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Agricultural land-use change alters the structure and diversity of Amazon riparian forests

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ABSTRACT

Riparian forests play key roles in protecting biodiversity and water resources, making them priorities for conservation in human-dominated landscapes, but fragmentation associated with expanding tropical croplands threatens their ecological integrity. We compared the structure of tropical riparian forests within intact and cropland catchments in a region of intensive soybean production in the southeastern Brazilian Amazon. We studied forest plots (varying from 120 to 210 m long) that bisected riparian zone forests and headwater streams in ten catchments. Four plots were within large areas of intact primary forest and six were in bands of protected riparian forest along streams within croplands as required by the Brazilian Forest Code. We found that riparian forests in croplands harbored fewer species of trees and seedlings/saplings, and had higher proportions of opportunistic, pioneer tree species. We also found greater variation in tree species composition, and higher internal dissimilarity in croplands compared with forests. The observed patterns in tree species composition were driven mainly by differences between riparian forest-cropland edges and those bordering intact upland forests. Forests nearest to streams in cropland and forested catchments were more similar to one another. Results suggest that wider buffers are needed at the edges of croplands to maintain riparian forest structure. The minimum 30-m riparian buffers now required by the Brazilian Forest Code may thus be insufficient to prevent long-term shifts in riparian forest species composition and structure.

1. Introduction

The riparian forests that grow adjacent to small streams serve important functions such as providing shade and maintaining microclimates near streams, reducing stream water temperatures, and providing inputs of leaf litter that support aquatic food webs and fish assemblages (Caissie, 2006; Farjalla et al., 2016; Gregory et al., 1991; Lorion and Kennedy, 2009; Macedo et al., 2013; Oldén et al., 2019). Protection of riparian forests may also mitigate some of the potential negative effects of crop production on streams by intercepting nutrients, maintaining stream channel structure, and reducing downstream nutrient transport (Mulholland et al., 2008; Peterjohn and Correll, 1984; Sweeney et al., 2004; Vannote et al., 1980). At larger scales, riparian forests can serve as corridors for movement of freshwater and terrestrial animals (Lees and Peres, 2008; Peres et al., 2010; Zimbres et al., 2018, 2017). Finally, riparian forests maintain and conserve plant species of tropical forests (Naiman et al., 1993).

Over the last two decades, the lowland, seasonally-dry tropical forests in Brazil's "Arc of Deforestation" in southeastern Amazonia have experienced some of the highest rates of forest loss in the world (Brando et al., 2013; Morton et al., 2016). Most of this deforestation occurred for cattle ranching, but beginning in the early 2000s large areas of forest

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were cleared directly for croplands and many former pastures were converted to soybean croplands (Macedo et al., 2012). The Brazilian Forest Code (Federal Law No. 12.651/2012) requires a minimum 30-m riparian forest buffer around headwater streams throughout Brazil. In many Amazon croplands, riparian forest buffers are wider than the legal minimum because riparian slopes and low-lying wet areas near streams are unsuitable for mechanized cropping.

Fragmentation and associated edge effects in lowland *terra firme* Amazon forest alter forest structure. Small forest fragments with edges adjacent to cattle pastures or croplands show greater mortality of canopy and emergent trees (Brando et al., 2014; Kapos, 1989; Laurance et al., 2002; Oosterhoorn and Kappelle, 2000; Williams-Linera, 1990). Forest fragments also typically have a higher abundance of disturbance-adapted trees near forest edges (Laurance et al., 2006, 1998). These pioneer species tend to have low-density wood, thus reducing carbon stocks as they replace slower-growing trees with high-density wood (Laurance et al., 2007, 2006, 2002). Tree species diversity is also reduced in forest fragments (Laurance et al., 2002; Terborgh et al., 2001; Turner and Corlett, 1996), as seedling and sapling densities usually declines near forest edges (Benitez-Malvido, 1998; Gascon et al., 2000). Disturbances along forest edges can create conditions that favor grasses, which subsequently alter tree reproduction, shift forest structure (Laurance et al., 2000; Silvério et al., 2013), and increase forest flammability (Cochrane, 2003). For example, burned forest edges are susceptible to windstorms that disproportionately kill larger trees (Silvério et al., 2019).

Although Amazon riparian forests are less studied than edges of upland forests, their linear shape and high edge-to-area ratios likely make them susceptible to many of the same edge effects. Amazon riparian forests near cropland edges are hotter and drier than forest interiors (Nagy et al., 2015), and colonization by pasture grasses can deter forest regeneration (Chaplin-Kramer et al., 2015). Riparian forests near croplands may experience additional stressors, including inputs of herbicides and sediments. Increases in the water table in riparian zones – caused by large reductions in catchment-scale evapotranspiration (Hodnett et al., 1997; Neill et al., 2013) – may further influence tree growth or mortality by increasing soil hypoxia (Nagy et al., 2015). Combined, these effects could alter riparian forest structure over time and degrade riparian forest tree species composition despite legal protections.

Here, we investigate the effects of ~40 years of riparian forest fragmentation (via edge effects) on tree diversity, floristic composition, and forest structure in an expanding cropland region of southern Amazonia. Comparing riparian forests within large intact forest catchments to riparian forests within cropland, we hypothesized that: (1) riparian forests within croplands have lower species richness than in forested catchments; (2) tree species composition in cropland forests are more heterogeneous due to a higher occurrence of disturbance-associated species; (3) these effects are greater near cropland edges; and (4) wetter conditions near streams in cropland forests would reduce the abundance of tree species sensitive to the high water table and high soil moisture.

