REVIEW

Meta-analysis contrasting freshwater biodiversity in forests and oil palm plantations with and without riparian buffers

Oscar Alberto Rojas-Castillo[1] │ Sebastian Kepfer Rojas[2] │ Leandro Juen[3] │
Luciano Fogaça de Assis Montag[3] │ Fernando Geraldo Carvalho[4] │
Thiago Pereira Mendes[5] │ Kenny Wei Jie Chua[6] │ Clare L. Wilkinson[6] │
Mohammad Noor Azmai Amal[7] │ Muhammad Fahmi-Ahmad[8] │ Dean Jacobsen[1]

[1]Freshwater Biology Section, Department of Biology, Faculty of Science, University of Copenhagen, Copenhagen, Denmark

[2]Department of Geosciences and Natural Resource Management, University of Copenhagen, Copenhagen, Denmark

[3]Laboratório de Ecologia e Conservação, Instituto de Ciências Biológicas, Universidade Federal do Pará, Belém, Brazil

[4]Programa de Pós-graduação em Ecologia, Universidade Federal do Pará, Belém, Brazil

[5]Programa de Pós-Graduação em Agricultura e Ambiente, Laboratório de Ciências Ambientais e Biodiversidade, Universidade Estadual do Maranhão, São Luís, Brazil

[6]Department of Biological Sciences, National University of Singapore, Singapore, Republic of Singapore

[7]Department of Biology, Faculty of Science, Universiti Putra Malaysia, Serdang, Malaysia

[8]Faculty of Science and Marine Environment, Universiti Malaysia Terengganu, Kuala Terengganu, Malaysia

Correspondence
Oscar Alberto Rojas-Castillo, Freshwater Biology Section, Department of Biology, University of Copenhagen, Universitetsparken 4, Third Floor, 2100 Copenhagen, Denmark.
Email: oscar.rojas.gua27@gmail.com

Article impact statement: Forest-to-oil palm conversion reduces stream taxa richness by 44%; riparian buffers prevent half the loss, but communities are altered.

Abstract

The expansion of oil palm plantations has led to land-use change and deforestation in the tropics, which has affected biodiversity. Although the impacts of the crop on terrestrial biodiversity have been extensively reviewed, its effects on freshwater biodiversity remain relatively unexplored. We reviewed the research assessing the impacts of forest-to-oil palm conversion on freshwater biota and the mitigating effect of riparian buffers on these impacts. We searched for studies comparing taxa richness, species abundance, and community composition of macroinvertebrates, amphibians, and fish in streams in forests (primary and disturbed) and oil palm plantations with and without riparian buffers. Then, we conducted a meta-analysis to quantify the overall effect of the land-use change on the 3 taxonomic groups. Twenty-nine studies fulfilled the inclusion criteria. On average, plantations lacking buffers hosted 44% and 19% fewer stream taxa than primary and disturbed forests, respectively. Stream taxa on plantations with buffers were 24% lower than in primary forest and did not differ significantly from disturbed forest. In contrast, stream community composition differed between forests and plantations regardless of the presence of riparian buffers. These differences were attributed to agrochemical use and altered environmental conditions in the plantations, including temperature changes, worsened water conditions, microhabitat loss, and food and shelter depletion. On aggregate, abundance did not differ significantly among land uses because increases in generalist species offset the population decline of vulnerable forest specialists in the plantation. Our results reveal significant impacts of forest-to-oil palm conversion on freshwater biota, particularly taxa richness and composition (but not aggregate abundance). Although preserving riparian buffers in the plantations can mitigate the loss of various aquatic species, it cannot

conserve primary forest communities. Therefore, safeguarding primary forests from the oil palm expansion is crucial, and further research is needed to address riparian buffers as a promising mitigation strategy in agricultural areas.

Metaanálisis contrastando la biodiversidad de agua dulce en los bosques y las plantaciones de palma de aceite con o sin bosques ribereños
Resumen: La expansión de las plantaciones de palma de aceite ha derivado en cambios en el uso de suelo y deforestación en los trópicos, afectando a la biodiversidad. Existe una revisión extensa del impacto de este cultivo sobre la biodiversidad terrestre, pero sus efectos sobre la biodiversidad de agua dulce todavía no están muy documentados. Revisamos las investigaciones que han evaluado el impacto de la conversión de bosque a plantación de palma de aceite sobre la biota de agua dulce y el efecto mitigante que tienen los bosques ribereños sobre este impacto. Buscamos estudios que compararan la riqueza de taxones, abundancia de especies y composición comunitaria de los macroinvertebrados, anfibios y peces en los riachuelos de los bosques (primarios y perturbados) y los sembradíos de palma de aceite con y sin bosques ribereños. Después realizamos un metaanálisis para cuantificar el efecto del cambio de uso de suelo en los tres grupos taxonómicos. Veintinueve estudios cumplieron con el criterio de inclusión. En promedio, las plantaciones carentes de bosques ribereños albergaron 44% y 19% menos taxones que los bosques primarios y perturbados. Los taxones en los sembradíos con bosques ribereños fueron 24% menos que en el bosque primario y no difirieron significativamente del bosque perturbado. Como contraste, la composición comunitaria del riachuelo difirió entre los bosques y los sembradíos sin importar la presencia de los bosques ribereños. Atribuimos estas diferencias al uso de agroquímicos y las condiciones ambientales alteradas en las plantaciones, incluidas los cambios térmicos, condiciones hidrológicas alteradas, pérdida de microhábitats y reducción de alimentos y refugios. En general, la abundancia no difirió significativamente entre los usos de suelo porque el incremento de especies generalistas en las plantaciones contrarresta la declinación poblacional de los especialistas de bosque vulnerables. Nuestros resultados revelan un impacto significativo de la conversión de bosque a plantación sobre la biota de agua dulce, particularmente la riqueza de taxones y la composición (pero no la abundancia agregada). Aunque mantener los bosques ribereños en las plantaciones puede mitigar la pérdida de varias especies acuáticas, no puede conservar las comunidades del bosque primario. Por lo tanto, es crucial salvaguardar los bosques primarios de la expansión del aceite de palma, además de que se necesitan más investigaciones para abordar los bosques ribereños como una estrategia prometedora de mitigación en las áreas agrícolas.

PALABRAS CLAVE
aceite de palma, bosque talado, amortiguador ribereño, cambio de uso de suelo, monocultivo, riqueza de especies

INTRODUCTION

Oil palm (*Elaeis guineensis* Jacq. 1763) is the most efficient source of vegetable oil worldwide (Vijay et al., 2016). It produces more oil than any other crop per hectare (>5 times that of soybean and rapeseed), and it is used in thousands of products (Basiron & Weng, 2004; Byerlee et al., 2016; Gupta, 2015; Meijaard et al., 2018). Currently, palm oil represents 40% of the world's vegetable oil demand (Meijaard et al., 2020), and it has been the most consumed edible oil globally since 2000 (Ngando-Ebongue et al., 2013). To meet this demand, the total area for oil palm agriculture has doubled in recent decades (FAO, 2020), reaching 19.6 million ha (Descals et al., 2021). At present, the Southeast Asian countries of Malaysia and Indonesia generate 85% of the global palm oil, followed by Thailand (3.9%), Colombia (2.1%), Nigeria (1.4%), Guatemala (0.9%), and other tropical countries (7.3%) (Murphy et al., 2021). Global demand for vegetable oils is expected to rise by 46% by 2050 (Meijaard et al., 2020), requiring an increase in oil production to meet this demand. Since optimal conditions for oil palm cultivation occur in lowland tropical environments, which often correspond with species-rich lowland tropical rainforests (recognized as biodiversity hotspots) (Myers et al., 2000; Sapey et al., 2012), its further expansion is likely to drive profound species loss (Donald, 2004; Koh & Wilcove, 2007). So far, this crop has been associated with dramatic declines in biodiversity

across various taxonomic groups (Meijaard et al., 2018, 2020) and has directly contributed to the deforestation of over 10.5 million ha in the last 2 decades (Goldman et al., 2020).

