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Effects of deforestation and other environmental variables on floodplain fish catch in the Amazon

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ABSTRACT

Floodplains comprise a complex mosaic of seasonally-flooded forests, lakes and channels that support productive fisheries. These habitats and their fish populations are increasingly threatened by a variety of human pressures, including floodplain deforestation. However, the effects of multiple human pressures on these floodplain fisheries have not been studied in the Amazon River. Here, we investigated the combined effects of forest cover, river water level, fishing effort and distance from nearest urban center on the catch of the most exploited fish taxa. Our study integrated fisheries, hydrological, geographical, and satellite land cover change data for 21 floodplain lake systems over a ten-year period. We found that an ANCOVA model explained 91% of the variation in catch ($p < 0.001$) and, as usual, fishing effort was the most influential variable. Floodplain forest exerted a positive effect on fish catch, implying that a loss of 1 km^2 of floodplain forest induces up to 9% decreasing in fish catches. In addition, high river water level and distance from urban centers also had a positive effect on fish catches; even though, low river water levels did not present such effect. These results provide support to previous findings regarding the effects of habitat, hydrological, and human variables on floodplain fish catch. More importantly, these results provide the first ever quantitative evidence of the effect of floodplain deforestation on fish catch. Our findings point out the need to develop an ecosystemical approach to manage floodplain fisheries in the Amazon and elsewhere in the world.

1. Introduction

River-floodplains of the Amazon River comprise a complex mosaic of seasonally-flooded forests connected by lakes and canals, including the Amazon River itself (Junk et al., 1989). The seasonal dynamics between dry and flooded phases of this ecosystem ensure the survival of many species of plants and animals, including fish populations, which are targeted by local fisheries (Batista and Petrere, 2007; Isaac et al., 2008). Within this environment, floodplain lakes regulate fishery productivity by providing refuge, nursery, breeding and feeding grounds to fish populations (Goulding, 1980; Welcomme, 1990).

Fishing in the Amazonian floodplain lakes constitutes a major economic activity (Almeida et al., 2011), providing food and income for local human populations (Cabral and Almeida, 2006; Isaac and Almeida, 2011). Previous studies have shown that fish catches in floodplains are strongly influenced by seasonal (Valderrama and Petrere, 1994; Mérona, 1995; Isaac et al., 2012) and inter-annual (Mérona and Gascuel, 1993; Castello et al., 2015a; Isaac et al., 2016) variations in river water levels. Other habitat factors are also known to influence fish catches, including flooded area (Welcomme, 1990), connectivity between aquatic and terrestrial zones (Nolan et al., 2009), and distance between lakes and cities (Silvano et al., 2014), and floodplain habitat type (Batista and Petrere, 2007; Martelo et al., 2008; Castello et al., 2018).

In the Amazon, around 12 fish taxa are intensely exploited, and the stocks of some large, slow-growing species (such as *Colossoma macropomum*, *Pseudoplatystoma tigrinum*, *Brachyplatystoma flavicans*, *Brachyplatystoma vaillantii*, and *Arapaima* spp.) have shown signs of overexploitation and even depletion (Isaac et al., 2004; Petrere et al., 2004; Ruffino, 2004; Castello et al., 2015b). In addition to fishing

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pressure, other thteats are causing impacts on the Amazonian floodplain fisheries, including deforestation and climate change (Freitas et al., 2013; Castello and Macedo, 2016).

Predictions of climate change effects in the Amazon Basin indicate that temperatures will increase during the dry season while rainfall will decrease (Ambrizzi et al., 2007; Betts et al., 2008; Christensen et al., 2013). Global climate phenomena such as the El Niño-Southern Oscillation leads to droughts in Amazonian rivers (Pinaya et al., 2016). Hotter and drier conditions may increase the mortality of trees in the Amazon through water stress and wildfires (Phillips et al., 2009; Doughty et al., 2015). Such increased tree mortality might exacerbate the ongoing destruction of floodplain forests, which have already been reduced by 70% for agricultural and cattle ranching purposes (Renó et al., 2016). Recent studies have estimated that the total area of forest in the Brazilian Amazon basin will decline from 7 to 34% in this century (Guimberteau et al., 2016), which is likely to have a knock-on effect on the commercially important fish populations that depend on floodplain forests (Ruffino, 2004; Castello and Macedo, 2016).

