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Original Article

Perception of Amazonian fishers regarding environmental changes as causes of drastic events of fish mortality

A percepção de pescadores amazônicos das mudanças ambientais como causas de drásticos eventos de mortalidade de peixes

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Abstract

Events of catastrophic fish mortality in the lakes of the Amazonian floodplains are not uncommon. They are generally associated with thermal inversion of the water column, which is provoked by cold air masses that originate from the south of the continent. These events occur in the period of high water when the lakes are stratified. This paper reports an event of fish mortality that occurred during the low water season in a large floodplain system on the right-hand margin of the Amazon River. Information from seasoned fishers, who live in the same area where the event happened, and hydrological and satellite image analysis was used to identify the potential cause of fish mortality events. The amplitude of the flood pulse and the duration of extreme ebb showed to be the key factors responsible for the occurrence of events of fish mortality. These factors determine connectivity patterns between the floodplain lakes and the river channel, which are essential for maintaining water quality and the biota in the systems.

Keywords: extreme ebbs, connectivity, floodplain lakes, Amazon basin.

Resumo

Eventos catastróficos de mortalidade de peixes em lagos de várzea da Amazônia não são incomuns, sendo, em geral, associados com a inversão térmica da coluna d'água, que é provocada por massas de ar frio que se originam no sul do continente. Esses eventos ocorrem no período de águas altas quando os lagos estão estratificados. Nesse artigo, relata-se um evento de mortalidade de peixes que ocorreu durante a estação de águas baixas em um grande sistema de várzea situado na margem direita do rio Amazonas. Usou-se o relato de pescadores residentes na área onde ocorreu o evento e com experiência na pesca, em conjunto com dados hidrológicos e imagens de satélite, para identificar potenciais causas do evento de mortalidade de peixes e propõe-se que a amplitude do pulso de inundação e a duração de secas extremas são os fatores chaves para a ocorrência dos eventos de mortalidade de peixes. Esses fatores determinam padrões de conectividade entre os lagos de várzea e o canal do rio, os quais são essenciais para a manutenção da qualidade da água e da biota nesses sistemas.

Palavras-chaves: secas extremas, conectividade, lagos de várzea, bacia Amazônica.

1. Introduction

The floodplains adjacent to the whitewater rivers are systems of essential ecological importance and contribute to the stability of the functioning of ecosystems during the hydrological cycle (Junk et al., 1989;). These rivers have headwaters in the Andean and pre-Andean areas and carry a high load of sediments, which causes the water to be the color of heavily creamed coffee (Freitas et al., 2013). These floodplains interact with the atmosphere via the cycling of water, carbon and nitrogen (Junk et al., 2020), and their lateral dimensions can vary between 20 and 200 km (Saint-Paul and Bayley, 1979). These large floodplains are the most productive systems in the Amazon basin and host a high diversity of plants and animals (Junk et al., 2020). They are also strongly affected by the annual oscillation in the water level, which has a significant effect on the functioning of the ecosystem and its biota (Junk et al., 1989; Freitas et al., 2010).

In general, catastrophic events, i.e., high natural mortality of fish, happen during periods of high water

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and are associated with a natural phenomenon that is regionally known as "*friagem*", which is the Portuguese word for a sudden fall in air temperature. The *friagem* is more common in the western Amazon during the winter months of the southern hemisphere and is caused by a polar cold air mass that passes through the depressions of the Paraná and Plata basins. The *friagem* alters the vertical mixture pattern of the lakes of the Amazonian floodplains and increases the concentration of methane, hydrogen sulfide, and other reduced gas species (Aprile and Darwich, 2009), and is fully described in Caraballo et al. (2014).

Nevertheless, the extreme ebbs that have occurred in the last 20 years have also promoted large fish mortalities in the lakes of the Amazonian floodplains. The severe ebb anomaly of 2005 resulted in a reduction of alpha and beta diversities of fish assemblages of the floodplain lakes, but with species-specific responses to the environmental disturbance (Freitas et al., 2013; Röpke et al., 2017). These extreme ebbs happen when the effects of the El Niño-South Oscillation (ENSO) in the Pacific Ocean are synchronized with abnormal warming of the South Atlantic Ocean (Gloor et al., 2013; Marengo and Espinoza, 2016). The increasing frequency of extreme climatic events in the last few years is probably associated with climate changes (Jiménez-Muñoz et al., 2016). However, the impacts of climate changes on the fish assemblages and fisheries remain scarcely discussed.