The displacement of forests by oil palm plantations results in significant structural habitat simplification and altered micro-climatic conditions, leading to the proliferation of disturbance-tolerant generalist species at the expense of forest specialists and species of conservation importance (Freudmann et al., 2015; Savilaakso et al., 2014). Furthermore, this land-use conversion affects biota from adjacent natural habitats through fragmentation, edge effects, and pollution (Fitzherbert et al., 2008; Freud-mann et al., 2015; Miller et al., 2011; Ocampo-Ariza et al., 2019; Tanalgo et al., 2019). The expansion of this crop is considered a significant hazard for at least 321 threatened species, including 54% of mammals, 39% of amphibians, and 64% of birds (Meijaard et al., 2018, 2020). To reduce these negative effects, an increasing number of countries have initiated schemes to drive the conservation and restoration of riparian buffers in the plantations. Riparian buffers are vegetation strips composed of native trees, shrubs, and other perennial plants adjacent to freshwater streams and rivers. These strips can maintain the riparian structure and habitat complexity and connectivity (wildlife corridor), protect against flooding, filter runoff, stabilize eroding banks, and preserve freshwaters (Cole et al., 2020; Hickey & Doran, 2004). But to date, the body of evidence on riparian buffers and biodiversity is geographically and taxonomically biased because most research comes from Europe and North America (Hughes et al., 2021; Luke et al., 2019).

Sustainability certification bodies, such as the Roundtable on Sustainable Palm Oil (RSPO), require new plantations to protect riparian buffers based on the width of the adjacent stream. For instance, streams 1- to 5-m wide require riparian buffers ≥5-m wide on each side, whereas streams 5- to 10-m wide necessitate riparian buffers 10-m wide. Similarly, streams 10- to 20-m wide require a 20-m-wide riparian buffer, and those wider than 50 m require riparian buffers 100-m wide. For plantations already established, RSPO requires either leaving these riparian areas to regrow naturally while leaving mature oil palms untouched or planting native trees (Barclay et al., 2017). Nevertheless, riparian buffer policies in tropical countries are often absent, poorly defined, or highly variable (Luke et al., 2019), and although RSPO and other certification bodies (ISPO and MSPO in Indonesia and Malaysia, respectively) may require riparian buffer conservation in certified plantations, only 19% of the global palm oil is RSPO certified (RSPO, 2021), 33% of the Indonesian palm oil is ISPO certified, and 51% of the Malaysian palm oil is MSPO certified (Cheong & Wong, 2022).

The impact of oil palm plantations on biodiversity has been reviewed a number of times (Fitzherbert et al., 2008; Savilaakso et al., 2014; Vargas et al., 2015). However, these reviews focused on terrestrial biota, and the literature on freshwaters has been relatively sparse. This research gap is particularly concerning given that oil palm agriculture been associated with significant impacts on aquatic ecosystems, such as decreased water quality and hydromorphological alterations (Comte et al., 2012) that negatively affect freshwater biota (Carvalho et al., 2018; Cunha & Juen, 2017; Konopik et al., 2015; Mercer et al.,

2014; Scriven et al., 2018). For instance, the removal of riparian vegetation by the conversion of forests into oil palm plantations increases water temperature, which affects the growth, metabolism, distribution, and survival of most ectotherms, including fish, amphibians, and macroinvertebrates (Durance & Ormerod, 2009; Faruk et al., 2013; Juen et al., 2016; Li et al., 2012; Masese et al., 2014). This agriculture also increases erosion, siltation, and sedimentation, damaging gill tissue and filtering organs, complicating foraging, and clogging spawning grounds in streams and lakes (Wantzen, 2006; Wilkinson et al., 2018). Agrochemical use in the plantations also affects vulnerable macroinvertebrate species (Chellaiah & Yule, 2018b), and dredging of streams in oil palm plantations is associated with the loss of anuran forest specialists due to microhabitat loss in the stream (e.g., stream-substrate material and vegetation matter) (Faruk et al., 2013). Therefore, it is imperative to compile and analyze these potential impacts to guide efforts to conserve freshwater biodiversity in the plantations.

Our primary objective was to review the impacts of oil palm plantations on freshwater biodiversity. We aimed to answer the following questions: does forest-to-oil palm conversion affect taxa richness and abundance of fish, macroinvertebrates, and amphibians in freshwaters; does forest-to-oil palm conversion modify the communities of these taxa by replacing disturbance-sensitive forest-specialist species with disturbance-tolerant generalists; and do riparian buffers in plantations mitigate the crop's negative impact on freshwater biota? To address these questions, we performed a thorough literature search and a meta-analysis of studies comparing taxa richness, abundance, and community composition in streams in forests (primary and disturbed) and oil palm plantations with and without riparian buffers.

METHODS

Literature search

We performed an exhaustive literature search for scientific papers in which freshwater biodiversity in forests (secondary, logged, regrowth, or primary forests) and oil palm plantations with and without riparian buffers were compared, following Brindle et al. (2017) and Pullin and Stewart (2006) (protocol in Appendix S1). First, we conducted a preliminary Web of Science search employing general keywords regarding freshwaters, biodiversity, and oil palm plantations (Appendix S1.6.1). We then screened the title and abstract of each article. Because very few publications addressed aquatic plankton (0), periphyton (1), and macrophytes (0), we directed the final searches to the groups addressed by at least 10 studies. These included amphibians, fish, and aquatic or semiaquatic macroinvertebrates. We included semiaquatic groups because they interact in stream food webs, play important roles in freshwaters (litter decomposition), and are highly affected by stream conditions (Thirumalai & Sharma, 2002).