The effects of deforestation on fish richness, diversity, and abundance have been demonstrated in several experimental studies in floodplain lakes (Lobón-Cerviá et al., 2015; Arantes et al., 2018). However, only one study has focused on commercial fisheries; Castello et al. (2018) found a positive relationship between the amount of floodplain forest and multispecies catch per unit effort (cpue), but the variance explained in that study was low, indicating that other factors affect fish catches.

Here, we examined the combined effects of fishing pressure, floodplain deforestation, fluctuations in river water levels, and distances from urban centers on fish catches in the lower Amazon. This question has not been addressed in the Amazon or any other river-floodplain ecosystem in the world, despite growing threats to these fisheries and ecosystems (Lo et al., 2020).

2. Methods

2.1. Study area

We conducted our study in '*várzea*' floodplain habitats of the lower Amazon, between the municipalities of Prainha and Juruti, in the northern Brazilian state of Pará (Fig. 1). The study area covers approximately 260 km along the Amazon River. The flood pulse in this region has an amplitude of approximately 6 m, with the highest water levels in June and the lowest in November. Several isolated, shallow lakes form in the low-lying areas during the dry phase (Petrere et al., 2007). When the river water level rises, the forest floods and the lakes become connected to the main channels of the Amazon River and its tributaries (Junk, 1984), transforming the várzea into extensive lake systems of varying size and duration (McGrath et al., 2009).

2.2. Delineation of lake systems

We used the lake systems delineated by Castello et al. (2018), who applied geomorphological differences in the floodplain and hydrological connectivity at intermediate water level stages in Landsat TM satellite images (spatial resolution of 30 m). We excluded river channels deeper than 100 m since they markedly differ from the floodplain channels in terms of depth and flow. We considered the whole area encompassed by a lake system as the unit of analysis, including adjacent edges to lakes that are not flooded; those edges represent important areas for fish movements and habitat availability during the high water phase. However, due to data availability (cf. Section 2.3), our analysis focused on only 21 of the 68 lake systems delineated by Castello et al. (2018; Fig. 1).

2.3. Data collection

2.3.1. Fishing effort and catch data

We used fishery data from the Middle Amazon Fishery Resources Administration and their Iara/IBAMA Project and the Natural Resources of the Várzea Management Project (ProVárzea/IBAMA Project). These projects used census methods, and produced the most complete fisheries dataset for our study area. Catch and fishing effort data from each trip were recorded daily (except on Sundays) through interviews with boat owners or captains at the landing time. Data were collected between 1993 and 2011, except for 2006 and 2007, when the monitoring system was interrupted. During the interviews, information on catch per fish species, type of vessel, location and type of fishing ground (river or lake), fishing gear, number of crew members, number of fishing days, and dates of departure and return were recorded. Due to forest cover data availability (cf. Section 2.3.2), the fisheries data were

