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Effects of Reduced-Impact Logging on Fish Assemblages in Central Amazonia

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Abstract: *In Amazonia reduced-impact logging, which is meant to reduce environmental disturbance by controlling stem-fall directions and minimizing construction of access roads, has been applied to large areas containing thousands of streams. We investigated the effects of reduced-impact logging on environmental variables and the composition of fish in forest streams in a commercial logging concession in central Amazonia, Amazonas State, Brazil. To evaluate short-term effects, we sampled 11 streams before and after logging in one harvest area. We evaluated medium-term effects by comparing streams in 11 harvest areas logged 1–8 years before the study with control streams in adjacent areas. Each sampling unit was a 50-m stream section. The tetras* Pyrrhulina brevis *and* Hemigrammus *cf.* pretoensis *had higher abundances in plots logged ≥3 years before compared with plots logged <3 years before. The South American darter (*Microcharacidium eleotrioides*) was less abundant in logged plots than in control plots. In the short term, the overall fish composition did not differ two months before and immediately after reduced-impact logging. Temperature and pH varied before and after logging, but those differences were compatible with normal seasonal variation. In the medium term, temperature and cover of logs were lower in logged plots. Differences in ordination scores on the basis of relative fish abundance between streams in control and logged areas changed with time since logging, mainly because some common species increased in abundance after logging. There was no evidence of species loss from the logging concession, but differences in log cover and ordination scores derived from relative abundance of fish species persisted even after 8 years. For Amazonian streams, reduced-impact logging appears to be a viable alternative to clear-cut practices, which severely affect aquatic communities. Nevertheless, detailed studies are necessary to evaluated subtle long-term effects.*

Keywords: Amazonia, deforestation, fish fauna, ichthyofauna, logging, management, streams

Efectos de la Explotación Maderera de Impacto Reducido sobre Ensambles de Peces en la Amazonía Central

Resumen: *En la Amazonía, la explotación maderera de impacto reducido, que tiene por objetivo la reducción de la perturbación ambiental mediante el control de las direcciones de caída y la minimización en la construcción de caminos de acceso, ha sido aplicada en áreas extensas que contienen miles de arroyos. Investigamos los efectos de la explotación maderera de impacto reducido sobre variables ambientales y la composición de peces en arroyos en una concesión maderera comercial en la Amazonía central, Estado Amazonas, Brasil. Para evaluar los efectos a corto plazo, muestreamos 11 arroyos antes y después de la cosecha de madera en una área. Evaluamos los efectos a mediano plazo mediante la comparación de arroyos en 11 áreas cosechadas 1–8 años antes del estudio con arroyos control en áreas adyacentes. Cada unidad de muestreo era una sección de 50 m del arroyo. Los tetras* Pyrrhulina brevis *y* Hemigrammus *cf.* pretoensis *tuvieron mayor abundancia en parcelas cosechadas ≥3 años antes en comparación con parcelas cosechadas <3 años antes.* Microcharacidium eleotrioides *fue menos abundante en parcelas cosechadas que en parcelas control. En el corto plazo, la composición total de peces no difirió dos meses antes e inmediatamente después de la cosecha de impacto reducido. La temperatura y el pH variaron antes y después de la cosecha, pero esas diferencias fueron compatibles con la variación estacional normal. En el mediano plazo, la temperatura y cobertura de*

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los maderos fueron menores en las parcelas cosechadas. Las diferencias en los valores de ordenación sobre la base de la abundancia relativa de peces entre arroyos en áreas control y cosechadas cambiaron con el tiempo desde la cosecha, principalmente porque la abundancia de algunas especies comunes incrementó después de la cosecha. No hubo evidencia de pérdida de especies en la concesión maderera, pero las diferencias en la cobertura de maderos y en los valores de ordenación derivados de la abundancia relativa de especies de peces persistió aun después de 8 años. En los arroyos de la Amazonía, la explotación maderera de impacto reducido parece ser una alternativa viable a las prácticas de tala rasa, que afectan severamente a las comunidades acuáticas. Sin embargo, se requieren estudios detallados para evaluar efectos sutiles a largo plazo.