2. Materials and methods

2.1. Study area

We conducted this study at Fazenda Tanguro, a soybean farm in the

Fig. 1. Location of riparian forest plots in the Amazon-Cerrado transition zone (Querência, Mato Grosso state, Brazil). Left: Fazenda Tanguro; Right: example of one cropland riparian transect (top) and one forested riparian transect (bottom). See also Appendix: Fig. A1.

municipality of Querência (Mato Grosso, Brazil; Fig. 1), located in the transition zone between the Cerrado savanna and Amazon tropical forest biomes. Forest height of these seasonally dry, evergreen forests is lower (20 ± 1 m; mean ± SE) than the moist Amazon rainforests to the north and west (Balch et al., 2008). Currently, about 60% of Fazenda Tanguro is composed of primary forest. The remaining 40% was converted from forest to pasture beginning in 1976, and subsequently to soybean cropland in the early 2000s (Nagy et al., 2015). Mean annual air temperature varies between 24 and 26 °C. Annual rainfall varies from 1700 to 2200 mm, with a marked dry season from May–September (Alvares et al., 2013), when rain events $\geq$10 mm are rare.

At Fazenda Tanguro, the structure of riparian forests located in catchments covered mostly by croplands is a legacy of about 40 years of land use and land-cover change. Similar to what happened in other regions of the Amazon-Cerrado agricultural frontier, forest conversion began during the 1980s when forests were cleared for cattle ranching expansion (Riskin et al., 2013). Cattle frequently traversed riparian zones in those pasturelands to access streams, which potentially compacted soils, trampled regenerating vegetation, and altered stream water quality (Fearnside, 2005). By the early 2000s, large-scale crop production began to replace pasturelands with single-cropped soybeans, soon followed by double-cropped soybeans and maize (Fig. 1). At Fazenda Tanguro, this process of pasture replacement by croplands occurred between 2004 and 2009. No cattle were present in forested catchments.

2.2. Experimental design

In cropland catchments, riparian forests exist as narrow strips of vegetation adjacent to stream channels, legally protected by the Brazilian Forest Code and designated as “permanent preservation areas” (Portuguese acronym, APP). We sampled woody vegetation in ten riparian forests in 2015 (four within undisturbed, forested catchments (3.2 ha total sampled area) and six within catchments dominated by cropland (3.92 ha); Fig. 1). In each catchment, we established a 40-m wide transect perpendicular to the stream. Transects in forested catchments extended 100 m on each side of the stream, but in cropland catchments they varied between 40 and 160 m, depending on the width of the remaining riparian forest fragment (Table 1). Along the length of each transect, we marked every 10 m to examine the effects of distance from the riparian forest-upland forest transition and from cropland edges. We sub-divided each transect along its 40-m width into zones of three different widths (5, 20 and 40 m), where we sampled different size classes of the adult tree community (Fig. 1, Appendix: Fig. A1). In the 5-m zone, we sampled individuals with diameter at breast height (DBH, 1.30 m above ground level) between 5 and 10 cm (sampled area ranged from 0.06–0.11 ha). In the 20-m band, we sampled individuals with DBH between 10 and 30 cm (0.24–0.42 ha). In the entire 40-m zone, we inventoried individuals with DBH $\geq$ 30 cm throughout (0.48–0.84 ha). We identified all individuals to the species level using the nomenclature of the Brazilian Flora (Flora do Brasil 2020, 2018), which follows the Angiosperm Phylogeny Group classification system (APG IV, 2016).

Table 1

Descriptive parameters for trees and seedling/sapling species in riparian-forest sites within forested and cropland catchments. Student’s *t*-test comparing the mean number of species in each land use (trees: $t_{(6.6)} = -4.16$; $p < 0.01$; seedling/sapling: $t_{(3.9)} = -5.35$; $p < 0.01$). R = right (south); L = left (north); * = represents the distances from the stream to the edge of the cropland catchments; $^{\mathbf{a}}$ = small trees (5-m transect, where trees with DBH from 5 to 10 cm were sampled); $^{\mathbf{b}}$ = mid-sized trees (20-m transect, where trees with DBH $\geq$ 10 cm and < 30 cm were sampled); $^{\mathbf{c}}$ = large trees (40-m transect, where trees with DBH $\geq$ 30 cm were sampled throughout the transect).

Site name	Transect length (R/L)	Watershed land use	Number of individuals	Number of individuals/ha^{-1}	Total basal area (m^2. ha^{-1}) ^{a}	Total basal area (m^2. ha^{-1}) ^{b}	Total basal area (m^2. ha^{-1}) ^{c}	Average plant height (m)	Number of species
Trees									
APP 2	100/100	Forest	354	1472.50	0.36	4.74	12.80	15.57	64
APP 2A	100/100	Forest	372	1610.00	0.38	5.35	6.88	16.19	69
APP CN	100/100	Forest	330	1455.00	0.33	3.57	9.22	15.73	63
APP M	100/100	Forest	321	1210.00	0.24	3.84	15.53	16.95	55
Mean (SD)					0.33 (0.06)	4.38 (0.82)	11.11 (3.82)	16.10 (7.43)	63 (6)
Total			1377						112
APP 4	60/140 *	Cropland	339	1561.25	0.48	3.31	12.80	13.98	48
APP 5	130/60 *	Cropland	272	1400.00	0.40	2.65	15.64	15.05	50
APP 6	50/70 *	Cropland	168	1095.84	0.13	2.96	1.85	11.79	40
APP AR3	80/40 *	Cropland	210	1610.42	0.26	2.87	5.22	13.47	53
APP Cascavel	160/50 *	Cropland	229	903.57	0.22	2.56	9.08	13.40	52
APP Nascente	100/50 *	Cropland	239	1578.34	0.34	2.52	5.81	12.18	40
Mean (SD)					0.30 (0.13)	2.81 (0.30)	8.39 (5.14)	13.47 (7.25)	47 (6)
Total			1457						119
Seedling/ sapling									
APP 2		Forest	71	–	–	–	–	–	33
APP 2A		Forest	141	–	–	–	–	–	41
APP CN		Forest	167	–	–	–	–	–	44
APP M		Forest	166	–	–	–	–	–	34
Mean (SD)				–	–	–	–	–	38 (5)
Total			545	–	–	–	–	–	68
APP 4		Cropland	95	–	–	–	–	–	22
APP 5		Cropland	83	–	–	–	–	–	21
APP 6		Cropland	267	–	–	–	–	–	22
APP AR3		Cropland	211	–	–	–	–	–	27
APP Cascavel		Cropland	92	–	–	–	–	–	24
APP Nascente		Cropland	110	–	–	–	–	–	20
Mean (SD)				–	–	–	–	–	23 (3)
Total			858	–	–	–	–	–	65

