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Trends and environmental drivers of giant catfish catch in the lower Amazon River

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Abstract. The giant catfishes *Brachyplatystoma rousseauxii*, *Brachyplatystoma vaillantii* and *Brachyplatystoma filamentosum* are important environmental, social and economic resources in the Amazon. However, anthropogenic environmental changes, such as climate change, deforestation, overexploitation of water resources and damming of rivers, threaten the conservation of this fishery. The aims of this study were to investigate temporal trends and elucidate global and regional environmental drivers of catch for these species of giant catfish in the Amazon. Using annualised catch data (1993–2010), we tested for linear trends using Mann–Kendall tests and built multilinear models of fish catch using effort and a variety of regional and global hydrological and meteorological series. We found a significant decline in the catches of *B. rousseauxii* and *B. filamentosum*, whereas the B. *vaillantii* catch increased. Total catch had a significant positive correlation with fishing effort, and variation in sea surface temperature (SST) explained an additional 19–38% of the variability of catches. Other hydrological and climate variables were weakly correlated or uncorrelated with catch. Overall, these results argue strongly for a resumption the collection of fishing statistics in the Amazon. In addition, associations between SST and catch suggest that conservation of these long-distance migrants must consider both regional and global drivers of fisheries change.

Keywords: artisanal fishery, climate change, Pimelodidae, sea surface temperature, time series analysis.

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Introduction

Many of the jobs and much of the income that is generated throughout the world is due to either continental or inland fishing activities (Welcomme *et al.* 2010; Bartley *et al.* 2015; De Graaf *et al.* 2015; Lynch *et al.* 2016; Doria *et al.* 2017). These fisheries are also a major source of food (animal protein) in developing countries (Welcomme *et al.* 2010). In Brazil, more than half the extractive fishery production comes from the Amazon region (Ministério da Pesca e Aquicultura 2013). Fishing in the Amazon is traditionally an artisanal activity, which targets a large number of species using multiple types of fishing gear (Bayley and Petrere 1989; Barthem *et al.* 1997). In the main channel of the Amazon River, artisanal fishing generates ~155 000 jobs and an estimated gross annual revenue of US$278 million (Almeida 2004; Almeida *et al.* 2010).

The giant catfish of the family Pimelodidae (Siluriformes) are of economic importance in the fisheries in the Amazon (Batista *et al.* 2018). The main target species are dourada *Brachyplatystoma rousseauxii*, piramutaba *Brachyplatystoma vaillantii* and filhote *Brachyplatystoma filamentosum* (Barthem and Goulding 1997, 2007; Petrere *et al.* 2004; Ruffino 2014). Together, these three fish yield an annual production of 40 000 tonnes (Mg) (Ministério da Pesca e Aquicultura 2013), directed mainly at the national and international market (Barthem 1990; Barthem *et al.* 1991; Isaac *et al.* 1996; Parente *et al.* 2005). Approximately 16 000 fishermen exploit these resources along the river and estuary (Parente *et al.* 2005). Estimated production per year for the three species is 14 486 Mg of *B. rousseauxii*, 24 789 Mg of *B. vaillantii* and 3310 Mg of *B. filamentosum* (Ministério da Pesca e Aquicultura 2013). In the Lower Amazon region, these species are on the list of the 10 most captured, with dourada ranking as the second-most captured species (Pinaya *et al.* 2016).

In addition, the giant catfish play an important role in the structure and function of the aquatic environment because they represent the main predators of the ecosystem (Nootmorn *et al.* 2008; Pavlovic *et al.* 2015). Most are piscivorous, have large body sizes (≥105 cm) and exhibit complex and geographically extensive reproductive migrations (Barthem and Goulding 1997). A good example of these characteristics is *B. rousseauxii*, which undertakes the longest known freshwater fish migration (Barthem and Goulding 1997; Duponchelle *et al.* 2016; Barthem *et al.* 2017). Therefore, changes in their abundance may have profound consequences for the ecosystem (Angelini *et al.* 2006), because these species may be considered keystone species that have cascade effects on other species of the food chain if they are greatly affected by fishing pressure and other anthropogenic factors.

The dynamics of fish capture in the Amazon are complex and depend on the environments available, which vary according to fluctuations in river levels and various environmental and meteorological factors (Petrere 1985; Junk *et al.* 1989; Pinaya *et al.* 2016; Lima *et al.* 2017). The seasonal flood pulse affects the limnological, ecological and biological characteristics of the fishery and thus drives the economic dynamics of Amazonian waterbodies (Barthem and Fabré 2004). This is fundamental for biota in the large river systems of Neotropical regions (Lowe-McConnell 1987; Junk *et al.* 1989) and is strongly tied to fishing yield (Bayley 1995; Doria *et al.* 2012; Fearnside 2013; Castello *et al.* 2015; Pinaya *et al.* 2016, 2018). Regular periods of high and low water are predictable events (Junk *et al.* 1989; Castello *et al.* 2015) for organisms living in the river–floodplain system and for the population surviving from fishing activity. Despite the predictability of the fluvial regime, the intensity and duration of each phase varies annually (Castro and McGrath 2001), controlled by seasonal and interannual variability in water levels (Isaac *et al.* 2016).

