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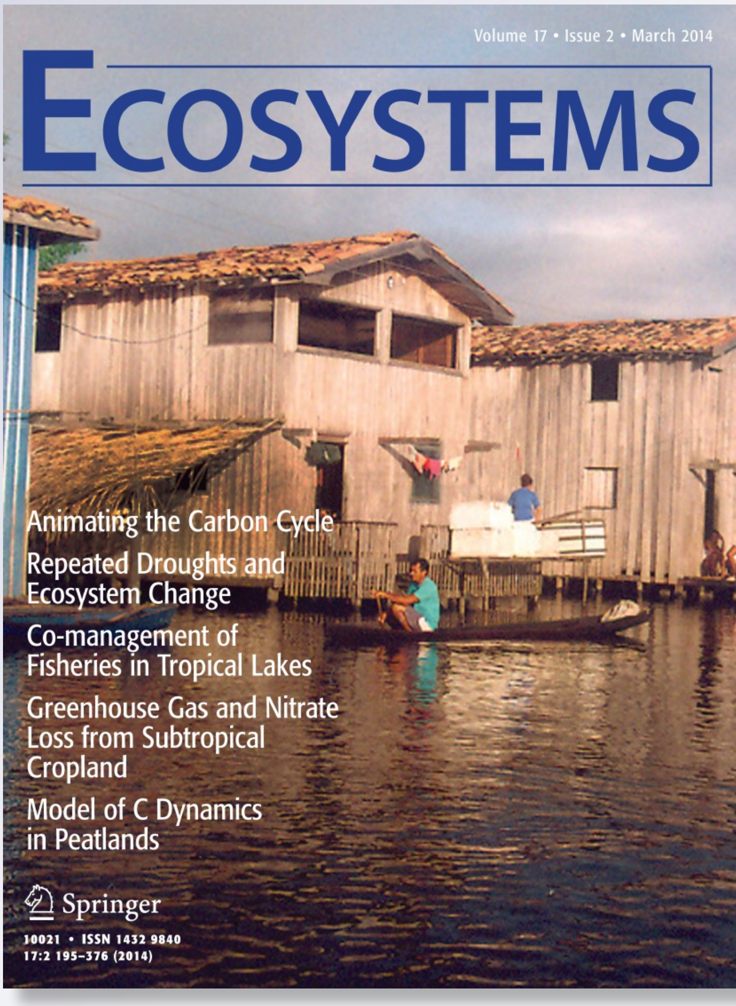
Ecosystems

ISSN 1432-9840
Volume 17
Number 2

Ecosystems (2014) 17:271-285
DOI 10.1007/s10021-013-9722-8



Springer

Ecosystems (2014) 17: 271–285
DOI: 10.1007/s10021-013-9722-8

ECOSYSTEMS

Co-management and Spatial Features Contribute to Secure Fish Abundance and Fishing Yields in Tropical Floodplain Lakes

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Abstract

Empirical data are needed to show the efficacy of co-management, which is regarded as a promising approach to achieve conservation goals. In this study, we addressed the potential influence of fisheries co-management to increase fish abundance and fishing yields in the lower Tocantins River Basin (Brazilian Amazon), downstream from a large dam. We analyzed 590 fish landings (6.7 t of fish) from five fishing villages and 48 fish samples obtained using gillnets (10,378 fish from 101 species) in 12 floodplain lakes in four regions: two with incipient co-management and two unmanaged. The fish species richness did not differ among the regions, but the lakes in the regions that were co-managed had higher fish abundance (biomass and number of individuals) and a higher mean proportion of fish reproducing during the high water season. Fishers had higher catches per unit of effort in the co-managed regions than fishers in the non-managed regions. These results were also influenced by geographic factors (distance and accessibility of lakes), as fish biomass was higher in lakes that were distant from the main river and from the main city in the region. Managers should thus consider strategic selection of the geographic locations of managed sites, even in remote areas. However, the fish biomass sampled in lakes was more related to region than to the lakes' geographical location. Therefore, co-management has at least partially contributed to increased fish abundance and fishing yields in the studied region, through the protection of an important fish habitat (lakes). We provide empirical evidence that co-management can contribute to the maintenance of fish abundance, sustainability of fisheries, and food security in large tropical rivers impacted by damming.

Key words: tropical rivers; community-based conservation; sustainability; adaptive management; Amazon basin; small-scale fisheries; reservoirs.

Received 20 May 2013; accepted 15 September 2013;
published online 22 October 2013

Author Contributions: R.A.M.S. designed the survey, conducted research, analyzed data, and wrote the manuscript. G.H. conducted research, analyzed data, and edited the manuscript. P.F.L. conducted research, analyzed data, and edited the manuscript. A.R R. conducted research. R.P.L. conducted research. H.H. analyzed data. A.A.J. conducted research and provided additional data on fish sampling. A.B. analyzed data and edited the manuscript.

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Introduction

A critical challenge to conservationists is how to reconcile biological conservation, poverty alleviation, and sustainable resource use in tropical aquatic ecosystems (Mills and others 2011; Obura 2012). Most top-down fisheries management measures aimed at addressing these challenges are inappropriate for small-scale fisheries (Ruddle and Hickey 2008). For example, protected areas closed to fishing are difficult to implement and enforce in developing tropical countries, where poor people are in great need of fishing resources (Obura 2012). However, communities of resource users, including fishers, have developed rules and restrictions that can reduce the risk of resource over-exploitation (Berkes and others 2000). Governments and research institutions may recognize and support these local rules in co-management arrangements, which can reduce conflicts among users and managers, improve compliance with management recommendations, and enhance enforcement of management rules (Carlsson and Berkes 2005; Begossi 2010).

Although some co-management initiatives aim to increase the abundance of fishing resources (McClanahan and others 2006; Gelcich and others 2008a; Hamilton and others 2011; Solomon and others 2012), some initiatives are motivated by other purposes, such as reducing conflicts among fishers, guaranteeing food security, or protecting religious practices (McClanahan and others 1997; Cinner, 2005; Sultana and Thompson 2007; Campbell and others 2012). However, co-management may not always be successful in reducing fishing pressure (Shepherd and others 2004). There is thus a need for empirical data about the efficacy of co-management, especially in complex aquatic tropical ecosystems (Mills and others 2011). The ecological and socio-economic outcomes of co-management have been assessed through indirect measures, such as experts' opinions (Mills and others 2011) and interviews with fishers about fishing activities (Solomon and others 2012). Furthermore, most of the studies that have analyzed co-management efficacy in increasing fish catches, fish abundance, and fish diversity have been conducted in coastal ecosystems (McClanahan and others 1997, 2006; Cinner and others 2005; Gelcich and others 2008a; Hamilton and others 2011; Campbell and others 2012); relatively few studies have analyzed tropical freshwater ecosystems (Lorenzen and others 1998; Sultana and Thompson 2007).

The Brazilian Amazon is an ideal setting for implementing and testing alternative systems of fishing management and conservation, including co-management. The Brazilian Amazon has intense small-scale fisheries that have resulted in overfishing of some target fish (Castello and others 2011), but some fishing communities have engaged in co-management, regulating fishing efforts, and controlling access to outside fishers (Almeida and others 2009; Lopes and others 2011). Co-management in the Brazilian Amazon includes 'fishing agreements', which are basically government support of local initiatives by fishers (Castro and McGrath 2003), sustainable development reserves (Castello and others 2009) and extractive reserves (Begossi and others 1999), although the reserves sometimes do not constitute true co-management (Begossi 2010; Lopes and others 2011). Although some studies have addressed these co-management systems (Almeida and others 2009; Castello and others 2009; Silvano and others 2009b), to the best of our knowledge, no survey has analyzed the fishing and ecological outcomes of co-management simultaneously in the Brazilian Amazon.