To sample seedlings/saplings, we established six 1 × 2 m plots along each riparian forest transect, three on each side of the stream. We stratified these seedling/sapling plots according to their distance from the stream: near the stream (near: 5–28 m), middle of transect (mid: 21–68 m), and far from the stream (far: 32–108 m) (see, Fig. 1, Appendix: Fig. A1). Within each plot, we sampled all individuals with a diameter at ground level > 0.20 mm and < 80 mm.

Information on slope of the terrain, time-since-deforestation, and soil texture are available for each catchment (Appendix: Table A1), as is shallow soil moisture (Appendix: Fig. A2). To calculate slope, we used the *terrain* function from the *raster* package in R (Hijmans, 2017; R Core Team, 2018), using images from the Shuttle Radar Topography Mission (SRTM), a product supplied by NASA (National Aeronautics and Space Administration) at 30-m resolution (Farr et al., 2007). To estimate time-since-deforestation, we used the Landsat time series to identify the year of deforestation for each catchment. To estimate soil texture, we extracted the average content of sand, clay, and silt for each watershed sample at depths of 0–30 cm (i.e. 0–5 cm, 5–15 cm, and 15–30 cm) from the *SoilGrids* maps at 250-m resolution (Hengl et al., 2017). We measured soil moisture at 10-m intervals along each transect (N = 15–22; Appendix: Fig. A1), using a Hydrosense II sensor (HS2, Campbell Scientific) at 12-cm depth every two months between September 2015 and July 2017.

2.3. Statistical analysis

We compared the average species richness of adult trees across forest and cropland riparian plots using an Analysis of Variance (ANOVA). We then compared the richness of seedling/sapling species at the three distances (near, mid, and far transects) from the stream channel within forest and cropland riparian catchments. We used Generalized Linear Models with a Poisson error distribution to evaluate species richness within land-use classes as a function of distance to the stream for trees and seedlings/saplings.

To compare species richness between forest and cropland riparian forests, we built rarefaction curves for trees and seedling/sapling species, standardizing the sample effort per number of individuals in the area sampled (Gotelli and Colwell, 2001), with the *iNEXT* function from the *iNEXT* package in R version 2.0.20 (Chao et al., 2014; Hsieh et al., 2016; R Core Team, 2018). To provide a direct comparison of species richness between cropland and forested riparian forests, we extracted the number of tree species estimated by the rarefaction curves procedure, standardizing the sample effort to individuals. We then compared species richness between cropland and forested riparian forests using a Student's t-test. We obtained the average dissimilarity of tree communities within each riparian forest (i.e., by pairwise contrast among transects within each forest) using the Bray-Curtis dissimilarity index. We then used an ANOVA to test if tree communities were more heterogeneous within cropland than forested catchments. Additionally, we ordinated species composition of adult trees and seedlings/saplings with a Principal Coordinate Analysis (PCoA), using the Bray-Curtis dissimilarity index (Legendre and Legendre, 2012) followed by an Analysis of Similarities (ANOSIM), to evaluate whether communities differed between forested and cropland catchments (Clarke and Warwick, 1994). Finally, we analyzed the proportion of unique and shared species between forest and cropland catchments with the function *draw.pairwise.venn* from the package *VennDiagram* (Chen, 2018).

We calculated the Importance Value Index (IVI) of each species in the community for all plots (Curtis and McIntosh, 1950). The IVI showed which tree species were most important in terms of relative abundance, dominance, and frequency. We used a PCoA – Bray-Curtis dissimilarity index (Legendre and Legendre, 2012) followed by an ANOSIM test to confirm the a priori groups (Clarke and Warwick, 1994) and compare the floristic-structural composition of forest communities near the stream (Forest-Stream; Cropland-Stream) and far from the stream (Forest-Upland; Cropland-Edge). To compare the size distribution of trees in forested and cropland catchments, we first calculated the size distribution of individual trees by diameter class (5-cm intervals) and then standardized them per hectare within each size class. In addition, we compared the frequency of individuals in each class using the Generalized Linear Models with a *quasipoisson* error distribution and also compared the total heights of the trees, using Wilcoxon's non-parametric test. First we averaged the monthly soil moisture collected in each riparian forest transect at 10-m intervals. We then compared these soil water averages between forest and cropland catchments, using the non-parametric Wilcoxon test to analyze differences. We performed all analyses in the R Programming Environment (R Core Team, 2018). Throughout the text, we report the means of measured attributes followed by standard deviation (±SD).