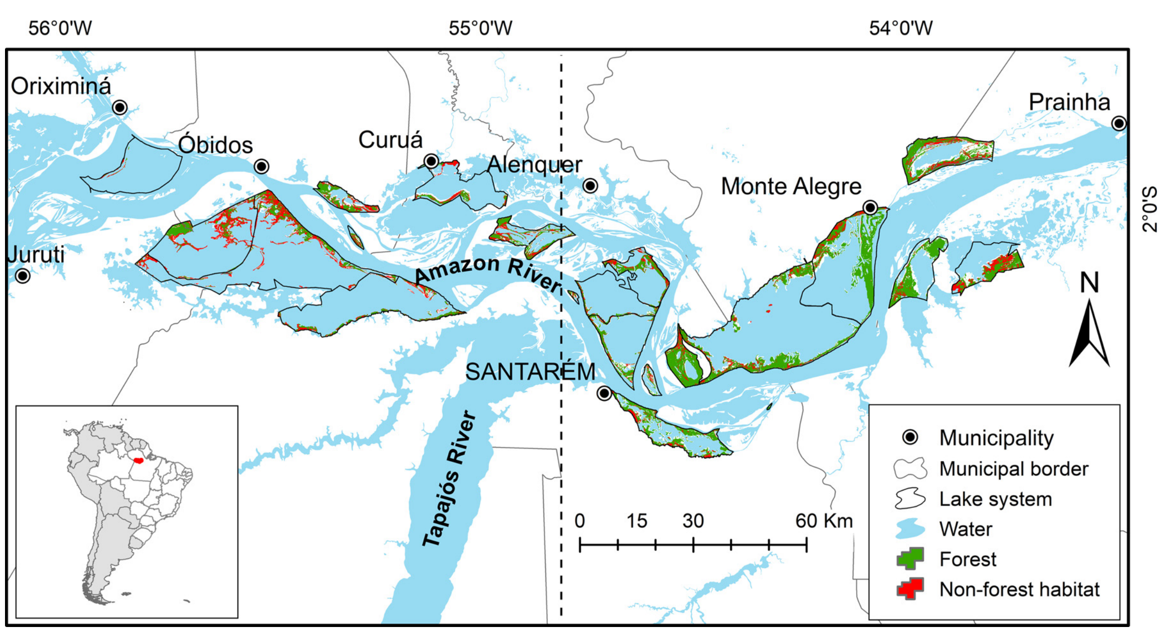

Fig. 1. Location of the lacustrine systems monitored in the present study on the lower Amazon River. The dotted line separates the Óbidos and Santarém hydrological sectors.

Table 1
Contribution of the main fish species or group of species caught in the lake systems of the lower Amazon river.

Order	Family	Scientific name	Local name	Catch (%)
Siluriformes	Pimelodidae	*Hypophthalmus edentatus, H.marginatus*	Mapará	47.58
Perciformes	Scianidae	*Plagioscion squamosissimus; P. surinamensis*	Pescada Branca	12.54
Siluriformes	Pimelodidae	*Pimelodina flavipinnis*	Fura Calça	10.91
Characiformes	Anostomidae	*Schizodon fasciatus, S. vittatus, Leporinus* spp., *Rhytiodus argenteofuscus, Laemolita taeniata*	Aracú/ Piau	6.86
Characiformes	Prochilodontidae	*Prochilodus nigricans*	Curimatã	3.33
Siluriformes	Pimelodidae	*Pseudoplatystoma fasciatum, P, tigrinum*	Surubim	2.99
Siluriformes	Loricariidae	*Squaliforma emarginata, Pterygoplichthys pardalis*	Acarí-Bodo	2.63
Characiformes	Serrasalmidae	*Colossoma macropomum*	Tambaqui	2.13
Siluriformes	Pimelodidae	*Brachyplatystoma rousseauxii*	Dourada	1.88
Characiformes	Serrasalmidae	*Metynnis* spp., *Mylossoma duriventre, M. aureum*	Pacú	1.42
Perciformes	Cichlidae	*Astronotus crassipinnis, Geophagus proximus*	Acará	1.17
Perciformes	Cichlidae	*Cichla monoculus, Cichla* sp,	Tucunaré	0.99
Clupeiformes	Pristigasteridae	*Pellona flavipinnis, P. castelnaeana*	Apapá	0.97

filtered in order to keep the ones that had full spatial and temporal coverage (i.e., years 2000–2005 and 2008–2011), totaling 10 years of data.

We only include a type of gillnet catches, named '*malhadeira*' used by motorized boats (see Isaac et al., 2004), which represented 98% of all gillnet catches. As suggested by Petrere et al. (2010), such filtering might reduce the catchability heterogeneity. Finally, we selected the 13 fish taxa, based on common names, which in total comprised 95% of the total catch in weight. The resulting data totaled 42,979 catch records (Table 1). Fishing effort was calculated by multiplying the number of fishers and fishing days, following the recommendation of Petrere (1978) as the most appropriate effort measure for the fisheries in the Amazonian lakes. The data on the total catch (kg) of the 13 species by weight (kg) per year and their fishery effort were considered for each lake system, thus producing a final set of 210 data points.

