 2012).

There are few empirical studies on the carbon dynamics of riparian buffers in tropical agriculture, and only one on the effects of buffers on GHG emissions. Further research is urgently needed.

2.6. Agricultural services

Riparian buffer habitat could improve agricultural yields and production costs via pollination, pest control, decomposition, and water provision services; or agricultural productivity could fall due to increased exposure to pest and predators (Zhang et al. 2007, Power 2010). In Costa Rica, pollination rates in coffee farms decreased near riparian forest buffers compared to those by a non-riparian remnant (Ricketts 2004). In Borneo, oil palm sites near and far from buffers had a similar diversity of ants and dung beetles, as well as similar levels of dung decomposition (Gray et al. 2016), ant scavenging (Gray et al. 2015), and defoliating pests (Gray and Lewis 2014). Moreover, the presence of forest remnants, including buffers, had little impact on oil palm yield in Borneo (Edwards et al. 2014).

Evidence for 'spillover' of diversity and services from riparian buffers is limited. However, there is likely a balance between services and disservices provided by buffers in tropical farmland.

3. Directions for science and policy

Although additional research on tropical riparian buffers is clearly needed, several policy-relevant conclusions can be made from the existing literature:

1. **Riparian buffers should be maintained and restored**. Sufficient evidence exists to confirm buffers improve water quality and hydrological processes, support biodiversity, and contribute to landscape-wide carbon storage in tropical farmland. However, further studies are needed on connectivity, GHG balance, and ecosystem service provision. As biodiversity, carbon storage, hydrology and water quality improve when vegetation heterogeneity, canopy cover and biomass in buffers are high, retaining natural vegetation in buffers is essential. Research exploring thresholds or tipping points of habitat quality effects on riparian functions is currently lacking, and would be informative for restoration.

2. **Wider buffers are better than narrow ones.** Effective buffer widths will vary by function (Figure 1). Currently, width thresholds are largely based on hydrology and water quality research, with guidelines usually recommending widths of 10-100m (Table S1). However, biodiversity studies from Latin America and Southeast Asia indicate 40-200m on each riverbank is needed, depending on the taxon studied, and whether the buffer is isolated within the agricultural matrix. Larger or wider-ranging species may require large buffer widths, and so decision trees that allow context-specific recommendations are needed.

3. **Catchment-level processes should be considered alongside riparian processes**. The effectiveness of buffers for aquatic functions can be confounded by how land is managed upstream. Similarly, the value of buffers for terrestrial biodiversity is linked to habitat availability over the broader landscape. Efforts should be made to protect habitat in stream headwaters, and the location of roads and agricultural activities should be carefully planned across whole catchments to maximise benefits. The relative roles of riparian- versus catchment-level land cover remains poorly understood, especially in the tropics, and studies that quantify variation on both these scales (Iñiguez-Armijos et al. 2014) will be very valuable to inform policy.

We suggest four critical components needed to implement effective riparian policies in tropical countries:

1. **Clear buffer design protocols** are needed to decide how much riparian habitat should be retained in tropical agriculture. A wide range of variables are assessed to determine riparian buffer widths in some temperate locations (Figure 1), and could form a basis for similar function-specific policies in the tropics, noting that a one-size-fits all width threshold is insufficient. For example, the High Carbon Approach (http:// highcarbonstock.org) uses a decision tree incorporating patch area as a criterion for forest conversion, but could be

expanded by incorporating minimum width thresholds for riparian buffers under varying contexts. Such decision-making tools should facilitate buffer design for the landscape in question, incorporating key factors (e.g. size of river, connectivity, and matrix type) and automated computational processes.

2. **Rapid riparian survey protocols** to assess and monitor buffer effectiveness should be developed using a suite of standard indicator species and functions. We suggest expanding existing toolkits, such as the forest integrity assessment tool (www.hcvnetwork.org/resources/forest-integrity-assessment-tool) and the Toolkit for Ecosystem Service Site-based Assessment (TESSA) (Peh et al., 2017), to riparian contexts.
3. **Guidelines for rehabilitation and restoration** of riparian areas in tropical agriculture are notably absent from the published literature, but sorely needed. Recent oil palm certification standards offer some suggestions (Barclay et al. 2017), and experiments in Sumatra are testing various approaches (http://oilpalmbiodiversity.com/). The Riparian Ecosystem Restoration in Tropical Agriculture (RERTA) project provides a research design template that could be adapted and replicated in other countries and agricultural systems to allow informed guidelines at landscape-scales. We also suggest expanding on existing initiatives such as the Riparian Restoration Plant Database (https://www.ctahr.hawaii.edu/rnre/Riparian_Restoration_Plant_Database.asp)
4. **Local technical support** including capacity to map streams and land boundaries; expertise to help with monitoring and restoration; and schemes to increase policy awareness amongst land managers, are often lacking, meaning that riparian guidelines may fail to deliver benefits on the ground (Nunes et al. 2015). In addition to the open sharing of topographical data to accurately delimit watercourses, historical maps would be particularly useful to overcome shifting baselines, whereby deforested landscapes tend to lose perennial streams that could otherwise retain some functioning if buffered appropriately. Addressing this requires closer collaboration and improved data sharing between scientists, policy-makers, environmental

managers and local practitioners to build local capacity, and to ensure that riparian science is translated into policy where it is needed most.