3. Results

3.1. Species diversity

We sampled a total of 2834 individuals ($\text{DBH}_{1.30\text{ m}} \geq 5$ cm) distributed across 152 tree species, with 52% (79 species) occurring in both land use types. The remainder occurred exclusively in riparian forests of cropland (26%) or forested (22%) catchments (Appendices: Table A2, Fig. A3). Cropland riparian forests had higher cumulative species richness than riparian forests located in forested catchments (119 versus 112). However, the average tree species richness was lower in cropland riparian forests (47 ± 6) compared to forested areas (63 ± 6) (Table 1; $t_{(6.6)} = -4.16$; $p < 0.01$). This difference in richness persisted when we controlled for the number of individuals in each transect, which was lower in cropland-dominated riparian forests (Fig. 2A). Rarefaction curves standardizing the sample effort to 300 individuals also show that the number of riparian forest tree species was lower in cropland watersheds (51 ± 6) compared to forested catchments (60 ± 5; $t_{(7.89)} = -2.546$, $p = 0.034$; Fig. 2A).

In total, we sampled 1693 seedlings and saplings distributed across 93 species, with 43% (40 species) occurring in both forested and cropland catchments. The remainder occurred exclusively in cropland (27%) or forest (30%) catchments. The average seedling/sapling species richness was also less diverse in cropland riparian forests. On average, there were 15 fewer seedling/sapling species in cropland compared to forested catchments (Fig. 2B, Table 1; $t_{(3.9)} = -5.35$; $p < 0.01$). Rarefaction curves standardizing the sample effort to 140 individuals also show that the number of seedling and sapling species was lower in cropland riparian forests (24 ± 4) than in forested areas (41 ± 8; $t_{(4.13)} = -4.146$, $p = 0.013$; Fig. 2B).

On average, species richness was lower in cropland riparian forests for seedlings/saplings and trees than in forested catchments. In some cases, though, these differences were strongly influenced by distance from the stream channel. For trees (individuals with DBH ≥ 5 cm), cropland and forested catchments had comparable species richness near streams, but the patterns diverged with increasing distance from the stream channel. Average species richness increased as a function of distance from the stream channel in forested catchments, but decreased in cropland catchments (Fig. 4A, Appendix: Table A3). These results point to edge effects strongly influencing tree species richness and community composition in cropland riparian forests. In contrast, we observed no influence of distance from the stream channel on species richness for seedlings and saplings, with species richness being lower in cropland catchments across all distances from the stream channel.

3.2. Difference in structure and composition

The structure and composition of riparian forests in croplands differed substantially from that of forested catchments. Results from our PCoA and ANOSIM analyses indicate that the largest differences in species composition between forests and croplands occur furthest from stream channels ("Forest-Upland" vs. "Cropland-Edge"; Fig. 5A;

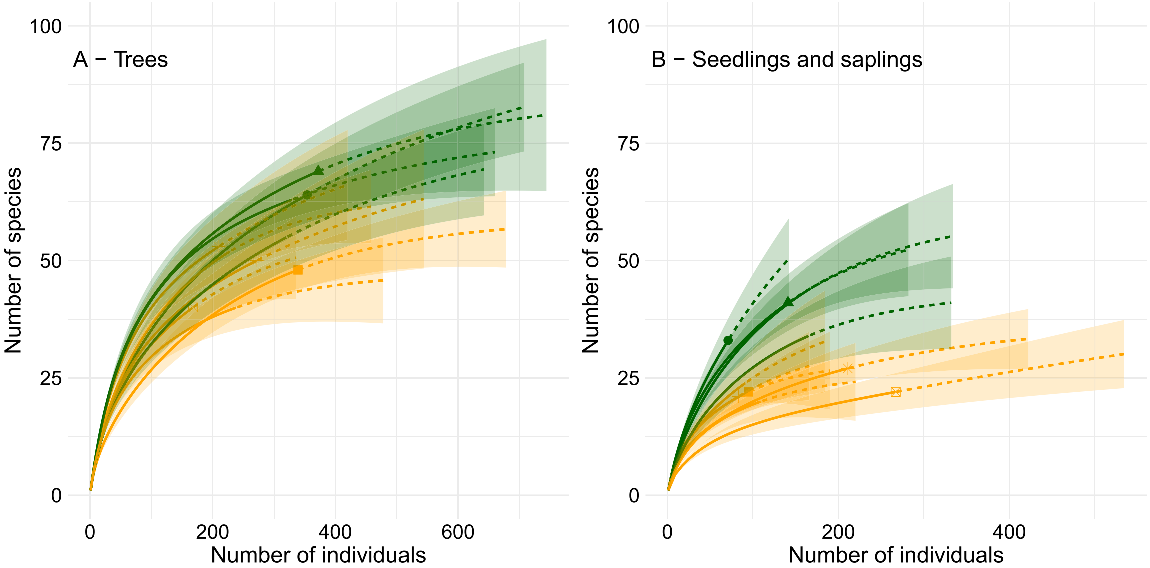

Fig. 2. Richness of woody species in ten riparian forest transects in the southeastern Amazon. Species diversity based on the Hill numbers ($q = 0$) for riparian forest trees ≥5 cm DBH (A) and seedlings/saplings (B) in forested catchments (green) and cropland catchments (orange). Solid line = interpolation; Dashed line = extrapolation. Confidence intervals (95%). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ANOSIM: $R = 0.26$; $p = 0.001$). For example, upland riparian forests in forested catchments were comprised of a subset of the larger community. In contrast, the composition of upland riparian forest in croplands strongly differed from all other riparian forests. Riparian forests in cropland catchments had a more heterogenous plant community than those located in forested catchments, with a high degree of dissimilarity from primary forests (cropland: 0.76 ± 0.03; forest: 0.62 ± 0.02 mean dissimilarity ± SE) (Fig. 3, Appendix: Fig. A4). In general, community composition of seedlings/saplings also differed significantly (Fig. 5B; ANOSIM: $R = 0.22$; p = 0.001).