2.3.2. Landscape data

We considered forest cover data for each of the 21 lake systems from annual maps of land use and land cover (collection 2) generated from mosaics of Landsat TM images (30 m resolution) by the MapBiomas Project (http://mapbiomas.org/pages/database/mapbiomas, accessed February 15, 2018). Those data are only available from 2000 to 2016, so data for 2000–2005 and 2008–2011 was used to match the temporal availability of fisheries data.

We then masked the mosaics in ArcMap version 10.4 (Environmental Systems Research Institute (ESRI, 2016) to retain the area corresponding to the 21 lake systems of the study area and reclassified them into three classes: forest, non-forest, and water. The "forest" class included dense forests, flooded forests, and secondary forests (Souza, 2017; Table 2). The "non-forest" class included all remaining natural habitats (e.g., grassland), farmland and pasture, areas with no vegetation, and those with no data in the imagery. We used only the forest class in our analysis, with its area (km^2) being calculated using the number of pixels of forest within each lacustrine system each year. Each pixel represented an area of about 900 m^2. In ArcMap, we calculated the total area of each system and the Euclidean distance between the center of each lake and the corresponding nearest urban center.

2.3.3. Hydrological data

We used mean monthly river water levels (in cm) at the municipalities of Óbidos and Santarém from the Hydrological Information System (HidroWeb) for 2000–2005 and 2008–2011 (http://www.snirh.gov.br/hidroweb, accessed May 13, 2017). We associated the data from Óbidos to the lakes located to the west of the dotted line in Fig. 1, and those from Santarém to the lakes to the east of this line. The monthly minimum and maximum (cm) levels recorded in each study year were used for the analyses, and of the 12 means recorded for each year, only the lowest and highest values of the annual river level were used.

2.4. Data analyses

We used exploratory and descriptive statistical approaches to inspect relationships between pairs of the explanatory variables (see Supplementary Table S1). Before using cpue as an index of fish abundance, we assessed whether the relationship between catch and effort was linear and by the origin (i.e., presence of strict proportionality) to assess if the slope of the line measured the actual catchability of the stocks (Ricker, 1975; Pereira et al., 2009; Petrere et al., 2010). Therefore, catch and fishing effort data were transformed into their natural logarithms and fitted by a simple linear regression. However, that relationship did not pass through the origin (Fig. 2). Given the absence of strict proportionality, we decided not to use cpue for the remainder of our analysis, as it could represent a biased abundance estimate. For this reason, we used catches as the response variable and fishing effort as one of the covariables, as recommended in Petrere et al. (2010).

We assessed the effects of habitat features and fishing effort on catch of each lake system using an Analysis of Covariance (ANCOVA). The covariables we used were: fishing effort (fisher number × day), area (km^2) of forest cover within each lake system, distance (km) between the lake and the nearest urban center, annual minimum and maximum river levels (cm), and the catch year. The model used was

$$\ln Y_i = \mu + \tau_i + \sum_{j=1}^{5} \beta_j \ln X_{ij} + \tau_i \sum_{k=1}^{5} \beta_{ik} \ln X_{ik} + \varepsilon, \tag{1}$$

where Y_i is the catch (kg) of the ith year; μ is the model intercept; τ is the effect of the ith year (i = {1,..., 10}); β_j is the angular coefficient associated with the jth covariable (j = {1,..., 5}); X_{i1} is fishing effort

Table 2
Definition of the three types of forest included in the "forest" class applied to the analysis of the satellite images in the present study (Souza, 2017).

Class	Definition
Forest	*Dense forest*: dense ombrophilous forest, seasonal evergreen forest, and forested or wooded campinarana. *Flooded forest*: open alluvial ombrophilous forest, found on the seasonally or permanently flooded plains, referred to in the present study as várzea forest or swamp. *Secondary forest*: areas that have been deforested for land use and then abandoned and are currently at some stage of natural succession or have been planted for silviculture.