In this study, we aim to compare several ecological and fishing parameters among four regions in the Tocantins River basin in the Brazilian Amazon, downstream from a large reservoir. Each studied region included one (or two) villages of small-scale fishers and three floodplain lakes, and these regions differ in their involvement in co-management initiatives. We evaluated the ecological parameters by comparing fish abundance (number of individuals and biomass), fish sizes, proportions of fish that were reproducing, and richness and composition of fish species among lakes in the four regions. We evaluated fishing parameters by comparing the catch per unit of effort (CPUE) of fishing among villages in these same four regions. Therefore, we checked if these regions differ regarding their ecological or fishing parameters, and evaluated to what extent differences in fish biomass could be partially explained by environmental differences (abiotic limnological parameters, lake area and lake distance from the main city, river margin, and nearest fishing village). We expected that those regions in which fishers had been involved in co-management would show higher CPUE in fishing villages and greater fish abundance and diversity, fish of larger sizes and more fish reproducing in lakes. We also expected fish biomass in lakes to be more affected by regional differences (related to co-management) than by environmental differences among lakes. This study thus represents one of the most comprehensive analyses ever conducted on the potential effects of co-management in freshwater ecosystems, as well as one of the first studies to analyze co-management in less productive and clear-water rivers impacted by large dams, such as the Tocantins River (Petrere 1996; Silvano and others 2009a).

Methods

Site Description

The Tocantins River is a clear-water river 2,750 km long that drains the Araguaia–Tocantins basin, a region of 343,000 km^2. This river basin has suffered environmental damage such as deforestation and intensification of fisheries and dams (Ribeiro and others 1995). The Tocantins River was dammed in 1984 by the Tucuruí reservoir, which might have affected fisheries in the lower Tocantins River basin, downstream from the dam (Ribeiro and others 1995; Petrere 1996; Fearnside 1999). Considering that fishing is one of the main economic activities in the area (Hallwass and others 2011), the reservoir may have had economic consequences in terms of reductions in the populations of some commercial fish, decreased fishery productivity and changes in catch composition (Mérona 1990; Merona and others 2010; Hallwass and others 2013a).

We studied five fishing villages (referred to hereinafter as villages) along the lower Tocantins River, downstream from the Tucuruí reservoir: Açaizal, Calados, Ituquara, Joana Peres, and Umarizal (Figure 1). We selected these villages based on advice from the staff of Eletronorte, the Brazilian company in charge of the Tucuruí reservoir, and from local leaders and fishing organizations, who indicated that these villages are important fishing sites. Baião

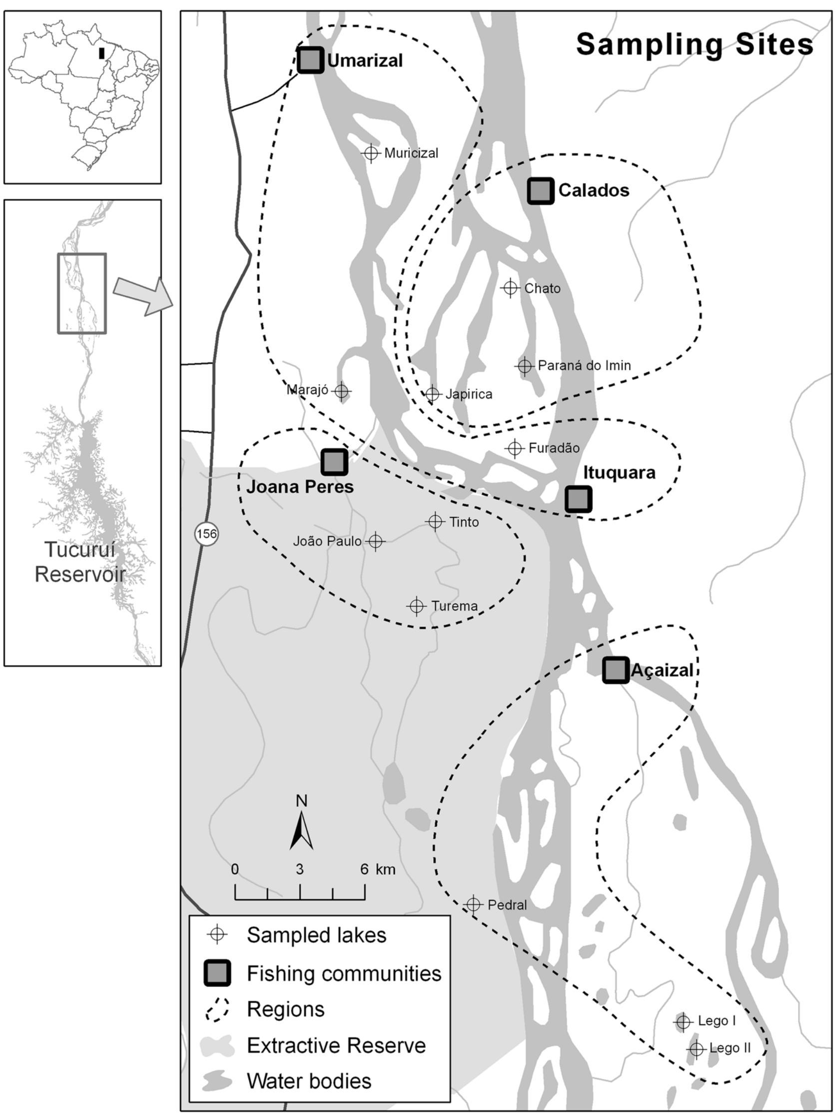

Figure 1. The sampled lakes, fishing villages, and regions in the lower Tocantins River, Brazilian Amazon.

Table 1. General Characteristics of Fishers and Fishing Activities

Villages	Açaizal	Calados	Ituquara	Joana Peres	Umarizal
Number of fishers	46	28	47	44	46
Education level					
Primary school incomplete	93	89	91	80	87
Secondary school incomplete	2	7	2	11	7
Secondary schoolcomplete	0	4	4	5	7
Economic activities (fishers)					
Fishing	100	76	96	100	100
Agriculture	26	82	57	64	78
Retired	0	3	9	7	9
Carpentry	0	3	0	2	0
Hunter	0	0	0	5	2
Commerce	4	3	6	2	11
Livestock	0	0	0	0	2
Economic activities (fathers)					
Fishing	83	36	68	80	59
Agriculture	28	79	55	39	83
Hunter	7	0	2	2	7
Carpentry	13	0	2	0	0
Commerce	0	11	6	11	7
Destination of fish caught					
Commerce	100	61	89	86	83
Do not sell	0	39	11	14	17
Where fish is sold					
Main city (Baião)	54	4	9	7	4
Village	2	61	89	82	83
Middlemen	74	0	4	2	0
Main fish caught[1]					
Tucunare (*Cichla* spp.)	83	61	72	73	59
Curimata (*Prochilodus nigricans*)	87	64	57	64	43
Pescada (*Plagioscion squamosissimus*)	26	61	74	18	76
Piau (aracu) (*Leporinus* spp., *Schizodon vittatus*)	54	75	47	36	46
Piranha (*Pygocentrus nattereri*, *Serrasalmus* spp.)	57	39	21	73	33
Acará (*Geophagus* spp.)	41	29	11	48	13
Branquinha (*Curimata* spp., *Psectrogaster* spp.)	22	36	40	25	13
Mapará (*Hypophthalmus marginatus*)	11	14	40	32	30
Traira (*Hoplias malabaricus*)	37	29	9	23	26
Caratinga (*Geophagus* spp.)	0	4	28	5	43

