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

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Summary

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 highly variable between countries.
2. From a rapid evidence appraisal we find that riparian buffers are beneficial for hydrology, water quality, biodiversity, and other 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.

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 other 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 environmental policies in tropical countries (Lucey et al. 2017). 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 1). 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 Supporting Information). The search returned 847 publications. After including manual additions of papers we knew had been missed by the search, there was a total of 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. The majority of these 107 studies were from Brazil (31%), Malaysia (14%), and Costa Rica (11%) (Figure 2). 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 dead 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 river water, 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).

Crucially, 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). Although macroinvertebrate abundance may not be affected by land use change (Chellaiah and Yule 2018a), 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, Mendoza et al. 2014, 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; lizards, Ledo and Colli 2016; 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. 2015a) 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. Nevertheless, 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), at least in Amazonia.

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. 2015b). 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 3), while in sugarcane in Queensland widths >90m are needed to support forest specialist birds (Keir et al. 2015b).

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, Knowlton et al. 2017), 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. Carbon storage and emissions

Depending on how they are managed, riparian buffers could exacerbate greenhouse gas (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 important 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 found 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 provide key benefits in tropical landscapes, including improving water quality and hydrological processes, supporting higher levels of freshwater and terrestrial biodiversity, and contributing to landscape-wide carbon storage in tropical farmland. However, further studies are needed on connectivity, greenhouse gas emissions mitigation, 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 particularly informative for restoration efforts.
2. **Wider riparian 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 between 10-100m (Table 1). However, studies on tropical biodiversity 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 (see below).

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, isolation from nearby forest, matrix type, and local community use) and designation could be automated by 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 riparian restoration approaches in oil palm (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 awareness of policies amongst local 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 capacity on the ground, and to ensure that riparian science is translated into policy where it is needed most.

Author 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 with input from all authors.

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Table S1. Examples of riparian buffer policies in tropical countries compared to the RSPO certification standard. The area of land, forest, and agriculture for each country is taken from http://fao.org/faostat (18 January 2018). Policy documents are listed in Supporting Information.

Country	Area of land, forest and agriculture (FAO 2017)	Main agricultural crops by land area (>50% of farmland area)	Buffer policies, and prescribed width (from each riverbank)	Source
Brazil	Land: 8,515,767 km^2 Forest: 5,028,560 km^2 (59%) Agriculture: 2,879,181 km^2 (34%)	Soya Maize	The Brazilian Forest Code requires landowners to restore/maintain a PPA (Permanent Preservation Area) alongside watercourses. Previously, this ranged from 30-500 m wide depending on the size of the river. 2012 reforms changed the restoration liability for areas cleared before July 2008, linking this to property size rather than river size. Buffers to be restored are now much narrower (5-15 for most properties; although up to 100 m for very large ones).	Law 12651/2012. http://www.planalto.gov.br/ ccivil_03/_ato2011-2014/ 2012/lei/l12727.htm Nunes et al. (2015)
Colombia	Land: 1,141,748 km^2 Forest: 602,044 km^2 (53%) Agriculture: 459,668 km^2 (40%)	Coffee Rice Sugarcane Plantains	The National Code of Renewable Natural Resources and the Protection of the Environment dictates that all land 30m from each riverbank are the property of the state and should be preserved.	(Rubiano 2011)
Democratic Republic of Congo	Land: 342,000 km^2 Forest: 230,166 km^2 (67%) Agriculture: 39,535 km^2 (12%)	Cassava Maize	National operational guidelines require protection of land around watercourses of: - 20 m for streams or tributaries - 50 m for rivers >10m wide - 150 m for headwaters	Ministère de l'Environnement, Conservation de la Nature et Tourisme (MECNT 2010)

				(widths from each banks).	
Gabon	Land: Forest: (89%) Agriculture: (20%)	267,668 km^2 238,921 km^2 53,614 km^2	Cassava Plantains Yams	No specific national legal requirements. Producers are referred to best practice guidelines.	
Ghana	Land: Forest: (21%) Agriculture: (69%)	238,533 km^2 50,164 km^2 164,588 km^2	Cocoa Cassava Maize	National Buffer Zone Policy of Ghana requires: - 10-15 m from minor perennial streams - 10-20 m from important intermittent streams - 10-60 m for major perennial rivers and streams Prescribed buffer zones are dependent on slope, more steeper river banks requiring more land to be protected: - If 15-20%, add 3 m - If 20-25%, add 10 m - If 25-30%, add 20 m	(RSPO Ghana National Interpretation Working Group (GNIWG) 2015)
Indonesia	Land: Forest: (50%) Agriculture: (32%)	1,910,931 km^2 960,052 km^2 601,179 km^2	Rice Oil palm	National guidelines require protecting: - 50 m from rivers <30 m wide - 100 m from rivers >30 m wide - 200 m from water springs and rivers in swampy areas. Interpretation and implementation now rests with regional and local governments following decentralisation.	Minister of Agriculture Decrees 837/Kpts/Um/11/1980 and 683/Kpts/Um/8/1961; Presidential Decree No: 48/1983
Malaysia	Land: Forest: (68%) Agriculture: (24%)	330,803 km^2 223,457 km^2 78,930 km^2	Oil palm	Guidelines vary across the country. In peninsular Malaysia and Sarawak: - 5 m from watercourse <5 m wide - 10 m if 5-10 m wide - 20 m if 10-20 m wide - 40 m if 20-40 m wide	Ministry of Natural Resources and Environment (State of Sabah 1998, Malaysian Ministry of Natural Resources and Environment 2009, Environment Protection Department (EPD) 2011)