In general, riparian forests in cropland catchments had a greater abundance of fast-growing pioneer tree species and many of these were concentrated near forest edges. Four important Amazon pioneer species occurred exclusively or almost exclusively along forest edges (*Cecropia distachya*, 100% along edges, *Pera glabrata*, 100%, *Mabea fistulifera*, 100% and *Tachigali vulgaris*, 83%). The Importance Value Index (IVI) showed 11 dominant species in forested catchments, and eight in cropland catchments (Appendix: Table A2). Only three of these species were common between forested and cropland catchments (*Ruizterania wittrockii*, *Sloanea sinemariensis* and *Protium spruceanum*). The IVI indicated seven dominant species (51.7% of observed species) in forest-stream plots, 11 (50.1%) in forest-upland, six (50.6%) in cropland-stream, and eight (51.7%) in cropland-edge (Fig. 6, Table 2). Of these, three species were common between forests and croplands (*R. wittrockii*, *S. sinemariensis* and *Licania longistyla*), and only one was shared between forest-uplands and cropland-edges (*R. wittrockii*).

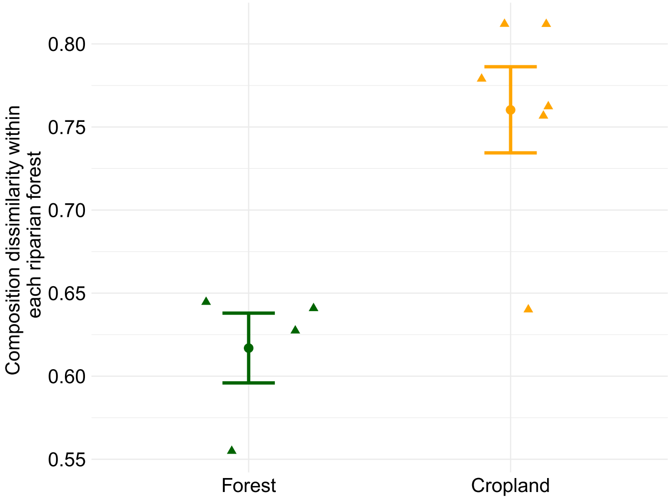

Fig. 3. Average tree species dissimilarity among riparian forest transects in forested and cropland catchments ($F_{(1,8)} = 15.51$; $p < 0.01$) in the Amazon-Cerrado transition (Fazenda Tanguro, Querência-MT, Brazil). Bars represent standard error.

Despite the similarity in the distribution of individuals across diameter classes between forested and cropland catchments (Fig. 7; $t = -0.133$; $p = 0.89$), forested catchments had 27.1% more basal area than cropland catchments per hectare (Table 1). Also, trees in forested catchments were 16% taller than trees in cropland catchments (Table 1; W = 764,860; p = 0.001).

4. Discussion

4.1. Species diversity and environmental filters

Our results show that the conversion of forested areas to croplands in southern Amazonia has exposed remaining riparian forests to edge effects that have altered forest species richness and composition, particularly near cropland edges and among seedlings and saplings. Riparian forests within croplands had lower mean species richness for both trees and seedlings, than those in forested catchments. Among trees, these differences were concentrated near crop field edges; seedling and sapling communities were less diverse both near the stream channel and at the field edge. The patterns reported here are consistent with findings from previous studies indicating that Amazon forest fragments and edges are strongly affected by environmental filters (Kapos, 1989; Laurance et al., 2002; Mitchell, 2013; Oosterhoorn and Kappelle, 2000; Silvério et al., 2019; Williams-Linera, 1990). Our results were also consistent with studies showing an increased abundance of disturbance-adapted and light-demanding trees near forest edges (Laurance et al., 2006, 2002, 1998; Oliveira-Filho et al., 1997; Oosterhoorn and Kappelle, 2000).

Although riparian forests within cropland catchments had fewer species per unit area sampled, they contained more total species. This is because the riparian species composition of cropland plots varied more than that of forest plots. The conditions imposed by cropland edges