General characteristics of fishers and fishing activities in the five studied fishing villages in the Tocantins River, Brazilian Amazon, according to the fishers responses to interviews (n = 211 fishers interviewed). Numbers correspond to the percent of interviewed fishers who mentioned each information (number of fishers interviewed in each village is shown in the first row); the sum of percentages may be more than 100%, because some fishers mentioned more than one information.
[1]*Fish species follow previous studies (Hallwass and others 2011, 2013a).*

is the major town in the region and has a major urban market that receives fish caught in these villages and other places (Hallwass and others 2011). Before sampling fish landings, we interviewed 211 fishers from these villages, following a standard questionnaire with questions about education level and fishing activities (Table 1). Details of the interview methodology are described in a previous survey (Hallwass and others 2013a). These interviews indicated that most fishers did not complete primary school, and the five most caught fish species were similar among the five villages (Table 1). In a previous survey, we showed that fishers in all villages use mostly gillnets followed by hook and line (Hallwass and others 2013b). However, these fishers differ regarding their commitment to fishing as a commercial activity, as well as their fishing tradition. In Açaizal, all the interviewees were full-time fishers who sell the fish caught mainly to middlemen or in the main city; fishing was also the main activity of the fishers' fathers, and only few fishers (and their fathers) practiced agriculture as well (Table 1). On the other hand, in Calados and Umarizal many fishers (and their fathers) also do agriculture besides fishing, whereas fish is sold mostly in the village (in Calados 39% of the interviewed fishers do not sell the fish caught) (Table 1). More information about the five studied villages can be found in previous surveys (Hallwass and others 2011, 2013a).

Theses villages differed with respect to their involvement in co-management at the time of the survey (2006–2008). There was no co-management in the villages of Umarizal and Ituquara. In the Calados village, fishers had initiated a management system that involved closing some lakes to fishing. However, this management system and the corresponding fishing restrictions were no longer valid because the fishers were incapable of maintaining management rules without governmental support. The fishers of the village of Açaizal had implemented incipient management measures, such as restrictions on the use of fishing gear (gillnets) in lakes during the receding water season. These measures were enforced by the villagers themselves, with neither official recognition nor governmental support. The co-management of the village of Joana Peres was more developed and better enforced: fishers adopted fishing restrictions in floodplain lakes, allowing a quota of 50 kg of fish per week to each fisher (this rule has been in place and enforced since 2007). Some lakes were closed to fishing (no-take), and at least one of these (João Paulo) was included in our survey (Figure 1). This co-management in Joana Peres has been formally recognized and supported by the Brazilian government through the establishment of the Extractive Reserve of Ipau–Anilzinho in 2005 (2 years before our survey). This reserve has an area of 558.16 km^2, and it is managed by representatives of the local people, by the government and by other institutions (Lopes and others 2011).

Ecological Parameters: Fish

We sampled 10,378 fish from 101 species in 12 floodplain lakes scattered around the studied region (Figure 1). We collected 60 samples (five samples from each lake), during the four hydrological seasons, at the same time as the sampling of fish landings in villages (see below). We grouped together two samples collected when the river was high and when fewer fish were caught, thus analyzing 48 samples (four per lake). For each sample, we used two sets of seven gillnets, with mesh sizes of 40, 60, 80, 100, 120, 140, and 160 mm between opposite knots. We measured the weight and the standard length (cm) of all collected fish.

We analyzed the CPUE of biomass ($g \times m^2 \times h$) and of abundance (number of fish $\times m^2 \times h$) of fish caught, because the sampling efforts varied slightly among the sampled lakes. We also analyzed commercial fish species only, which were considered fish species that represented more than 1% of the total biomass landed in the studied fishing villages (Hallwass and others 2011). The mean duration of the fish sampling was 9.5 $\pm$ 3.5 h, usually from 08:00 to 17:00 h, and the mean fishing effort was 3.2 $\pm$ 1.1 km^2 of gillnets. We compared biomass, abundance and size (standard length) of fish with respect to two spatial scales: among sampled lakes (four samples from each lake) and among four regions, each one including three lakes and one fishing village located nearby, except for the Ituquara region, which included three lakes and two fishing villages (Ituquara and Umarizal) (Figure 1). Although these regions were arbitrarily defined, they are geographically separated (Figure 1), and these regional divisions have been recognized by fishers in their management initiatives. We used the generalized linear model (GLM) to analyze the influence of the independent variables (regions and lakes nested in regions) on the following dependent variables: biomass, abundance, and size (standard length) of fish (one model for each dependent variable). We sampled three lakes in each of the four regions (12 replicates) and each lake was sampled during each of the four seasons the year (48 replicates).

We analyzed the reproductive status of a random sampling of 1,713 individual specimens of 55 fish species, through visual inspection of gonadal development (color and size). We measured fish reproduction in terms of the proportion of fish observed to be in the reproductive stage (with ripe gonads or empty gonads) in relation to the total number of fish analyzed for reproduction in each lake. We compared the proportion of fish in the reproductive stage among regions (considering lakes as replicates) using the non-parametric Kruskall–Wallis test. We conducted this analysis for the entire sampling period and for the high water season, which is the fish spawning season in the studied region (Silvano and others 2009a). We cannot compare the proportions of fish reproducing in the different lakes because some did not have fish in the reproductive stage.

We identified and deposited individuals of each fish species as voucher specimens in the National Institute for Amazonian Research (INPA), except for some larger and more common fish, which were identified on site. We compared the fish species richness of the regions (summing all species collected in the four samples from each lake) through an analysis of variance (ANOVA). We were not able to compare species richness among individual lakes because we caught too few individual fish (10 or fewer) in some lakes.

We checked the similarities in fish species composition among the studied regions using a non-metric multidimensional scale analysis (NMDS), considering each lake as a replicate. We used the Bray–Curtis similarity index, the values of which we calculated using the proportion of biomass of each fish species in each sample unit (lake). We also checked for statistical significance in the observed similarities in fish assemblages through an analysis of similarities (ANOSIM), followed by a similarity percentage (SIMPER) analysis to verify which species contributed most to the observed patterns. We included 96 fish species in these multivariate analyses. Some fish species from the same genus were grouped together because the species were morphologically similar and we could not distinguish among them in our samples.

Environmental Influences on Fish Biomass

We recorded the values of six environmental parameters at each lake, on a local scale: depth (m), pH, dissolved oxygen, conductivity, water transparency (measured using a Secchi disc), and temperature. We made from one to three measures of these parameters at each lake (usually at the middle of the lake), depending on the lake size, but we used the average of all measures of each parameter for each lake. We converted these six local parameters into a single local environmental index for use in the analyses. We ordered the 12 lakes according to these six local parameters (normalized as value − mean × standard deviation^{-1}) through a principal component analysis (PCA) using the Bray–Curtis similarity index. The scores of the first axis generated by the PCA analysis, which accounted for 40% of the variance in the local environmental data among the lakes, were then used to determine the value of a local environmental index for each lake. All score values were made positive by adding a constant (5) to all. We also analyzed the following geographic parameters for each lake: the lake's area, the distance from the Tocantins River, the distance from the city (Baião), and the distance from the nearest village. We made these measures from a reference map of the study region during the low water season at a 1:100,000 scale, considering linear distances. We compared local and geographic parameters among the four studied regions, considering lakes as replicates to avoid pseudo-replicates of geographic parameters, which were measured only once at each lake.