Palabras Clave: Amazonía, arroyos, deforestación, explotación maderera, fauna de peces, ictiofauna, manejo

Introduction

In Amazonia forest use and conversion is still largely uncontrolled and, if current trends continue, by 2050 only about 50% of forested areas will remain (Soares-Filho et al. 2006). Reduced-impact logging for timber harvesting is a promising alternative land use because timber resources have high value and reduced-impact logging practices (e.g., targeting stem-fall direction, use of cables to pull logs, reduction of access roads) reduce the damage to forest cover in comparison with conventional logging (Johns et al. 1996; Barreto et al. 1998). With increasing demand for sustainable products (Azevedo-Ramos et al. 2004), the search for new and less-destructive methods has led to an increase in the number of companies that have been certified as practicing sustainable forestry (Zarin et al. 2007). Certified companies use forest management approaches that are environmentally sustainable, socially beneficial, and economically viable (Forest Stewardship Council 2008).

The effectiveness of reduced-impact logging as a way to combine forest use and conservation has been debated (e.g., Bowles et al. 1998; Gascon et al. 1998). Nevertheless, reduced-impact logging in tropical forests could reduce impacts on biodiversity and on ecological processes until better alternatives are available (Bawa & Seidler 1998). Despite the general acceptance of reduced-impact logging and forest certification, few studies conducted in the Amazon have evaluated their effects on biodiversity (e.g., Azevedo-Ramos et al. 2006; Presley et al. 2008). Unwanted effects of certified reduced-impact logging need to be documented in order to reduce negative impacts. In Brazil, concession of public forests for logging (Law 11284/2006), mainly in Amazonas State, which has the largest proportion of primary forests in the basin, will probably increase the area being logged with reduced-impact approaches (Zarin et al. 2007).

Concession areas may be drained by kilometers of headwater streams (Franken & Leopoldo 1984), and ecological processes and natural-history characteristics of organisms in streams are closely associated with adjacent forests (e.g., Kawaguchi et al. 2003). Most studies of effects of forest management on aquatic systems have focused on specific taxonomic groups, mainly insects (e.g., Wallace & Gurtz 1986; Haynes 1999; Kreutzweiser et al. 2005), and knowledge of logging effects generated in temperate regions may not be applicable to tropical systems. In fact, the relationship between tropical fish and forest management practices (including reduced-impact logging) is still little understood in the Amazon (Araújo-Lima et al. 2004). In Malaysian streams, some groups, such as fish that feed on benthic microalgae, are more affected by logging than others (Martin-Smith 1998*a*; Meijaard et al. 2005). Furthermore, some factors that influence the richness and spatial distribution of fish species in streams can also be altered by logging, such as current speed, depth (Martin-Smith 1998*b*), substrate type, microhabitat type, and water flow (Mendonça et al. 2005).

In several studies of the effects of logging on streams, the scales used were considerably smaller than the scale of areas managed by the timber industry (Bawa & Seidler 1998). In large forest areas, such as the Amazon, studies on a small spatial scale may not adequately represent ecosystem functioning in the face of disturbance (Magnusson et al. 1999; Vasconcelos et al. 2000; Costa & Magnusson 2002). Additionally, temporal persistence of effects may be equally important. If the immediate effect of logging on a biological community is great but with time the community returns to its initial state (high resilience), logged forests may have high conservation value.

We analyzed the effects of reduced-impact logging in a certified commercial-logging area in central Amazonia. We quantified differences in physical and chemical characteristics and fish composition in headwater streams over short- and medium-term time frames.

Methods

Study Area

The Mil Madeireira Itacoatiara logging concession (2° 57' N, 58° 42' W) is near the city of Itacoatiara, 250 km from Manaus, Amazonas. The company is certified by the Forest Stewardship Council and uses reduced-impact logging in accordance with regulations of the Brazilian Institute of the Environment and Natural Renewable Resources (IBAMA). Logging activities began in 1995 and, on average, 15 $m^3 \cdot ha^{-1} \cdot year^{-1}$ are harvested (approximately 3 trees/ha). The total management area is 122,729 ha and is divided into subunits (approximately 8000 ha), known as annual production units (APU) that have been logged once and that are not expected to be logged again for at least 25 years. The APU boundaries were established to coincide wherever possible with natural boundaries, such as drainage basins, to reduce bridge and road construction near water bodies. Under Brazilian law, logging cannot be undertaken within 30 m of stream margins.