			- 50 m if >40 m wide. In Sabah all permanent watercourses >3 m wide need at least 20 m from the top of each riverbank. Oil palm producers are also required to maintain: - 5 m for rivers <3 m wide - 50-100 m for areas that are steep, environmentally sensitive, or important for wildlife.	
Papua New Guinea	Land: 462,840 km^2 Forest: 342,964 km^2 (74%) Agriculture: 13,885 km^2 (3%)	Coconut Oil palm Fruit Cocoa	National guidelines produced for the PNG oil palm industry require protection zones of 5 m from watercourses 1-5 m wide, to 100 m for rivers >50 m wide.	Papua New Guinea National Interpretation Working Group (PNG NIWG), 2012
			Elsewhere, the PNG Logging Code of Practice requires: - 10 m from watercourses 1-5 m wide - 50 m if >5 m wide - 50 m from any watercourse used by the local community. Prescribed widths are from the riverbanks where vegetation is 10 m or higher (which therefore excludes grasslands).	(Papua New Guinea Forest Authority & Department of Environment and Conservation 1996)

Certification organisation	**Certified extent**	**Crops**	**Buffer guidelines**	**Source**
Fair Trade International	1.65 million farmers; 74 countries (area information unavailable)	Bananas, Coffee, Sugar, Cotton., Cocoa, Tea	Member organisations must maintain buffer zones around bodies of water and watershed recharge areas and between production areas and areas of high conservation value, either protected or not. No further guidance is given, other than pesticides, other hazardous	Fairtrade Standard for Small Producer Organizations, Current version: 01.05.2011_v1.5, https://www.fairtrade.net/standards/our-standards/small-producer-standards.html

			chemicals and fertilizers must not be applied in buffer zones.	
Rainforest Alliance	Certified area: 3.5 million ha	Bananas, Coffee, Cocoa, Tea, Palm oil	Existing native vegetation outside natural ecosystems is maintained, including existing vegetated zones adjacent to aquatic ecosystems. Farm managers should "implement a plan to progressively increase or restore native vegetation…including restoration of zones adjacent to aquatic ecosystems. No further guidance is provided.	Rainforest Alliance Sustainable Agriculture Standard For farms and producer groups involved in crop and cattle production, July, 2017 Version 1.2 https://www.rainforest-alliance.org/business/sas/resource-item/rainforest-alliance-sustainable-agriculture-standard/
Roundtable for Sustainable Palm Oil (RSPO)	Certified area: 33, 010 km^2	Oil palm	In the absence of specific national guidelines all permanent watercourses, wetlands and water bodies should have minimum buffer widths of: - 5 m for rivers 1-5 m wide - 10 m for rivers 5-10 m wide - 20 m for rivers 10-20 m wide - 40 m for rivers 20-40 m wide - 50 m for rivers 40-50 m wide - 100 m for rivers >50 m wide.	RSPO (Barclay et al. 2017)