We then performed 3 final searches on the Web of Science and complemented our results by contacting experts in the field

for their recommendations on articles and data sets on the topic (additional information in Appendix S1.6.7). Search query 1 (A) was (("*biodiversity*" OR "*species richness*" OR "*species*" OR "*taxon*" OR "*taxa*" OR "*assemblage*" OR "*amphibian*" OR "*anuran*" OR "*herpetofauna*" OR "*fish*" OR "*macroinvertebrates*" OR "*crustacean*" OR "*mollusk*") AND ("*oil palm*" OR "*palm oil*" OR "*Elaeis guineensis*" OR "*palm-oil*") AND ("*freshwater*" or "*riparian*" OR "*aquatic*" OR "*water*" OR "*stream*" OR "*amphibian*" OR "*anuran*" OR "*herpetofauna*" OR "*fish*" OR "*macroinvertebrates*" OR "*crustacean*" OR "*mollusk*")). Search query 2 (B) was (("*biodiversity*" OR "*species richness*" OR "*species*" OR "*taxon*" OR "*taxa*" OR "*assemblage*") AND ("*oil palm*" OR "*palm oil*" OR "*Elaeis guineensis*" OR "*palm-oil*") AND ("*freshwater*" or "*riparian*" OR "*aquatic*" OR "*water*" OR "*stream*" OR "*amphibian*" OR "*anuran*" OR "*herpetofauna*" OR "*fish*" OR "*macroinvertebrates*" OR "*crustacean*" OR "*mollusk*")). Search query 3 (C) was (("*biodiversity*" OR "*species richness*" OR "*species*" OR "*taxon*" OR "*taxa*" OR "*assemblage*" OR "*amphibian*" OR "*anuran*" OR "*herpetofauna*" OR "*toad*" OR "*frog*" OR "*fish*" OR "*macroinvertebrates*" OR "*crustacean*" OR "*mollusk*" OR "*ephemeroptera*" OR "*odonata*" OR "*plecoptera*" OR "*trichoptera*" OR "*insect larvae*" OR "*hemiptera*" OR "*flies*" OR "*fly*") AND ("*oil palm plantation*" OR "*palm oil plantation*" OR "*Elaeis guineensis*" OR "*palm agriculture*" OR "*palm plantation*") AND ("*forest*" OR "*rainforest*" OR "*jungle*") AND ("*freshwater*" or "*riparian*" OR "*aquatic*" OR "*water*" OR "*stream*" OR "*amphibian*" OR "*anuran*" OR "*herpetofauna*" OR "*toad*" OR "*frog*" OR "*fish*" OR "*macroinvertebrates*" OR "*crustacean*" OR "*mollusk*" OR "*ephemeroptera*" OR "*odonata*" OR "*plecoptera*" OR "*trichoptera*" OR "*insect larvae*")).

Search A focused on general biota in oil palm, search B focused on biodiversity metrics in oil palm, and search C focused on studies contrasting forests and oil palm plantations (additional information on Appendix S1.6). Across search queries, we incorporated several repeated search terms (e.g., amphibian, fish, insect larvae) to ensure the display of studies focused on aquatic taxa that did not specify a freshwater habitat in the abstract or title (additional information in Appendix S1.6). The search involved all articles published before early 2023 (1978 was the oldest found) (eligibility criteria in Appendix S1.6.5).

We screened the titles and abstracts of the studies for relevance. Whenever they appeared fitting (e.g., contrasted freshwater communities between oil palm plantations and forests), we performed an additional screening of the methods and results sections to check for admissibility according to the inclusion criteria (Appendix S1.6.5). For example, we only accepted studies that sampled streams, rivers, or riparian areas (terrestrial studies were rejected); reported species, genera, or family richness or abundance of communities (studies addressing 1 or a few species were rejected); and reported relevant summary statistics for the biota (i.e., mean species richness and abundance, standard deviations, and sample sizes; or where it was possible to calculate these statistics from graphs, data sets, or standard error).

From each accepted article, we recorded abundance and species richness per land use, the presence and absence data, forest type, age of plantation, presence of riparian buffers, sampling method, and country of study. When different forest types (primary and secondary or logged) were present in the same article, they were separated and compared independently with the oil palm plantations from the study. Whenever plantations with and without riparian buffers were present in the same article, they were also separated. Because multiple treatment groups were compared with the same forest or plantation, this led to nonindependence among effect sizes (Lajeunessei, 2011; Sánchez-Tójar et al., 2020). We addressed this nonindependence by adjusting the sample size of the group contrasted with more than 1 treatment to be equal to its original sample size divided by the number of times that it was compared, following Noble et al. (2017) and Sánchez-Tójar et al. (2020).

Statistical analyses

To assess the impacts of land-use change on freshwater biodiversity, we compared richness and aggregated abundance across all taxonomic groups and for each taxonomic group between oil palm plantations without riparian buffers and primary and disturbed forests and between oil palm plantations with riparian buffers and primary and disturbed forests. For this, we used standardized mean differences estimated using the Hartung–Knapp–Sidik–Jonkman method (Balduzzi et al., 2019; Borenstein et al., 2009). The standardized mean differences and their 95% confidence intervals (CIs) were calculated from each study's abundance and taxa richness data (means, standard deviations, and number of samples) in the different land uses. The standardized mean difference is applicable when contrasting different sampling methods (Borenstein et al., 2009), and the Hartung–Knapp–Sidik–Jonkman is effective with small sample sizes and high heterogeneity (IntHout et al., 2014). Because the true effect might vary from study to study, due to differences in sampling methods and taxonomic groups, we utilized a random effect model and included each study's weight calculated from the inverse of the variance (Borenstein et al., 2009). For addressing publication bias (Appendix S3), the fill and trim method was employed whenever the Egger's test results were significant. This method involves adding unpublished studies with nonsignificant results and removing extreme studies with significant findings to estimate the potential impact of unpublished studies on the overall meta-analysis results (Shi et al., 2019). To provide a simplified measurement of richness and abundance differences among treatments, we calculated the percentage change with their 95% coefficient intervals. All these analyses were executed in R 3.5.3 (R Core Team, 2020) with the meta package (Balduzzi et al., 2019).

For analyzing community composition differences among land uses, we collected each article's presence and absence data and built a distance matrix based on the Jaccard index. For comparing primary and disturbed forests with oil palm plantations with and without riparian buffers, we performed an analysis of similarities (ANOSIM) and a permutational multivariate analysis of variance (PERMANOVA) in each distance
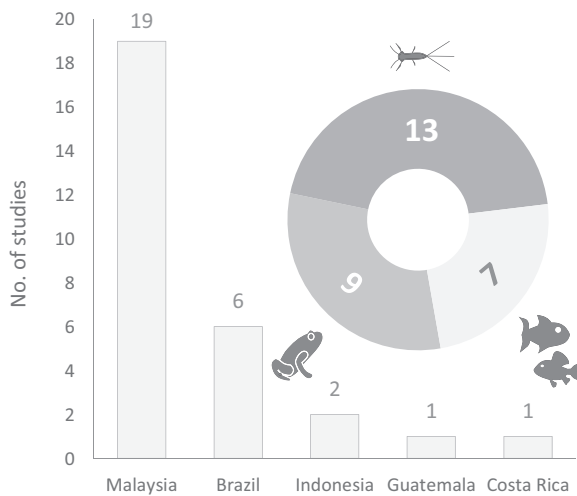
FIGURE 1 Number of studies comparing freshwater biodiversity in oil palm plantations and forests per country (bar graph) and taxa (pie chart). These 29 studies met the inclusion criteria (Appendix S1.6.5).

matrix. We included studies in which data were unavailable only if they reported results of an analysis of variance, PER-MANOVA, or clustering results. To summarize these results, we calculated the percentage of studies that reported significant differences and the Jaccard distances (mean and SD) among land uses. The similarity indexes and analyses employed were selected because they are the least sensitive to sampling error (Schroeder & Jenkins, 2018) and 2 of the most commonly used in ecology (Anderson & Walsh, 2013). To describe the changes in the community among land uses, we quantified the number of shared taxa (nestedness) and the taxa present only in forests or plantations (turnover) per study. To identify the taxa associated with each land use, we performed indicator species analyses with a point biserial correlation coefficient (r.g.) because it corrects the measure for unequal group sizes (Borcard et al., 2011). We employed the vegan package (Oksanen et al., 2022) in R 3.5.3 (R Core Team, 2020).