There are no cities or highways in the immediate vicinity of the logging concession, which is in an unlogged forest matrix. The landscape characteristics (as seen by satellite images) and the understory of the matrix are similar to logged areas. The topography is typical of central Amazonia, with areas of plateau (higher areas with well drained clay soils), slopes (transition from plateau to valley bottoms), and valley bottoms (stream floodplains with sandy soils). The main rivers that drain the area are the Uatumã, Urubu, and Anebá. The studied headwater streams are similar to those in other areas in central Amazonia; forest canopy heavily shades the stream bed and the water is acidic due to plant decomposition (e.g., Mendonça et al. 2005; Espírito-Santo et al. 2009). Generally, the wet season is from November to May, and the dry season is from June to October. Average rainfall is 2000 mm/year, and mean annual temperature is 26 °C. Seasonal temperature variation is small (Ribeiro & Nova 1979).

Sampling

We selected first- and second-order streams for sampling of fish following Strahler's modification of Horton's scale (Petts 1994): the junction of two first-order streams form a second-order stream, and two second-order streams form a third-order stream. We sampled 44, 50-m reaches between May and July 2007. Rainfall was low during this period, so there was little fluctuation in the daily water volume in the stream channels, as reported for nearby areas (Espírito-Santo et al. 2009).

We used two experimental designs to evaluate the effects of reduced-impact logging on fish assemblages: a before-after design to evaluate short-term effects and paired samples to evaluate overall medium-term effects (up to 8 years) (Fig. 1). In the short-term study, we sampled sections of 11 streams in the APU E1a in May (before logging) and in July (postlogging survey). In the postlogging survey, we sampled the same streams but to minimize possible effects of the previous survey event, we sampled sections that were either immediately upstream or downstream of the section sampled in the short-term study.

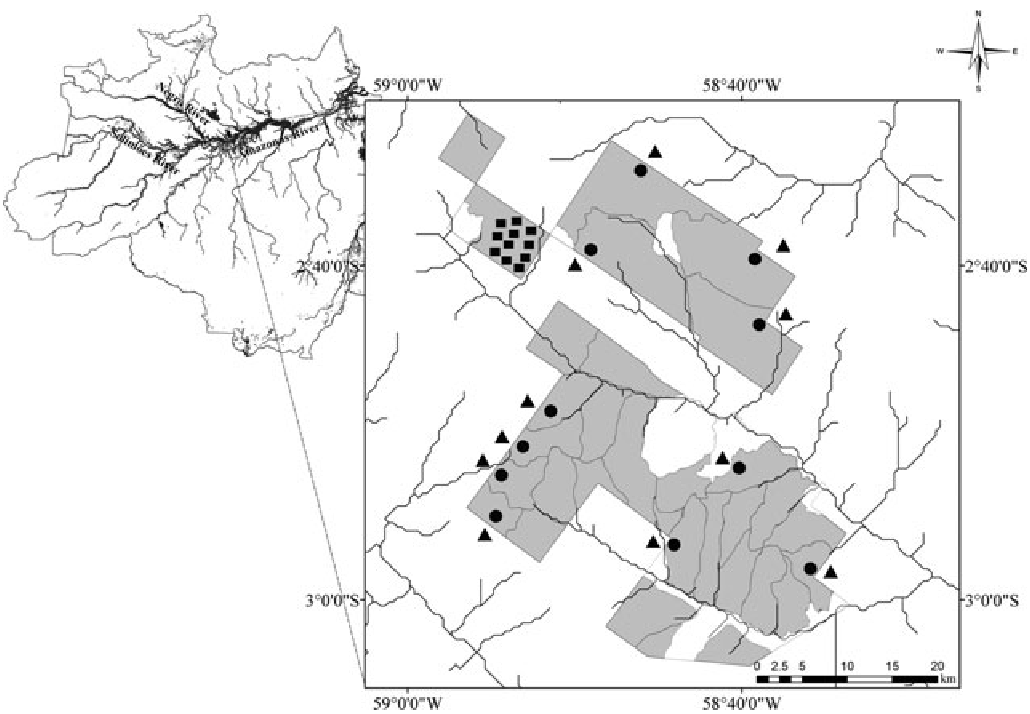

Figure 1. Sites where streams were sampled for fish in the Mil Madeireira Itacoatiara logging concession (gray areas, logged [annual production units]; white, unlogged; squares, sampled before and after logging; triangles, control plots; circles, logged areas used in the medium-term paired-plot protocol).

