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Assessment of efficiency and impacts of gillnets on fish conservation in a tropical freshwater fishery

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ABSTRACT

1. Gillnets are commonly used in tropical multi-species fisheries and there is a need to investigate the comparative efficiency and impacts of this gear on fish populations and diversity. The efficiency and the impact of gillnets of distinct mesh sizes were compared in the Lower Tocantins River (Brazilian Amazon).
2. Fish sampling was conducted in 12 floodplain lakes using gillnets of distinct mesh sizes and 345 fish landings were recorded. Indicators of gillnet efficiency were: (1) catch per unit of effort (CPUE) of total fish sampled; (2) CPUE of fish caught by fishers; (3) CPUE of commercial fish sampled; and (4) proportion of biomass of commercial fish sampled. Indicators of impact were: (1) the number of non-commercial fish (by-catch); (2) the proportion of fish above the length at first maturity; (3) mean fish size (length); (4) total number of fish species and of rare fish species caught.
3. Gillnets of 8 cm mesh size showed a higher CPUE in fish samples and fish landings. This mesh size also showed reduced impacts (lower numbers of non-commercial fish caught and higher proportion of adult fish).
4. Gillnets of 6 cm mesh size caught a smaller proportion of adult fish, smaller fish, more species and more rare species. Therefore, intensive use of these gillnets could increase the risk of regional species extinctions and impair the provision of ecosystem services by target fish.
5. Gillnets of 8 cm mesh size could improve fish catches while minimizing adverse effects of gillnet fishing. The practical management recommendation would be to replace the more damaging small mesh gillnets by gillnets with intermediate mesh size. This recommendation could simultaneously protect small-sized rare species and larger fish, being broadly applicable to other small-scale and multi-species fisheries that use gillnets intensively in tropical countries with high fish diversity.
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KEY WORDS: catchment management; environmental impact assessment; fish; fishing; floodplain; gillnet; lake; mesh sizes; river; sustainability

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INTRODUCTION

Small-scale multi-species and multi-gear inland fisheries are an important source of food and income for millions of people, especially in tropical developing countries (Abbott *et al.*, 2007; Coomes *et al.*, 2010), but management and research needs of these fisheries have not been properly considered (Welcomme *et al.*, 2010). Managing such fisheries is necessary for biodiversity conservation, especially in tropical environments with rich aquatic biodiversity, where there is an increasing demand for fish to sustain many impoverished fishers (Allan *et al.*, 2005). Fishers' behaviour is a potential driver of overfishing and is thus one of the most important aspects of fisheries management and biodiversity conservation (Hilborn, 2007; Fulton *et al.*, 2011). Fishers' behaviour and knowledge are linked to the choice of fishing gear and habitats, which influences the amount of fish caught, economic yields, kind of fishing resource exploited and associated fishing impacts (Wiyono *et al.*, 2006; Silvano *et al.*, 2008; Cinner *et al.*, 2009).

Fixed gillnets are passive gears set in a fishing ground for several hours, selecting fish according to the gillnet mesh size and the corresponding fish size and shape (Reis and Pawson, 1999; Petriki *et al.*, 2014). Intensive use of gillnets, especially those with smaller mesh sizes, can threaten biodiversity through by-catch of juvenile commercial fish or endangered species of megafauna, such as cetaceans, caimans, turtles or seals (Stewart *et al.*, 2010; Shester and Micheli, 2011). Increasing fishing effort with fixed gillnets can also increase the conflicts and negative interactions between fishers and aquatic predators, such as sea lions or dolphins (Gonzalvo *et al.*, 2015; Machado *et al.*, 2016). Gear restrictions, including those on the mesh sizes of fishing nets, can reduce fishing impacts in an ecosystem-based management framework, especially when spatial closures are socially unacceptable (McClanahan and Cinner, 2008; Cinner *et al.*, 2009; Hicks and McClanahan, 2012). However, gear restrictions that have sometimes been imposed by managers without empirical evidence may have caused social conflicts and affected the local economy and food security of small-scale fishers (Mati'c-Skoko *et al.*, 2011; Hicks and McClanahan, 2012; Hallwass *et al.*, 2013a).

In inland fisheries that rely on gillnets, the intensity of overfishing and its ecological consequences are usually aggravated by the fishing-down process, by which mesh sizes are reduced to catch smaller fish and maintain fishing yields (Welcomme, 1999; Welcomme *et al.*, 2010). Several studies have compared the efficiency and impacts of fishing gear and potential outcomes of gear restrictions in tropical marine multi-species fisheries (McClanahan and Mangi, 2004; Mangi and Roberts, 2006; McClanahan and Cinner, 2008; Cinner *et al.*, 2009). Nevertheless, fewer studies have investigated the yields and impacts of gillnets with distinct mesh sizes in inland fisheries (Schindler *et al.*, 1998; Petriki *et al.*, 2014), especially in tropical biodiversity hotspots, such as in the Brazilian Amazon.