We conducted regression analyses for each environmental parameter (the independent variables being the local environmental index, the lake's area, the distance from the river, the distance from the city, and the distance from the nearest village) versus the CPUE of the biomass of fish (dependent variable, Table 2).

We compared all models containing the three independent variables that influenced fish biomass among lakes (Table 2) through the Akaike Information Criterion (AIC). We calculated the ΔAIC, which is the difference between the current model and the best model of those considered (the one with the lowest AIC), w_i, which is the probability of a given model being the best model, and pseudo-r^2, which is the amount of variance explained by the model. We transformed the CPUE using natural logarithm, which allowed the use of the Gaussian distribution in the GLM models. The variables distance from the city and distance from the nearest village were also transformed (distance^2) for a better adjustment of the residuals. The models were

Table 2. Influence of Independent Variables on Fish Biomass

Independent variable (s)	r^2 (model)	df[3]
Lake area (m^2)	0.001	10
Lake's distance from the Tocantins River (m)	0.45*	10
Lake's distance from the main city (m)[1]	0.4*	10
Lake's distance from the nearest fishing village	0.004	10
Lake's environmental data[2]	0.01	10

Simple linear regression results of the influence of environmental variables on the dependent variable catch per unit of effort of biomass of fish sampled ($g \times h \times m^2$) in floodplain lakes (n = 12) of the Tocantins River, Brazilian Amazon.
[1]*The main city is Baião, where there is a major city market in the studied region (Hallwass and others 2011).*
[2]*Values of the first PCA axis for each lake, based on data of six environmental variables: pH, temperature, depth, dissolved oxygen, conductivity, and water's transparency.*
[3]*Degrees of freedom for the residuals.*
**Significant at $P < 0.05$.*

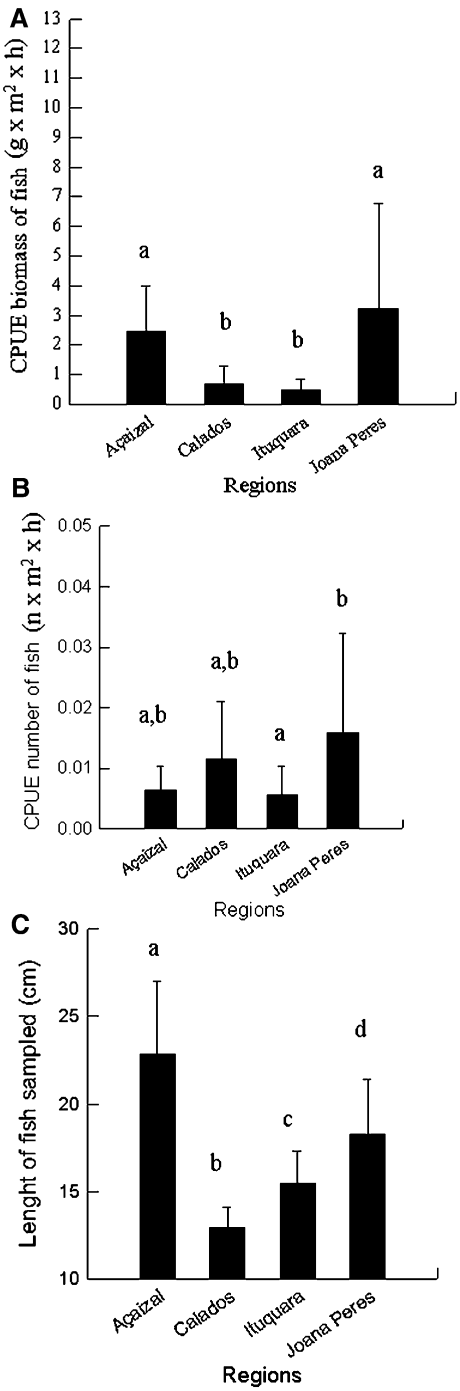

Figure 2. Comparison among lakes in the four studied regions in the Lower Tocantins River (Brazilian Amazon) regarding mean (±standard deviation) of **A** catch per unit of effort (CPUE) of fish biomass (g × m^2 × h); **B** CPUE of fish abundance (individuals × m^2 × h); and **C** fish standard length. *Letters above bars* refer to significant distinct means according to the Tukey post hoc test.

run on R statistical package (Team 2008). We analyzed environmental influences on fish biomass only because this parameter reflects fishing production in the studied region (Hallwass and others 2011).

We also compared the mean values of each environmental parameter among the studied regions using ANOVA analyses and post hoc Tukey tests when the ANOVA revealed significant effects.

Fishing Parameters

We sampled 590 fish landings (6.7 t of fish caught) in the five studied villages on 67 non-consecutive days in four hydrological seasons: flooding (December 2006), high water (March 2007 and February 2008), receding water (June 2007), and low water (September 2007). Fish landings were sampled throughout the day (07:30–18:00 h) on 2–5 days in each village. We sampled the fish landings in the villages on consecutive days, except for some occasions when two observers surveyed two villages simultaneously. We weighed the fish caught and we interviewed fishers about the fishing grounds and habitats exploited, fishing gear used, and duration of fishing. We used these data to calculate the CPUE of fisheries (kg of fish caught × h^{-1} × $fisher^{-1}$). Fishers caught 57 fish species (or groups of species), but nearly half of the biomass of fish caught (48%) corresponded to three fish species: the pescada, *Plagioscion squamosissimus* (Sciaenidae); curimata, *Prochilodus nigricans* (Prochilodontidae); and mapara, *Hypophthalmus marginatus* (Pimelodidae) (Hallwass and others 2011). We compared the CPUE of fish landings among the five fishing villages using the Kruskall–Wallis test.

For all above analyses comparing mean values, for the regressions and the GLM, the data were previously transformed ($\log_{10} + 1$) to attempt to obtain normal distributions. We used non-parametric tests, such as Kruskall–Wallis, in cases in which normal distributions were not obtained.