Human-induced environmental changes, such as climate change, deforestation, habitat degradation, overexploitation of water resources and damming of rivers following the construction of large hydroelectric projects, represent threats to the regularity of the hydrological regime, and therefore to the conservation of water biodiversity (Freitas *et al.* 2012; Castello and Macedo 2016; Winemiller *et al.* 2016). These factors affect the flood pulse (Timpe and Kaplan 2017) and the connectivity between waterbodies (Anderson *et al.* 2018), markedly reducing aquatic and terrestrial production (Junk *et al.* 1989), which may, in turn, affect a region's fishing productivity and have potentially high socioeconomic effects.

When time series data of fish landings are available, they can be used to characterise temporal trends and associate the catch dynamics with potential predictive variables (Castello *et al.* 2013, 2015; Isaac *et al.* 2016; Lima *et al.* 2017), as well as to make predictions of future changes in yields. Several studies have shown a relationship between the hydrological regime and freshwater fisheries around the world (Welcomme 1985; Moses 1987; De Graaf 2003). However, although research into the effects of external phenomena on resource abundance and fishery productivity is common in marine and temperate or subtropical environments (Stenseth *et al.* 2002; Badjeck *et al.* 2010), it is less common in tropical freshwater environments. Critically, no studies have yet been done on the relationship between the catch of giant catfish and regional and global environmental variation in the Amazon Basin.

Thus, it was necessary to conduct this investigation. Given the important role of giant catfishes in the Amazonian aquatic environment and the sensitivity of species of the genus *Brachyplatystoma* to anthropogenic changes, such as increased effort, deforestation and dams (Angelini *et al.* 2006; Lima *et al.* 2020*a*), this study investigated the effects of regional and global environmental variables on the capture of three giant catfishes, namely *B. rousseauxii*, *B. vaillantii* and *B. filamentosum*. It is also intended that in the future it will be possible to create scenarios for Amazonian fisheries in order to contribute to the development of the management of these resources. The questions posed in this study were: (1) does the time series of capture have trends over the years; (2) is there an association between the time series of capture and the environmental series; (3) which environmental variables are most strongly correlated with fishing data; and (4) how may different species react to possible future changes in environmental variables?

Material and methods

Study area

The study area comprised the Lower Amazon region, which extends from Parintins (Amazonas State) to Almeirim (Pará State) in Brazil, at latitudes between 1 and 3°S and longitudes between 58 and 53°W (Isaac *et al.* 1996; Fig. 1). The climate is predominantly hot and humid, with a mean temperature of ~26.6°C and mean precipitation of 2200 mm year^{-1}. The river level has an annual variation of ~6–7 m between the dry and rainy seasons, with a regular period of higher water levels from May to June and low water levels from October to November (Bonnet *et al.* 2008; Isaac *et al.* 2016).

In this region, the Amazon River is wide and forms large floodplain lakes and interconnecting channels (Hess *et al.* 2003; Barthem and Goulding 2007). These environments are exploited by fishing boats that operate in the region (Isaac *et al.* 2004; Barthem and Goulding 2007), and there are 6506 fishermen registered in the region according to the General Record of Fishing Activity (Cruz *et al.* 2017). In these catfish fisheries, there is a mean (±s.d.) of 5 ± 5 fishers per boat and 5 ± 4 days of travel (Cruz *et al.* 2017; Pinaya *et al.* 2016), with a wide variety of gears used (predominantly gill-nets; Isaac *et al.* 2004). The mean fishing yield for the region is 9.1 kg fishermen^{-1} day^{-1} (Pinaya *et al.* 2016). Santarém is the main port of landing.

Fisheries data

Fish landing data for dourada *B. rousseauxii*, piramutaba *B. vaillantii* and filhote *B. filamentosum* were obtained from the IARA (Administração dos Recursos Pesqueiros na Região do Médio Amazonas) and PROVÁRZEA (Projeto Manejo dos Recursos Naturais da Várzea) Projects, coordinated by the Brazilian Institute for the Environment and Renewable Natural Resources (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis, IBAMA), using the census collection system. The data used were collected from 1993 to 2010 (except between June 2005 and February 2008) in nine cities on the Amazon River (Fig. 2). Data collection was from Monday to Saturday and included interviews with fishers and boat captains at the landing ports. Information on boat type, fishing environment, number of fishermen, fishing days, fishing gear and catch per

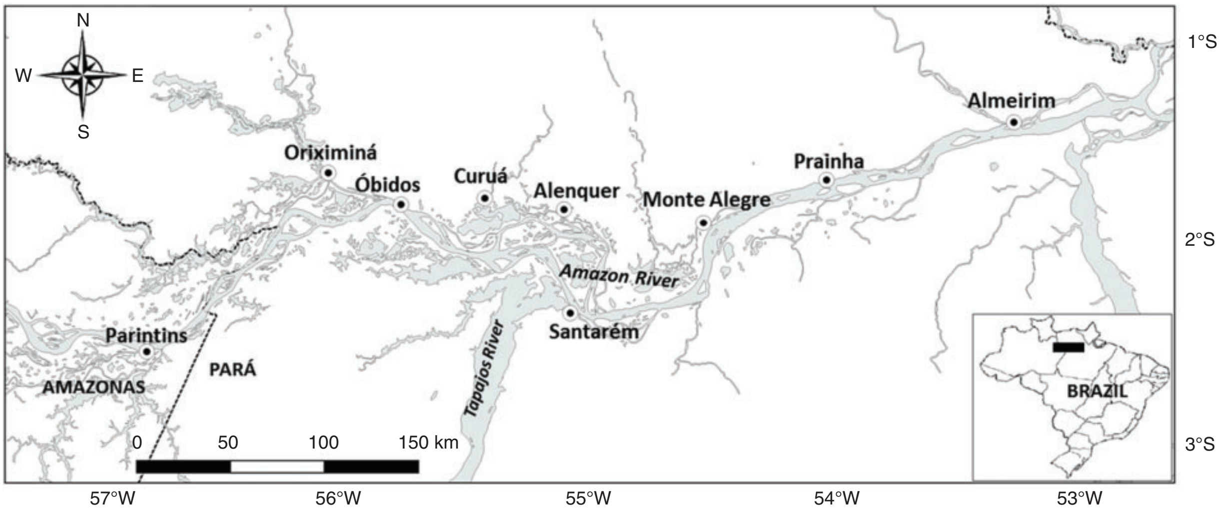

Fig. 1. Map of the study of the Lower Amazon region with the nine fishing landing sites indicated.