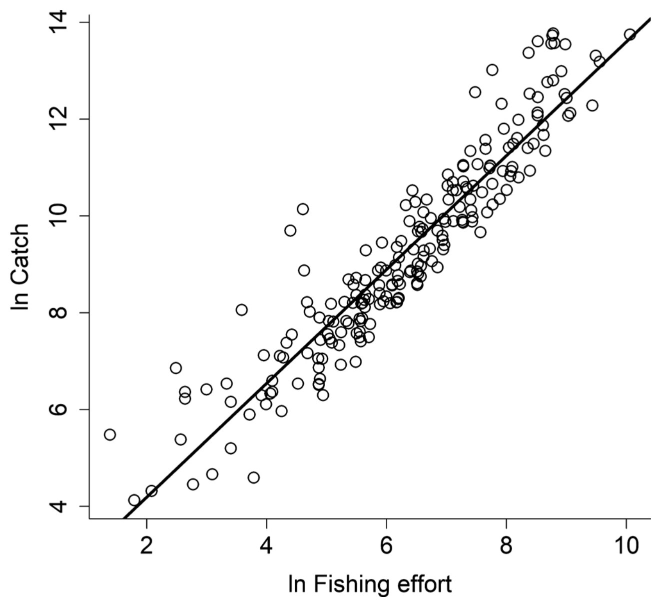

Fig. 2. Relationship between catches (kg) and fishing effort (fisher × day) of the fisheries operating in the lacustrine systems of the lower Amazon River in 2000–2005 and 2008–2011, based on the log-transformed data (n = 210). $\ln C = 1.84 + 1.18 \ln f$ ($s_\alpha = 0.206$; $t_\alpha = 8.96$; $p < 0.001$; $s_\beta = 0.031$; $t_\beta = 37.34$; $p < 0.001$), where C represents the catches and f the fishing effort.

recorded in the ith year; X_{i2} forest cover in the ith year; X_{i3} is distance to the nearest urban center in the ith year; X_{i4} is minimum annual river level in the ith year; X_{i5} is maximum annual river level in the ith year; β_{ik} is the angular coefficient associated with the interaction between the ith year and the kth covariable; and ϵ is a random variable, following the regular assumptions of a classic linear model.

All data were log-transformed for model fitting. We evaluated possible collinearity between explanatory variables using Pearson correlation coefficients and the two-tailed Pearson's product-moment for correlation testing. The residuals of the final model were evaluated for normality using quantile-quantile plots with simulated envelopes, Lilliefors test for normality, and Levene test for homoscedasticity, both with a 5% significance level (Flack and Flores, 1989; Thode, 2002).

We estimated the effects of floodplain deforestation on fish catches based on the final predictive equation calculated from the ANCOVA for areas of forest cover varying from 1 to 150 km^2 during 2011 as the baseline year, given this was the most recent year whose catch could be predicted. The predicted fish catches were generated by substituting the mean values of the natural logarithms of each covariable (except forest cover) in the final equation.

We evaluated the relative importance of each covariable in terms of its influence on catch weight by refitting the final model using standardized covariables (Z). However, we note that model fitting with the standardized variables hampers interpretation and prediction, so this approach is valid only in the absence of multicollinearity (Draper and Smith, 1998). The collinearity between explanatory variables were < 0.33. The only significant correlation was between lake area and forest cover ($r = 0.89$; $n = 210$; $p < 0.001$) (see online Supplementary Material). In order to avoid any potential issues with collinearity, we included only the area of forest cover in the model, given that this is the main factor determining the biological productivity of a lake, on which fish depend both directly and indirectly (Junk et al., 1989).

We used R (R Core Team, 2016), and its packages 'car' (Fox and Weisberg, 2011), 'corrplot' (Wei and Simko, 2017), 'hnp' (Moral et al., 2016), 'multcomp' (Hothorn et al., 2008), 'nortest' (Gross and Ligges, 2015) and 'lawstat' (Gastwirth et al., 2019), for linear model fitting and to perform the proper diagnostics and predictions.

Table 3
Results of the ANCOVA for the catches (kg) recorded in the lake systems of the lower Amazon River in 2000–2005 and 2008–2011. Significant ($p < 0.05$) probabilities are highlighted in bold type (n = 210).

	Df	SS	F	p
Fishing effort	1	611.87	1441.04	**< 0.001**
Forest cover	1	7.33	17.26	**< 0.001**
Distance to nearest urban center	1	15.09	35.55	**< 0.001**
Factor (year)	9	8.00	2.09	**0.032**
Annual maximum river level	1	4.53	10.88	**0.001**
Annual minimum river level	1	0.37	0.86	0.354
Residual	195	82.80		

df = degrees of freedom; SS = sum of squares.