RESULTS

Literature search

The search resulted in 1244 studies. After the screening of titles and abstracts, only 36 potential studies remained; 44% (524 studies) were related to palm oil diet, 31% (377) did not address freshwaters, and 8% (101) focused on palm oil effluents (Appendix S2.1). Following the screening of methods, results, and supporting information; the revision of suggested articles by experts; and the removal of duplicated studies (or studies based on the same data set), we acquired 29 studies (17 articles and 12 data sets [Appendix S2]). These were mainly from Malaysia (19 studies) and Brazil (6 studies) and addressed aquatic macroinvertebrates (13 studies), amphibians (9 studies), and fish (7 studies) (Figure 1).
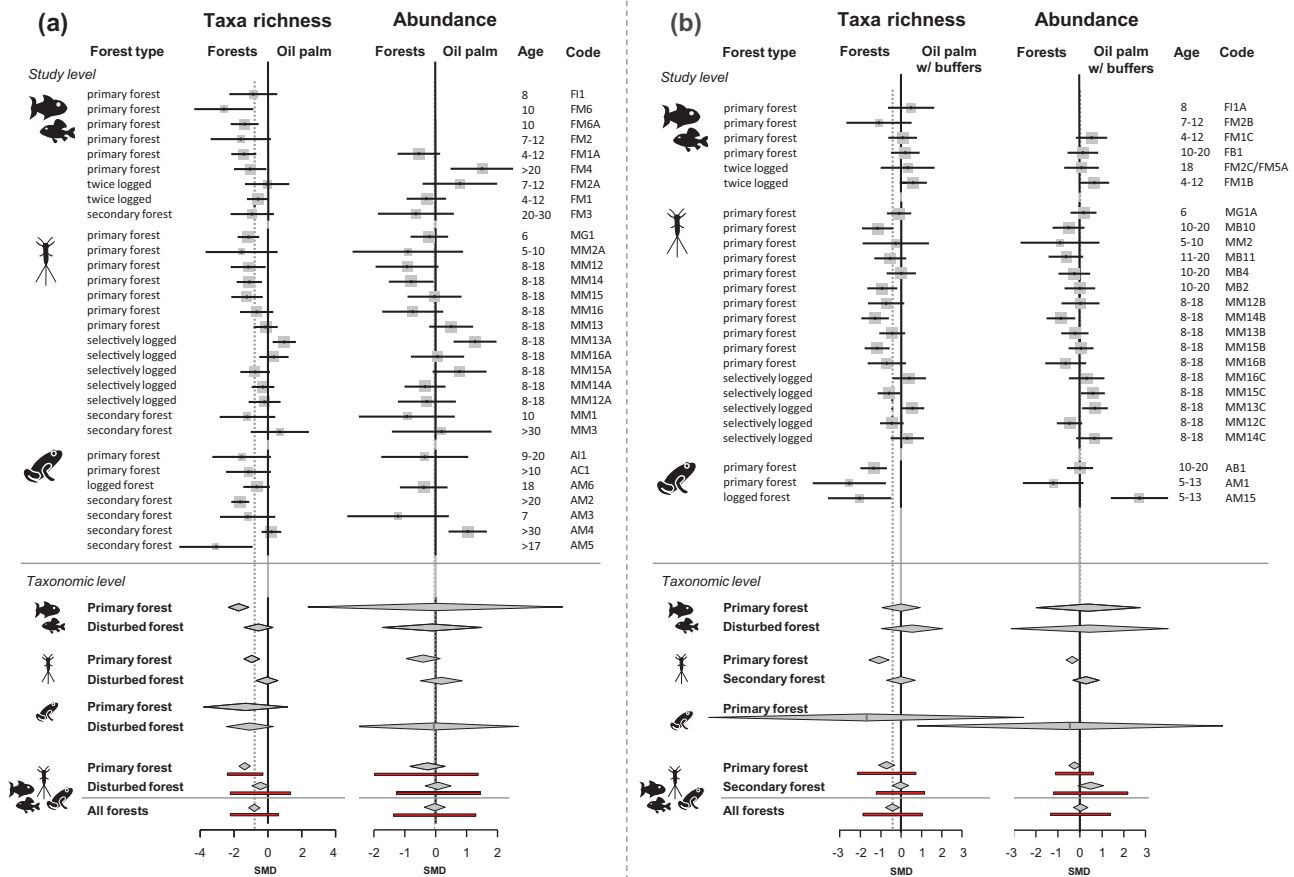
Stream taxa richness and abundance

Stream taxa richness was significantly lower in oil palm plantations lacking riparian buffers compared with primary forests ($I^2 = 27\%$, $t = -8.58$, $p < 0.001$, 95% CI -1.4 to -0.84) and disturbed forests ($I^2 = 78\%$, $t = -1.98$, $p = 0.068$, CI -0.92 to 0.04). Fish, macroinvertebrate, and, to a lesser degree, amphibian taxa richness was lower in the plantations ($I^2 = 0\%$, $t = -7.27$, $p > 0.001$, CI -1.9 to -0.92; $I^2 = 46\%$, $t = -5.1$, $p = 0.002$, CI -1.4 to -0.48; and $I^2 = 0\%$, $t = -6.7$, $p = 0.09$, CI -3.7 to 1.17, respectively) than in primary forests. However, only amphibians ($I^2 = 84\%$, $t = -2.1$, $p = 0.10$, CI -2.4 to 0.3) and to a lesser degree fish ($I^2 = 0\%$, $t = -2.7$, $p = 0.11$, CI -0.37 to 0.3) had lower taxa richness in the plantation than in disturbed forests (Figure 2a).

On average, stream taxa richness was 44% (95% CI 0.32 to 0.53) lower in plantations that lacked buffers than in primary forests. Richness was lower by 46% (0.27 to 0.60) for fish, by 46% (0.16 to 0.65) for macroinvertebrates, and by 29% (−0.38 to 0.70) for amphibians in plantations lacking buffers than primary forests. Furthermore, stream taxa richness in plantations lacking buffers was 19% (−0.04 to 0.37) lower than in disturbed forests. Richness was 24% (−0.26 to 0.57) lower for fish, 29% (CI −0.02 to 0.51) lower for amphibians, and 0% (−0.45 to 0.45) lower for macroinvertebrates in plantations lacking buffers than in disturbed forest.

Abundance in the streams did not differ between forests (primary and disturbed) and plantations lacking riparian buffers ($I^2 = 63\%$, $t = -0.21$, $p = 0.83$, 95% CI -0.36 to 0.29). On average, fish were equally abundant in plantations and in forests, whereas macroinvertebrates were less abundant in the plantations by 24% (95% CI −0.26 to 0.57) and amphibians were less abundant by 25% (−0.68 to 0.82) (Figure 2a).