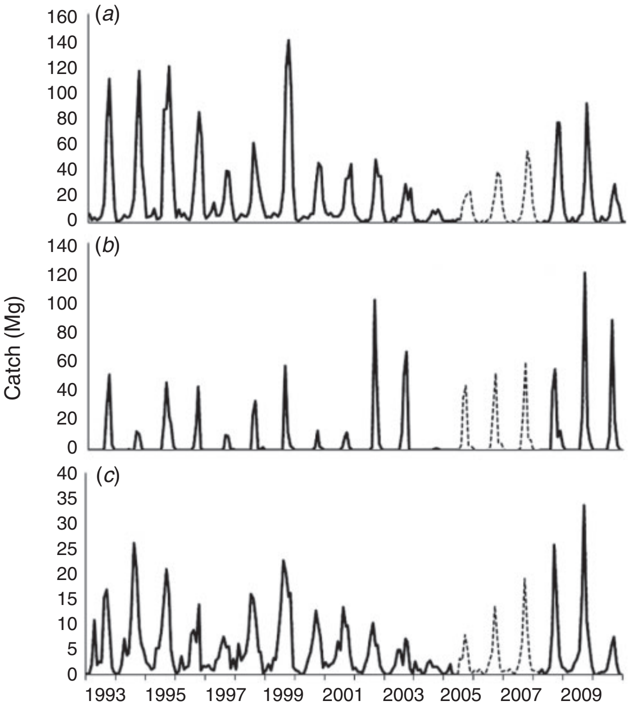

Fig. 2. Time series of catches per month for the three giant catfish, namely the (*a*) dourada *Brachyplatystoma rousseauxii*, (*b*) piramutaba *Brachyplatystoma vaillantii* and (*c*) filhote *Brachyplatystoma filamentosum*, landed in the Lower Amazon region from 1993 to 2010. Dotted lines indicate months that had catches rebuilt, between June 2015 and February 2008. Note the change in the *y*-axis scale.

species (kg) was recorded. The species were registered by their common local name. For the analysis in this study, only fishing trips by motorised boats using gill-nets were considered, which is the main combination used to catch catfish (representing 75% of the total catch; Cruz *et al.* 2017). The boats are wooden, with a mean (±s.d.) length of 15 ± 1 m. The gill-nets have a mean length of 790 ± 249 m and a mean height of 4 ± 1 m, with a distance of 16–20 cm between opposing nodes (Cruz 2020).

The research reported herein meets the ethical guidelines, including adherence to legal requirements, of the Brazil. Thus, the data used are official data of the fishing statistics of Brazil and approval from an ethics committee was not necessary.

Environmental data

Hydrological, meteorological and climatic data are summarised in Table 1. Daily water level data were obtained from the Brazilian Water Management Agency (www.ana.gov.br, accessed 8 April 2019). From the information recorded at the Santarém station (ID 00254004), the annual minimum, maximum and mean river level (cm) were calculated, as well as the amplitude of variation (maximum minus minimum) and the number of days per year that the level of the river flooded above the historical mean (>475 cm), which was calculated over 42 years (from 1970 to 2011).

Mean annual sea surface temperature (SST) data were obtained in a 4 × 4-km grid along the coast of Pará and Amapá in the Brazilian Amazon, as well as at the mouth of the Amazon River. These meteorological data are available online (www.esrl.noaa.gov/psd/data/gridded/, accessed 14 October 2019) and were made available from the global database of the Pathfinder project (ver. 5.0) developed by the National Oceanographic Data Center and the Rosenstiel School of Marine and Atmospheric Science, University of Miami, and made available by the Physical Oceanography Distributed Active Archive Center. The annual Multivariate ENSO (El Niño–Southern Oscillation) Index (MEI) was obtained from the National Oceanic and Atmospheric Administration records (www.esrl.noaa.gov/psd/data/climateindexes/list, accessed 14 October 2019).

Data analysis

Reconstruction of missing catch data

Between June 2005 and February 2008, the collection of fish landing data was interrupted, with no data available for

Table 1. Summary of the environmental variables used in this study

ENSO, El Niño–Southern Oscillation

Series type	Variable	Description	Factor
Hydrological	WL_{mean}	Mean annual water level (cm) in the Amazon River at Santarém	Regional
	WL_{max}	Maximum annual water level (cm) in the Amazon River at Santarém	
	WL_{min}	Minimum annual water level (cm) in the Amazon River at Santarém	
	AMP	Difference between the maximum and minimum river water level in each year	
	$Days_{flooded}$	Number of days in a year when the water level exceeded 475 cm (historical average of 42 years)	
Meteorological	SST	Annual mean sea surface temperature of the Atlantic Ocean (°C)	Global
Climatological	MEI	Annual multivariate ENSO index	Global

this period. Therefore, we reconstructed this period using the local polynomial regression fitting (LOESS) method (Cleveland *et al.* 1992; Venables and Ripley 2002). For each species, the estimates were made per month separately; that is, the missing values for January were estimated based on recorded values for January in the other years. This strategy was used to reduce the number of successive missing values and to maintain sensitivity to seasonal variations. For the adjustments, spans of 0.4, 0.5 and 0.6 were used. The span corresponds to the parameter that controls the degree of smoothing. Estimates calculated with less smoothing were preferably used, when negative values where obtained by lowest spans (Fig. 2). After reconstruction, data were summarised by year for all subsequent analyses.