There is strong spatial variation in the structure of the fish assemblage in the Mil Madeireira concession (M.S.D., unpublished data). Therefore, for the medium-term study, we used a paired-site approach. We surveyed streams in APUs ($n = 11$ pairs) logged 1–8 years before sampling. We surveyed streams in logged areas that were close to the concession boundaries to facilitate access to adjacent unlogged streams. We sampled pairs of streams (Fig. 1), one within the APU and another outside the concession (control). Both stream sections were 50 m long, and controls had depths and widths similar to streams sampled in logged areas. Fish faunas can differ greatly between adjacent catchments (Mendonça et al. 2005). To reduce possible basin effects, we located each stream pair in the same small drainage basin.

We used the standardized protocol recommended by the Biodiversity Research Program (PPBio) (Mendonça et al. 2005) to evaluate the fish fauna. To avoid disturbing the substrate, we obtained data on stream structure and physical and chemical characteristics of the water prior to fish sampling. We measured dissolved oxygen, temperature, pH, and conductivity at the downstream extremity of each sampling section. We measured structural characteristics in each 50-m stream stretch ($n = 4$; transects spaced 16 m apart). Superficial water velocity was estimated by registering the time it took for a plastic disk 30 mm in diameter to cover 1 m on the water surface. We recorded total channel width, depth, and substrate type at each of nine sampling points within a transect. Substrate categories were sand, logs (wood with diameter over 10 cm), litter (leaves, small branches, detritus), and roots. We used digital photographs of the vegetation cover above the stream channel to estimate percent canopy openness. Prior to fish sampling, we isolated stream reaches with block nets (5-mm mesh when stretched) to prevent fish from escaping. We used two additional nets to further subdivide the stretch and facilitate fish capture. Two workers with hand and seine nets (2-mm mesh stretched) captured fish during a 2-h period or until no fish were observed moving in the stream stretch. We did not use minnow traps, fyke nets, or electric fish-signal detectors (Mendonça et al. 2005) because of logistical difficulties. We anesthetized specimens with clove oil and preserved them in 10% formalin. We used taxonomic keys to identify specimens or had experts identify them. Voucher specimens were deposited in the INPA collection and the access numbers, data, and metadata are available from http://ppbio.inpa.gov.br/.

Data Analyses

We used multivariate analysis of covariance to evaluate the overall short- and medium-term effects of reduced-impact logging on the physical and chemical characteristics of streams. For short- and medium-term data, we included discharge as a covariate. To evaluate trends in physical and chemical characteristics over time, we regressed the paired differences between logged and control plots against log-transformed time since logging. We log transformed the predictive variable of time analyses to meet the assumptions of linearity and homogeneity of variances.

We used abundance and presence and absence data to describe fish composition because abundance data generally reveal patterns based on the most common species, whereas presence and absence data give more weight to rarer species that do not occur in most sampling units. We standardized abundance data by dividing species abundances by total plot abundance (relative abundance data) in order to reduce differences between sampling units related to number of individuals collected per plot (mean = 66; range = 24–178). We used the Bray–Curtis index to generate dissimilarity matrices for short- and medium-term designs and applied nonmetric multidimensional scaling (MDS) to summarize the species composition in a single dimension because one axis captured more than 50% of variation for all association matrices. We based the percentage of explanation provided by the axes on the r^2 value generated by regression of the original distances on distances created by the MDS analysis (McCune & Grace 2002).