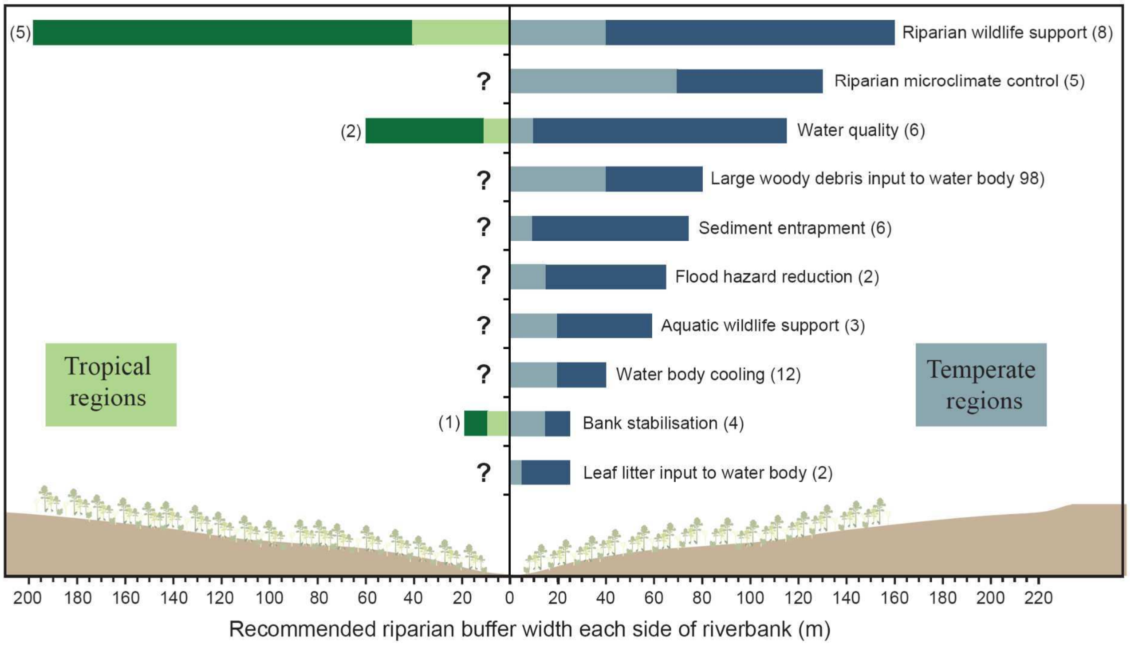

Figure 1. Minimum (light shading) and maximum (dark shading) riparian buffer widths recommended to protect riparian functions in temperate (evidence for North America in Collins et al. 2006) and tropical regions (material in this manuscript and (Barclay et al. 2017). The number of studies on which the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

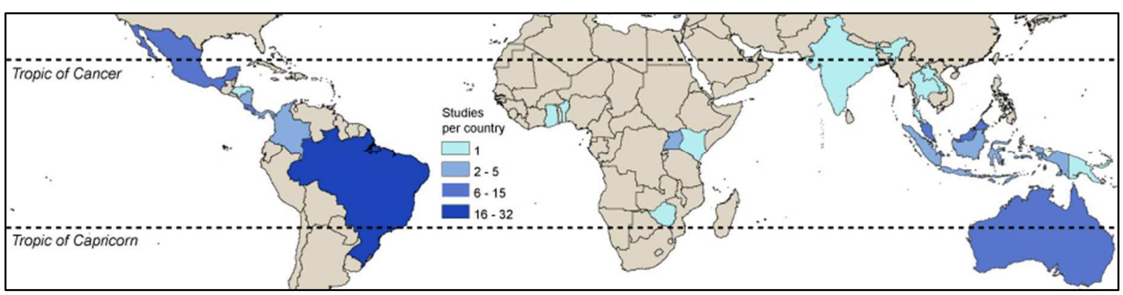

Figure 2. Geographic representation of riparian buffer research across countries within, or partially within, the tropical zone (106 publications; see Table S2).

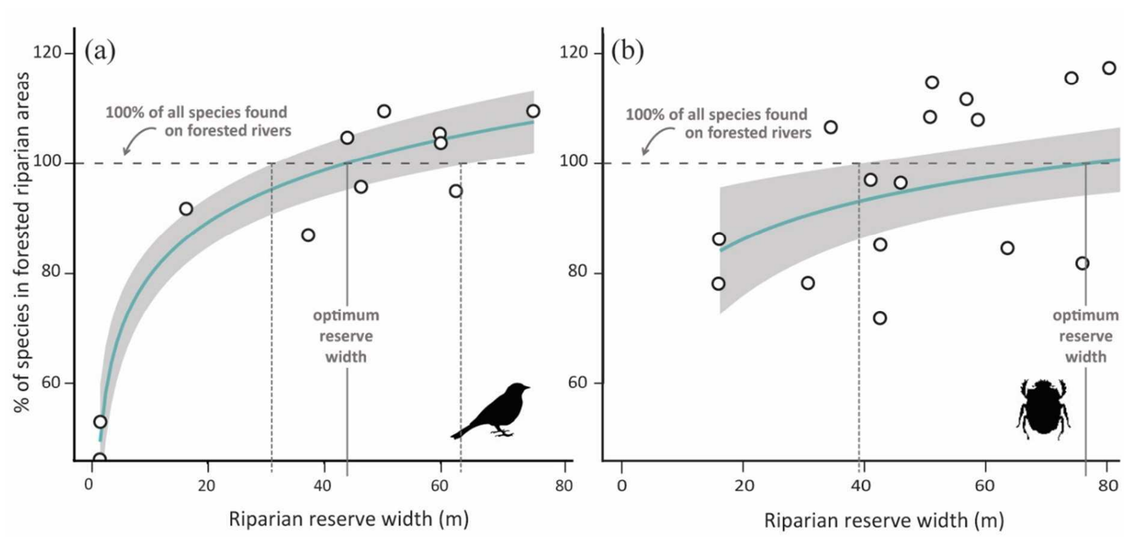

Figure 3. The proportion of a) bird and b) dung beetle species found in riparian buffers of increasing width in oil palm plantations compared to riparian areas in nearby forest (figures redrawn from Mitchell et al. (2018) and (Gray et al. (2017a)).