The Brazilian Amazon Basin, an important hotspot for freshwater fish diversity, is also home to widespread small-scale inland fisheries that rely mostly on gillnets (Bayley and Petrere, 1989; MacCord *et al.*, 2007; Isaac *et al.*, 2008). In some Amazonian regions fishing pressure may have driven a large commercial fish, the pirarucu (*Arapaima gigas*), to local extinction (Smith, 1985; Castello *et al.*, 2015), and excessive fishing may have had an impact on ecological functions of frugivorous and detritivorous fishes (Mcintyre *et al.*, 2007; Anderson *et al.*, 2011). Besides intensive fishing of some preferred larger fish species, Amazonian fish fauna have been threatened by large-scale habitat changes owing mainly to deforestation and river impoundment (Petrere, 2006; Junk *et al.*, 2007, Winemiller *et al.*, 2016), which may have caused regional extinctions of commercial fish species (Hallwass *et al.*, 2013b). Such large-scale habitat changes in aquatic ecosystems of the Brazilian Amazon have not been adequately addressed by current development policies of the Brazilian government (Fearnside, 2001), nor by existing conservation areas, which aim to protect terrestrial ecosystems (Castello *et al.*, 2013). Moreover, these other impacts external to fisheries, such as deforestation or river impoundment, may adversely affect fish

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production or act synergistically with overfishing to impair ecological functioning and reduce aquatic biodiversity (Allan *et al*., 2005; Winemiller *et al*., 2016).

According to official regulations, beach seines of any kind and gillnets with mesh sizes smaller than 7 cm are forbidden in Brazilian continental waters. However, the remote and widespread small-scale fisheries in the Brazilian Amazon are difficult to enforce and many fishers continue to use gillnets with forbidden mesh sizes (Fernandes *et al*., 2009). Such lack of compliance with fishing restrictions may be partly a result of the lack of incentives for impoverished fishers to change their fishing practices (Hanna, 1998; Begossi *et al*., 2011). Studies comparing the efficiency and potential impact of gillnets with distinct mesh sizes can provide empirically based advice to managers on mesh sizes that could achieve the highest yields with the lowest impacts (Rueda and Defeo, 2003). Moreover, experimental fishing methods can be useful for assessing the ecological effects of fishing gear (Jennings and Polunin, 1997; McClanahan and Cinner, 2008).

The goal of this study was to compare the fishing efficiency and impacts of gillnets of distinct mesh sizes in a large Amazonian river, through fish sampling and fisheries data. The catch per unit of effort (CPUE) was calculated to measure fishing efficiency, and four indicators were adopted to measure fishing impacts: (1) number of non-commercial fish caught (by-catch); (2) proportion of fish caught that were above the length at first maturity, as an indirect inverse measure of recruitment overfishing (Froese, 2004), since catching fish below length at first maturity will reduce the reproductive potential of the population; (3) average size of fish caught, as gillnets with smaller mesh sizes would catch small fish and reduce the overall size structure of the fish assemblage (Allan *et al*., 2005; Froese *et al*., 2015); and (4) total number of fish species and of rare species caught, as an indicator of potential threats to fish biodiversity. Identifying which gillnet mesh sizes catch more fish with less impact can provide scientific support to management decisions aimed at maximizing the trade-off between conservation and socioeconomic outcomes.

METHODS

Study site

The Tocantins River is a 2750 km clear-water river on the eastern Brazilian Amazon, draining an area of 343 000 km^2. The Tucuruí Dam was built on this river in 1984 to supply hydroelectric power

Table 1. Dependent variables included in the analyses to compare the efficiency and impacts among four gillnet mesh size categories (06, 08, 10–12, and 14–16 cm), which were the independent (predictor) variable, in lakes in the Lower Tocantins River, Brazilian Amazon

Dependent variable	Data transformed ($\log_{10}$ +1) to achieve normality	Unit	Purpose
CPUE of all fish	Yes	g km^{-2} h^{-1}	Efficiency: food security
CPUE of commercial fish[a]	Yes	g km^{-2} h^{-1}	Efficiency: economic return
Individuals of non-commercial fish caught	Yes	number	Impact: indirect measure of potential by-catch[b]
Proportion of individuals of fish caught that were larger than the size at first maturity[c]	No	%	Impact: inverse measure of recruitment overfishing[d]
Fish standard length	No	cm	Impact: potential reduction in fish size
Number of fish species and rare fish species caught	No	number	Impact: potential threat to biodiversity

[a]Commercial fish were defined as those fish species that corresponded to more than 1% of biomass landed, according to fisheries data for the region studied (Hallwass *et al*., 2011)
[b]These fishes could possibly have been discarded if caught by fishers on a regular basis.
[c]The analysis of this variable included a subset of replicates (*n* = 44 lakes), because some gillnet mesh sizes did not catch any of the 16 selected commercial fish species (Table 2) in some lakes, thus precluding estimation of size at first maturity.
[d]The desirable target for this variable would be 100% of fish caught above the size at first maturity (Froese, 2004), hence if a gillnet mesh size caught a lower proportion of individuals larger than the size at first maturity (less than 50%), it can be considered prone to cause recruitment overfishing.

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Table 2. Size at first maturity (total length in cm) of 16 commercial fish species regularly caught by fishers in the Lower Tocantins River, Brazilian Amazon

Fish species	Size at first maturity (cm) [a]	Percentage of total biomass landed [b]
Astronotus crassipinnis[c]	15.2	5.3
Astronotus ocellatus[c]	26.8	5.3
Chaetobranchus flavescens[c]	13.5	5.3
Cichla kelberi[d]	17.2	5.6
Cichla pinima[d]	30	5.6
Curimata inornata[e]	9.2	8.4
Curimata vittata[e]	12.2	8.4
Geophagus altifrons[c]	14.3	5.3
Geophagus proximus[c]	14.3	5.3
Hypophthalmus marginatus	29.3	11.2
Leporinus affinis[f]	15.7	5.6
Leporinu sfriderici[f]	26.7	5.6
Plagioscions quamosissimus	21.8	28.6
Prochilodus nigricans	22.3	10.7
Psectrogaster essequibensis[e]	11.1	8.4
Satanoperca jurupari[c]	12	5.3