We tested for differences in fish composition in the short-term study with an analysis of covariance in which MDS axes were response variables, logging was the categorical variable, and discharge was a covariate. To test for temporal effects of reduced-impact logging on the fish assemblage in the medium term, we plotted the difference between each logged plot and its respective control against time since logging. Because the relationship was not linear and heteroscedasticity could not be corrected by simple transformations, we used nonparametric serial-runs tests (Zar 2009) and tested whether there was a tendency for values greater or less than values for the control plots to be grouped over time. We used the nonparametric paired-samples Wilcoxon analysis to test for differences between control and logged plots. All analyses were carried out in R 2.8.1 (R Development Core Team 2008).

Results

Stream Characteristics

On average, streams were 1.3 m wide (0.68–2.18), 0.08 m deep (0.03–0.23), and had 0.02 m^3/s discharge (0.004–0.148). The water was acidic (mean pH 4.52; range 1.57–6.00) and had low conductivity (mean 7.64 μS/cm; range 6.74–9.95), high oxygen saturation (mean 6.44 mg/L; range 5.12–7.06), and relatively stable temperatures (mean 24.6 °C; range 23.3–25.4). Canopy openness was small (mean 7%; range 2–19), and the dominant substrate types were sand (mean 29%; range 3–61), litter (mean 41%; range 17–72), and roots (mean 20%; range 2–52).

The physical and chemical conditions in the streams were significantly different before and after logging in the short-term study (MANCOVA: $F_{7,13} = 4.5$, Pillai trace $= 0.685$, $n = 22$, $p = 0.01$). Only pH and litter cover on the stream bottom differed significantly after logging: pH increased ($F_{1,19} = 16.03$, $p < 0.001$) and litter decreased ($F_{1,19} = 5.91$, $p = 0.025$). Temperature tended to be about 0.5 °C higher ($F_{1,19} = 3.78$, $p = 0.067$).

In the medium-term study, MANCOVA with discharge as a covariate indicated an overall difference in physical and chemical characteristics between streams in logged and control plots (MANCOVA: $F_{7,13} = 3.77$, Pillai trace = 0.670, $n = 22$, $p = 0.02$). Univariate analyses indicated significant differences only for temperature ($F_{1,19} = 4.68$, $p = 0.04$) and log cover ($F_{1,19} = 13.12$, $p = 0.002$). Only temperature ($a = 0.594$, $b = -0.755$, $r^2 = 0.483$, $n = 11$, $p = 0.01$) and root cover ($a = -0.147$, $b = 0.119$, $r^2 = 0.364$, $n = 11$, $p = 0.02$) differed significantly between control and logged plots with time since logging. There was no significant temporal trend in the other physical and chemical variables ($p > 0.31$ in all cases).

Root cover was less in streams in logged plots than in streams in control plots initially, but these differences approached zero within a few years (Fig. 2a). Initially, temperature in logged plots was similar to that in control plots, but temperature in logged plots decreased relative to control plots over time (Fig. 2b). There were fewer exposed logs in streams in logged areas than in control areas, irrespective of the time since logging (Fig. 2c).

Fish Composition

We collected 3005 fish specimens of 32 species belonging to six orders and 14 families. Most of the fish were Characiformes (12 species, 80% of collected specimens). The most abundant species were short-lined pyrrhulina (*Pyrrhulina brevis*) and the characin *Hemigrammus* cf. *pretoensis*, which accounted for 49% and 20% of all captured specimens, respectively.

In the short-term study, the single MDS axis captured 71% of the variation in abundance-based distances and 68% of the presence–absence distances in the association matrices. More fish were collected in the survey after logging (773) than in the survey before logging (560). *P. brevis* (after logging = 399, before logging = 324), a killifish *Rivulus* aff. *micropus* (76, 5), *H. pretoensis* (85, 117), and a pencilfish (*Copella nattereri*, 27, 7) had the greatest differences in total abundance. The loricariids *Ancistrus* sp. (0, 1), *Rineloricaria lanceolata* (0, 4), and South American darter (*Microcharacidium eleotrioides*, 0, 3) were only collected before logging. The loricariid *Acestridium discus* (1, 0), the catfish *Rhamdia quelen* (2, 0), and the armored catfish (*Callichthys callichthys*, 1, 0) were only collected after logging. Multiple regression detected no significant difference in overall composition as summarized by MDS axes before and after logging (abundance: $p = 0.81$; presence and absence: $p = 0.19$), although there was a strong effect of discharge (abundance: $p = 0.001$, $r^2 = 0.36$; presence and absence: $p < 0.001$, $r^2 = 0.71$).