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Supporting information for Luke et al. Policy Direction manuscript

Search terms used to find relevant publications:

We undertook a rapid evidence appraisal of the scientific literature using the search engine Scopus (www.scopus.com). The following search terms were used (last updated 27th July 2018).

“TITLE-ABS-KEY (("riparian" OR "river*") AND ("tropic*") AND ("agricultur*" OR "plantation" OR "farm*" OR "graz*" OR "pastur*" OR "rice" OR "maize" OR "wheat" OR "sorghum" OR "soy*" OR "millet" OR "bean" OR "sugar*" OR "cassava" OR "groundnut*" OR "oil palm" OR "palm oil" OR "cowpea*") AND ("buffer" OR "margin" OR "zone" OR "corridor" OR "reserve" OR "forest" OR "strip" OR “connect*”)) AND (LIMIT-TO (LANGUAGE , "English"))”.

The selection of crop terms was based on a list of the most important tropical crops in Phalan et al. (2013). Using “tropic*” in the term assured the geographic reach of search was broad, and included countries that are partially within the tropical zone (e.g. Australia, India) as well as those wholly within it. This search returned 847 papers.

We sought to cover as wide a range of search terms as possible whilst keeping within the bounds of the relevant literature. Inevitably, a small number of publications did not include sufficient information or key words in bibliographic databases to be detected by our search. We therefore added any papers that we knew had been missed, or were evident from the references contained within the searched papers (17 papers added – italicized in Table S2). Although we acknowledge that the list is still unlikely to be exhaustive, particularly for publications published in languages other than English, we believe it offers an ample overview of the literature available on the topic.

Paper selection criteria:

Based on the title and abstract, papers were screened and placed into three categories (Table S2):

1. Those that generally considered the impacts of tropical agricultural on riparian zones and freshwater waterways (158 papers).
2. Those that explicitly considered the benefits of riparian buffers for mitigating impacts (107 papers). For this category we:
    - Included papers that studied the effects of isolated riparian buffers surrounded by agriculture.

- Excluded papers that considered riparian areas that were part of continuous habitats (either natural, or agricultural) rather than buffers *per se,* and those that considered forest fragments (unless the text of the paper indicated that these fragments were specifically designed or designated as riparian buffers).
- Did not require there to be a comparison of riparian buffer size with a non-buffered control site.
- Included additional papers that we knew had been missed by the search or from references contained within the searched papers (17 papers added- italicized in Table S2).

3. Those that were not relevant to either 1) or 2) above. These papers were excluded, and are not considered in this article.

Use of papers to produce summaries in Section 2:

For the papers considered relevant (categories 1 and 2, above), we recorded the country in which the study was conducted, and the topic(s) it considered under six key categories of benefits:

1. Hydrology and water quality
2. Freshwater biodiversity
3. Terrestrial biodiversity
4. Landscape connectivity
5. Carbon storage and emissions
6. Agricultural services

All relevant papers, their study countries, and topics are summarised in Table S1 and Table S2. We then used the papers from Table S2 as a basis for writing summaries of the existing knowledge-base on each topic (Sections 2.1-2.6). Owing to constraints of space, we were not able to discuss the results of each paper that fell within each category, but instead aimed to provide a balanced summary of the current state of knowledge, exemplified with details from a subset of the studies.

Supporting references

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Table S1- Publications that consider the impacts of tropical agriculture on riparian zones and waterways (158 papers)

Reference	Country	Crop	Water quality/hydrology	Freshwater biodiversity	Terrestrial biodiversity	Connectivity	Carbon and emissions	Agricultural services
(Abram et al. 2014)	Malaysia	Oil palm						✓
(Abrantes and Sheaves 2010)	Australia	Pasture	✓	✓			✓	
(Adyasari et al. 2018)	Indonesia	Mixed	✓					
(Alemu et al. 2017)	Ethiopia	Mixed	✓		✓			
(Alemu et al. 2018)	Ethiopia	Mixed	✓		✓			
(Altaf et al. 2018)	Pakistan	Mixed			✓			
(Amarathunga and Kazama 2016)	Sri Lanka	Mixed	✓					
(Armacost and Capparella 2012)	Peru	Mixed			✓			
(Awoke et al. 2016)	Ethiopia	Mixed	✓					
(Azhar et al. 2014)	Malaysia	Oil palm			✓			
(Azhar et al. 2015)	Malaysia	Oil palm			✓	✓		
(Barasa et al. 2016)	Uganda	Mixed	✓					
(Béliveau et al. 2009)	Brazil	Slash and burn agriculture	✓					
(Bello et al. 2017)	Malaysia	Mixed	✓					
(Benstead et al. 2003)	Madagascar	Mixed		✓				
(Benstead and Pringle 2004)	Madagascar	Mixed		✓				
(Boron et al. 2016)	Colombia	Mixed			✓	✓		
(Bott and Newbold 2013)	Peru	Pasture	✓	✓				
(Bramley and Roth 2002)	Australia	Mixed	✓					
(Brauman et al. 2015)	Hawaii	Mixed	✓		✓		✓	✓