Stream macroinvertebrates had lower taxa richness in oil palm plantations with riparian buffers than in primary forests ($I^2 = 55\%$, $t = -4.9$, $p < 0.001$, 95% CI -1.1 to -0.4), but fish and amphibians did not differ ($I^2 = 16\%$, $t = 0.03$, $p = 0.98$, CI -0.9 to 0.9 and $I^2 = 57\%$, $t = -2.9$, $p = 0.21$, CI -9.7 to 6.1, respectively). No difference was detected between disturbed forests and oil palm plantations with riparian buffers (Figure 2b).

On average, stream taxa richness was 24% (95% CI 0.05 to 0.39) lower in oil palm plantations with riparian buffers than in primary forests. Richness was lower by 1% (−0.34 to 0.36) for fish, by 29% (−0.01 to 0.51) for macroinvertebrates, and by 34% (−0.63 to 0.84) for amphibians in plantations with buffers than primary forests. However, stream taxa richness in the plantations with buffers was 2% (−0.32 to 0.34) higher than in disturbed forests. Richness was higher by 24% (−0.15 to 0.51) for fish, 2% (−0.55 to 0.56) lower for macroinvertebrates, and 30% lower for amphibians in the plantations with buffers than in disturbed forests. Fish were 18% (−0.84 to 0.89) more abundant in the plantations with buffer ($I^2 = 0\%$, $t = 2.7$, $p = 0.07$, 95% CI −0.07 to 0.8) than in primary forests, whereas macroinvertebrates were 35% (−0.13 to 0.63) more abundant in primary forests ($I^2 = 34\%$, $t = -2.5$, $p = 0.03$, CI -0.6 to -0.04) than

FIGURE 2 Freshwater taxa richness and abundance (as standard mean difference [SMD]) in different forest types versus oil palm plantations (a) lacking riparian buffers and (b) with riparian buffers (gray squares, results of studies; square center, average SMD; black horizontal lines, 95% confidence interval [CI] of SMD; square size, proportional study weight based on inverse variance; vertical black lines, no differences between land uses; gray diamonds, pooled SMD 95% CI; red bars, prediction interval 95% CI; gray vertical dashed lines, average SMD among all studies; age, plantation age; codes, study code [additional information for each study in Appendix S2.6]).

plantations with buffer, and amphibians had similar abundance in both land uses (Figure 2b).

Community composition, nestedness (shared taxa), and turnover

Every study showed significant differences ($p \leq 0.05$) in the stream community composition between primary forests and oil palm plantations with no riparian buffers (13 studies: 4 of fish, 7 of macroinvertebrates, and 2 of amphibians). Seventy-three percent of studies showed significant differences between disturbed forests and the plantations lacking buffers (11 of 15 studies: 2 of 3 on fish, 5 of 6 on macroinvertebrates, and all 4 on amphibians) (Appendix S4). In contrast, 88% of the studies showed significant differences between the communities from primary forests and oil palm plantations with riparian buffers (14 of 16 studies: 2 of 3 on fish, 10 of 11 on macroinvertebrates, and all 2 on amphibians). In 75% (6 of 8 studies) of the studies, communities differed significantly between disturbed forest and oil palm plantations with riparian buffers (6 of 8 studies: 1 of 2 on fish, 4 of 5 on macroinvertebrates, and the 1 on amphibians) (Appendix S5).

The Jaccard distance was 0.72 between oil palm plantations lacking buffers and primary forests and 0.68 between the plantations and disturbed forests. The Jaccard distance for fish was 0.63 and 0.64, for macroinvertebrates 0.75 and 0.69, and for amphibians 0.78 and 0.78 between the plantations lacking buffers and the primary and disturbed forests, respectively. The Jaccard distance was 0.60 between the plantations with riparian buffers and primary forests and 0.50 between the plantations and disturbed forests. The Jaccard distance for fish was 0.51 and 0.57, for macroinvertebrates 0.64 and 0.48, and for amphibians 0.55 and 0.44 between oil palm plantations with buffers and primary forests and between oil palm plantations with buffers and disturbed forests, respectively (Appendices S4 & S5).

Primary forests and oil palm plantations lacking riparian buffers shared on average 32% of the stream taxa (45% of fish, 26% of macroinvertebrates, 33% of amphibians). Fourteen percent were found only in the plantations (15% of fish, 13% of macroinvertebrates, 17% of amphibians) and 54% only in primary forests (45% of fish, 61% of macroinvertebrates, 50% of amphibians). The plantations and disturbed forests shared 36% of the stream taxa. Seventeen percent occurred only in the plantations and 47% only in disturbed forests (Figure 3a). In contrast, the plantations with riparian buffers shared 48% of
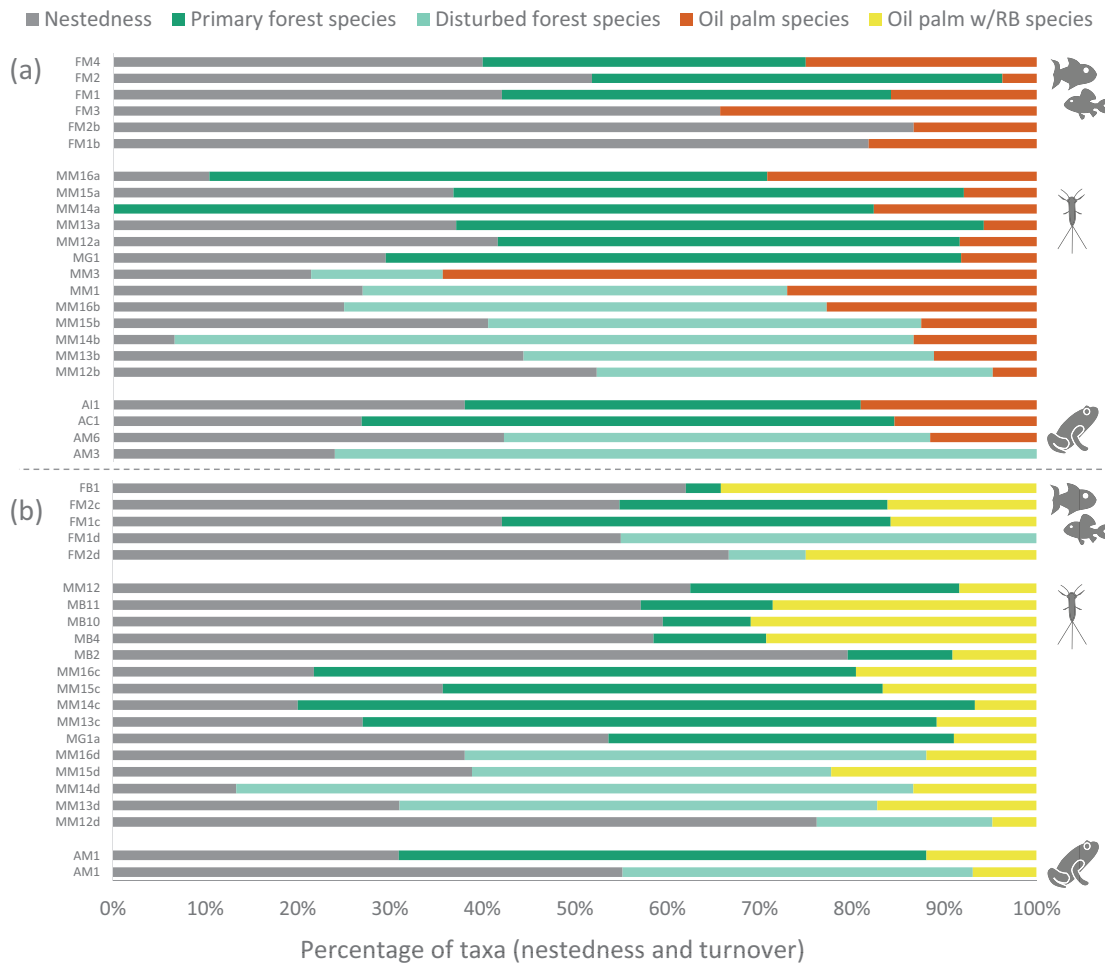
FIGURE 3 Nestedness (gray [percentage of shared taxa]) and turnover of taxa in (a) forests and oil palm plantations and in (b) forests and oil palm plantations with riparian buffers for each study (code on *y*-axis) included in the review (dark green, percentage of taxa only in primary forests; light green, percentage of taxa in secondary forests; yellow, percentage of taxa in oil palm plantations with riparian buffers [RB]; orange, percentage of taxa in oil palm plantations without riparian buffers). Additional information for each study is in Appendix S2.6.