[a]Based on information in Fishbase (Froese and Pauly, 2011).
[b]Data about composition of fish landings from Hallwass *et al.* (2011), total landed biomass =6.85 t of fish.
[c]These species were grouped in fish landings according to the local name *carás* and hence have the same percentage value (Hallwass *et al.*, 2011).
[d]These species were grouped in fish landings according to the local name *tucunarés* and hence have the same percentage value (Hallwass *et al.*, 2011).
[e]These species were grouped in fish landings according to the local name *branquinhas* and hence have the same percentage value (Hallwass *et al.*, 2011).
[f]These species were grouped in fish landings according to the local name *aracus* and hence have the same percentage value (Hallwass *et al.*, 2011).

and flooded an area of 2830 km^2, affecting fish communities and fisheries in the region downstream (Petrere, 2006; Silvano *et al.*, 2009; Hallwass *et al.*, 2013b).

A survey was conducted in the Lower Tocantins River (between 02°50′944″; 49°45′511″ and 03°06′ 210″; 49°37′872″), about 100 km downstream from the Tucuruí Dam. People living along the Tocantins River are riverines (descendants from Portuguese and Indians, as well as immigrants from north-eastern Brazil) who make a living from small-scale fisheries, agriculture and cattle husbandry (McGrath *et al.*, 2008; Hallwass *et al.*, 2011). Small-scale fishers in the Lower Tocantins River use small paddled canoes, the main fishing gears are gillnets and hand-lines, and the main fish caught for commerce and subsistence are pescada (*Plagioscion squamosissimus* – Sciaenidae), curimata (*Prochilodus nigricans* – Prochilodontidae) and mapara (*Hypophthalmus marginatus* – Pimelodidae) (Hallwass *et al.*, 2011). The data on fish communities in lakes (fish sampling) and on fishing are from the same database that supported previous studies in this same region (Hallwass *et al.*, 2011, 2013a; Silvano *et al.*, 2014).

Fisheries sampling: fishing efficiency of gillnets

In the Lower Tocantins River 345 fish landings (each landing corresponded to a fishing trip) were recorded in five field trips (67 days in total) in all major hydrological seasons: flooding (11 days in December, 2006), high water (26 days in March, 2007 and in February, 2008), receding water (14 days in June, 2007) and low water (16 days in September, 2007). Fish landings were sampled from 07:30 to 18:00 at the most frequently used landing sites in five fishing villages, from 2 to 5 consecutive days in each village. Fishers were interviewed upon arriving for a fishing trip about the fishing gear used, the fishing ground visited and duration of the fishing trip; fish caught were weighed in species groups according to their local names (one or more biological species). Fishers used gillnets to catch 5.03 t of fish. More details about the sampling of fish landings and fishing dynamics in the region studied are in Hallwass *et al.* (2011).

The mesh sizes of gillnet used by fishers were grouped in four categories for analysis: 6 cm (5, 6 and 7 cm, n = 200 fish landings), 8 cm (8 and 9 cm, n = 65), large (10–14 cm, n = 13), mixed (any other size combinations – for example, gillnets with mesh sizes of 6 and 12 cm, n = 67). These categories were assigned to allow comparisons with categories adopted in fish sampling (see below). The CPUE (g km^{-2} h^{-1}) of all fish caught (dependent variable) in each sampled fish landing (replicate) was compared among the four categories of mesh sizes (independent variable) through a non-parametric Kruskal–Wallis (H) analysis. This analysis was used because data were not normally distributed, even after log transformation. The aquatic habitats exploited by fishers were grouped in two

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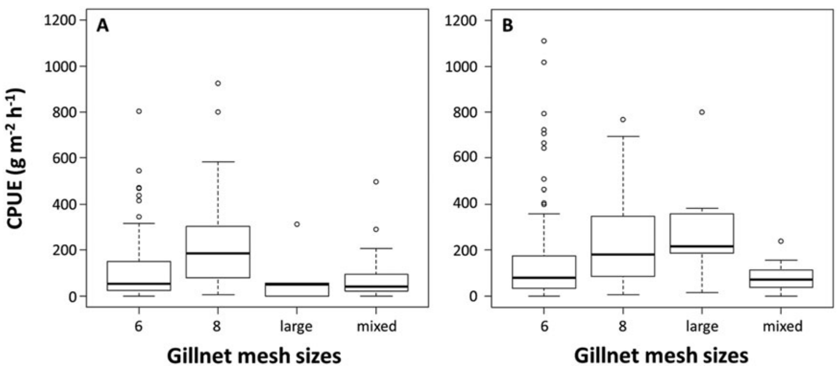

Figure 1. Comparison of the catch per unit of effort (CPUE) among categories of mesh sizes of gillnets (cm between opposite knots), recorded in fish landings in the Lower Tocantins River, Brazilian Amazon, showing the median (line inside the box), minimum and maximum values (vertical lines), 25% and 75% quartiles (outer lines of the box), and outliers (dots), for (a) floodplain lakes: 6 cm (5, 6 and 7 cm, *n* = 78 fish landings), 8 cm (8 and 9 cm, *n* = 29), large (10 cm and larger, *n* = 6), mixed (any combination of previous categories, *n* = 37); (b) main Tocantins River channel and tributaries: 6 cm (*n* = 122), 8 cm (*n* = 36), large (*n* = 7), mixed (*n* = 30). One outlier of CPUE =1964 g m^{-2} h^{-1} for mixed gillnets in the Tocantins River is not shown in Figure 1(b)

major categories: lakes (all lentic habitats) and river (the main channel of the Tocantins River and their tributaries, or all lotic habitats). Fish landings from lakes (*n* = 150) and from the river (*n* = 195) were analysed separately to check for habitat influences on gillnet efficiency and because fish were sampled only in lakes (see below).