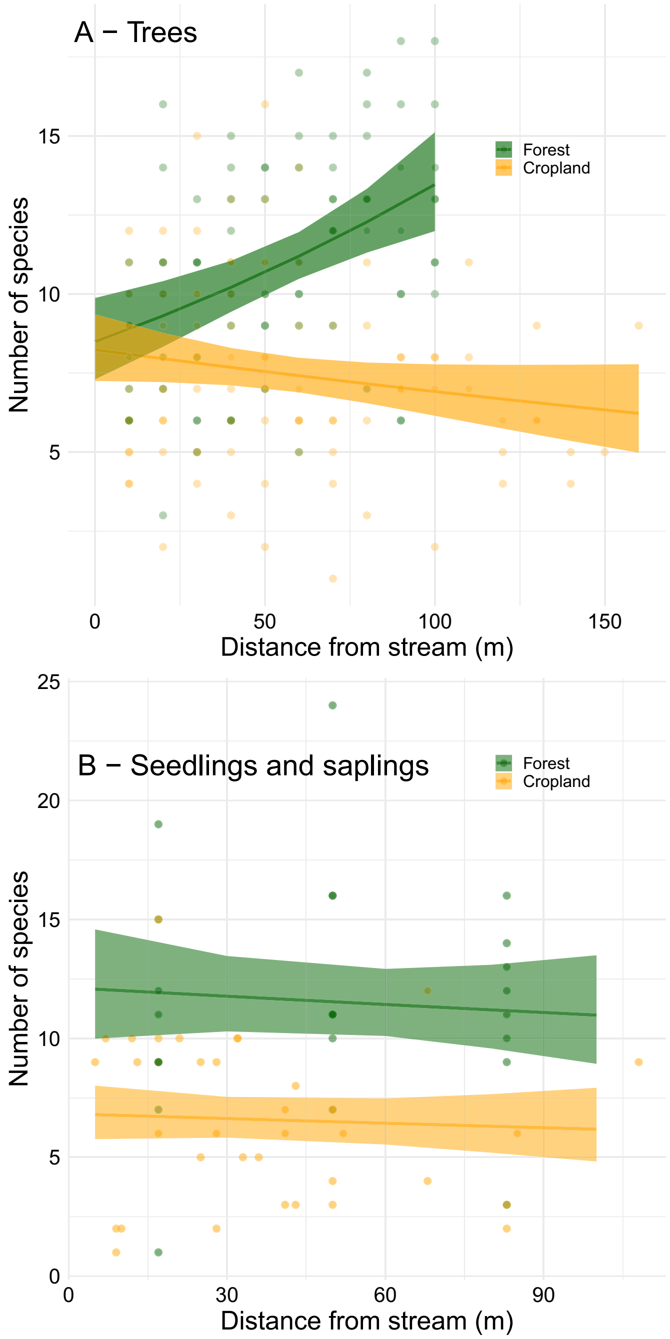

Fig. 4. Average number of woody species in ten riparian forest transects in the southeastern Amazon. (A) Average number of riparian-forest tree species in forested (green) and cropland (orange) catchments ($W = 709$; $p < 0.001$); (B) Average number of seedlings/saplings species in each land-use as a function of distance from the stream (near, mid, and far transect) ($t_{(13)} = 7.17$; $p < 0.001$) in the Amazon-Cerrado transition (Fazenda Tanguro, Querência-MT, Brazil). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

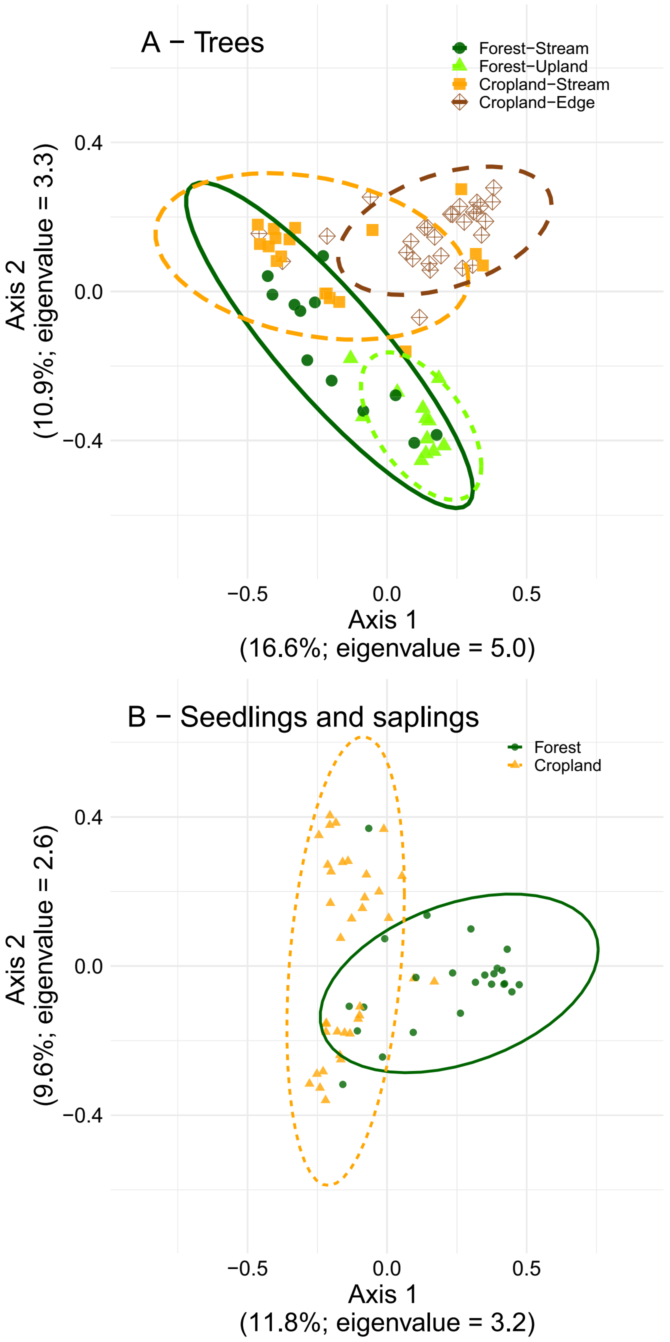

Fig. 5. Composition of woody species in ten riparian-forest transects in the southeastern Amazon, both near (Forest-Stream; Cropland-Stream) and far (Forest-Upland; Cropland-Edge) from streams at Fazenda Tanguro, Querência, MT. (A) Principal Coordinates Analysis (PCoA - Bray-Curtis dissimilarity index) for species composition and mean density of trees (ANOSIM: $R = 0.26$; $p = 0.001$). (B) Species composition and mean density of seedlings and saplings in the plots (ANOSIM: $R = 0.22$; $p = 0.001$).

likely create a broad range of conditions and disturbances that provide opportunities for fast growing species (Magnabosco Marra et al., 2018). This pattern was consistent with diversity-disturbance relationships observed elsewhere in the tropics (Molino and Sabatier, 2001; Roxburgh et al., 2004; Shea et al., 2004). An observed rise in the water table – associated with lower evapotranspiration rates in cropland catchments (Appendix: Fig. A2; (Silvério et al., 2015)) – may increase tree mortality, particularly during the rainy season (Hayhoe et al., 2011; Riskin et al., 2017) when prolonged flood events can effectively drown tree species adapted to the seasonally dry southeastern Amazonian climate (Flores et al., 2017; Parolin and Wittmann, 2010).