(Brito et al. 2018)	Brazil	Mixed	✓	✓				
(Burgos-Caraballo et al. 2014)	Puerto Rico	Pasture	✓	✓				
(Casatti et al. 2015)	Brazil	Mixed		✓				
(Castillo 2010)	Venezuala	Mixed	✓					
(Causse et al. 2015)	Laos	Mixed	✓					✓
(Chappell and Thang 2007)	Malaysia	Oil palm	✓					
(Chappell et al. 2005)	Multiple	Mixed	✓					
(Da Cunha et al. 2006)	Brazil	Mixed			✓			
(Dalmagro et al. 2017)	Brazil	Mixed	✓					
(Datiko and Bekele 2014)	Ethiopia	Mixed			✓			
(David et al. 2016)	India	Mixed	✓					
(Davis et al. 2000)	Malaysia	Tree plantation			✓			
(Davis and Moore 2016)	Australia	Sugarcane		✓				
(de Alcântara et al. 2004)	Brazil	Pasture			✓			
(de Paula Ferreira et al. 2015)	Brazil	Mixed	✓	✓				
(Deegan et al. 2011)	Brazil	Pasture	✓					
(Descloux et al. 2011)	Laos	Mixed					✓	
(Devlin et al. 2001)	Australia	Mixed	✓					
(Dias et al. 2015)	Brazil	Mixed	✓					
(Echeverría-Sáenz et al. 2012)	Costa Rica	Pineapples	✓	✓				
(Edwards et al. 2014)	Malaysia	Oil palm						✓
(Encalada et al. 2010)	Ecuador	Pasture		✓				
(Evans 2015)	Malaysia	Oil palm		✓	✓			
(Faruk et al. 2013)	Malaysia	Oil palm		✓	✓			
(Fernandes et al. 2016)	Brazil	Mixed			✓			
(Ferreira Marmontel et al. 2018)	Brazil	Mixed	✓					
(Ficetola et al. 2008)	Costa Rica	Pasture		✓	✓			
(Figueiredo et al. 2018)	Brazil	Pasture	✓	✓				
(Franz et al. 2014)	Brazil	Mixed	✓					
(Fritsch 1993)	French Guiana	Tree plantation	✓					
(Gabiri et al. 2018a)	Uganda	Mixed	✓					
(Gabiri et al. 2018b)	Tanzania	Mixed	✓					

(Gama et al. 2017)	Brazil	Mixed	✓					
(Gandaseca et al. 2014)	Malaysia	Oil palm	✓					
(Gandaseca et al. 2015)	Malaysia	Oil palm	✓					
(García-García et al. 2017)	Mexico	Mixed	✓	✓				
(Gardner et al. 2007)	Brazil	Tree plantation			✓			
(Germer et al. 2010)	Brazil	Pasture	✓					
(Gillespie et al. 2012)	Malaysia	Oil palm		✓	✓			
(Graham et al. 2002)	Mexico	Mixed			✓			
(Griscom et al. 2007)	Panama	Pasture			✓			
(Groffman et al. 2001)	Costa Rica	Mixed			✓		✓	
(Gücker et al. 2016)	Brazil	Mixed	✓					
(Habel et al. 2018)	Kenya	Mixed			✓			
(Harun et al. 2016)	Malaysia	Oil palm	✓					
(Hein et al. 2011)	Puerto Rico	Mixed		✓				
(Huerta et al. 2007)	Mexico	Mixed			✓			
(Ikhwanuddin et al. 2017)	Malaysia	Mixed		✓				
(Iñiguez-Armijos et al. 2016)	Ecuador	Pasture	✓	✓				
(Iwata et al. 2003)	Malaysia	Slash and burn agriculture	✓	✓				
(Jacobs et al. 2017)	Kenya	Mixed	✓					
(Jacobs et al. 2018)	Kenya	Mixed	✓					
(Jayawardana et al. 2017)	Sri Lanka	Mixed	✓	✓				
(Kasangaki et al. 2008)	Uganda	Mixed	✓	✓				
(Kjærandsen 2005)	Ghana	Mixed		✓				
(Kundu and Bei 2016)	Indonesia	Oil palm	✓					
(Leitão et al. 2015)	Brazil	Pasture		✓				
(Leitão et al. 2018)	Brazil	Mixed	✓	✓				
(Levy et al. 2018)	Brazil	Mixed	✓					
(Li et al. 2014)	China	Mixed	✓					
(Liljeström et al. 2012)	Multiple	Mixed	✓					
(Lima et al. 2012)	Brazil	Tree plantation	✓					
(Litt et al. 2015)	Panama	Mixed	✓					
(Lucas et al. 2016)	Brazil	Pasture			✓			