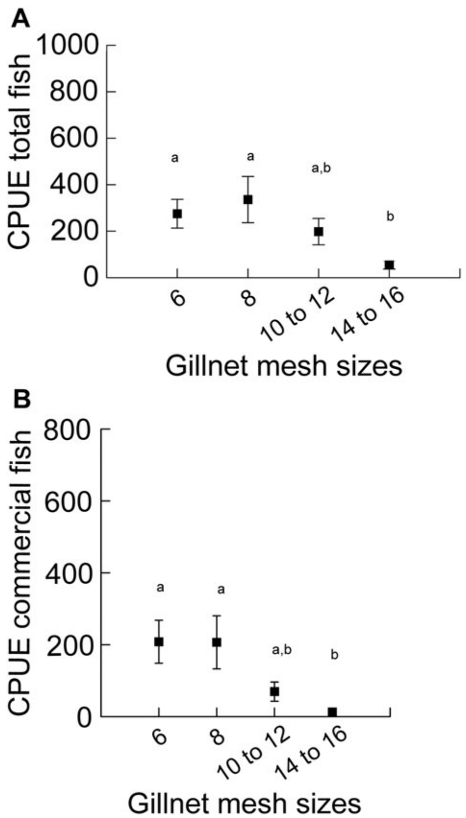

Figure 2. Mean ± standard error (SE) catch per unit of effort (CPUE, g m^{-2} h^{-1}) of four categories of mesh sizes of gillnets (cm between opposite knots): 6 cm (*n* = 12), 8 cm (*n* = 12), 10–12 cm (*n* = 12), and 14–16 cm (*n* = 12), from fish samples in 12 lakes in the Lower Tocantins River, Brazilian Amazon, considering (A) all fish; and (B) commercial fish only. Distinct letters indicate means that differed from each other (Tukey test, $P > 0.05$)

Fish sampling: indicators of fishing efficiency and impacts

Twelve floodplain lakes in the region studied were sampled (*n* = 48 samples, four samples per lake) during four hydrological seasons (high, receding, low and rising water, respectively in the months of February, June, August/ September and November/ December), using gillnets with mesh sizes of 6, 8, 10, 12, 14 and 16 cm. Each sample had a mean duration of 7.8 ± 0.9 h during daytime (from 09:00 to 17:00 h) and occurred simultaneously with fish landings' sampling in the villages (see above). Lakes were sampled twice during the high water season, when it is more difficult to catch fish, but these repeated samples were pooled for analyses. These samples yielded 3933 individuals and 1.3 t of fish, which were individually weighed, measured (standard length, cm) and voucher specimens of one or more individuals of each species were deposited in the collection of the Instituto Nacional de Pesquisas da Amazônia (Inpa). Some large and conspicuous fish were identified in the field, by consulting the literature (Santos *et al*., 2004).

Data were pooled for the four hydrological seasons and for larger mesh sizes (10–12, and

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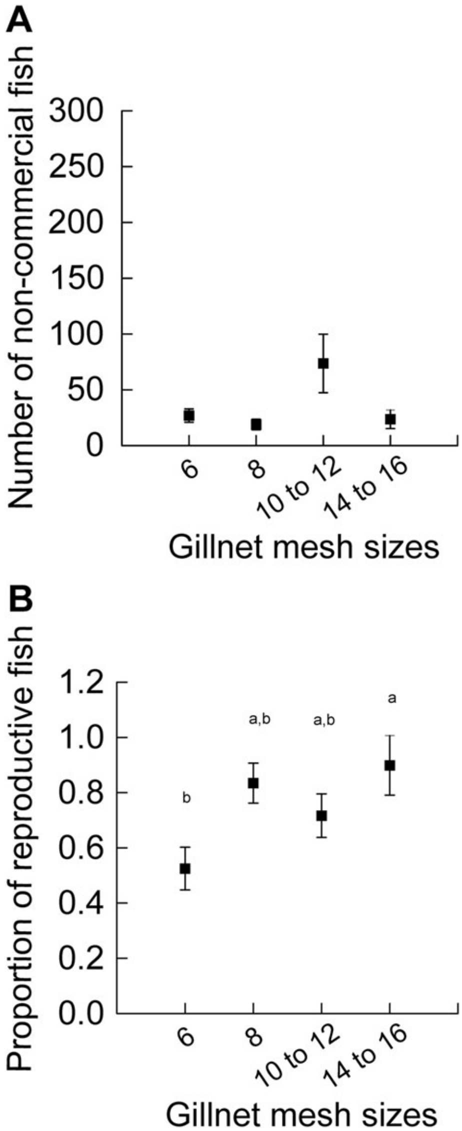

Figure 3. Measures of impacts (mean ± SE) of four categories of mesh sizes of gillnets in 12 lakes in the Lower Tocantins River, Brazilian Amazon: 6 cm (n = 12), 8 cm (n = 11), 10–12 cm (n = 12), and 14–16 cm (n = 9). (A) Number of individuals of non-commercial fish caught (by-catch); (B) proportion of fish caught that were larger than the size at first maturity. Letters a and b indicate means that differed from each other (Tukey test, $P > 0.05$)