Authors' Contributions

MJS and EMS conceived the ideas, and planned the paper. SHL, EMS, KVA, JD, JW reviewed the literature. SHL, EMS, CLG, and MJS led the writing. All authors contributed to the drafts and approved the final manuscript.

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Data accessibility

Data have not been archived because this article does not use data.

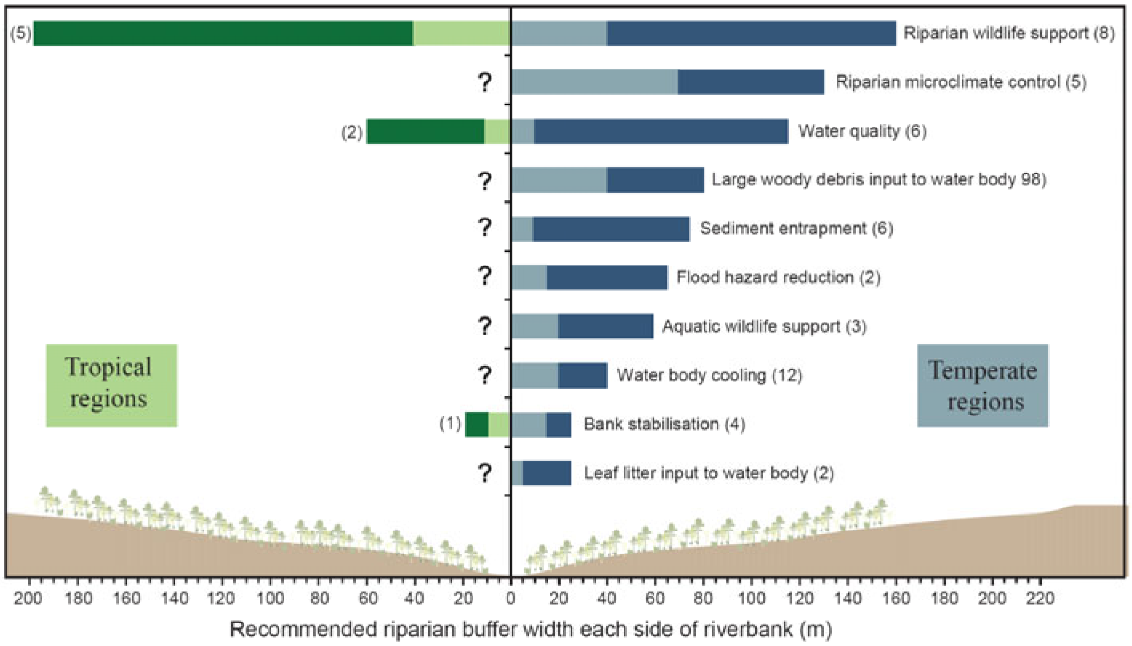

Figure 1. Minimum (light shading) and maximum (dark shading) riparian buffer widths recommended to protect riparian functions in temperate (evidence for North America in Collins et al. 2006) and tropical regions (material in this manuscript and (Barclay et al. 2017). The number of studies on which the recommendations are based are in parentheses.

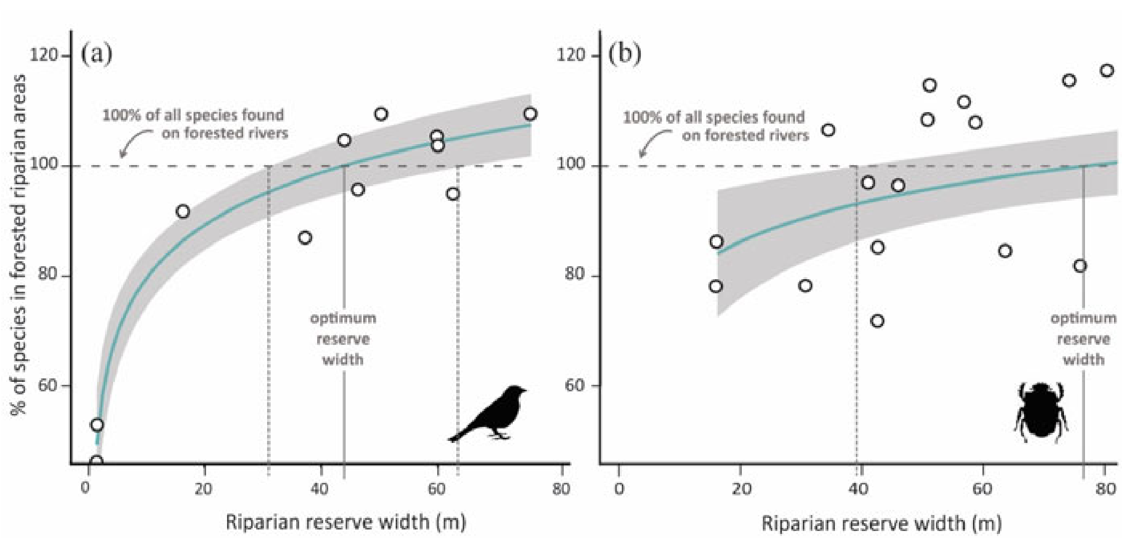

Figure 2. The proportion of a) bird and b) dung beetle species found in riparian buffers of increasing width in oil palm plantations compared to riparian areas in nearby forest (figures redrawn from

Mitchell et al. (2018) and Gray et al. (2017a)).

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