(Luo et al. 2013)	China	Mixed	✓					
(Mardamootoo et al. 2015)	Mauritius	Sugarcane	✓					
(Martinelli et al. 1999)	Brazil	Mixed	✓	✓				
(Martínez et al. 2009)	Mexico	Mixed	✓		✓			
(Masese et al. 2014a)	Kenya	Mixed		✓				
(Masese et al. 2014b)	Kenya	Mixed	✓	✓				
(Masese et al. 2017)	Kenya	Mixed	✓				✓	
(Mayfield et al. 2006)	Costa Rica	Pasture			✓			
(Mayfield and Daily 2005)	Costa Rica	Pasture			✓			
(Mbaye et al. 2016)	Multiple	Mixed	✓					
(Mello et al. 2017)	Brazil	Mixed	✓					
(Mello et al. 2018)	Brazil	Mixed	✓					
(Mendenhall et al. 2011)	Costa Rica	Mixed			✓			
(Meng et al. 2015)	China	Mixed	✓					
(Miguel Ayala et al. 2016)	Brazil	Soybean	✓					
(Minakawa et al. 2005)	Kenya	Mixed		✓				✓
(Minaya et al. 2013)	Kenya	Mixed	✓	✓				
(Molina et al. 2012)	Ecuador	Mixed	✓					
(Mumeka 1986)	Zambia	Mixed	✓					
(Munga et al. 2009)	Kenya	Mixed		✓				✓
(Neill et al. 2001)	Brazil	Pasture	✓					
(Neill et al. 2006a)	Multiple	Pasture	✓					
(Nóbrega et al. 2018)	Brazil	Pasture	✓				✓	
(Nowakowski et al. 2015)	Costa Rica	Mixed		✓				
(Oliveira et al. 2016)	Brazil	Mixed	✓					
(Piazza et al. 2018)	Brazil	Mixed	✓					
(Pinto et al. 2006)	Brazil	Pasture		✓				
(Pramual and Kuvangkadilok 2009)	Thailand	Mixed		✓	✓			
(Ragosta et al. 2010)	Hawaii	Pasture	✓					
(Ramírez et al. 2017)	Colombia	Slash and burn agriculture	✓					
(Rasmussen et al. 2016)	Costa Rica	Rice	✓					
(Rizinjirabake et al. 2018)	Rwanda	Mixed	✓					

(Roa-Fuentes and Casatti 2017)	Brazil	Mixed	✓	✓				
(Rodrigues et al. 2011)	Brazil	Mixed			✓			
(Rodrigues et al. 2018)	Brazil	Mixed	✓					
(Rodriguez-Iruretagoiena et al. 2016)	Brazil	Mixed	✓					
(Rossi et al. 2010)	French Guiana	Slash and burn agriculture			✓			
(Saadati et al. 2012)	Malaysia	Mixed	✓					
(Sabo et al. 2005)	Multiple	Mixed			✓			
(Sahara et al. 2007)	Brazil	Tree plantation		✓				
(Salemi et al. 2013)	Brazil	Mixed	✓					
(Sapis et al. 2018)	Malaysia	Oil palm	✓	✓				
(Siegloch et al. 2014)	Brazil	Mixed	✓	✓				
(Silva-Junior et al. 2014)	Brazil	Mixed	✓	✓				
(Somura et al. 2016)	Indonesia	Rice	✓					
(Stephen and Sánchez 2014)	Costa Rica	Bananas			✓			
(Stephens et al. 2018)	Fiji	Tree plantation	✓					
(Strauch et al. 2014)	Hawaii	Mixed	✓					
(Suazo-Ortuño et al. 2017)	Mexico	Pasture			✓			
(Subramanian et al. 2005)	India	Mixed			✓			
(Suga and Tanaka 2013)	Brazil	Sugarcane	✓	✓				
(Suganuma et al. 2014)	Brazil	Mixed			✓			
(Sunil et al. 2016)	India	Mixed			✓			
(Tanaka et al. 2015)	Brazil	Sugarcane	✓	✓				
(Taniwaki et al. 2017)	Brazil	Mixed	✓					
(Tan-Soo et al. 2016)	Malaysia	Mixed	✓					✓
(Thomas et al. 2004)	Brazil	Pasture	✓					
(Thomas et al. 2015)	India	Mixed	✓					
(Toriman et al. 2015)	Thailand	Mixed	✓					
(Torres and Ramírez 2014)	Puerto Rico	Pasture		✓				
(Tripathi and Singh 2009)	India	Tree plantation			✓			
(Tsatsaros et al. 2013)	Australia	Mixed	✓					
(Vanacker et al. 2003)	Ecuador	Mixed	✓					
(Venkatesh et al. 2014)	India	Tree plantation	✓					