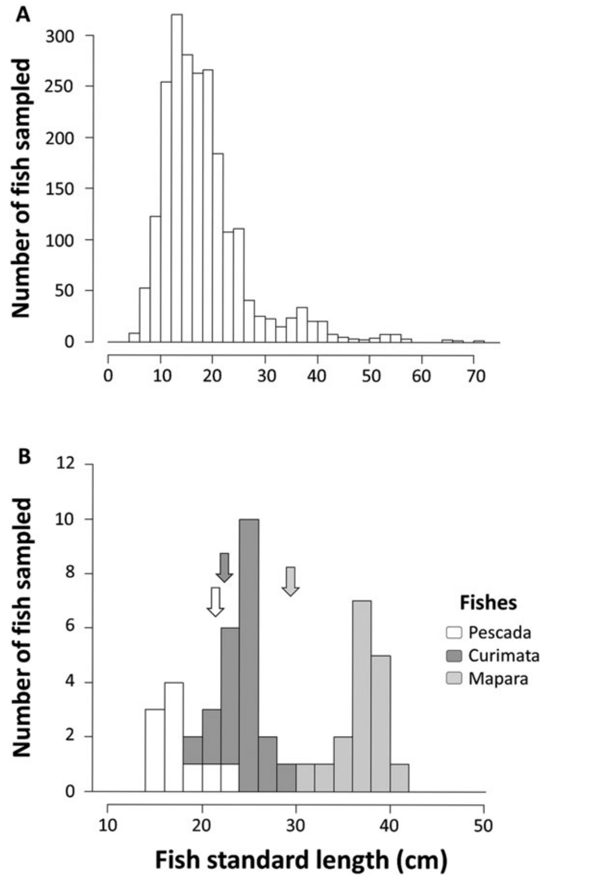

Figure 4. Length–frequency distribution of fish sampled using gillnets in 12 lakes in the Lower Tocantins River, Brazilian Amazon, considering (A) all commercial fish species (n = 2216) caught with all mesh sizes; (B) the three main commercial fish species caught with 8 cm mesh size: pescada, *Plagioscion squamosissimus* (n = 10, mean length = 18.1 ± 2.8 cm), curimata, *Prochilodus nigricans* (n = 24, mean length = 24.1 ± 2.3 cm) and mapara, *Hypophthalmus marginatus* (n = 17, mean length = 37.7 ± 2.6 cm). The arrows indicate the sizes at first maturity of these three species according to the literature (Table 2), pescada and curimata have approximately the same size (22 cm)

14–16 cm) to avoid a large number of no-catches (zero data), thus the analyses included four categories of gillnet mesh sizes (6, 8, 10–12, and 14–16 cm) in 12 lakes (48 replicates). Three indicators of efficiency regarding economics and food security and four indicators of impacts (dependent variables) were compared among these four mesh sizes (independent variables) through analysis of variance (one-way ANOVA) and Kruskal–Wallis for non-normal data (Table 1). Size at first maturity (one of the indicators of impact) were obtained from the literature (Froese and Pauly, 2011) for 16 commercial fish species, each comprising more than 5% of total fish biomass landed in the region studied (Table 2). Before running the ANOVA analyses, the normality of data was checked through Kolmogorov–Smirnov One Sample Test analysis. Data that were not normal were $\log_{10}$ transformed before analysis (Table 1). The residuals of the ANOVA analyses were checked for problems of heteroscedasticity.

The total number of fish species sampled (species richness) with each category of gillnet mesh size was compared. Because each mesh size caught a

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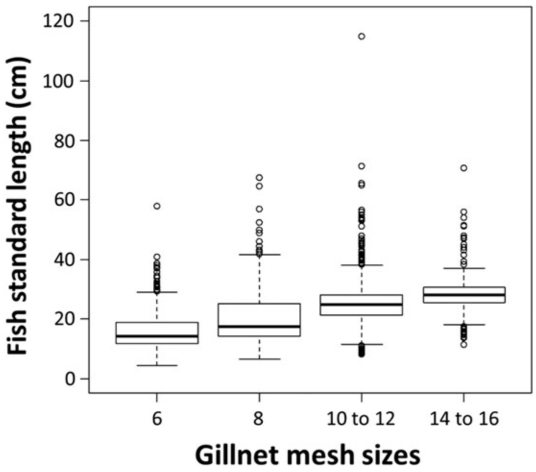

Figure 5. Median (line inside the box), minimum and maximum values (vertical lines), 25% and 75% quartiles (outer lines of the box), and outliers (dots), for size of fish (standard length in cm, n = 3933 individuals) sampled with the four mesh sizes in the Lower Tocantins River, Brazilian Amazon

different number of individuals, rarefaction curves were calculated using the software of Krebs (1989) to compare the total species richness among mesh sizes. A fish species was considered rare in the samples if its abundance corresponded to less than 1% of the total number of individuals (n = 10 378) of 101 fish species sampled in floodplain lakes of the Tocantins River (Silvano *et al*., 2014). This criterion of 1% abundance follows a previous study of fish diversity in the Brazilian Amazon (Hercos *et al*., 2013). The total number of rare fish species caught was also compared among mesh sizes. A similar analysis was not possible for fish caught by fishers, because species in the catches are usually grouped in more inclusive categories that combine distinct species or genera (Hallwass *et al*., 2011), which may hide rare species.

RESULTS

Efficiency: fisheries

Fish landings from the 8 cm mesh size gillnet category had a higher CPUE than other mesh sizes in lakes (H = 22.1, df = 3, $P < 0.001$, Figure 1(a)). Similarly, fish landings from the 8 cm mesh size and from the large categories had a higher CPUE than other mesh sizes in the Tocantins River (H = 20.7, df = 3, $P < 0.001$, Figure 1(b)). The CPUE did not differ between lakes and rivers (Mann–Whitney U = 12900.5, df = 1, P = 0.06) and a higher CPUE was observed for gillnets with 8 cm mesh size in both habitats (Figure 1(a), 1(b)).