Statistical trends and models

The Mann–Kendall (MK) test was used to identify trends in the time series of annual catch for each species, as well as for environmental data. Because it is a non-parametric method, the MK test does not require normal data distribution (Yue *et al.* 2002; Yue and Pilon 2004). MK tests were conducted using the procedure outlined by Gilbert (1987).

The variance inflation factor (VIF) was used to detect the presence of multicollinearity between two or more independent variables in the multiple linear regression model (Akinwande *et al.* 2015; Gómez *et al.* 2016). The VIF was calculated (Belsley *et al.* 2004) for seven environmental variables: maximum water level (WL_{max}), mean water level (WL_{mean}), minimum water level (WL_{min}), number of days in 1 year when the water level exceeded 475 cm ($Days_{flooded}$), water level amplitude (AMP), mean surface sea temperature (SST) and MEI using the equation:

$$VIF = \frac{1}{1 - R_i^2}$$

where R^2 is the multiple correlation coefficient of X_i regressed on the remaining explanatory variables. Variables with VIF values >5 were eliminated from the model because they can increase the variance of the regression coefficients (Kaplan *et al.* 2010), making them unstable (Akinwande *et al.* 2015). After collinearity tests, the environmental variables used here were reduced to AMP, days flooded, SST and MEI (Table 2).

Using these variables, two general linear models (GLMs) were developed to explain variation in the response variables (annual fish catch). Model 1 used both environmental variables (hydrological, meteorological and climatological) and fishing effort, whereas Model 2 ignored effort. The initial models used are given by the following expressions:

Table 2. Variance inflation factors (VIF) for the environmental explanatory variables for each catfish studied

AMP, difference between the maximum and minimum river water level in each year; $Days_{flooded}$, number of days in a year when the water level exceeded 475 cm (historical average of 42 years), MEI, multivariate El Niño–Southern Oscillation index; SST, sea surface temperature

	VIF		
	Brachyplatystoma rousseauxii	*Brachyplatystoma vaillantii*	*Brachyplatystoma filamentosum*
Variables			
AMP	2.04	1.79	1.95
$Days_{flooded}$	1.33	1.39	1.44
SST	3.68	2.27	1.91
MEI	1.19	1.18	1.22
Mean VIF	2.06	1.66	1.63

$$Y_{i,j} = \alpha + \beta_1 AMP + \beta_2 Days_{flooded} + \beta_3 SST + \beta_4 MEI + \beta_5 \mathrm{Effort} + \varepsilon \quad (1)$$

$$Y_{i,j} = \alpha + \beta_1 AMP + \beta_2 Days_{flooded} + \beta_3 SST + \beta_4 MEI + \varepsilon \quad (2)$$

where $Y_{i,j}$ is the dependent variable (log + 1 annual catch; Mg), AMP is the amplitude of the water level (cm), $Days_{flooded}$ is the number of days in a year when the water level exceeds the historical average, SST is annual mean sea surface temperature (°C) and Effort is the log annual sum of fishing effort (number of fishermen × fishing days).

The initial model was moderately reduced by the exclusion of non-significant factors (Faraway 2006). Thus, only significant explanatory variables were maintained ($\alpha = 5\%$).

Results

Capture, trends and effort

In all, 6223 Mg of catfish was caught between 1993 and 2010, with an annual mean of 345 ± 142 Mg. The highest production (635 ± 33 Mg) was recorded in 1995, and the lowest (68 ± 3 Mg)

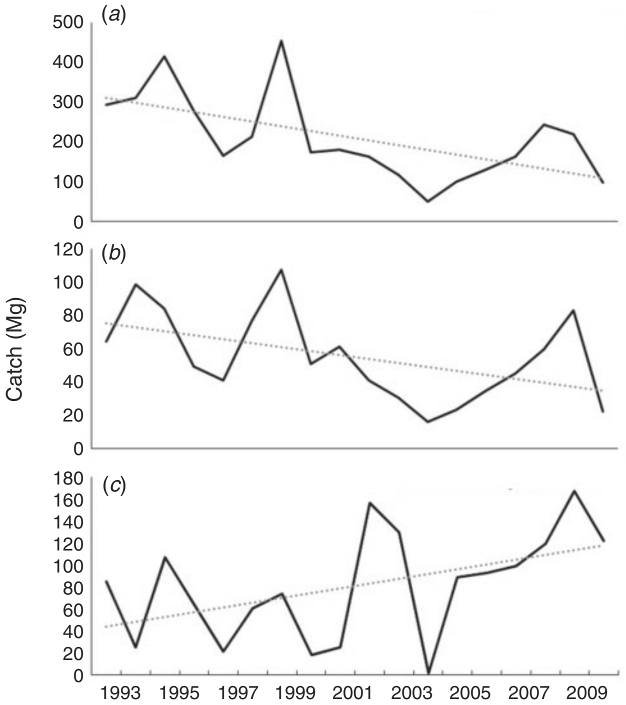

Fig. 3. Time series of total catch per year for three giant catfish, namely the (*a*) dourada *Brachyplatystoma rousseauxii*, (*b*) piramutaba *Brachyplatystoma vaillantii* and (*c*) filhote *Brachyplatystoma filamentosum*, landed in the Lower Amazon region from 1993 to 2010. Note the change in the *y*-axis scale.