the taxa with primary forests (53% of fish, 47% of macroinvertebrates, and 31% of amphibians), whereas 18% were found only in the plantations (22% of fish, 17% of macroinvertebrates, and 12% of amphibians) and 35% only in primary forests (25% of fish, 36% of macroinvertebrates, 57% of amphibians). Disturbed forests and the plantations with riparian buffers shared 47% of the stream taxa. Thirteen percent occurred only in plantations and 40% only in disturbed forests (Figure 3b). The indicator species analysis associated 67 stream taxa with primary forests, 20 with disturbed forests, 26 with oil palm plantations lacking riparian buffers, and 35 with plantations with buffers (Appendix S6).

DISCUSSION

Our findings showed that the conversion of forests to oil palm plantations drastically decreased stream biodiversity by 44%.

This loss could be reduced to 24% by conserving riparian buffers in the plantations, which also improves the community composition by 20%. Furthermore, there is great potential for improvement because many conventional plantations lack adequate riparian buffers (Konopik et al., 2015). However, the buffers alone cannot replace the ecological role of large protected areas because even plantations with riparian buffers had a community composition that differed greatly from that of primary forests.

Forest-to-oil palm conversion effects on taxa richness and abundance of fish, macroinvertebrates, and amphibians

Streams in oil palm plantations with no riparian buffers supported considerably lower taxa richness than streams in primary forests (46% lower for fish, 46% for macroinvertebrates,

and 29%, for amphibians) and disturbed forests (24% and 29% lower for fish and amphibians, but similar values for macroinvertebrates). These results prove a significant biodiversity loss when forests, especially primary ones, are converted to plantations. This has been primarily attributed to altered environmental conditions, such as temperature increase, shading decrease, microhabitat loss, worsened water conditions, and food and shelter depletion, that result from the removal of riparian vegetation and the use of agrochemicals in the plantations (Chellaiah & Yule, 2018b; Comte et al., 2012; Juen et al., 2016). Disturbances associated with habitat quality may decrease as the palm trees grow, decreasing the differences in biodiversity between forests and plantations (Turner et al., 2011), as observed in the studies addressing >30 years old plantations (MM3 and AM4 in Figure 2). But, due to the limited plantation age range in the reviewed articles, we avoided exploring the effect of plantation aging on freshwater biota.

Loss of riparian vegetation is one of the most critical factors affecting stream taxa richness (Deere et al., 2022). It increases water temperature and erosion and homogenizes the physical complexity of stream habitat (Kano et al., 2020). Additionally, it reduces sources of food, such as terrestrial insects (Kano et al., 2020), and woody and litter debris that can act both as food and shelter for macroinvertebrates, fish, and amphibians (Chellaiah & Yule, 2018a; Faruk et al., 2013; Ferreira et al., 2018; Sazima et al., 2006; Wilkinson et al., 2018). Removing riparian vegetation also allows more sunlight to reach the streams, resulting in algal blooms, particularly during the addition of fertilizers in the plantations (Chakraborty et al., 2017; Ng, 2017).

Agrochemicals generally used in the plantations may affect the dynamics of organisms sensitive to changes in habitat quality, such as *Mnesarete aenea* (Odonata) and *Cylindrostethus palmaris* (Heteroptera). These show higher levels of intoxication (detoxification response: Glutathione S-transferase activity) in the plantations than in forests (Mendes et al., 2020). Fertilizers that increase potassium and phosphorus have been associated with losses of sensitive taxa, especially macroinvertebrates (Chellaiah & Yule, 2018b). The absence of coleopterans and hemipterans has been related to the use of insecticides to control the Asiatic rhinoceros beetle (*Oryctes rhinoceros*), a major oil palm pest (Mercer et al., 2014). Moreover, the larvae of stoneflies, mayflies, caddisflies, and true flies are considered highly sensitive to pesticides in different land uses (Berenzen et al., 2005; Leonard et al., 2000), and this indirectly affects amphibians due to prey shortage (Zainudin et al., 2019).

These impacts were expected to affect the aggregate and group abundance negatively because they decrease the quantity of forest specialists and sensitive taxa. However, this loss was likely offset by an increase in the number of generalists, opportunists (Correa et al., 2015; Konopik et al., 2015; Paoletti et al., 2018), and even invasive species (Rojas-Castillo et al., 2023; Wilkinson et al., 2018). The absence of significant change in abundance between the land uses may suggest ecosystem functioning preservation resulting from species asynchrony (density decrease of 1 species compensated by the increase of another [Ma et al., 2021]). However, the biotic homogenization in the plantations, resulting from the removal of forest

specialist and increase of generalist and the changes in species composition and dominance, may still decrease the resistance and resilience of the community and ecosystem functions and services (Petsch, 2016). Furthermore, these alterations have significant implications for conservation, particularly concerning forest-specialist species, which often exhibit narrow geographic ranges and consequently face a higher risk of extinction compared with more widely distributed species (Newbold et al., 2018).

The conversion of disturbed forests into oil palm plantations also decreased fish and amphibian taxa richness but to a lesser extent than the conversion of primary forest to oil palm plantations. There are distinct differences between stream habitats in primary and disturbed forests. Even though disturbed forests maintain primary forest water temperature and stream canopy cover, these do not preserve stream substrate (Iwata et al., 2003; Luke, Barclay, et al., 2017). Secondary forests have finer substrates, more eroded banks, and larger deposition areas than primary forests (Iwata et al., 2003) and therefore sustain a different habitat than those in primary forests. Conversely, logged forests preserve similar erosion and deposition banks with primary forests but maintain less dead wood (Luke, Barclay, et al., 2017) and thus fewer potential microhabitats and food sources. However, both types of disturbed forests still have a more primary-forest-like habitat than oil palms and thus a higher taxa richness of amphibians, fish (Figure 2a), and, in some cases, vulnerable taxa of macroinvertebrates (e.g., Ephemeroptera, Plecoptera, Trichoptera, Hemiptera [in selective logging]) and Odonata larvae (Luke et al., 2022; Luke, Barclay, et al., 2017; Mercer et al., 2014).