Efficiency: fish

The analyses of all fish biomass indicated a lower CPUE for the largest mesh size of 14 to 16 cm (n = 48, r^2 = 0.3, $F_{3,44}$ = 7, $P < 0.01$, Figure 2(a)), and a higher CPUE for 6 and 8 cm mesh sizes, whereas gillnets with 10–12 cm mesh size showed an intermediate value (Figure 2(a)).

This same pattern was observed for commercial fish as a subset of the total catch: mesh sizes of 6 and 8 cm had a higher CPUE, whereas the largest mesh sizes had the lowest CPUE (n = 48, r^2 = 0.53, $F_{3,44}$ = 16.5, $P < 0.001$) (Figure 2(b)).

Impacts: fish

The number of non-commercial fish caught did not differ among the four mesh size categories (n = 48, r^2 = 0.731, $F_{3,44}$ = 0.13, P = 0.11), despite the trend of a higher number of non-commercial fish being caught by gillnets of 10–12 cm (Figure 3(a)). A lower proportion of fish above the size at first maturity were caught by gillnets of 6 cm, compared with the other mesh sizes (n = 44, r^2 = 0.22, $F_{3,40}$ = 3.7, $P < 0.05$, Figure 3(b)). Indeed, about half of the individuals caught with 6 cm mesh size were below the size at first maturity (non-reproductive) (Figure 3 b). Nevertheless, most of the fish sampled in lakes were smaller than 24 cm (mean length = 18 cm ± 8.4 cm, median length = 16.8 cm, Figure 4(a)). Of the three main commercial fish species sampled in lakes with gillnets of 8 cm mesh size, most of the individuals of curimata (*P. nigricans*) and mapara (*H. marginatus*) were caught above the size at first maturity, whereas most of the individuals of pescada (*P. squamosissimus*) were non-reproductive (Figure 4(b)).

Size of fish caught differed among mesh sizes (H = 1534.9, df = 3, $P < 0.001$): smaller fish were caught with gillnets of 6 cm mesh size (Figure 5). The range of fish sizes caught (minimum,

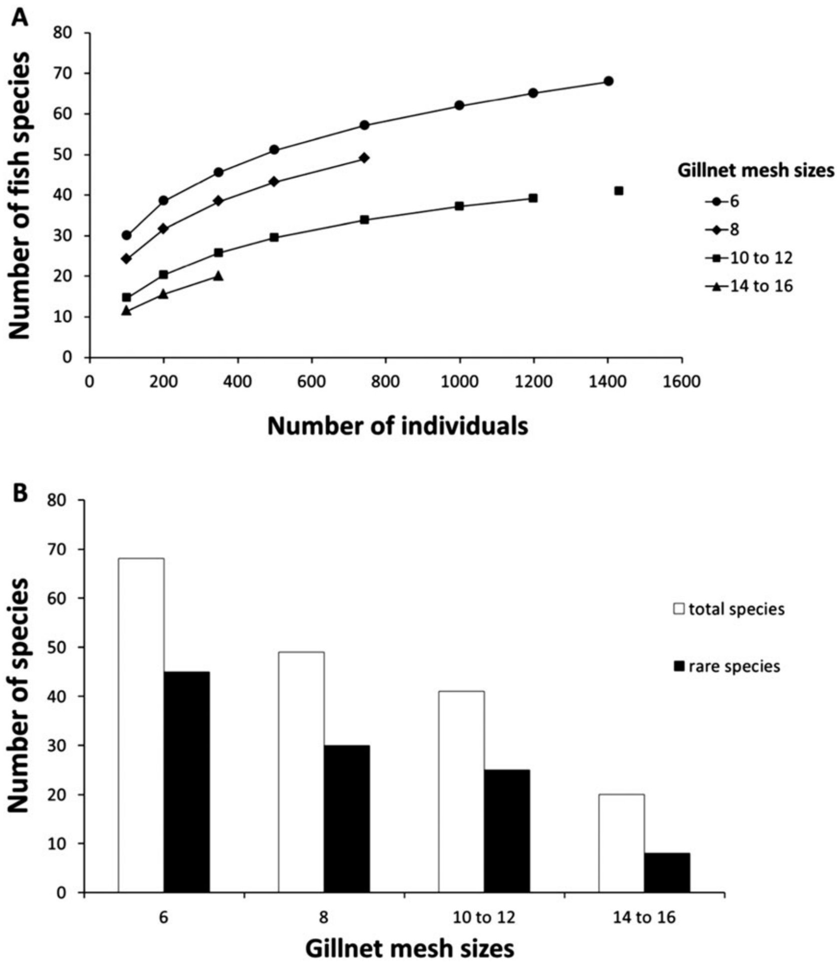

Figure 6. Fish species sampled in the Lower Tocantins River, Brazilian Amazon. (A) Rarefaction curves estimating the number of fish species sampled with each gillnet mesh size. (B) Number of fish species and rare fish species sampled with the four gillnet mesh sizes

maximum and median size in standard length) in each mesh size were: 6 cm mesh size (min. = 4.2 cm, max. = 57.8 cm, median = 14.5 cm); 8 cm mesh size (min. = 6.5 cm, max. = 67.5 cm, median = 17.5 cm); 10–12 cm mesh size (min. = 8.3 cm, max. = 115 cm, median = 25 cm); and 14–16 cm mesh size (min. = 11.5 cm, max. = 70.6 cm, median = 28 cm).