was recorded in 2004 (Fig. 2). Of the total landed, more than half of the capture was *B. rousseauxii* (61%), followed by *B. vaillantii* (23%) and *B. filamentosum* (16%). For all three species, there was a period of extremely low catch in 2004, followed by an increase soon thereafter. *B. rousseauxii* and *B. filamentosum* presented decreasing trends in annual catch from 1993 to 2010 (MK, $S = -68$ ($P = 0.01$) and $S = -54$ ($P = 0.04$) respectively), whereas *B. vaillantii* showed an increasing trend (MK, $S = 52$, $P = 0.05$; Fig. 3). Total capture had a significant linear positive correlation ($P < 0.05$) with effort for all three species, as expected (Fig. 4), although the correlation was strongest for *B. rousseauxii* and *B. filamentosum*.

Environmental variables (hydrological, meteorological and climatological) had variable annual dynamics, with no obvious trends observed over the study period for water level, amplitude, MEI and days flooded. However, there was a significant positive trend in SST (MK, $S = 86$, $P = 0.001$; Fig. 5).

General linear models

Model 1 provided a highly significant correlation and excellent fit for the three species ($0.67 \leq R^2 \leq 0.82$; Fig. 6). The effect of fishing effort was positively related to fish catch (at $P \leq 0.002$) and explained most of the variance in catch (between 48 and 82%; Table 3). All other variables were not significant, with the exception of SST, which explained 19% of the variation in *B. vaillantii* catch (Table 3).

Model 2 had significant correlations ($P \leq 0.016$) for two of the three species, with lower explanatory power than Model 1 ($0.31 \leq R^2 \leq 0.55$; Table 3). The fit of Model 2 to the observed data is shown in Fig. 6. The importance of each explanatory variable for each species of fish is given by the magnitude and significance of the coefficients (Table 3). SST had the highest value and was a negative predictor ($P \leq 0.016$) for two species, explaining 31–38% of the variation in fish catch. Thus, the increase in SST influences the reduction in fish catch (Table 3). AMP was positively related to the capture of *B. rousseauxii* ($P = 0.028$). Therefore, increases in AMP interfere with increases in capture (Table 3).

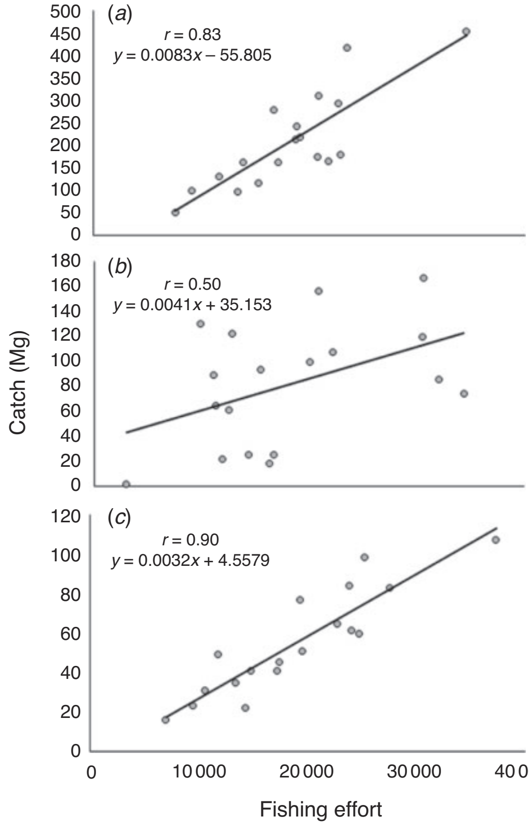

Fig. 4. Relationship between annual catch (tonnes, Mg) and effort (number of fishers × days fishing) for the three species of catfish, namely the (*a*) dourada *Brachyplatystoma rousseauxii*, (*b*) piramutaba *Brachyplatystoma vaillantii* and (*c*) filhote *Brachyplatystoma filamentosum*. Note the change in the *y*-axis scale.

Discussion

During the study period, there was a trend for a decline and significant increases in annual catch depending on the species. The variation in catch is largely due to the effort employed. Added to this was the effect of two environmental variables that interfered with capture rates. Changes in SST have a significant effect for all three species, whereas changes in river levels affected the catch of least one of them. These observations suggest that for future discussions of management strategies for these species, it is necessary to consider sea water temperatures and river levels in policy and action planning.