Our results point to three distinct ways that tree species may respond to the formation of riparian forest fragments within Amazon croplands. First, resistant species may persist in the landscape and be commonly found across forested and cropland catchments. These species include *Amaioua guianensis*, *Bocageopsis mattogrossensis*, *Sloanea sinemariensis*, *S. erismoides*, *Vochysia vismiifolia* and *Xylopia amazonica* (Appendix:

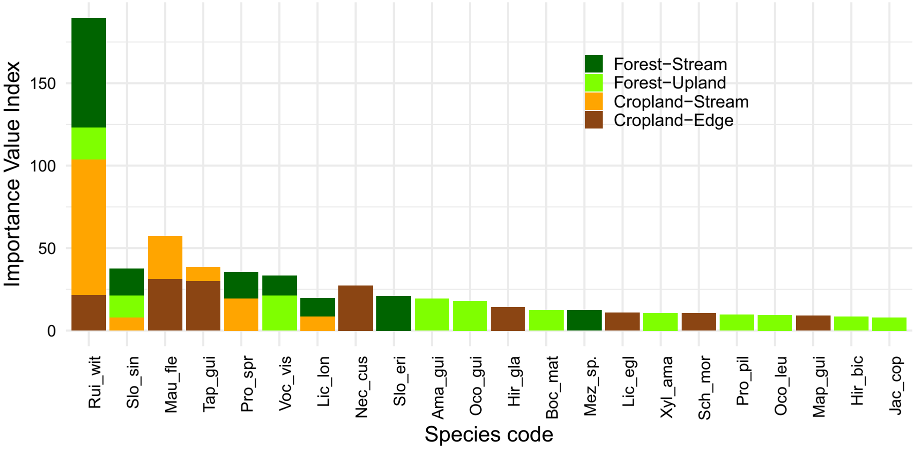

Fig. 6. Most abundant species (50% of total IVI - relative abundance, dominance and frequency) of riparian-forest trees, for plots near (Forest-Stream, Cropland-Stream) and far (Forest-Upland, Cropland-Edge) from streams in the southeast Amazon (Fazenda Tanguro, Querência, MT). See description of the codes in Table 2.

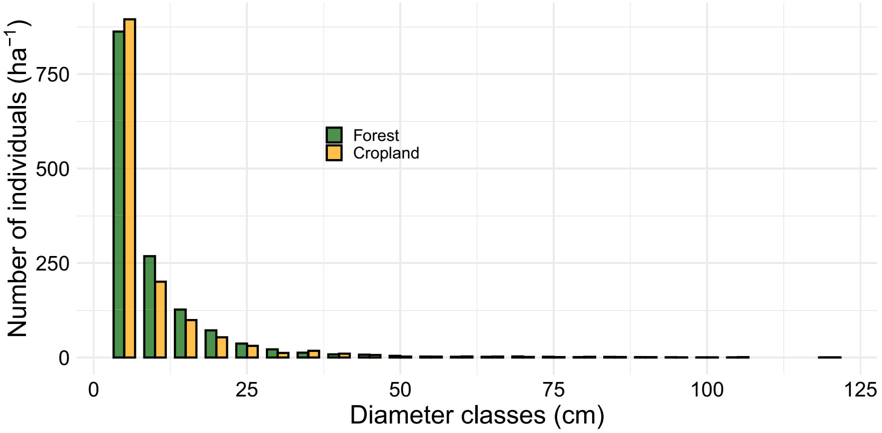

Fig. 7. Distributions of DBH (diameter measured at 1.30 m from the ground) in riparian forests within forested and cropland catchments in the southeast Amazon (Fazenda Tanguro, Querência, MT). The distribution of individuals by diameter classes was similar between forests and croplands ($t = -0.133$; $p = 0.89$).

Table A2). Second, sensitive species may disappear from cropland fragments and be found exclusively within intact forests. Examples of these species include *Hirtella bicornis*, *Miconia punctata*, *Mouriri brachyanthera*, *Ocotea guianensis* and *Pseudolmedia macrophylla* (Appendix: Table A2). Third, opportunistic species may arrive after forest clearing or thrive under the new conditions along edges in cropland riparian catchments. Examples of these species are *Euterpe longibracteata*, *Nectandra cuspidata*, *Protium spruceanum*, *Tapirira guianensis* and *Ruizterania wittrockii* (Appendix: Table A2). These processes may explain why tree species composition in cropland catchments strongly diverged from that of forested catchments near field edges and close to stream channels.

4.2. Management implications

The Brazilian Forest Code requires protection of riparian forest buffers in agricultural landscapes (Soares-Filho et al., 2014), with a minimum width of 30 m for riparian forest buffers along small headwater streams. Although these legal requirements exist mostly to protect water resources, they also contribute to regional forest conservation. While the riparian buffers at Fazenda Tanguro are generally wider than the legal minimum, our results show that these forest buffers maintained forest structure and species composition only in areas far from cropland edges. This suggests that the minimally compliant 30-m buffer may experience edge effects that strongly affect tree species composition and richness in cropland riparian forests over the long run. Based on observed changes with distance from the edge, our results suggest that wider riparian buffers could mitigate edge effects associated with agricultural fields and, thus, contribute to preserving riparian-forest diversity. Although our study only addressed the impacts of riparian buffer width on plant communities, previous studies suggest that even the minimum buffer width can preserve important stream functions such as temperature regulation (Macedo et al., 2013).

The Brazilian Forest Code also requires farmers to restore riparian forest buffers where they fall short of minimum width requirements. The lists of riparian tree species found in this study to be resistant (likely to survive) or sensitive (likely to be lost) to cropland edges can help guide ongoing efforts to restore riparian forests on private properties. This includes local efforts near the study site such as the *Y'Ikatu Xingu* campaign for restoration in the upper Xingu River Basin (Durigan et al., 2013). Although we cannot guarantee that our findings apply to the roughly 8 million ha of soybean cropping in Mato Grosso, the vast majority of soybeans are grown in areas with soils, topography and land-use history (variables that define the geomorphology and hydrology of riparian zones) similar to Fazenda Tanguro (Ivanauskas et al., 2003; Neill et al., 2017). This suggests that our findings may be useful for guiding riparian forest conservation and management across one of the world's most important regions of deforestation and cropland expansion.