3. Results

We found that all but one of the variables tested had an effect on lake system fish catches. The final linear model was globally significant ($F = 143.20$; $p < 0.001$) and explained 91% of the variation in catches. Catch was significantly related to fishing effort ($F = 1441.04$; $p < 0.001$), forest cover ($F = 17.26$; $p < 0.001$), distance from the nearest urban center ($F = 35.55$; $p < 0.001$), year ($F = 2.09$; $p = 0.032$), and annual maximum river level ($F = 10.88$; $p = 0.001$; Table 3), albeite not significantly related to the annual minimum. The parameter estimates of models fitted with standardized and non-standardized covariables showed that the most important covariable explaining variability in catch was fishing effort (Table 4). The second most important covariable was the annual maximum river water level, followed by distance to the nearest urban center and forest cover. The residual analysis (see online Supplementary Material for the quantile-quantile plot) indicated that the errors of the final model were normally distributed ($D = 0.06$, $p = 0.069$) and that the variances were homogeneous ($F = 1.90$, $p = 0.053$).

We predicted the catches according to forest cover areas in Fig. 3 using the equation $C_F = 4847.534F^{0.13555}$, where C_F is the predicted catch (kg) in 2011 and $F > 0$ is the area of forest cover (km^2). For reproducibility, the mean values in the log scale of each covariable are available in the Table S1 of the Supplementary Material. The 95% confidence intervals in Fig. 3 show that the greater the forest cover the greater is the uncertainty over the catch amount – which is mostly an expected result due to the scale-dependence in log-linear models –; thus, predictions for small forest areas are more precise, which are the most relevant cases for which to predict catch loss.

In this context, we used another equation to better reflect the loss in catches associated with forest cover reduction,

$$PCL_1 = 100\frac{C_F - C_{F-1}}{C_F},$$

where PCL_1 is the predicted percentage catch loss due to the deforestation of 1 km^2, C_F is the predicted catch with forest cover F km^2 and C_{F-1} is the predicted catch with forest cover with $(F - 1)$ km^2 (Fig. 4). We found that a loss of 1 km^2 of forest cover in a lake system that originally possessed 2 km^2 of forest cover would reduce catch by 8.97%. But such an effect depended on the size of the lake systems, which tend to have more forest cover. A loss of 1 km^2 of forest cover in a lake that originally possessed 150 km^2 of forest cover would reduce catch by 0.09%.

4. Discussion

Our results reflect the complex dynamics of small-scale floodplain fisheries and the roles of various human and environmental factors at multiple spatial and temporal scales. The striking contribution of this study is relating historical data on fish catches with floodplain forest loss. Previous studies, based on comparisons of fish catches or cpue in

Table 4
Models parameters of the ANCOVA, both unstandardized and standardized. Significant values are highlighted in bold.

Explanatory variable	Model parameters				Model parameters with standardized covariables (*Z*)			
	Coef	SE	*t*	*p*	Coef	SE	*t*	*p*
Intercept	−57.10	18.11	−3.15	0.002	9.14	0.18	50.78	< 0.001
Fishing effort	1.16	0.03	37.96	< 0.001	1.94	0.05	37.96	< 0.001
Forest cover	0.13	0.03	4.15	< 0.001	0.20	0.05	4.15	< 0.001
Distance to nearest urban center	0.77	0.13	5.96	< 0.001	0.27	0.05	5.96	< 0.001
Annual maximum river level	8.65	2.65	3.26	0.001	0.61	0.18	3.26	0.001
Annual minimum river level	−0.16	0.18	−0.93	0.354	−0.11	0.11	−0.93	0.354
Factor (year) 2001	−0.04	0.24	−0.17	0.866	−0.04	0.24	−0.17	0.866
Factor (year) 2002	0.41	0.26	1.57	0.119	0.41	0.26	1.57	0.119
Factor (year) 2003	0.58	0.30	1.94	0.054	0.58	0.30	1.94	0.054
Factor (year) 2004	0.99	0.34	2.91	0.004	0.99	0.34	2.91	0.004
Factor (year) 2005	0.13	0.39	0.34	0.735	0.13	0.39	0.34	0.735
Factor (year) 2008	−0.31	0.23	−1.36	0.175	−0.31	0.23	−1.36	0.175
Factor (year) 2009	−0.75	0.38	−1.97	0.051	−0.75	0.38	−1.97	0.051
Factor (year) 2010	0.53	0.40	1.33	0.184	0.53	0.40	1.33	0.184
Factor (year) 2011	−0.22	0.22	−0.99	0.322	−0.22	0.22	−0.99	0.322

Coef = coefficients; SE = standard errors.