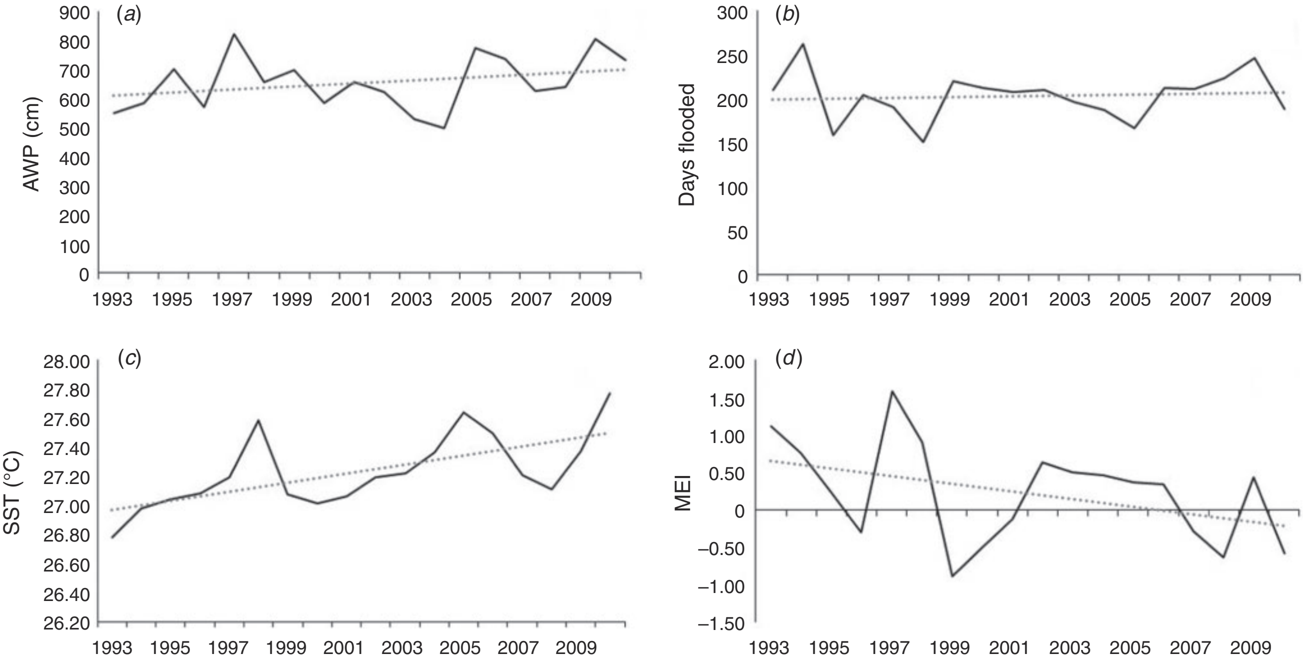

Fig. 5. Time series of environmental variables from 1993 to 2010: (*a*) mean water level amplitude (AMP), (*b*) number of days above the historical average for the region, (*c*) mean sea surface temperature (SST) and (*d*) multivariate El Niño–Southern Oscillation index (MEI).