(Vijaykrishna and Hyde 2006)	Australia	Mixed		✓				
(Visser et al. 2007)	Australia	Sugarcane	✓					
(Wagner et al. 2008)	Benin	Mixed						✓
(Wantzen et al. 2012)	Brazil	Mixed					✓	
(Welsh et al. 2018)	Costa Rica	Coffee	✓					
(Wilk et al. 2001)	Thailand	Mixed	✓					
(Wösten et al. 2006)	Indonesia	Oil palm	✓					
(Yamada et al. 2016)	Malaysia	Oil palm			✓			
(Zeni et al. 2017)	Brazil	Mixed		✓				
(Zorzal-Almeida et al. 2018)	Brazil	Mixed	✓					

Table S2- Publications that consider the effectiveness of riparian buffers for mitigating the impacts of tropical agriculture on riparian zones and waterways * (107 papers)

* references shown in italics were not found by the Scopus search, and were added to the list manually.

Reference	**Country**	**Crop**	**Water quality/hydrology**	**Freshwater biodiversity**	**Terrestrial biodiversity**	**Connectivity**	**Carbon and emissions**	**Agricultural services**
(Almeida et al. 2016)	Brazil	Oil palm			✓			
(Avila-Cabadilla et al. 2012)	Mexico	Pasture			✓			
(Barlow et al. 2010)	*Brazil*	*Tree plantation*			✓			

(Bengsen and Pearson 2006)	Australia	Pasture			✓			
(Boëchat et al. 2013)	Brazil	Mixed	✓					
(Boëchat et al. 2014)	Brazil	Mixed	✓					
(Brito et al. 2017)	*Brazil*	*Oil palm*			✓			
(Cabra-García et al. 2012)	Colombia	Sugarcane			✓			
(Celentano et al. 2017)	Brazil	Slash and burn agriculture	✓		✓			
(Chará-Serna et al. 2015)	Colombia	Mixed	✓	✓				
(Chaves et al. 2009)	Brazil	Pasture	✓					
(Chellaiah and Yule 2018a)	Malaysia	Oil palm	✓	✓				
(Chellaiah and Yule 2018b)	Malaysia	Oil palm	✓					
(Connolly and Pearson 2005)	Multiple	Mixed	✓					
(Connolly et al. 2015)	Australia	Sugarcane	✓					
(Connolly et al. 2016)	Australia	Sugarcane		✓				
(Connor et al. 2013)	Australia	Sugarcane	✓					
(Cultid-Medina and Escobar 2016)	Colombia	Mixed			✓			
(Cunha and Juen 2017)	*Brazil*	*Oil palm*		✓				
(Cunha et al. 2015)	Brazil	Oil palm	✓	✓				
(de la Peña-Cuéllar et al. 2015)	Mexico	Pasture			✓			
(de Rouw et al. 2018)	Laos	Mixed	✓	✓				
(Duku et al. 2016)	Benin	Mixed						✓
(Estrada and Coates-Estrada 1996)	Mexico	Mixed			✓	✓		
(Fujita et al. 2014)	Indonesia	Tree plantation			✓			
(Galindo-González and Sosa 2003)	Mexico	Pasture			✓			
(Garcés-Restrepo et al. 2018)	Costa Rica	Mixed			✓	✓		
(García-Martínez et al. 2017)	Mexico	Mixed			✓	✓		
(Giam et al. 2015)	*Indonesia*	*Oil palm*		✓				
(Gillies et al. 2011)	Costa Rica	Pasture				✓		
(Gillies and St. Clair 2008)	Costa Rica	Pasture				✓		
(Gillies and St. Clair 2010)	Costa Rica	Pasture				✓		
(Graham and Blake 2001)	Mexico	Mixed			✓			
(Gray and Lewis 2014)	Malaysia	Oil palm						✓
(Gray et al. 2014)	Malaysia	Oil palm			✓			