Results

Ecological Parameters: Fish

The CPUE of biomass ($r^2 = 0.43$, $F = 7.7$, df = 3, $P < 0.01$; Figure 2A) and abundance ($r^2 = 0.38$, $F = 3.3$, df = 3, $P < 0.05$; Figure 2B) of fish differed among the regions, but not among the lakes (biomass, $F = 0.49$, df = 8, $P = 0.86$ and abundance, $F = 1.44$, df = 8, $P = 0.21$, respectively). We observed a greater fish biomass (Figure 2A) in the regions of Açaizal and Joana Peres and greater fish abundance in Joana Peres (Figure 2B). The fish sizes were different among the regions ($r^2 = 0.82$, $F = 0.82$, df = 3, $P < 0.01$; Figure 2C) and among the lakes ($F = 3.7$, df = 8, $P < 0.01$): fish of smaller sizes were caught in Calados, and fish of larger sizes

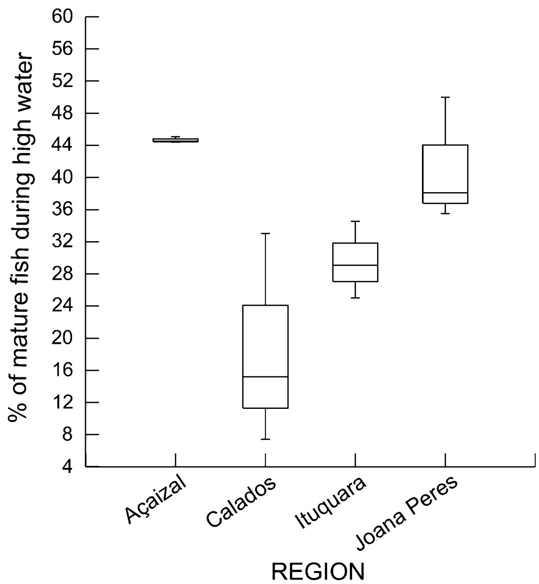

Figure 3. Comparison of median (*lines inside boxes*) values of the proportion of reproductive fish among lakes in the four studied regions in the lower Tocantins River, Brazilian Amazon, during the high water season.

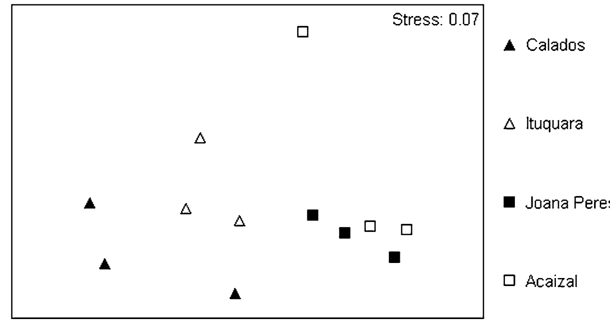

Figure 4. Ordination plot of the 12 studied lakes in the four regions in the Lower Tocantins River generated by NMDS analysis based on composition of fish species (biomass).

were caught in Açaizal and Joana Peres (Figure 2C). The CPUE of biomass of commercial fish also differed among the regions but not among the lakes, and the commercial fish sizes were different among the regions and lakes ($P < 0.05$ in all analyses). However, the CPUE of abundance of commercial fish did not differ among the regions ($H = 5.1$, df = 3, $P = 0.17$) or among the lakes ($H = 16.5$, df = 3, $P = 0.12$).

The fish species richness in lakes did not differ among the regions ($F = 1.3$, df = 3, $P = 0.35$) and ranged from 27 to 53 species, with a mean of 42 (±9) species per lake. The relative amount of fish reproducing did not differ among the four regions ($H = 6.3$, df = 3, $P = 0.1$) for all seasons considered together, but the relative amount of fish reproducing was higher in the lakes of the villages of Açaizal and Joana Peres during the high water season ($H = 8.7$, df = 3, $P < 0.05$; Figure 3).

The NMDS ordination showed a low stress value (0.07), which indicates a reliable pattern. The composition of fish assemblages (on biomass) differed among the four regions (ANOSIM, $P > 0.05$ for all paired comparisons between regions) (Figure 4). The SIMPER analysis identified nine fish species that contributed most to the observed differences among the regions: the armored catfish (*Pterygoplichthys joselimaianus*) was more abundant in Açaizal and Joana Peres, the catfish (*Oxydoras niger*) was more abundant in Açaizal, the commercial fish curimata and tucunare (*Cichla kelberi*) were more abundant in Joana Peres, the commercial fish pescada was more abundant in Calados, and the ueua (*Acestrorhynchus falcirostris*), which is of low value, was more abundant in Calados and Ituquara (Figure 5).

Environmental Influences on Fish Biomass

We did not observe any relationship between the CPUE of fish biomass and the local environmental parameters (pH, temperature, depth, dissolved oxygen, conductivity, and water transparency), the lake's area, or the lake's distance from the nearest fishing village (Table 2). However, we observed a positive relationship between the biomass of fish caught and the lake's distance from the Tocantins River (Figure 6A) and the distance from the main city in the region (Baião) (Figure 6B; Table 2). Both the distance from the river ($F = 4.5$, df = 3 $P < 0.05$; Figure 6A) and the distance from the main city ($F = 31.1$, df = 3, $P < 0.01$; Figure 6B) differed among the regions: the lakes sampled in Açaizal and Joana Peres were more distant from the Tocantins River (although the post hoc Tukey comparison did not detect any significant differences, possibly due to the large variances) and from the main city, compared to the lakes sampled in Calados, which were closer to the Tocantins River (Figure 6A) and the city (Figure 6B).

The AIC value was lower for the model containing all three variables (region, distance from the river, and distance from the city), but only region was significantly related to the fish biomass (Table 3). Furthermore, all models containing region showed lower (and thus better) values of AIC and ΔAIC, besides higher values of w and pseudo-r^2, compared with those models without region