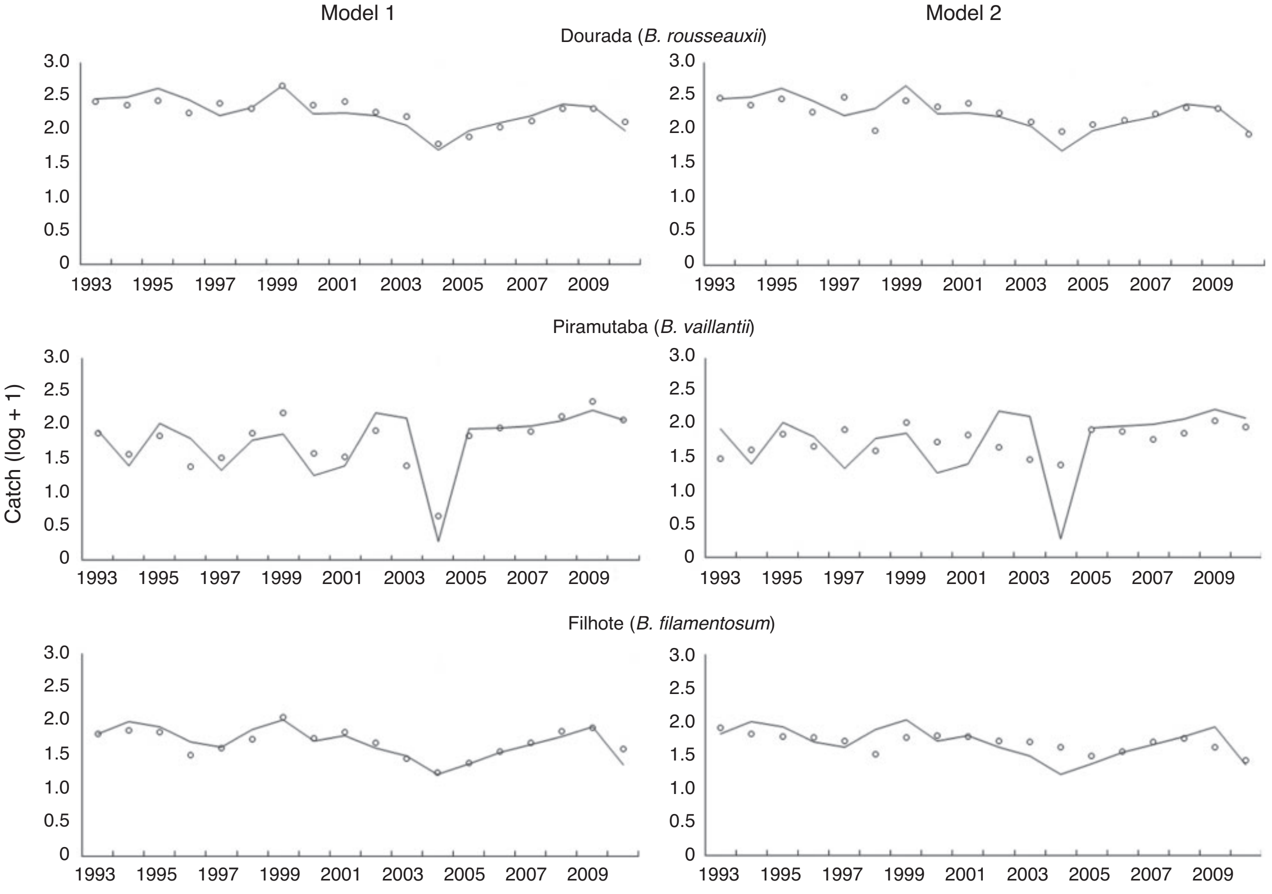

Fig. 6. Observed catch data (lines) and estimated points (open circles) for the three species of catfish, namely dourada *Brachyplatystoma rousseauxii*, piramutaba *Brachyplatystoma vaillantii* and filhote *Brachyplatystoma filamentosum*, as determined using two general linear models, Model 1 and Model 2. Model 1 used environmental variables (hydrological, meteorological and climatological) and fishing effort, whereas Model 2 ignored effort.

Table 3. Results of the general linear model (GLM) for three giant catfish, the dourada *Brachyplatystoma rousseauxii*, piramutaba *Brachyplatystoma vaillantii* and filhote *Brachyplatystoma filamentosum*, landed in the Lower Amazon, Brazil

Model 1, annual catch *v.* fishing effort and environmental variables (difference between the maximum and minimum river water level in each year, AMP; number of days in a year when the water level exceeded 475 cm, $\text{Days}_{\text{flooded}}$; sea surface temperature, SST; and multivariate El Niño–Southern Oscillation index, MEI); Model 2, annual catch *v.* environmental variables (AMP, $\text{Days}_{\text{flooded}}$, SST and MEI)

Species	Intercept		AMP		$\text{Days}_{\text{flooded}}$		SST		MEI		Effort		R^2	*P*-value for model
	Mean ± s.e.m.	*P*-value	Mean ± s.e.m.	*P*-value	Mean ± s.e.m.	*P*-value	Mean ± s.e.m.	*P*-value	Mean ± s.e.m.	*P*-value	Mean ± s.e.m.	*P*-value		
Model 1														
Dourada	0.856 ± 0.400	0.002									0.309 ± 0.087	0.002	0.75	0
Piramutaba	−28.693 ± 8.708	0.000					−0.870 ± 0.299	0.001			1.688 ± 0.309	0.000	0.67	0
Filhote	−3.100 ± 0.558	0.000									1.129 ± 0.131	0.000	0.82	0
Model 2														
Dourada	22.370 ± 4.727	0.002	0.001 ± 0.001	0.028			−0.767 ± 0.178	0.003					0.55	0.002
Piramutaba													0.17	0.623
Filhote	15.252 ± 5.049	0.000					−0.498 ± 0.185	0.016					0.31	0.016

Temporal trends

There was a significant decrease in catches of *B. rousseauxii* and *B. filamentosum* in the study region. This decline is a global trend for both marine and freshwater fisheries, driven by anthropogenic pressure on aquatic resources and global changes (Pauly *et al.* 2002, 2005). Specific to the Amazon, similar declining trends have been found for several catfish fisheries (Petrere *et al.* 2004; Santos *et al.* 2018; Barros 2019; Lima *et al.* 2020*b*). Specifically, fish production data from the Upper Amazon (Leticia, Colombia and Tabatinga, Brazil) showed a decline in *B. filamentosum* capture from 4000 Mg in 1983 to insignificant values in 2001 (Petrere *et al.* 2004), and Lima *et al.* (2020*b*) found a reduction of up to 74% in catches of *B. rousseauxii* between 1990 and 2014 in the Brazilian portion of the Madeira River.

In contrast, there was an upward trend in the catch of *B. vaillantii* (piramutaba). This may be due to the fact that this is the only species (of the three catfish studied here) that is actively managed, including regulation of industrial trawling and protection of its nursery area in the Amazon estuary. The management of piramutaba is aimed at preventing overfishing of this resource, and the Brazilian government has adopted measures over the years to prevent the capture and disposal of juvenile fish, such as minimum mesh sizes of tunnel bags, closed seasons, vessel control and monitoring and restricting fishing areas (Barthem and Petrere 1995; Barthem *et al.* 2015). These measures may have helped reduce the impact of such fishing, with the result of a recovering fishery. Overall, stocks of dourada *B. rousseauxii* and piramutaba *B. vaillantii* are currently recorded as overexploited (Alonso and Picker 2005). However, as supported the results of the present study, *B. vaillantii* has shown a recovery after years of low production (Ruffino 2014).

Effort and environmental drivers

When included in Model 1, fishing effort explained most of the variability in catch for the three catfish, exhibiting a positive relationship. This significant association was expected and is in agreement with other studies (Petrere *et al.* 2010; Castello *et al.* 2015; Isaac *et al.* 2015, 2016; Cruz *et al.* 2017; Batista *et al.* 2018). However, in addition to fishing effort, there are other biophysical variables that are likely to affect fishing yield. Specifically, fishing effort and climate change are stressors that can act together to reduce the abundance or distribution of tropical fish species (Barlow *et al.* 2018).