In the medium-term study, the single MDS axis captured 76% and 53% of abundance-based and presence–absence distances, respectively. More fish were collected in streams in logged areas (1311) than streams in control areas (798). *H. pretoensis* (streams in logged areas $n = 310$, streams in control areas $n = 136$), *M. eleotrioides* (15, 28), *C. nattereri* (37, 21), *R. micropus* (45, 31), and the electric-fish *Gymnotus anguillaris* (22, 9) had the greatest differences in abundance. The number of species collected was higher in streams in control areas ($n = 24$) than in logged areas ($n = 18$).

For abundance-based ordination scores, there was a significant temporal trend in differences between streams in control and logged plots (serial randomness test, $u_{3,8} = 2$, $p = 0.05$). Differences in ordination scores were negative in streams sampled <3 years after logging and positive thereafter (Fig. 3). Even 8 years after logging, ordination-score differences for streams in logged and control sites were more positive than expected if there was no effect of logging (mean difference = 0), and there was no apparent trend to return to prelogging composition.

The species with the greatest differences in mean number collected in plots logged ≥3 years before compared with plots logged <3 years before were *P. brevis* (<3 years: 18, ≥3 years: 43) and *H. pretoensis* (13, 36), *R. micropus* (<1, 3), and *C. nattereri* (1, 4). The killifish *Rivulus geayi* (10, <1) and the characin *Hyphessobrycon* cf. *agulha* (4, <1) were collected in higher numbers in the recently logged plots. Differences in other species were small, and it was not possible to distinguish sampling from logging effects for most species.

For ordination scores based on presence–absence data, there was no significant temporal trend in differences between streams in control and logged plots (serial randomness test, $u_{3,8} = 7$, $p > 0.25$), and there was no significant difference in the scores of logged and unlogged plots (Wilcoxon paired-samples test: $V = 19$, $n = 11$, $p = 0.24$).

Discussion

Our results indicate that the physical and chemical characteristics in rainforest streams in central Amazonia changed little in the short term because of certified reduced-impact logging. Changes in temperature, pH, and litter cover were within natural seasonal variations