In this paper, a sudden and catastrophic event of natural fish mortality is described based on the perception of fishers, hydrological data, and satellite image analysis. This event occurred in November 2020, in a large system of floodplain lakes, known as Lago do Rei, which is located within a fluvial island, immediately below the confluence of the Solimões and Negro Rivers. Our basic premise is that the duration of loss of connectivity between the lake system and the main channel of the Amazon River is a key driver of disruptive events.

2. Materials and Methods

2.1. Study area

The fluvial island Ilha do Careiro possesses a huge floodplain lake known as Lago do Rei, which is approximately 100 km² (Odinetz-Collart and Moreira, 1993). It is a typical floodplain lake system with several small lakes that appear during the period of low water and is a unique aquatic waterbody during the period of high water (Figure 1). The depth varies from one meter, during low-water period, to more than 10 meters, during the high-water period (Merona and Bittencourt, 1993). The fishes of this lake system have been exploited since the eighteenth century and there is no local management of the fisheries.

2.2. Data collection and analysis

Historical data on the daily water level of the Negro River was obtained from the administrator of the Port of Manaus. The data series analyzed covers the period from 1992 to 2020. As the threshold, Pereira et al. (2018) define the value of 29.01 m (meters above sea level) for a flood to be considered an extreme event, which is equivalent to the sum of the historical average plus one standard deviation of the maximum levels of the Negro River in Manaus. For extreme ebbs, the value of 15.80 m is considered an extreme event, which corresponds to the value of the historical average minus one standard deviation of the minimum levels of the Negro River in Manaus. For the Lago do Rei, the minimum water level reference took into account the perception and assessment of the people of the riverine communities, who indicated that the intensification of the phenomenon is related to the occurrence of broader flood pulses (i.e., large floods followed by intense ebbs).

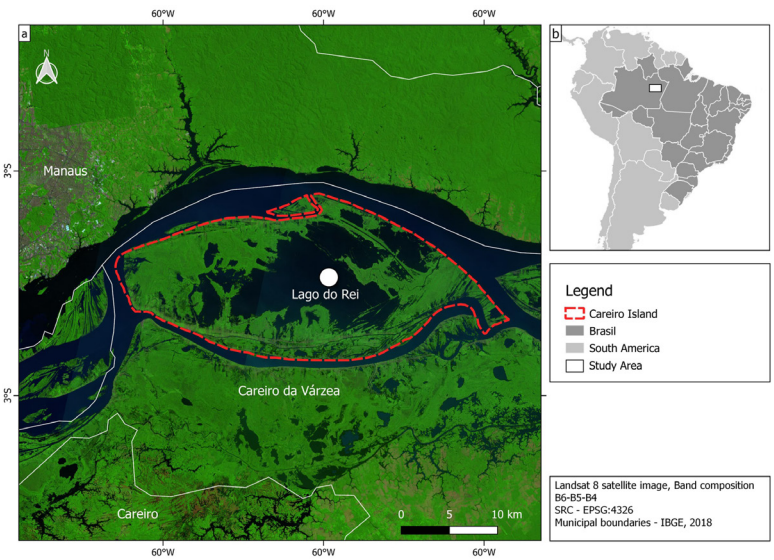

Figure 1. Image of the Ilha do Careiro, immediately below the confluence of the Negro and Solimões rivers (Amazonas state), area of black and whitewaters mixing and, inside, the huge floodplain system known as Lago do Rei.

A snowball sampling procedure was conducted to find seasoned fishers of the riverine community of the Lago do Rei. It is a nonprobability method of sample selection that relies primarily on the more seasoned respondents to provide information and then indicate other persons believed also to have had experiences regarding the issue of interest (Biernacki and Waldorf, 1981). Beginning with the head of the group of fishers, five artisanal fishers who live in the community of Lago do Rei were interviewed using a semi-structured questionnaire, which was structured after a visit to the area impacted during the event of fish mortality. The main questions were focused on the causes of extreme flood events and their impacts, and their responses were recorded and then transcribed and analyzed.