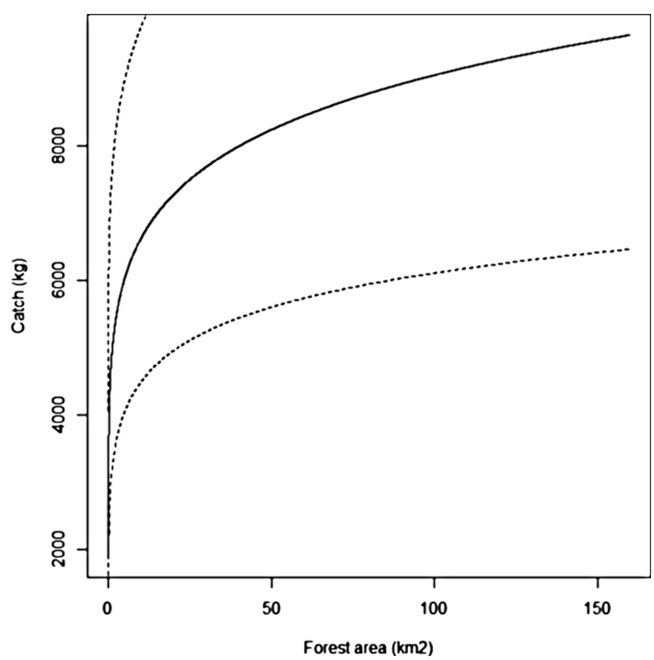

Fig. 3. Catch prediction according to forest cover in 2011. Dashed lines represent the 95% confidence interval.

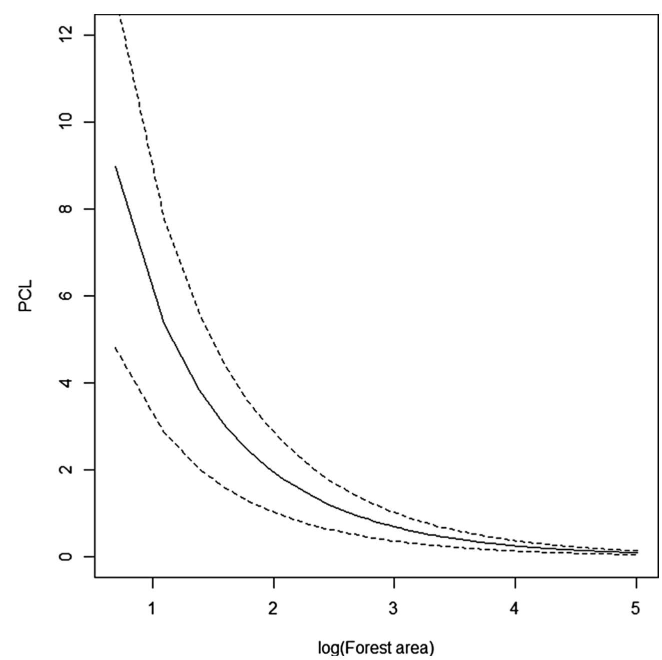

Fig. 4. Predicted percentage catch loss due to the deforestation of 1 km^2, according to different values of initial forest cover (in log scale). Dashed lines represent the 95% confidence interval.

lakes with varying degrees of forest cover, pointed out strong inferential data supporting the notion that floodplain deforestation lowers fish catch (e.g., Lobón-Cerviá et al., 2015; Arantes et al., 2018; Castello et al., 2018). Our results corroborate such studies and extend them further by quantitatively showing that floodplain deforestations do indeed lower fish catch. Such effect occurs because floodplain forests are the major source of energy and carbon for fish populations, forming the basis of the food chain (Bayley and Petrere, 1989; Araújo-Lima and Oliveira, 1998; Oliveira et al., 2006; Carvalho et al., 2018; Correa and Winemiller, 2018).