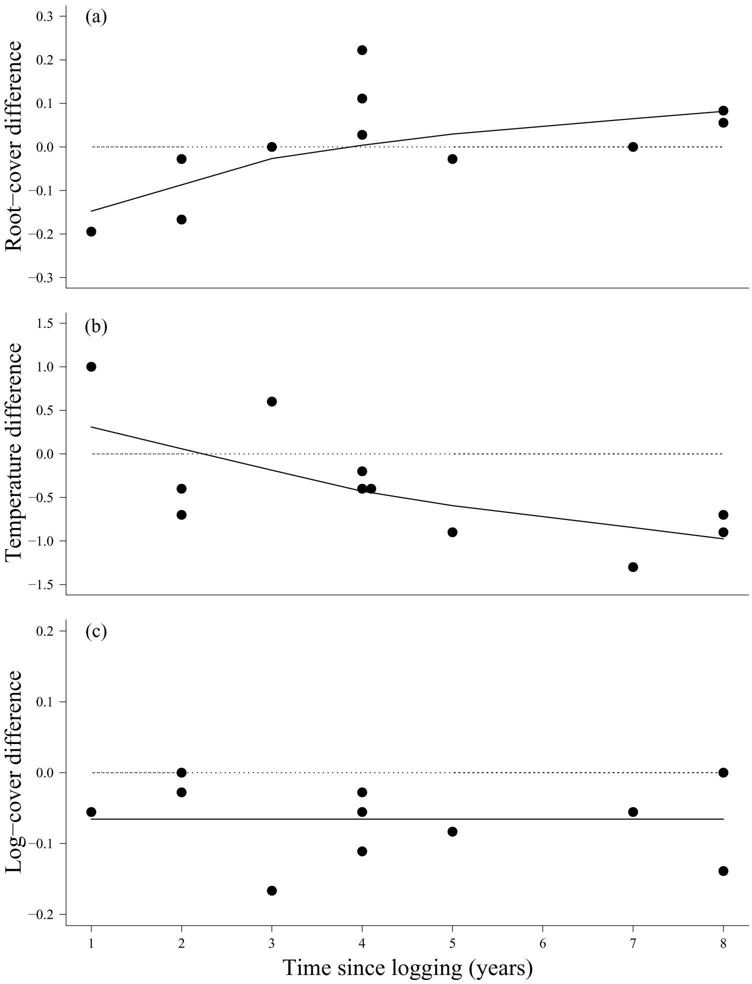

Figure 2. Differences between logged and corresponding control stream sections relative to time since logging for (a) root cover, (b) temperature, and (c) log cover (dotted line, no difference [logged – control = 0]; solid line, predicted values for the log-linear regression).

recorded in nearby areas (Espírito-Santo et al. 2009), and no other differences were detected. Therefore, the short-term effects, if any, were subtle compared with clear-cutting, which causes loss of habitat complexity, decreased organic matter input, increased entry of woody material, alteration in nitrogen and phosphorus concentrations, and erosion in streams (Douglas et al. 1992, 1999; Neill et al. 2001; Davies et al. 2005).

Changes in physical and chemical characteristics of streams in the medium-term study were related to temperature and substrate. Temperatures tended to be lower in streams in logged plots than in control plots, but the effect was due primarily to one pair of plots, and this tendency may not be maintained over the long term. Reduction in root cover soon after logging and the long-term reduction in exposed logs were concordant with an increase in erosion, which would cover logs and roots in streams. Opening roads and clearings can increase the amount of sediment and organic material (leaves, twigs, decomposition products) that washes into streams (Meijaard et al. 2005). Kreutzweiser et al. (2005) detected an increase in fine sediment after logging that persisted for 3 years after disturbance in Canadian streams. Sediment loads decrease with time after logging in Malaysian streams, but storm events can restore the sediment input and restart erosion processes (Douglas et al. 1999). There were large amounts of sediment in unsampled streams near secondary roads in the APUs in our study, and aquatic organisms may be affected negatively by erosion (e.g., Kreutzweiser et al. 2005; Meijaard et al. 2005). We, however, evaluated only the general effects of logging. Changes in drainage due to road construction may explain the subtle effects of reduced-impact logging on stream characteristics and fish relative abundances we detected, even under the low density of tree removal (approximately 3 trees/ha) in the study area.

The fish we found were similar to those found in headwaters streams elsewhere in central Amazonia. Several species are widely distributed in the region, and the average local species richness we found is similar to that in similar environments (Mendonça et al. 2005; Anjos & Zuanon 2007; Espírito-Santo et al. 2009). Although surveys of larger sections of streams would have allowed us to record a higher number of species per plot (Anjos & Zuanon 2007), our objective was to use a rapid protocol

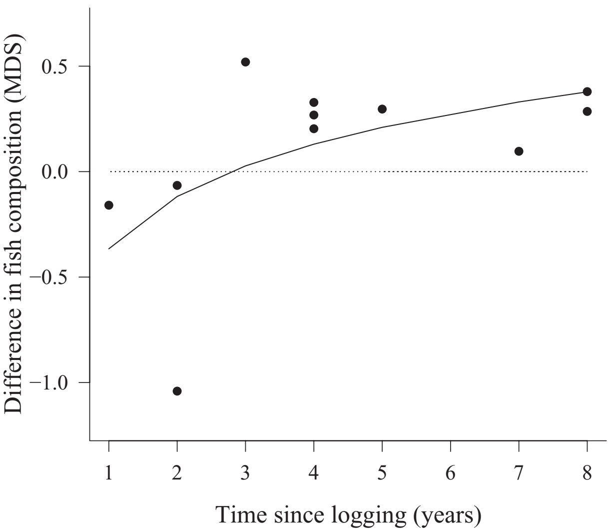

Figure 3. First axis of a nonmetric multidimensional scaling (MDS) analysis summarizing differences in fish assemblage composition between logged and control plots relative to time since logging. The dotted line indicates no difference (logged − control = 0), and the solid line indicates the mean value of the difference.