In our models, SST had a significant negative correlation with *B. vaillantii* (Model 1) and *B. rousseauxii* and *B. filamentosum* (Model 2; Table 3). These relationships imply that rising SST is associated with a decrease in the catch of large Amazon giant catfish, although the findings do not support a causal relationship. Several studies have indicated that the hydrological cycle of the great rivers in the Amazon integrates SST anomalies of the Equatorial Pacific and Tropical Atlantic, influencing the rainfall regime of the Amazon Basin (Cox *et al.* 2008; Marengo *et al.* 2008*a*, 2008*b*; Yoon and Zeng 2010; Marengo *et al.* 2011; Pinaya *et al.* 2016, 2018). The warming of SST in the Tropical Atlantic North and South is directly reflected by below-normal flows, especially during the rainiest season, but also during subsequent seasons (Marengo *et al.* 2011). Although variations in the intensity and extent of the dry season associated with changes in frequency will likely have profound biological, economic and social effects for fishing in the region, mechanistically connecting SST and fish catch is not possible with the data presented here.

Another potential connection between SST and giant catfish is due to their migratory behaviour, particularly through their use of the Amazon River estuary as a nursery area (Barthem and Goulding 1997; Barthem *et al.* 2017). During periods of high rainfall, increased water flow and the transport and deposition of sediments to the estuary region (Aller and Aller 1986; Luiz *et al.* 1998) provide a favourable environment for fish growth due to the great availability and richness of nutrients. However, reduced flows during periods of increased SST may lead to nutrient depletion in the estuary region, which will affect the environment that was previously conducive to larval development and increased species survival and abundance, and, in this way, fewer individuals will continue their migration upstream.

Finally, hydrological changes can result in desynchronisation of favourable conditions for giant catfish migration to occur (Visser and Both 2005). Drought, in particular, reduces the availability of migratory corridors between habitats, such as canals and flood plains, although unexpectedly we found very little correlation among fish catch and selected hydrological variables analysed here. Physicochemical changes in water can affect primary productivity and modify the trophic structure of food networks (Ficke *et al.* 2007; Lake 2003), directly or indirectly affecting large migratory catfish, modifying the abundance of their food sources. As the volume of water decreases, its temperature may increase and its oxygen concentration drop, becoming harmful or lethal to fish species (Lake 2003; Ficke *et al.* 2007; Frederico *et al.* 2016). Because the energy reserve in adult fish is divided between maintenance, growth and reproduction metabolism (Wootton 1998), the increase in energy used to compensate for unfavourable thermal conditions will compromise growth and reproduction and increase susceptibility to disease (Ficke *et al.* 2007; Freitas *et al.* 2012).

Looking forward

The Amazon Basin is a region that receives among the highest rainfall globally and is a major source of atmospheric water vapour (Figueroa and Nobre 1990); however, in recent decades, the Amazon Basin has experienced a more variable climate, with severe droughts in 2005, 2010 and 2016. Increased water stress is a dominant feature of some 21st century modelled climate scenarios for the Amazon (Cox *et al.* 2008;). Hadley Center's climate models predict the transformation of the Amazon rainforest into savanna vegetation from the middle of this century (Oyama and Nobre 2003). According to Betts *et al.* (2008), the synergistic effects of global climate change and deforestation will likely reduce rainfall in the eastern Amazon. Both global climate change and deforestation contribute to a reduction in flood areas and connectivity between aquatic environments. These changes will affect the life strategy of many fish species, especially migrators, with negative effects on recruitment and the abundance of stocks (Vazzoler 1996), as well as on local human populations that exploit these stocks as sources of protein and income (Freitas *et al.* 2012).

It is also worth mentioning that catastrophic scenarios for fishing in the Amazon can occur through other human actions, such as the construction of dams (Santos *et al.* 2018; Lima *et al.* 2020*b*). According to Finer and Jenkins (2012), there are plans to build at least 151 new hydroelectric plants for all the Andean tributaries of the Amazon River. Dam construction affects the frequency and intensity of river flow, alters water temperature and the transport of sediment and nutrients, reduces flow, decreases fertilisation of adjacent flood plains and blocks fish migration routes (Agostinho *et al.* 2004; Freitas *et al.* 2012; Forsberg *et al.* 2017; Latrubesse *et al.* 2017; Timpe and Kaplan 2017), changing the hydrological regime (Arias *et al.* 2014) and consequently interfering with fishing productivity (Santos *et al.* 2018). In this way, dams have social and economic effects (Ferreira *et al.* 2014) that affect fishermen who depend financially on the fishing resource for their consumption and family subsistence or for sale in local and regional markets.

This study emphasises the potential for global changes to affect Amazonian catfish stocks and capture. Thus, climate change may adversely affect the future of commercial fishing in the region, with ecological, economic and social ramifications. Thus, plans for the protection of the natural hydrology of Amazonian rivers are necessary to avoid the degradation of these important fisheries. Perhaps even more important is resuming the collection of fishing statistics in Brazil, especially in the Amazon, using consistent methods and variables so that it is possible to observe and monitor changes to the fishery in the future. Continuity of national fisheries statistics is also necessary for developing actions to support the sustainable management and conservation of these resources. Finally, we suggest the creation of an international working group or committee with government participation from all countries (primarily Brazil, Peru, Bolivia and Colombia) that share these catfish species, especially because *B. rousseauxii* and *B. vaillantii* are long-distance migrants. This committee should bring together all actors that exploit these resources to plan for and discuss the conservation status of the giant catfishes and possible management measures to protect them.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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