(Gray et al. 2015)	Malaysia	Oil palm			✓			
(Gray et al. 2016)	Malaysia	Oil palm			✓			✓
(Gray et al. 2017a)	*Malaysia*	*Oil palm*				✓		
(Gray et al. 2017b)	*Malaysia*	*Oil palm*			✓			
(Greenler and Ebersole 2015)	Costa Rica	Cacao			✓			
(Griscom et al. 2011)	Panama	Pasture			✓			
(Griscom et al. 2009)	Panama	Pasture			✓	✓		✓
(Habel et al. 2015)	Kenya	Mixed			✓			
(Harvey et al. 2006)	Nicaragua	Mixed			✓			
(Hausmann et al. 2005)	Australia	Pasture			✓			
(Hawes et al. 2008)	*Brazil*	*Tree plantation*			✓			
(Heartsill-Scalley and Aide 2003)	Puerto Rico	Mixed	✓					
(Hill 1995)	*Australia*	*Sugarcane*			✓	✓		
(Houston et al. 2015)	Australia	Pasture			✓			
(Juen et al. 2016)	Brazil	Oil palm		✓				
(Kachenchart et al. 2012)	Thailand	Maize					✓	
(Keir et al. 2015)	Australia	Sugarcane			✓			
(Keuroghlian and Eaton 2008)	Brazil	Pasture			✓	✓		
(Knowlton et al. 2017)	*Brazil*	*Oil palm*				✓		
(Konopik et al. 2014)	Malaysia	Oil palm			✓			
(Konopik et al. 2015)	Malaysia	Oil palm			✓			
(Kraker-Castañeda et al. 2013)	Mexico	Pasture			✓			
(Leal et al. 2016)	Brazil	Tree plantation	✓					
(Leal et al. 2018)	Brazil	Mixed		✓				
(Ledo and Colli 2016)	*Brazil*	*Mixed*			✓			
(Lees and Peres 2008)	*Brazil*	*Pasture*			✓			
(Ligtermoet et al. 2009)	Malaysia	Oil palm	✓					✓
(Lorion and Kennedy 2009a)	Costa Rica	Pasture	✓	✓				
(Lorion and Kennedy 2009b)	Costa Rica	Pasture		✓				
(Lourenço et al. 2014)	Brazil	Mixed			✓			
(Luke et al. 2017a)	Malaysia	Oil palm	✓					
(Luke et al. 2017b)	Malaysia	Oil palm		✓				

(Mangadze et al. 2016)	Zimbabwe	Mixed	✓	✓				
(Martucci do Couto et al. 2016)	Brazil	Sugarcane			✓			
(McKergow et al. 2004)	Australia	Bananas	✓					
(McLennan and Plumptre 2012)	Uganda	Cacao			✓	✓		
(Medina et al. 2007)	Nicaragua	Pasture			✓	✓		
(Mendoza et al. 2014)	Multiple	Pasture			✓			
(Metzger 1997)	Brazil	Coffee			✓	✓		
(Metzger et al. 1997)	Brazil	Mixed			✓			
(Michalski et al. 2006)	Brazil	Pasture						✓
(Mitchell et al. 2018)	*Malaysia*	*Oil palm*			✓			
(Nagy et al. 2015)	Brazil	Soybean			✓		✓	
(Neill et al. 2006b)	Brazil	Pasture	✓					
(Niemeyer et al. 2014)	Nicaragua	Mixed	✓					
(Norris and Michalski 2010)	Brazil	Pasture			✓			
(Qureshi and Harrison 2002)	Australia	Mixed						✓
(Ragosta et al. 2011)	Hawaii	Pasture	✓					✓
(Ricketts 2004)	Costa Rica	Coffee			✓			✓
(Rivera et al. 2011)	Honduras	Mixed						✓
(Rodriguez-Mendoza and Pineda 2010)	Mexico	Pasture		✓	✓			
(Salemi et al. 2012)	Multiple	Pasture	✓					
(Salemi et al. 2016)	Brazil	Mixed					✓	
(Seaman and Schulze 2010)	*Costa Rica*	*Mixed*			✓			
(Seidu et al. 2017)	Ghana	Mixed	✓	✓				
(Sekercioglu et al. 2007)	*Costa Rica*	*Mixed*			✓	✓		
(Sheaves et al. 2018)	Papua New Guinea	Oil palm			✓			
(Silva-Junior 2016)	Multiple	Mixed	✓	✓				
(Singh et al. 2015)	*Malaysia*	*Oil palm*			✓		✓	
(Tanaka et al. 2016)	Brazil	Mixed	✓	✓				
(Tanaka and dos Santos 2017)	Brazil	Mixed	✓	✓				
(Thompson et al. 2018)	Costa Rica	Pasture			✓			
(Tomasella et al. 2009)	Brazil	Pasture	✓					
(Vono and Barbosa 2001)	Brazil	Tree plantation		✓				

(Wantzen et al. 2006)	Brazil	Mixed	✓					✓
(Wanyama et al. 2012)	Uganda	Mixed	✓					
(Williams et al. 1997)	Brazil	Slash and burn agriculture	✓					
(Williams-Linera et al. 1998)	Mexico	Pasture			✓			
(Wishnie and Socha 2003)	Costa Rica	Mixed	✓					
(Wordley et al. 2018)	India	Tea			✓			
(Yaap et al. 2016)	*Indonesia*	*Tree plantation*			✓	✓		
(Zimbres et al. 2017)	*Brazil*	*Pasture*			✓			

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