Considering that the duration of the connectivity loss could be a driver to fish mortality, a graphic analysis was performed using the number of days that the Negro River was below 18 m in each year of the time series, using the minimum river level of 2019 as a reference, when there was no mortality and the amplitude of the flood pulse of the respective year.

The maps generated using GEE platform were the base for estimating the water surface of the Lago Rei floodplain area. The Google Earth Engine (GEE) platform (https://earthengine.google.com/platform/) was used to generate maps and process satellite images. The GEE is a cloud-computing platform that enables geospatial analysis at planetary scales and facilitates access to high-performance cloud computing with a large catalog of Earth observation data, as well as enabling processing on a global scale (Midekisa et al., 2017). It is carried out via processing on multiple servers, thus accelerating the analysis (Dong et al., 2016; Gorelick et al., 2017).

A spectral index, known as modified normalized difference water index (MNDWI), was also used for surface water mapping and extraction of waterbodies in wetlands (Xu, 2006). In this study, images from the Sentinel 2 satellite were used due to their higher spatial resolution and absence of cloud cover. The equation for calculating the MNDWI is (Equation 1):

$$MNDWI = \frac{p3 - p11}{p3 + p11} \quad (1)$$

Where p3 is the top of atmosphere (TOA) reflectance of band 3 (green band) and p11 is the TOA reflectance of band 11 (SWIR Band), both being from the Sentinel 2 MSI satellite. In the MNDWI index, waterbodies have positive values since they absorb more light. At the same time, areas of vegetation, soil and urbanized areas receive negative values, as they tend to reflect more light (Du et al., 2016). From this index, it was possible to calculate the seasonal variation in the lake area and determine the months in which the retraction of the aquatic system occurred.

An analysis was also performed to compare the variations in the Oceanic Niño Index (ONI) and the level of disconnection between the river and the lake. The ONI identifies anomalies in the sea surface temperature using a moving average of three months (NOAA, 2021). Data from the hydrological station of Manaus (14990000) and data for El Niño for the same period (NOAA, 2021) were used to determine the period in which the river and the lake were disconnected. Subsequently, the water level of the river on the day on which the phenomenon of fish mortality in Lago do Rei was recorded. Station 14990000, located in Manaus, was defined as the base for the study because it is the nearest station to Lago do Rei with daily registering of water levels since 1901, and its level is strongly influenced by the flow of both the Negro and Solimões Rivers (Gualtieri et al., 2019).

3. Results

With ages varying between 24 and 63 years and with more than 24 years residing on the banks of Lago do Rei, three fishers reported that the phenomenon had previously occurred in November, and two of them also indicated the month of October (Table 1). Most of the interviewees reported that the mortality of the fish happens in all environments of the lake system, but two did not cite the branch of the river as an environment where fish mortality happens. The fishers who were interviewed proposed that the predominant cause of fish mortality involved low oxygen, lake ebb and water temperature. There were no conclusive opinions on the frequency and intensification of extreme events of ebb and fish mortality since only three of them cited that these events had become more frequent and intense. However, it must be recognized that the low number of interviewed fishers is an obstacle to obtaining conclusive opinions (Table 1).

Considering the perception and evaluation of the fishers, who cited that the intensification of fish mortality events is related to the occurrence of broader flood pulses (large floods followed by intense ebbs), a graph was plotted to correlate the number of days that the Negro River was below 18 m and the amplitude of the flood pulse of each year (Figure 2). Based on these two measurements, annual patterns were determined that clustered the years into three groups. Group A is composed of the years in which the river was below 18 m for less than 30 days, which includes the year 2019. The intermediate group (B) corresponds to the years with a wide variation in the number of days in which the river was below 18 m though presented intermediate flooding amplitudes (10 to 13 m).

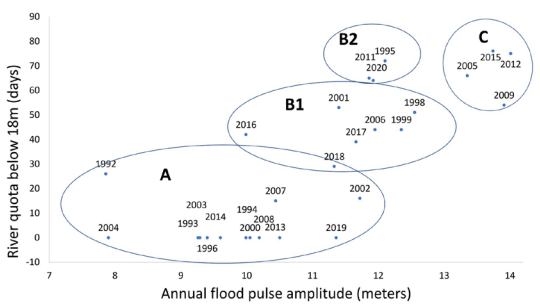

Figure 2. A biplot is showing the years by the number of days with river level below 18 meters and the amplitude (meters) of the annual flood pulse.