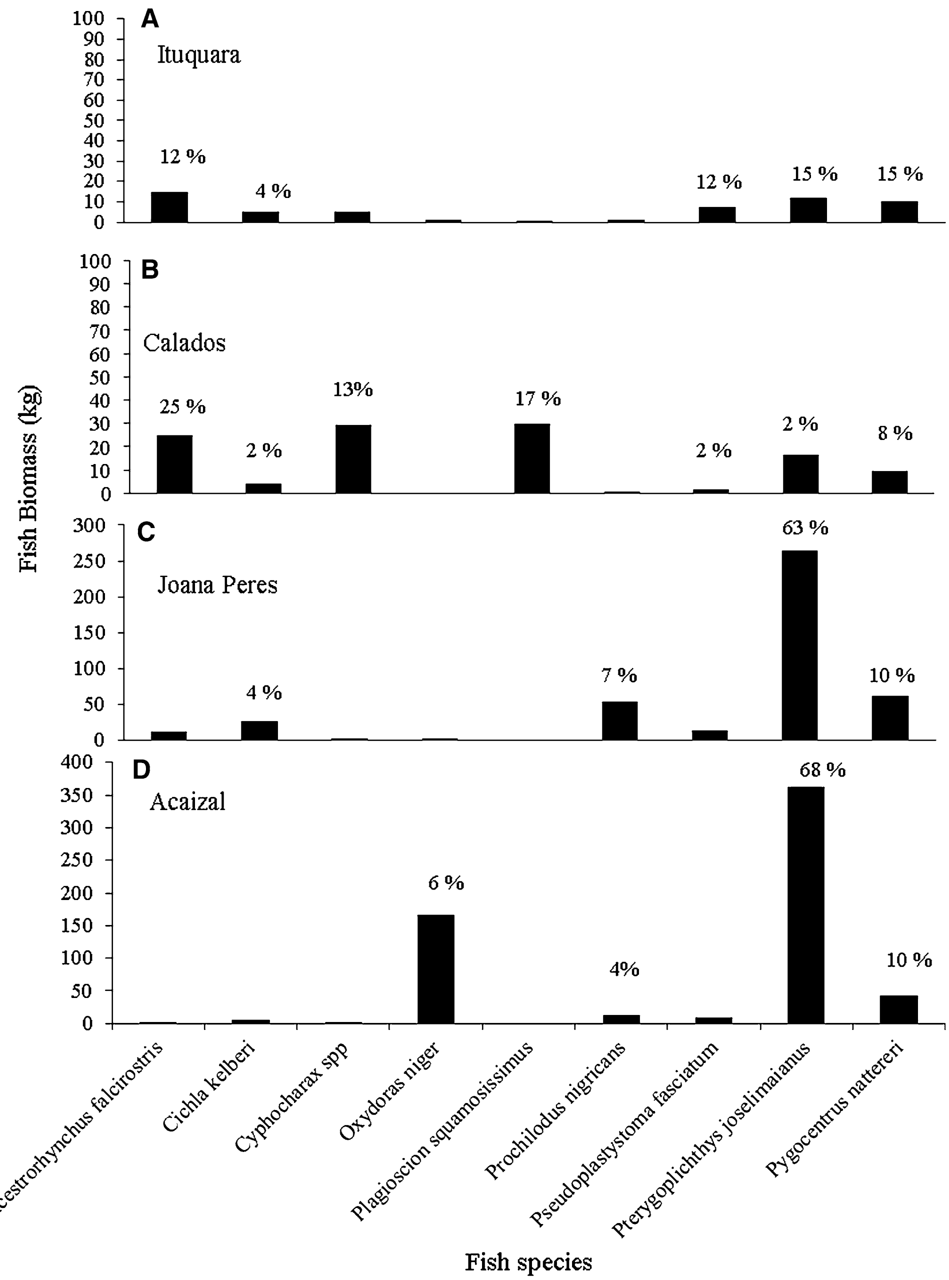

Figure 5. Biomass of fish species that contributed most to the observed similarities among lakes in the studied regions of **A** Ituquara, **B** Calados, **C** Joana Peres, and **D** Açaizal, in the Lower Tocantins River (Figure 4), according to SIMPER analysis. *Numbers above bars* are the percent contribution of each species in each region; notice the smaller scale in Ituquara and Calados.

(Table 3). The model containing only region showed the second smallest AIC value (Table 3). Therefore, the model comparison indicated that region, and possibly co-management, was a more important factor influencing the biomass of fish sampled in lakes than the lake's geographical location. This may be due to three lakes in the co-managed regions, two from Joana Peres and one from Açaizal, which were outliers, having higher fish biomass than expected given their distances from the Tocantins River (Figure 6A). Considering their distances from the main city (Baião), two lakes from Joana Peres (co-managed) had higher fish biomass than expected, whereas one lake from Ituquara (unmanaged) had lower fish biomass than expected (Figure 6B).

Fishing Parameters

The villages of Açaizal and Joana Peres had a higher CPUE of fish caught, considering all fish landings together ($H = 15.8$, df = 4, $P < 0.01$; Figure 7A) and considering only the fish landings from lakes (H = 12.7, df = 4, $P < 0.01$; Figure 7B). The Tocantins River was the habitat most often exploited by the fishers (n = 216 fish landings, $\chi^2 = 128.4$, df = 3, $P < 0.01$), considering the 573 fish landings sampled over the four seasons that had habitat data, whereas lakes were exploited in 151 fish landings, mostly during the seasons of low and receding water (103 of 258 fish landings).

Discussion

Our first hypothesis of a potential influence of co-management was confirmed: the lakes in the regions where fishers have been more involved in co-management (Açaizal and Joana Peres) have yielded fish of larger sizes, greater fish abundance, and greater fish biomass (considering either all fish or only commercial fish), as well as a higher proportion of reproducing fish in high-water season. We observed differences in the biomass and abundance of fish among the regions, but not among the lakes within regions, indicating that these differences reflected regional patterns, which could have been at least partially influenced by co-management. Furthermore, the regions, which were arbitrarily defined, have had ecological significance, because each region had a distinct fish assemblage. Although the higher fish biomass in the lakes of Açaizal could be due to a predominance of fish of low value and large size, such as armored catfish and catfish, the lakes of Joana Peres had a higher biomass of commercial fish, such as curimata and tucunare. In the Mamirauá reserve (in the central Amazon), the lakes that are closed to fishing also have a higher abundance of commercial fish (Silvano and others 2009b). Furthermore, in the two villages engaged in co-management, the fishers caught more fish, indicating that the higher fish biomass in the lakes near these villages may have increased fish catches. We did not conduct detailed interviews to investigate the social status and welfare of the fishers, as done in other studies (Cinner 2005; Sultana and Thompson 2007; Solomon and others 2012). However, knowing that the fishers in the studied region rely heavily on fish for food and income (Hallwass and others 2011), we considered that any improvement in fish catches would also improve their socioeconomic conditions and increase their food security (Sultana and Thompson 2007). Although not regularly exploited in the Tocantins River basin, the armored catfish is an important commercial fish in other Amazonian regions (Castello and others 2011). Therefore, the higher abundance of this fish in the lakes in the co-managed regions (Figure 5) may serve as insurance against future fish shortages.

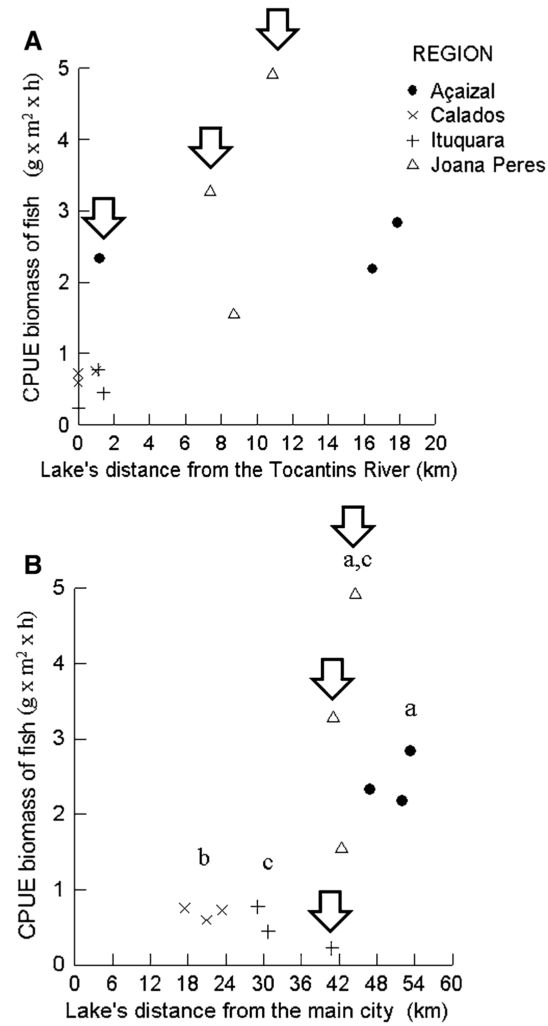

Figure 6. Relationships between catch per unit of effort fish biomass (g × m^2 × h) and lake's distance from **A** the Tocantins River's margin and **B** the main city (*letters* refer to significant distinct means of distance according to the Tukey post hoc test), in the four studied regions in the Lower Tocantins River, Brazilian Amazon. Outliers (lakes that had fish biomass higher or lower than expected given their distances) are indicated by *arrows*.