CRediT authorship contribution statement

The questions and project were developed by L.M.-S., D.V.S., M.N. M., L.M., K.J.J., L.N.P., C.N., and P.M.B. Data collection was conducted

Table 2
List of main woody species (defined as 50% of total IVI) of riparian forests, ranked by the Importance Value Index (IVI), in the southeast Amazon (Fazenda Tanguro, Querência, MT). FR = frequency; DA = absolute density; DO = dominance; FP = frequency percent; DaP = density percent; DoP = dominance percent; IVI = Importance Value index.

Codes	Species	Families	FR	DA	DO	FrP	DaP	DoP	IVI
Forest-stream (7 species)									
Rui_wit	*Ruizterania wittrockii*	Vochysiaceae	0.83	40	11.74	5.59	11.27	49.44	66.30
Slo_eri	*Sloanea erismoides*	Elaeocarpaceae	0.42	26	2.57	2.79	7.32	10.82	20.94
Slo_sin	*Sloanea sinemariensis*	Elaeocarpaceae	0.67	32	0.65	4.47	9.01	2.75	16.24
Pro_spr	*Protium spruceanum*	Burseraceae	0.67	27	0.94	4.47	7.61	3.95	16.03
Mez_sp.	*Mezilaurus* sp.	Lauraceae	0.25	7	2.07	1.68	1.97	8.73	12.37
Voc_vis	*Vochysia vismiifolia*	Vochysiaceae	0.50	15	1.04	3.35	4.23	4.40	11.98
Lic_lon	*Licania longistyla*	Chrysobalanaceae	0.58	21	0.33	3.91	5.92	1.38	11.21
Forest-upland (11 species)									
Voc_vis	*Vochysia vismiifolia*	Vochysiaceae	0.67	25	1.90	3.17	5.52	12.67	21.37
Rui_wit	*Ruizterania wittrockii*	Vochysiaceae	0.33	7	2.47	1.59	1.55	16.49	19.63
Ama_gui	*Amaioua guianensis*	Rubiaceae	0.83	49	0.68	3.97	10.82	4.56	19.35
Oco_gui	*Ocotea guianensis*	Lauraceae	0.58	20	1.61	2.78	4.42	10.76	17.95
Slo_sin	*Sloanea sinemariensis*	Elaeocarpaceae	0.75	27	0.60	3.57	5.96	4.00	13.53
Boc_mat	*Bocageopsis mattogrossensis*	Annonaceae	0.92	24	0.41	4.37	5.30	2.74	12.40
Xyl_ama	*Xylopia amazonica*	Annonaceae	0.92	16	0.41	4.37	3.53	2.73	10.63
Pro_pil	*Protium pilosissimum*	Burseraceae	0.83	21	0.16	3.97	4.64	1.05	9.65
Oco_leu	*Ocotea leucoxylon*	Lauraceae	0.50	17	0.49	2.38	3.75	3.30	9.43
Hir_bic	*Hirtella bicornis*	Chrysobalanaceae	0.58	15	0.33	2.78	3.31	2.20	8.29
Jac_cop	*Jacaranda copaia*	Bignoniaceae	0.42	8	0.62	1.98	1.77	4.17	7.92
Cropland-stream (6 species)									
Rui_wit	*Ruizterania wittrockii*	Vochysiaceae	0.83	68	15.66	7.69	17.22	56.99	81.90
Mau_fle	*Mauritia flexuosa*	Arecaceae	0.50	30	3.75	4.62	7.59	13.65	25.86
Pro_spr	*Protium spruceanum*	Burseraceae	0.67	38	1.01	6.15	9.62	3.66	19.43
Lic_lon	*Licania longistyla*	Chrysobalanaceae	0.33	19	0.18	3.08	4.81	0.64	8.53
Tap_gui	*Tapirira guianensis*	Anacardiaceae	0.33	13	0.54	3.08	3.29	1.97	8.34
Slo_sin	*Sloanea sinemariensis*	Elaeocarpaceae	0.39	14	0.20	3.59	3.54	0.73	7.87
Cropland-edge (8 species)									
Mau_fle	*Mauritia flexuosa*	Arecaceae	0.11	33	3.54	1.35	6.80	23.32	31.47
Tap_gui	*Tapirira guianensis*	Anacardiaceae	0.50	53	1.97	6.28	10.93	13.00	30.21
Nec_cus	*Nectandra cuspidata*	Lauraceae	0.61	51	1.39	7.62	10.52	9.17	27.31
Rui_wit	*Ruizterania wittrockii*	Vochysiaceae	0.21	16	2.40	2.69	3.30	15.81	21.80
Hir_gla	*Hirtella glandulosa*	Chrysobalanaceae	0.29	32	0.63	3.59	6.60	4.13	14.31
Lic_egl	*Licania egleri*	Chrysobalanaceae	0.29	23	0.37	3.59	4.74	2.41	10.74
Sch_mor	*Schefflera morototoni*	Araliaceae	0.25	12	0.72	3.14	2.47	4.78	10.39
Map_gui	*Maprounea guianensis*	Euphorbiaceae	0.29	17	0.28	3.59	3.51	1.83	8.93

by L.M.-S., D.V.S., and L.M. The analyses and the first draft of the manuscript were conducted by L.M.-S., D.V.S., M.N.M., L.M., L.N.P., and P.M.B. All authors contributed substantially with reviews and approved the final manuscript.

Declaration of competing interest

The authors declare that they know of no conflicts of interest that might have influenced this article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2020.108862.

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