Table 1. Summary of the answers to the interviews performed with fishers of the Igarapé do Lago do Rei community, Careiro da Várzea, Amazonas state.

Interview		1	2	3	4	5
Gender		Male	Male	Male	Male	Female
Age		24	63	49	44	31
Occupation		Fisher	Fisher	Fisher	Fisher	Fisher
Birthplace and state		Lago do Rei, Amazonas	Purus, Amazonas	Porto Velho, Rondônia	Manicoré, Amazonas	Janauacá, Amazonas
Current residence		Lago do Rei	Lago do Rei	Lago do Rei	Lago do Rei	Lago do Rei
Years residing in the area		24	42	39	36	31
Month of fish mortality	October	X	-	X	-	-
November		X	-	X	X	X
Season of fish mortality	Ebb	X	X	X	X	X
Place of fish mortality	Lake channel	X	X	X	X	X
Lake		X	X	X	-	
River branch		X	X		X	
Frequency of fish mortality		Don't know	annual	annual	annual	annual
Causes of fish mortality	Lake ebb	X	-	-	X	X
	High water temperature	X	X		X	-
	Low oxygen	X	X	X	X	-
	Deforestation	-	-	-	-	X
	Pollution	-	-	-	-	X
Fish mortality events are more frequent, in the last 10 years?		Yes	?	Yes	No	Yes
Fish mortality events are more intense		No	Yes	Yes	No	Yes
Causes of intensification of the fish mortality events?		Don´t know	Lake land filling	Big flood followed by ebb	There has been a reduction	Big flood followed by ebb

This group could be divided into two subgroups, B1 and B2, with the latter presenting a higher number of days with levels below 18 m and annual flood pulse amplitude around 12 meters, including 2020. 2018 was a year that fell between groups A and B1, with characteristics of both groups. A third group (C) is formed by years with more than 50 days of levels below 18 m and amplitudes greater than 13 m. Group C includes the years 2005 and 2015, which were highlighted by events of extreme ebbs (Freitas et al., 2013). Group C also includes the years 2009 and 2012, which are the two years in which record floods involving the Negro River occurred.

The MNDWI analysis shows the seasonal dynamics of the Lago do Rei for the period from August 2015 to August 2021. In August, there is a reduction in the lake area, which tends to reach its minimum values between October and December. The maximum water surface was consistently observed from April to June (Figure 3).

The satellite images of low-water and high-water periods from 2018 to 2020 show the alteration in the landscape during the hydrological cycle. Images of the low water periods, November 2018 and 2019 (Figures 4A and 4C), show that the water surface is substantially reduced and the connection among the lakes is lost. The lost connection between the largest lake, in the center of the system, is well accentuated in 2019. The images of the high-water periods in June 2018 and June 2020 (Figures 4B and 4D) show the complete connection between the lakes and the river channel.

Figure 5 compares the level of disconnection of Lago do Rei in 2020 with the minimum water level observed in previous years (2009 to 2020). There were verbal reports of fish mortality by the riverine community for all years in which there was an ebb below this water level. When comparing the ONI index with the periods of floods and ebbs in the region, it is noticeable that the climatic events El Niño and La Niña have a strong influence on the ebb in the lake and the rivers in the region. When this index is above 1 (identifying an occurrence of El Niño), there is the possibility of an ebb that promotes the disconnection of the lake, and the consequent mortality of fish.