that was sensitive to natural spatial (Mendonça et al. 2005) and temporal (Espírito-Santo et al. 2009) environmental variation and thus to different land-use effects. Habitat characteristics were similar among the stream sections we sampled, and the reduced-impact logging techniques applied to the APUs showed little evidence of direct impacts on the structure and local dynamics of the streams. In addition, we used control sites that were similar to logged sites. Therefore, it is unlikely that differences in fish-catching efficiency among the streams would affect our main conclusions. Our results indicate that the protocol we used to sample fish is a reliable tool for detecting environmental changes, as already noted in similar studies in headwater streams in Ecuadorian Amazonia (Bojsen & Barriga 2002).

Changes in forest cover can alter ecological processes and modify fish assemblages in Amazonian forest streams. In Ecuador fish assemblages in streams are composed mostly of Characiformes in intact forested areas and loricariids in deforested areas (Bojsen & Barriga 2002). This assemblage change is related to the decrease in forest cover in deforested areas, which allows more light to reach the stream, stimulates periphyton growth (e.g., Hansmann & Phinney 1973), and increases the abundance of periphytivores, such as loricariids. We did not find similar effects probably because of the low values of canopy openness that occur naturally over the streams in our study sites. Companies that practice reduced-impact logging are obliged by law to maintain permanent protection areas around water bodies. This conservation strategy helps avoid large modifications in the structure and functioning of streams (Boothroyd et al. 2004; Wright & Flecker 2004; Gomi et al. 2006) and changes in fish assemblages.

Short-term changes in physical and chemical characteristics of streams did not appear to cause direct mortality or induce migrations (e.g., Semlitsch et al. 2008) because the fish assemblage was little affected at that time scale. Small-scale temporal changes (months) are common in streams (Espírito-Santo et al. 2009), and the changes induced by certified reduced-impact logging, if any, are probably similar to those experienced by fish after heavy rainfall. Thus, it is perhaps not surprising that the fish fauna is resistant to these short-term changes.

Our data showed that reduced-impact logging affected the fish fauna and physical and chemical characteristics of streams in the medium term. Fish abundance differed significantly between control and logged plots, which suggests that reduced-impact logging may affect populations of common species, such as *H. pretoensis*, *R. micropus*, and *C. nattereri.* It is possible that habitat modification caused by reduced-impact logging affects growth processes (Martin-Smith 1998*a*) and recruitment patterns (Jones et al. 1999), especially 2–8 years after logging, and has repercussions in the medium to long term.

Our results on the effects of time since logging indicate a change in local ecological processes because even 8 years after logging, there was no indication of recovery of the fish assemblage to the compositions found in control areas. Longer time analysis is crucial to test whether changes we detected are maintained or decrease over time. Martin-Smith (1998*a*) did not identify clear differences in community composition in streams in old logged plots in Malaysia, but a few species had abundances and biomass differences related to recovery time.

Reduced-impact logging practices may not alter the overall composition of fish species in our study area, despite changes in relative abundance within individual stream stretches. Reduced-impact logging is not without impacts. It cannot be assumed that certification protects all elements of biodiversity and ecosystem processes in the same way. The certification process requires that workers be treated fairly, and that the production of timber species be maintained over the long term. Nevertheless, forest certification should be based on clear and specific principles related to nontimber species maintenance in managed areas (Putz & Viana 1996; Bennett 2000). Each company should invest in monitoring several components of the biota in order to detect and, if necessary, mitigate unexpected impacts on biodiversity and ecological processes.

The impacts of logging on fish communities we detected were subtle. All species occurred in the general area, and we have no evidence that any species was extirpated in logged areas. Nevertheless, fish assemblages in streams appear to be sensitive to environmental changes caused by logging in central Amazonia. Fish in Amazonian forest streams may be good biological indicators of forestry activities because they are easy to survey and are sensitive to spatial and temporal effects caused by logging. Employees of timber companies could easily be trained to undertake periodic surveys (Azevedo-Ramos et al. 2004), although researchers would be needed to identify species and analyze the data. One of the most promising ways to make certification more relevant to ecosystem management is to link the timber industry and ecological research.

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