Forest-to-oil palm conversion effects on community composition

The stream community composition in oil palm plantations with no buffers differed significantly from that of primary forests in every study and from that of disturbed forests in 73% of the studies. These consistent differences in community composition across studies suggest a high turnover of species when forests are converted into oil palm plantations. On average, 79% of the turnover was caused by the loss of forest species (e.g., vulnerable or forest specialists) and the remaining 21% by the arrival of species associated with the plantations (e.g., generalists), as observed in Savilaakso et al. (2014).

The plantations and primary forests shared almost half of the fish taxa, and most of the turnover was due to forest species loss; only 15% of the taxa were not found in forests. The taxa associated with the plantations included ubiquitous predatory species, such as the catfish *Hemibagrus baramensis* (Siluriformes) and *Rasbora einthovenii* (Cypriniformes) (Appendix S6) (Wilkinson & Hui, 2018). It also included insectivorous fish species with specialized mouthparts, such as *Esomus metallicus* (Chua et al., 2020). The abundance of these may be attributed to the increased input of terrestrial insects, as indicated by the higher abundance of generalist ants (Luke et al., 2014). The plantations also showed a reduction in benthic macroinvertebrates (Chella-

iah & Yule, 2018a; Mercer et al., 2014) and hosted, in some cases, introduced species, such as the Mozambique tilapia (*Oreochromis mossambicus*), which was absent in forests (Wilkinson et al., 2018). Conversely, species with specialized foraging or hiding behaviors, such as loaches and small catfishes, were absent or in low numbers in the plantations, possibly due to loss of shade and shelter (Giam et al., 2015).

Primary forests and plantations shared 26% of macroinvertebrate species. This was the highest turnover and can be attributed mainly to forest species loss. Primary forests were associated with high-temperature-sensitive taxa (e.g., *Anacroneuria* [Ephemeroptera] [Morabowen et al., 2019]). In addition, primary forests were associated with several functional feeding groups, including shredders (e.g., cranefly [Tipulidae] and caddisflies) (likely related to the high input of leaf litter [Cummins et al., 1989; Rojas-Castillo et al., 2023]) and predators (e.g., Dytiscidae [Coleoptera], *Rhagovelia* [Hemiptera], *Stridulivelia strigosa* [Hemiptera]) (likely related to the high diversity of prey [Bojsen & Jacobsen, 2003; Rojas-Castillo et al., 2023]) (Appendix S6). Conversely, plantations were associated with fewer vulnerable taxa (Appendix S6). Even though disturbed forests did not differ from oil palm plantations in taxa richness for most macroinvertebrate taxa, Mercer et al. (2014) found simpler communities in the plantations. These communities lacked grazers, filter feeders, and collector gatherers due to decreased fine particulate organic matter (FPOM) and simpler substratum. In Guatemala, the communities in plantations had few shredders, were dominated mainly by grazers, and were associated with 2 invasive snails, one linked to adverse ecological effects, such as species displacement (Gutiérrez et al., 1997) and alteration of nutrient cycling (Moslemi et al., 2012). These findings suggest that converting primary forests into plantations may have further ecological effects.

The conversion of primary and disturbed forests into plantations can affect amphibian communities greatly. All studies detected significant differences in the amphibian community between forests and plantations, which shared only 33% of taxa. The turnover was attributed primarily to forest-specialist loss and to a lesser degree to the colonization by generalists (26%). In Borneo, two thirds of the forest frog species were absent in plantations (Konopik et al., 2015), and more than half were absent in the plantations in the Amazonia (Correa et al., 2015). Forest microenvironments provide specialists with shelter, food, and breeding sites (e.g., tree holes for the Mission golden-eyed tree frog [*Trachycephalus resinifictrix*] [Schiesari et al., 2003]). In contrast, the open canopies in the plantations decrease humidity and shelter availability (Hardwick et al., 2015). This affects amphibians in particular because their skin is highly permeable (Akat Çömden et al., 2023) and is especially unbearable for forest specialists (Faruk et al., 2013; Foster et al., 2011; Zainudin et al., 2019). Conversely, generalist species, such as the Boie's wart frog (*Fejervarya limnocharis*) and the common greenback (*Hylarana erythraea*), prefer plantations due to the reduced competition and opportunistic spawning grounds (puddles or tracks) left by harvest trucks (Paoletti et al., 2018). Furthermore, the plantations promote biotic homogenization by increasing ecologically similar species in their communi-

ties (e.g., *Leptodactylus bolivianus* and *Leptodactylus fragilis*, all of which are nocturnal, ground-dwelling, explosive breeders, and build foam nests on the ground or in shallow waters) probably due to the reduced availability of niches for specialists in the plantations (Gallmetzer & Schulze, 2015).

Mitigation of plantation effects by riparian buffers

Stream taxa richness in plantations with riparian buffers was 24% lower than in primary forests and 2% higher than in disturbed forests. Furthermore, the communities in these plantations differed significantly from those in primary forests in 88% of the studies (as opposed to all studies for those lacking buffers). The plantations also shared half of the taxa with primary and disturbed forests (as opposed to 32% and 36%). These results suggest that conserving native forest strips surrounding the streams in the plantations mitigates, to some extent, the decrease in taxa richness from converting forests into plantations (Deere et al., 2022; Luke, Dow, et al., 2017). This is true for other agricultural lands even during riparian buffer restoration. Early growth of native riparian vegetation can enhance stream properties that favor abundance of sensitive taxa while reducing tolerant taxa (Giraldo et al., 2020). However, early and matured riparian buffers are insufficient to replace large protected areas (Marczak et al., 2010), especially regarding community composition.

Fish taxa richness was equal in the plantations with riparian buffers and primary forests, and its abundance was 18% higher in plantations with riparian buffers than primary forests. Furthermore, community composition between primary forests and plantations with riparian buffers differed in only 67% of the studies (as opposed to all for those lacking buffers). The high land-use-conversion resilience of fish when buffers were conserved, particularly notable in terms of richness and abundance, is likely due to the abundant leaf litter and forest-like substrate size promoted by the buffers. These conditions increase and concentrate fish food sources, such as invertebrates, biofilms, and algae (Pringle et al., 1988; Wallace et al., 1997). In addition, the substratum and shade generated by the buffers provide shelter for the fish (Sazima et al., 2006). The presence of riparian buffers doubled taxa richness and conserved forest functional diversity in some plantations (Giam et al., 2015). However, a few other plantations with riparian buffers and retaining a similar number of species as forests were associated with generalists or highly resilient species. These included the saddle cichlid (*Aequidens tetramerus*) and the dash-dot tetra (*Hemigrammus belottii*) in Brazil (Ferreira et al., 2018) and the Bornean bonylip barb (*Osteochilus chini*) and the Bornean river loach (*Gastromyzon ingeri*) in Malaysia (Wilkinson et al., 2018), which may explain the higher abundance of fish in the plantations.