The total number of fish species sampled differed among mesh sizes. According to the rarefaction curves, gillnets of 6 cm mesh size caught more fish species at all sample sizes (Figure 6(a)). The number of rare fish species was high and accounted for a relatively constant proportion of the total number of fish species sampled; both total number of species and number of rare species were inversely related to gillnet mesh size and gillnets with 6 cm mesh size caught more rare species (Figure 6(b)).

DISCUSSION

Fishers usually prefer to use fishing gear that shows a higher efficiency (CPUE) (Mati'c-Skoko *et al.*, 2011). In some tropical inland fisheries, the use of gillnets with varied mesh sizes can assure a greater diversity of fish and help secure fishing yields in seasons when fish availability is reduced (Silvano and Begossi, 2001). In the Lower Tocantins River, efficient gear include gillnets with small mesh sizes (5 and 6 cm) that are forbidden by law, but regularly used by fishers (Hallwass *et al.*, 2011,

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2013a, 2013b). However, results from both fish sampling and fish landings in this study indicated a higher efficiency (CPUE) of gillnets with 8 cm mesh size, which showed also lower impacts and caught a higher proportion of adult fish. Furthermore, a smaller mesh would not yield more predictable catches for fishers, as the coefficient of variation of the CPUE of gillnets of 8 cm mesh size (0.85) was lower than that of gillnets of 6 cm mesh size (1.3).

The practical recommendation to managers arising from this study would be to convince fishers to replace gillnets with 6 cm mesh size or smaller, which have the greater impacts and are forbidden by law, with 8 cm mesh size. Fishers would not experience reduced catches with gillnets of 8 cm mesh size, which could thus provide the required balance between fishers' needs and fish conservation. This recommendation of using an intermediate mesh size could simultaneously protect small and large fish, producing effects similar to the simultaneous adoption of minimum and maximum size limits (Brousseau and Armstrong, 1987). Similar gear management has been proposed in other tropical aquatic ecosystems. In heavily exploited coastal fisheries in Kenya, better enforcement of the legal minimum mesh size (6.35 cm), together with an increase in mesh sizes to 8.8 and 9.2 cm, could protect immature fish of two over-exploited reef fish species (Hicks and McClanahan, 2012). In a tropical estuary, experimental fishing showed that an increase in the mesh sizes of a type of encircling gillnet from 6.4 to 7.6 cm increased the median size of fish caught and reduced the probability of catching immature individuals of three of the most exploited estuarine fish species (Rueda and Defeo, 2003). Mesh with sizes of 6.4 cm can catch more fish but can also be harmful to spawning stocks, so in a risk-averse management strategy it is recommended that gillnets of 7.6 cm mesh size or of an intermediate size between these two are used (Rueda and Defeo, 2003). The mesh sizes recommended in previous studies are usually similar to that indicated here (8 cm) for the Lower Tocantins River, but this mesh size should not be considered a ubiquitous or generalized management measure, as the size of fish exploited can vary from place to place. For example, in Lake Victoria, East Africa, gillnets of 12.7 cm mesh size would be more effective in balancing the catches of the large and introduced fish *Lates* cf. *niloticus* with the need to reduce predation of this fish on smaller species of native fishes (Schindler *et al.*, 1998). The results from this study reinforce the management recommendations of adopting an intermediate mesh size among those commonly used by fishers and avoiding mesh sizes smaller than 6 cm. These recommendations could be broadly applicable to tropical multi-species fisheries where gillnets are used to catch small or medium sized fish (up to 30 cm) (Kyle, 1999; Mangi and Roberts, 2006; Hicks and McClanahan, 2012). The indicators and sampling approach adopted in this study could be useful for evaluating impacts of gillnets in other tropical inland fisheries lacking monitoring or detailed biological data, such as those in the Amazon (MacCord *et al.*, 2007; Hallwass and Silvano, 2015), Africa (Abbott *et al.*, 2007) or Southeast Asia (Valbo-Jorgensen and Poulsen, 2000; Gupta *et al.*, 2016).

A possible reason for the observed high CPUE of gillnets with 6 and 8 cm mesh size in the Lower Tocantins River could be that many commercial fish sampled were relatively small (less than 24 cm, Figure 4(a)) and the median lengths of fish caught by all categories of mesh sizes were less than 30 cm (Figure 5). This could be at least partly explained by the fact that smaller fish are usually more abundant in tropical fish assemblages (Silvano *et al.*, 2000, 2009). However, a predominance of small to medium sized fish (around 25 to 30 cm length) has been attributed to overfishing in other tropical ecosystems (lagoons) (Rueda and Defeo, 2003; Dankwa *et al.*, 2004). The fishing-down in inland fisheries occurs when fishers redirect fishing effort to small and fast growing species, after the sequential depletion of large fish (Welcomme, 1999; Allan *et al.*, 2005). Although there is evidence of fishing-down in some regions of the Brazilian Amazon (Castello *et al.*, 2013, 2015), fish species that decreased in abundance in the Lower Tocantins River according to experienced fishers were mostly small to medium sized migratory fish, which were possibly affected by the dam upstream (Hallwass

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et al., 2013b). Therefore, the predominance of small fish (less than 30 cm) in the Tocantins River might be attributable to several factors, including the natural dominance of smaller fish in fish assemblages, fishing pressure, habitat alterations (river damming) or the lower nutrient content of clear-water rivers.