4. Discussion

Despite the small number of interviewees, the fishers pointed out what they believe to be the factors associated

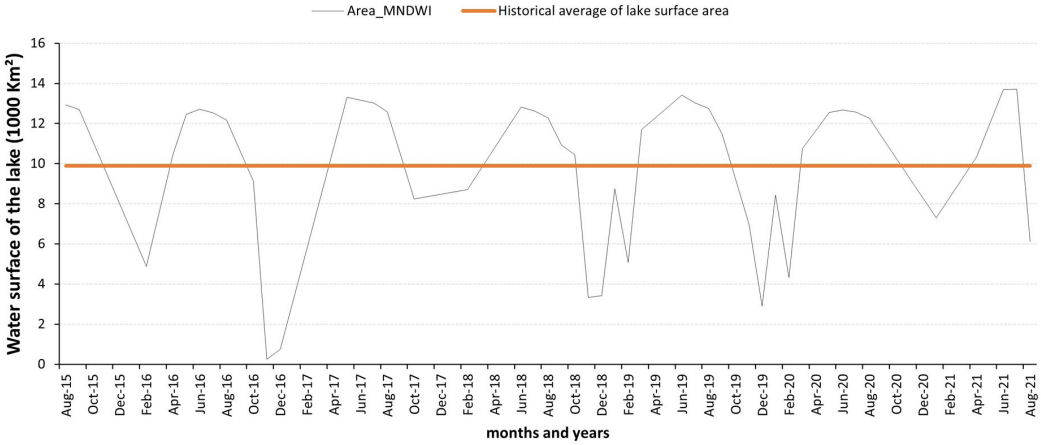

Figure 3. Analysis of the water surface of Lago do Rei using the modified normalized difference water index for the years 2015 to 2020.

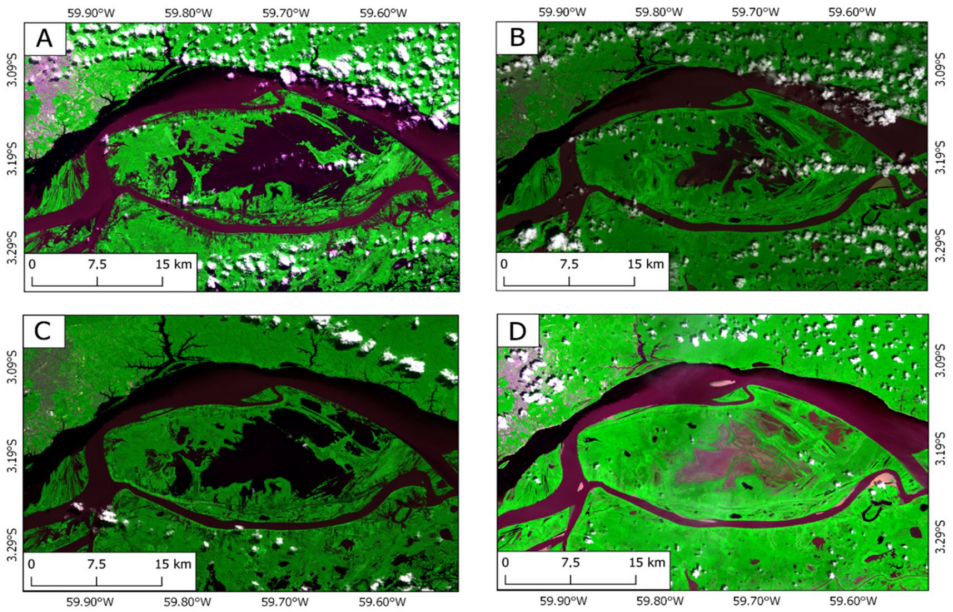

Figure 4. A - Sentinel 2 satellite image of Lago do Rei on 20th November 2018. B - Sentinel 2 satellite image of the Lago do Rei on 20th June 2018. C - Sentinel 2 satellite image of the Lago do Rei on 15th November 2019. D - Sentinel 2 satellite image of Lago do Rei on 6th January 2020.

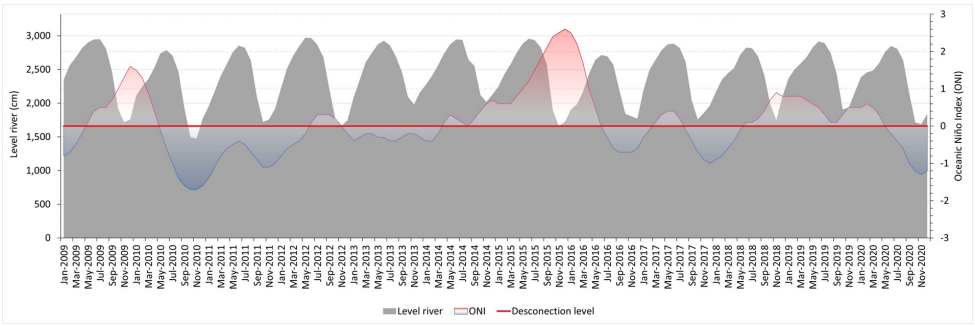

Figure 5. Relationship between the river level, measured in the Port of Manaus – Station 14990000, and the Oceanic Niño Index (ONI), from 2009 to 2020, taking as reference the level of disconnection between Lago do Rei and the Amazon River.