Although our predicted effects of floodplain deforestation on fish catch may appear to be small (e.g., ~9% for a loss of 1 km^2 of forest cover in a lake that originally possessed 2 km^2 of forest cover), it must be noted that it occurs after the fish assemblage is filtered and re-organized. Arantes et al. (2018, 2019) found that the species composition of floodplain fish assemblages differed along a gradient of floodplain lake forest cover, with forest loss being associated by a higher abundance of generalist species. Therefore, if such filtering and re-organization effect did not occur, the effect of floodplain deforestation on the catch of the 'native' fish assemblage would be stronger than that documented herein, primarily via biomass losses of specialist fish populations.

The positive effect of high river water levels on fish catches can be explained as high waters ease the access of fish to resources such as fruit, seeds, leaves, and detritus. High water levels also increase hydrological connectivity amongst rivers, lakes, and the floodplain forests (Junk et al., 1989; Hurd et al., 2016), further easing the access of migratory fish to the lake systems. These movements in the floodplains in a given year are likely to increase body growth and so fish biomass (Fernandes, 1997; Castello, 2008). In addition, the larger the area of flooded forest, the higher the diversity and availability of potential refuges from predators (Goulding, 1980; Mérona, 1990), which might decrease natural mortality rates. The intensity of flood events has also been found to lead to increased recruitment (Bayley et al., 2018; Castello et al., 2019) as well as decreased mortality rates by predation or fishing (Valderrama and Petrere, 1994; Mérona, 1995; Isaac et al., 2008).

Although we did not find an effect of low river water levels on fish catches, we expected it would affect fish catch as indicated in previous studies (Isaac et al., 1998; Saint-Paul et al., 2000; Batista et al., 2012; Garcez et al., 2017). Low water intensity has been shown to lead to higher mortality due to the greater vulnerability of the fish stocks to predation and fishing gear (Valderrama and Petrere, 1994; Mérona, 1995; Cardoso and Freitas, 2007; Garcez et al., 2009; Isaac et al., 2012). It could be that the main effect of low river water levels has a two-year lag, as found by previous studies in the region (Castello et al., 2015a; Fabré et al., 2017; Isaac et al., 2016).

The significant relationship we detected between catches and distance to urban centers supports the notion that fish stocks are larger in lakes under lower levels of fishing pressure (Endo et al., 2016). Since fishing in more distant lake systems requires more sailing time and involves higher fishing costs, particularly for fuel (Silvano et al., 2014), fishing effort was greater in lakes close to towns (Petrere, 1986; Cardoso and Freitas, 2007; Garcez et al., 2009).

5. Conclusions

Our results point out that floodplain fisheries are influenced by several human and ecological variables. A key factor documented here was that fish catches are adversely impacted by floodplain deforestation. This finding reinforces the need for an ecosystem perspective in the conservation and management of small-scale floodplain fisheries. Amazonian fisheries still are managed almost entirely based on fish size and catch season restrictions. Collectively with a number of other recent studies (e.g., Lopes et al., 2020), our results provide the baseline to develop more comprehensive, ecosystemical approaches to fisheries management in face of increasing threats to fish populations and their habitats.

Contribution of the authors

All authors made a significant contribution to the design of the study and approved the final version of the manuscript. Daniela de França Barros prepared and analyzed the data, interpreted the results, drafted the manuscript, and oversaw its preparation. Leandro Castello participated in the development of the idea and contributed to the first drafts of this study. Vincent Lecours contributed to the preparation and interpretation of the spatial data used in the analyses and provided feedback on drafts of the manuscript. Miguel Petrere Jr. and Davi Butturi-Gomes assisted the lead author in the analysis and interpretation of the results. Victoria Judith Isaac and Miguel Petrere Jr. were involved at all stages of manuscript preparation, helping to draft the manuscript and reviewing it.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi: https://doi.org/10.1016/j.fishres.2020.105643.

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