Despite showing a similar general profile among villages, fishers in Açaizal are more dependent on fishing as a commercial activity, which may be partially related to their commitment and interest to engage in co-management. Conversely, fishers from Calados are also dedicated to small-scale agriculture and do not regularly commercialize the fish caught (Table 1), which may partially explain the previous failure of a co-management established by these fishers that was dismissed due to difficulties of enforcement. It is noticeable that

Table 3. AIC Comparison of General Linear Models (GLM)

Model	Independent variables	Pseudo r^2	AIC	ΔAIC[3]	w[4]
1	Regions*[1] + distance from the Tocantins River (m) + distance from the main city (m)[2]	89.6	18.22	0	0.42
2	Regions* + distance from the Tocantins River (m)	84.3	21.05	2.83	0.10
3	Regions* + distance from the main city (m)	86.3	19.41	1.19	0.23
4	Distance from the Tocantins River (m) + distance from the main city (m)	42.3	32.65	14.43	0.00
5	Regions*	84.1	19.25	1.03	0.25
6	Distance from the Tocantins River (m)	34.4	32.19	13.97	0.00
7	Distance from the main city (m)	40.3	31.06	12.84	0.00

Akaike coefficients of information theory (AIC) of General Linear Models (GLM) checking the influence of three independent variables (region, lake's distance from river margin and lake's distance from the main city) in the dependent variable catch per unit of effort of biomass of fish sampled ($g \times h \times m^2$), in floodplain lakes (n = 12) of the Tocantins River, Brazilian Amazon.
[1]*Categorical variable with four levels: Açaizal, Calados, Ituquara and Joana Peres.*
[2]*The main city is Baião, where there is a major city market in the studied region (Hallwass and others 2011).*
[3]*Difference in the AIC value between the model and the best model considered.*
[4]*w is the probability that a model is the best model of the set.*
* *Significant at $P < 0.05$.*

most of the fishers' fathers also practiced fishing as their main activity in the villages of Açaizal and Joana Peres: such a tradition of fishing among generations may have influenced the stronger organization of fishers from these two villages towards co-management of exploited lakes.

Our second hypothesis of regional difference in fish biomass among lakes being more relevant than environmental differences was partially confirmed. Only two of all the environmental variables analyzed were found to have a positive relationship to fish biomass: the distance of the lakes from the main city and their distance from the river. Lakes that are closer and are thus connected to the river are expected to have higher fish biomass because some Amazonian fish do migrate between lakes and rivers (Fernandes 1997), especially during the flood pulse of the high-water season (Junk and others 1989). However, the distance of the lakes from the Tocantins River may be related to their accessibility to fishers, especially those from the city or from outside the studied villages. Hence, distant lakes may be less exploited due to the longer time required to reach them and the higher associated fuel costs. The interaction of the effects of the accessibility of lakes and co-management could have contributed to the higher fish biomass that we observed in the villages of Joana Peres and Açaizal. We could not fully discriminate between these two effects, but it is difficult to separate management and geographic effects in the Amazon, where management usually includes large areas (MacCord and others 2007). Moreover, a distinction between geographic and management effects may be meaningless in the studied region because the geographic effect can facilitate the enforcement of management measures: the tributaries that provide access to the managed lakes are located near the villages (Figure 1) and thus fishers can better guard the tributaries. In the Mamirauá reserve, hunting of caimans has been sustainable because large females are safe from hunters in distant lakes that are less accessible (Silveira and Thorbjarnarson 1999). On the other hand, in the co-management of coral reefs in the Pacific, reefs that are closer to fishing villages have been shown to have higher fish abundance because these reefs can be more easily guarded (Campbell and others 2012), and those reefs closer to fishing communities are considered as being more suited to co-management (Hamilton and others 2011). Therefore, the influence of distance in co-management may vary depending on the ecosystem and the intensity of fishing pressure: it may be that there are more potential intruders than people engaged in management in the studied region, making the accessible lakes more difficult to patrol. However, the AIC analysis indicated that models including region performed better than models including distance (without region). This may be due to some lakes in the managed regions (Açaizal and Joana Peres) that had higher fish biomass than expected considering their distances from the main river (Figure 6A), besides one lake in the unmanaged region (Ituquara) that had a lower fish biomass than expected considering its distance from the city (Figure 6B). Therefore, even considering the influence of geographical location, regional differences seemed to be a more important factor

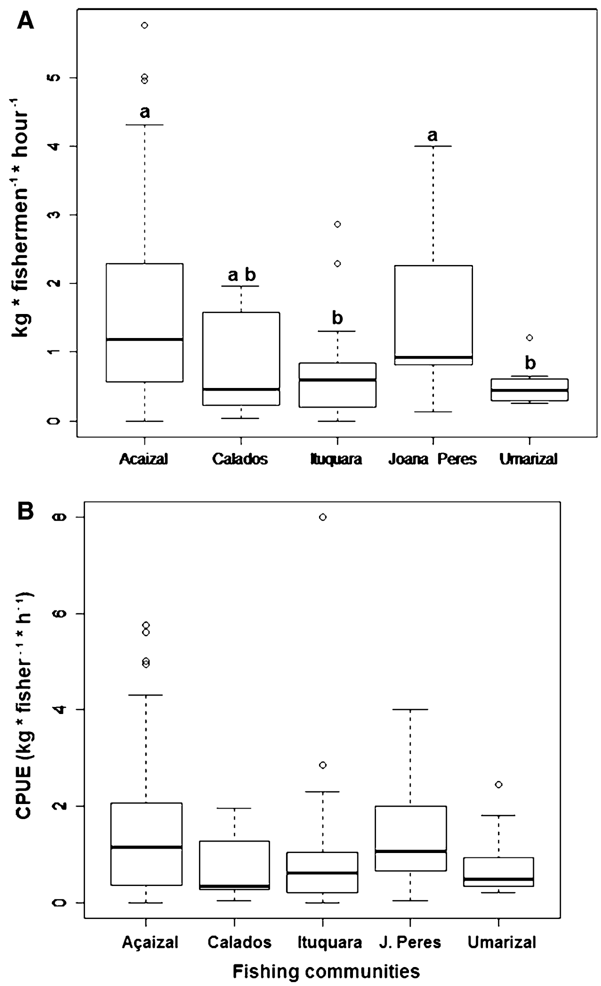

Figure 7. Comparison of median (*lines inside boxes*) values of the biomass catch per unit of effort of fish landings in the Lower Tocantins River among the five studied villages considering **A** all seasons and habitats; and **B** only fish landings from lakes during the low and receding water seasons.

affecting fish biomass sampled in lakes, indicating at least a partial influence of co-management.

One limitation of our survey is that we could not apply the rigorous before–after-control-impact (BACI) sampling design, which is usually required for studies on the efficacy of management interventions, such as reserves or protected sites (Guidetti 2002). We therefore cannot unambiguously associate the observed regional differences to co-management alone, due to the lack of this before–after comparison, even considering that we properly compared control-impact areas (the four regions and their fishing villages and lakes). For instance, we cannot guarantee that fish abundance increased in the lakes of Joana Peres and Açaizal because of co-management intervention, or if fishers decided to establish regulations for fishing in those lakes because they already had greater fish abundance. Considering that we observed an increased fish abundance in managed lakes, there would be four possible scenarios from before the co-management started: (1) fish abundances differed, being already higher in managed lakes; (2) fish abundances differed and were higher in non-managed lakes; (3) fish abundances did not differ and were lower than observed; (4) fish abundances did not differ and were higher than observed. Of all these previous scenarios, only (1) would indicate no influence of the co-management (fish abundance was already higher in managed lakes).