with the hydrology and water quality. In their opinion, lake ebb, water temperature, and low oxygen were the predominant causes of the fish mortality events. The accurate perception of Amazonian fishers on the implications of environmental changes on the aquatic environment and its biota has already been described in several studies (Begossi and Garavello, 1990; Batistella et al., 2005; Hallwass et al., 2013, 2019; Vasconcelos et al., 2021). In addition, the perception of environmental variability seems to be well disseminated among the fishers of the study area and other parts of the Amazon basin (Camacho-Guerreiro et al., 2016; Nunes et al., 2019).

The hydrological dynamics of the lake follow those of the river; when the river level starts to drop, the connections between the river and the floodplain are interrupted (Hurd et al., 2016). During flooding, the floodplain receives water from the river through diffuse flow. This movement occurs mainly by overbanking when the water level rises and exceeds the height of the lateral margins and contributes to the deposition of sediments on the floodplain (Dunne et al., 1998). As the water recedes, the degree of connectivity between the lakes and the main river channel declines and can disappear completely in years of intense ebb (Hurd et al., 2016).

The surface of the lake can be drastically reduced in years of intense ebb, as occurred in 2016 and 2019, and the aquatic biota, mainly fishes, can be dramatically affected. Up until a certain threshold, the signaling (positive, negative, or neutral) and intensity (weak or strong) of the ebb effect should be species-specific, since some species may exhibit plastic and evolutionary responses to increasing temperatures and declining oxygen levels (Crozier and Hutchings, 2014). Two omnivorous species *Colossoma macropomum* and *Mylossoma duriventre*, and *Serrasalmus spilopleura* (a species of piranha with a tendency to being an omnivore) show perceptible negative effects of an extreme ebb that happened in 2005; while *S. elongatus* (a strictly piscivorous piranha) did not show any apparent effects (Tribuzy-Neto et al., 2018).

Nevertheless, beyond these species-specific effects, intense ebbs may affect the structure and composition of the fish assemblages. For example, Freitas et al. (2013) evaluated the effect of the severe ebb that occurred in the Amazon in 2005 and observed a reduction in the beta diversity in lakes of the lower stretch of the Solimões River, near the Lago do Rei. Such a reduction indicates that the lakes were becoming less heterogeneous in species composition but exhibited a tendency toward recovering in the following years. In another study, the effects of the ebb in 2005 provoked changes in the taxonomic composition and functional structure of the fish assemblage in Lago Catalão, also located in the same area as Lago do Rei, with declines in the abundance of all trophic levels of the fish food web, except primary consumers (Röpke et al., 2017). In extreme ebbs events, besides the changes in the water quality, the fish movements among the environments of the floodplain are hampered due the loss of connectivity (Hurd et al., 2016). The connection among floodplain lakes is a key driver for structuring its fish assemblages. Some species groups, such as non-migratory ones, may exhibit metapopulational patterns and are vulnerable to disruption in patterns of connectivity (Fernandes et al., 2014; Hurd et al., 2016).

Nevertheless, a positive indirect effect could result from dramatic events of fish mortality in Amazonian floodplain lakes. Fish decomposition could improve the primary productivity in a process ecologically similar to the fertilization of riparian areas of temperate rivers due to salmon mortality after spawning (Ben-David et al., 1998). The climate change scenario indicates an increase in the frequency of extreme climate events in the Amazon basin, with distinct patterns in the eastern and western portions of the basin (Sorribas et al., 2016). These events could dramatically affect the fish assemblages of the Amazonian floodplains, and it is fundamental to identify the intensity and the signaling of their effects not only on the biota, but also on the riverine communities living in these areas.

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