Macroinvertebrate taxon richness in plantations with buffers was, on average, 29% lower than in primary forests, and the community composition differed between primary forest and plantations with buffers in 91% of the studies. The plantations with riparian buffers hosted 1.8 times more taxa and shared

1.6 times more species with primary forests than the ones without, possibly due to the retention of leaf and woody litter, low temperature, and low erosion preserved by the buffers (Juen et al., 2016; Mendes et al., 2019; Rojas-Castillo et al., 2023). Furthermore, these plantations were associated with a higher abundance of shredders, predators, and other riparian-buffer-dependent taxa, such as the caddisflies *Triplectides* and *Marilia* (Corbi et al., 2013; Henriques-Oliveira et al., 2015; Rojas-Castillo et al., 2023), the damselflies *Mnesarete smaragdina* and *Epipleoneura kaxuriana* (Carvalho et al., 2018), and the mayfly *Farrodes* (Marques et al., 2021; Rojas-Castillo et al., 2023), than the plantations lacking buffers.

Even when riparian buffers were conserved in the plantations, amphibians appeared to be highly affected because their community shifted in every study and shared only 31% of the taxa with primary forests. The plantations retaining buffers had only 9% more taxa than those without. In Brazil, Correa et al. (2015) detected a loss of 54% of the forest species between plantations and primary forest even when riparian buffers were protected. Several forest specialists, for example, Manaus slender-legged tree frog (*Osteocephalus taurinus*) and tropical bullfrog (*Adenomera* sp.), were completely absent in the plantations and were replaced by disturbance tolerant species (e.g., Steindachner's dwarf frog [*Physalaemus ephippifer*], rice field frog [*Fejervarya limnocharis*], and common tree frog [*Polypedates leucomystax*]) (Correa et al., 2015; IUCN, 2023; Konopik et al., 2015). It is important to state that our findings of amphibians in plantations with buffers were calculated from only 2 studies and therefore are limited and potentially biased.

The differences in the responses to land-use conversion among taxa may be associated with differences in resilience and variability among species within the taxonomic groups. When buffers were conserved, fish showed a higher resilience to land-use conversion than macroinvertebrates, and amphibians were the most affected group. This coincides partially with the findings of Deere et al. (2022), who reported that amphibians show the highest turnover among all aquatic taxa and fish the highest resilience. Amphibians are generally considered among the most vulnerable taxa to land-use conversion due to their unique life cycles, limited dispersal ability, and microhabitat specialization (Stuart et al., 2004). Fish assemblages have been reported to be more sensitive than macroinvertebrates to landscape disturbance (Montag et al., 2019) and stream hydrological perturbations (Marzin et al., 2012). However, macroinvertebrates tend to be more sensitive than fish to changes in substrates (Juen et al., 2016), riparian vegetation (Oliveira-Junior et al., 2019), forest loss, and local land-use intensity because insect larvae have a more limited motility and include more sensitive taxa than fish (Martins et al., 2021). Even though amphibians showed the highest turnover in the plantations, Deere et al. (2022) found that the taxa richness is completely recovered for amphibians, fish, and matured Odonata when ~45-m-wide riparian buffers are conserved. However, this was not the case for the rest of macroinvertebrates, which required buffers >420-m wide to conserve a similar taxa richness to that of disturbed forests (Deere et al., 2022). Even within the macroinvertebrate group, there is high variability regarding vulnerability of the taxa. Taxa such as Chironomidae, studied by Luke et al. (2022), include several genera adapted to anoxic and polluted conditions (Tull et al., 2023), whereas taxa such as Plecopteran, Ephemeroptera, and Trichoptera include highly sensitive species (LABECO, 2022; Luke et al., 2022; Shimano & Juen, 2016).

The data we used were limited geographically (Malaysia and Brazil) and numerically (only 29 studies or data sets). Furthermore, approximately 30% of the studies come from the SAFE project in Sabah, where only 5 streams were sampled in oil palm plantations. Thus, our results are highly influenced by region and by the characteristics of the few streams that have been sampled. Nevertheless, the relevance of our study lies in compiling the global evidence on freshwater biodiversity loss through oil palm agriculture and directing future efforts for filling research gaps. We focused on a very important, yet understudied, and highly vulnerable ecosystem, and our results suggest that by focusing on stream conservation it is possible to generate considerable gains for biodiversity in agricultural lands. We offer the following recommendations.

Prioritizing freshwater conservation

Focusing on freshwaters makes it possible to achieve most of the goals set by terrestrial conservation and also maintain freshwater species. The same is not true with terrestrial conservation, which provides only limited incidental benefits for freshwater species (Leal et al., 2020). To achieve freshwater species conservation, protecting native riparian buffers is crucial. However, practical details, such as buffer width, need consideration with respect to the freshwaters and species targeted for conservation (Deere et al., 2022). Furthermore, additional research regarding biodiversity and riparian buffers in the plantations is needed, especially in Africa and Mesoamerica, where oil palm is expanding rapidly but little research addresses the issue.

Exploration of research gaps and new technologies

Following the preliminary search results, more research in plantations should address understudied taxa, such as freshwater microorganisms (e.g., periphyton and plankton) because these groups are excellent bioindicators of freshwater quality and key elements for the functioning of aquatic ecosystems (Fonge et al., 2015; Omar, 2010). Studies on the effects on aquatic plants should also be promoted because these may supply food resources for organisms at higher trophic levels, oxygenate the water, increase nutrient retention, and act as biological engineers, contributing to the structure, function, and service provisioning of aquatic ecosystems (O'Hare et al., 2018).

The regulation and monitoring of pesticides and agrochemicals that pollute waterways are also necessary. This could be immensely improved by employing bioindicators and

biodiversity assessments that are more successful than chemical assessments alone (Eriksen et al., 2021). Furthermore, riparian buffer restoration in agricultural lands needs to be prioritized in conservation and research efforts because there is great potential for improvements that can enhance biodiversity. Certification agencies, such as RSPO, can greatly influence the regulation and monitoring of agrochemicals and riparian buffers. Therefore, their role in promoting the protection of riparian buffers and freshwaters, monitoring biodiversity and environmental quality, regulating management, and sanctioning poor practices is crucial for biodiversity and environmental conservation. In addition to bioindicator use, more molecular methods should be adapted to the study and monitoring of these plantations because these can provide higher taxonomic resolution leading to more sensitive environmental assessment tools (Uchida et al., 2020).

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ORCID

Oscar Alberto Rojas-Castillo https://orcid.org/0000-0002-0176-9685

Sebastian Kepfer Rojas https://orcid.org/0000-0002-1681-2877

Leandro Juen https://orcid.org/0000-0002-6188-4386

Luciano Fogaça de Assis Montag https://orcid.org/0000-0001-9370-6747

Fernando Geraldo Carvalho https://orcid.org/0000-0001-7272-1593

Thiago Pereira Mendes https://orcid.org/0000-0002-9369-3672

Kenny Wei Jie Chua https://orcid.org/0000-0002-1338-0781

Clare L. Wilkinson https://orcid.org/0000-0002-0022-2522

Mohammad Noor Azmai Amal https://orcid.org/0000-0002-7664-9821

Dean Jacobsen https://orcid.org/0000-0001-5137-297X

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SUPPORTING INFORMATION

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