Capture of immature fish may affect population growth and is among the most severe impacts of gillnets (Mangi and Roberts, 2006; Márquez-Farias, 2011; Hicks and McClanahan, 2012). One of the major challenges of gear restrictions in multi-species tropical fisheries is that a given gear (or in this case, mesh size) that is suitable for catching some species may be damaging for others (Froese *et al.*, 2015). Therefore, the widespread use of gillnets with 8 cm mesh size in the Brazilian Amazon and other regions could still be harmful to larger fish species, preventing the recovery of overfished stocks of large commercial fish (Castello *et al.*, 2015). The three commercial fish species caught the most, which at present account for 50.5% of total biomass landed in the Lower Tocantins River, are curimata, mapara and pescada (Hallwass *et al.*, 2011). The results of this study indicated that gillnets with 8 cm mesh size showed reduced impact on curimata and mapara. In an Amazonian estuary, pescada shows continuous spawning throughout the year and females mature earlier (at a shorter size of 16 cm) than males (Barbosa *et al.*, 2012). These characteristics of the reproductive life cycle may alleviate potential impacts of gillnet fishing on this fish, as adult females would have a greater chance to reproduce before being caught and continuous spawning increases the opportunities of reproduction. Nevertheless, gillnets with 8 cm mesh size could still have an impact on pescada in the Lower Tocantins River, as many fish sampled with this gillnet were below 16 cm (Figure 4(b)).

Gillnets with 8 cm mesh size may not be the fishing gear that causes the least impact in the Brazilian Amazon. However, more severe gear restrictions would probably not be accepted by fishers. Although recommended in the literature (Wiyono *et al.*, 2006; Shester and Micheli, 2011), a total ban of gillnets to reduce ecological impacts would considerably reduce the income of Brazilian inland fishers (Silvano and Begossi, 2001; Hallwass *et al.*, 2013a), who may not accept such a measure. For example, a total ban of gillnets in the Tocantins River would severely reduce fish catches, but prohibiting gillnets during the high water season (when fishers mostly use hand lines) would be more acceptable (Halwass *et al.*, 2013a). Therefore, gear restrictions could (and should) be applied in conjunction with other management tools (Hicks and McClanahan, 2012), such as spatial control of fishing areas by local fishers, no-take areas, fishing quotas or seasonal closures (Defeo and Castilla, 2005; Castello *et al.*, 2009; Silvano *et al.*, 2009; Begossi *et al.*, 2011). Indeed, co-management initiatives in the Lower Tocantins River have applied some of these management options, such as quotas and no-take lakes (Lopes *et al.*, 2011; Silvano *et al.*, 2014). These measures can protect larger fish species from potential harmful effects caused by gillnets (Hicks and McClanahan, 2012; Froese *et al.*, 2015). If stocks of large fish recover and the overall size of exploited fish increases, then minimum mesh sizes could be increased in an adaptive management scenario (Allan *et al.*, 2005; McClanahan and Cinner, 2008; Condy *et al.*, 2015).

Amazonian fish stocks that remain in good ecological condition (Junk *et al.*, 2007) can provide an invaluable opportunity to conserve aquatic ecosystems with a rich fish diversity. If fishers abandon gillnets of 6 cm mesh size in the Tocantins River, this may improve biodiversity conservation and the maintenance of ecosystem services, in accordance with guidelines for ecosystem-based management (Beard *et al.*, 2011). Gillnets with small mesh size can reduce fish size and exert high fishing pressure on small fish (Allan *et al.*, 2005; Welcomme *et al.*, 2010), which can lead to bottom-up impacts on the food chain (Essington *et al.*, 2015). Intensive fishing by gillnets in the Tocantins River could deplete populations or decrease the size of the large detritivorous fish from the genus *Prochilodus*, the curimata, which is important in recycling nutrients and transporting biomass in Neotropical rivers (Mcintyre *et al.*, 2007). Tropical fish assemblages, such as those in the Brazilian Amazon, usually

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have large numbers of rare species (Hercos *et al.*, 2013). The sampled lakes in the Tocantins River showed a high number of rare fish species with a dominance of five species that accounted for 38% of the total numerical abundance of fish. Although at least some of these species may be rare in the sampled lakes but more abundant in other aquatic habitats or in other Amazonian regions, the numerical distribution still shows many fish species with few individuals each. Gillnets with 6 cm mesh size caught more fish species and rare species in the Tocantins River, thereby increasing the risk of regional extinction of rare fish. Regional extinctions may further impair ecosystem services, as some rare fish species have relevant ecological functions in freshwater ecosystems (Pendleton *et al.*, 2014).

Small-scale inland and coastal fisheries are coupled socio-ecological systems and management has to address the trade-offs between potential impacts of fishing gear and fishers' economic needs (Hicks and McClanahan, 2012; Condy *et al.*, 2015). Comparing the efficacy of distinct fishing gear, or in this case gillnets with distinct mesh sizes, can contribute in reconciling fisheries management and conservation goals (McClanahan and Cinner, 2008), among other measures that address the needs of impoverished fishers to catch fish for food and sale (Begossi *et al.*, 2011). Most of the fishers studied are commercial fishers who regularly sell their catches (Hallwass *et al.*, 2011). The revenues obtained by fishers in the Lower Tocantins River are positively related to the biomass of fish caught per fishing trip, suggesting that the biomass of fish caught (or CPUE) can be considered a valid proxy of financial rewards (Hallwass *et al.*, 2013a). In such a context, the results of this study indicated that an increase in mesh size of gillnets would not reduce the CPUE and fishing rewards in the Lower Tocantins River, which may increase fishers' compliance with this management measure. This study provides comprehensive analyses of fish landings and experimental fishing, which support current fishing regulations regarding gillnet mesh size. The results also provide managers with reliable arguments for convincing fishers to change their current fishing practices and increase compliance with existing management regulations.

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