Moreover, all our results regarding fish abundance, fish size, and fishing yields converged to show higher values in lakes and regions involved in co-management: such a pattern is unlikely to occur by chance, and higher fish abundances should be partially related to co-management, besides the geographical strategic position of the managed lakes. Indeed, fishers from the village of Calados mentioned that they had co-management in the past and that increased fish catches for a while, but this co-management was no longer in place at the time of our survey. Therefore, fish stocks may respond relatively quickly to fishing restrictions in the studied region, as the main commercial fish species seem to be resilient to fishing and environmental impacts (Hallwass and others 2013a, 2013b). Also, our results agree with those from previous studies in the Brazilian Amazon, which show higher fish biomass or fish landing in sites subjected to co-management compared with unmanaged sites (MacCord and others 2007; Almeida and others 2009; Silvano and others 2009b; Castello and others 2011), but it should be noted that these surveys also lacked BACI sampling. Relatively few surveys have evaluated co-management effects in the Brazilian Amazon, only a few included short time series of data (Castello and others 2009, 2011), and none, to our knowledge, has employed the BACI approach. This is possibly due to the difficulty in implementing the BACI experimental design in the Brazilian Amazon, especially regarding co-management initiatives. Co-management arrangements are unpredictable and complex socio-ecological systems: they may suddenly appear and vanish, being largely controlled by political and social factors, which are usually out of the reach of researchers. In the Tocantins River (and in most existing co-management systems in the Brazilian Amazon), fishers usually decide to manage their floodplain lakes themselves, and only after co-management has started do they seek support from the government or researchers. Indeed, notwithstanding its importance, the BACI experimental design has been rarely adopted, even in the much better studied marine and reef fisheries (Francini-Filho and Moura 2008): most of the knowledge base and recommendations about the benefits of marine protected areas and other management approaches have been based on studies that lack BACI sampling (Guidetti 2002).

We thus consider that our results could be useful to improve knowledge on the potential ecological and fishing effects of co-management systems in tropical rivers. There are many co-management arrangements already in place or being implemented in the Brazilian Amazon and in other tropical developing countries, most of which lack any kind of regular monitoring or empirical scientific data. For example, in the Lower Amazon River Basin, 77 co-management arrangements (fishing accords) have been implemented from 1981 to 1996 (Castro and McGrath 2003), but only a few have evaluated the efficacy through fish or fisheries surveys (Almeida and others 2009; Castello and others 2011). Therefore, following a data-less management approach (Johannes 1998), any empirical data could contribute to improve management decisions. We recognize the risk of assuming positive outcomes of co-management when it had no effect, but we consider that this would be less risky than assuming that co-management had no effect when it actually had positive outcomes. Co-management may provide other benefits beyond increases in fish abundance or fish catches, for example, by strengthening community organization, promoting dialogue among fishers and government officers, reducing conflicts, and increasing fishers' environmental awareness (Shepherd and others 2004; Sultana and Thompson 2007; Gelcich and others 2008b). Nevertheless, even considering that our results provide partial support for the co-management in the Tocantins River, more research should be done there and elsewhere in the Brazilian Amazon, to improve experimental design and to accumulate temporal trends to more accurately address co-management outcomes. Meanwhile the best available empirical evidence should be used to support management decisions (Hallwass and others 2013b); otherwise decisions will continue to be based solely on political and social considerations.

The results of our analysis of the Tocantins River basin reinforce the available evidence elsewhere that co-management may increase fishing production (McClanahan and others 1997; Sultana and Thompson 2007; Campbell and others 2012), abundance of target species (McClanahan and others 2006; Hamilton and others 2011; Campbell and others 2012), or both (Lorenzen and others 1998; Castilla and Defeo 2001; Cinner 2005; Gelcich and others 2008a). Although co-management may exhibit poorer performance in conservation when compared to closed areas (McClanahan and others 2006), co-management may be a feasible conservation alternative in tropical developing countries in which closures of fisheries could cause conflicts and could threaten food security (Cinner 2005; Sultana and Thompson 2007). Few lakes and rivers have been closed to fishing in the Brazilian Amazon (Junk and others 2007), and such conservation measures have been weakly enforced; thus lakes and rivers that have been closed are vulnerable to poaching. However, spatially defined fishing closures (for example, a lake or a reef) have successfully enhanced fish biomass when embedded in co-management systems, as observed in this study and in studies in other tropical regions (Cinner 2005; Sultana and Thompson 2007; Silvano and others 2009b; Hamilton and others 2011). Co-management in the Tocantins River basin has increased the abundance and size of target fish but not fish diversity, as in other co-management systems in tropical countries (McClanahan and others 1997, 2006; Silvano and others 2009b). This may be because these co-management systems usually seek to increase the availability of fishing resources rather than maintain fish diversity (McClanahan and others 1997, 2006).

Compared to the co-management in the Tocantins River basin, other successful systems of co-management have strong governmental support, such as on the coast of Chile (Castilla and Defeo 2001), or have been implemented in relatively undisturbed environments with reduced fishing pressure (Lopes and others 2011). The studied co-management system in the Tocantins River basin is more similar to the fishing agreements in Amazonian lakes, which usually follow fishers' demands and have little or no external support (Castro and McGrath 2003). Although these agreements have increased fishing production (Almeida and others 2009), they occur in white water rivers, which carry larger amounts of nutrients and are more productive than rivers with black or clear water (Henderson and Crampton 1997; Crampton 1999; Junk and others 2007), such as the Tocantins River. In addition to the disadvantages imposed by a less productive ecosystem, fishers in the lower Tocantins River basin have to cope with the detrimental effects of a large dam upstream, such as reductions in the diversity and abundance of fish (Petrere 1996; Merona and others 2010; Hallwass and others 2013a). Although the co-management system of the village of Joana Peres has been formally recognized by the Brazilian government in the form of an extractive reserve (Lopes and others 2011), the fishers there have received little external support, such as funding or help to enforce management measures. Therefore, despite the adverse effects of a dam upstream, lower fishing productivity, and lack of external support, our results indicated that this co-management system may have been useful to maintain fish abundance and fish catches in managed regions. Among the factors that may influence the potential management efficacy in the studied region are the protection of lakes that are important spawning grounds for fish (Figure 3), the commitment of local fishers, and strategically located managed lakes. Similarly, community-based management has succeed to increase fish abundance in coral reefs, by protecting critical spawning habitats where these fish aggregate to spawn (Hamilton and others 2011).

The ecological and fishing benefits of the co-management initiatives in the Tocantins River basin are encouraging and indicate that co-management could be a viable strategy for addressing the heterogeneity of fisheries in the Amazon (Castello and others 2013), and a viable alternative to protected areas. Co-management may also help to maintain the sustainability of fisheries in large tropical rivers impacted by dams.

ACKNOWLEDGMENTS

We thank the fishers for their cooperation, Eletronorte Staff, S. Gasparotto and M. Clauzet for helping in the fieldwork, J.A.S. Zuanon for fish identifications, L.L. Silva and L. Locatelli for map drawing, the IBAMA for a permit to collect fish, the FAPERGS and PROPESQ/UFRGS for funding to present this work in a conference, the CNPq for Research Grants to R.A.M.S. (304377/2010-4) and to A.B., the FAPESP for Research Grant to R.A.M.S (2012/16722-2), and Eletronorte/ANEEL (Contract 4500057477) for funding the research and for Research Grants to G.H., P.F.L., A.R.R., R.P.L., H.H., A.B. and R.A.M.S.

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