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The droughts of 1997 and 2005 in Amazonia: floodplain hydrology and its potential ecological and human impacts

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Abstract It is well known that most of the severe droughts in Amazonia, such as that of 1997, are El Niño-related. However, in 2005, the Amazon was affected by a severe drought that was not El Niño-related, as most of the rainfall anomalies that have happened in southwestern Amazonia are driven by sea surface temperature anomalies in the tropical North Atlantic. Earlier studies have analyzed both droughts in terms of their meteorological causes and impacts in *terra firme* (non-flooded) forests. This study compares the hydrological effects of both droughts on the Amazonian floodplain and discusses their potential ecological and human impacts based on an extensive literature review. The results revealed that the effects of the 2005 drought were exacerbated because rainfall was lower and evaporation rates were higher at the peak of the dry season compared to the 1997 drought. This induced a more acute depletion of water levels in floodplain lakes and was most likely associated with higher fish mortality rates. Based on the fact that the stem growth of many floodplain species is related to the length of the non-flooded period, it is hypothesized that the 1997 drought had more positive effects on floodplain forest growth than the 2005 drought. The fishing community of Silves in central Amazonia considered both droughts to have been equally severe. However, the 2005 drought was widely broadcasted by the press; therefore, the governmental mitigation efforts were more comprehensive. It is suggested that the availability of new communication technology and greater public awareness regarding environmental issues, combined with the new legal framework for assessing the severity of calamities in Brazil, are among the primary factors that explain the difference in societal response between the two droughts.

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1 Introduction

It is well known that the strong interannual variability of rainfall over the Amazon basin has direct impacts on the water balance of the Amazon River (e.g., Marengo 2005). As a consequence of this variability, the Amazon basin is affected by periodic droughts of variable intensity. A minority of them can be characterized as extreme droughts, and, in general, they are associated with El Niño events due to the strong link between the northern, central and eastern Amazonian rainfall and the tropical Pacific sea surface temperature variability (Ronchail et al. 2002; Marengo 2005). This was the case for the 1997 drought, which heavily impacted river discharges in the Amazon main-stem during the low water season (Tomasella et al. 2010).

In 2005, however, Amazonia experienced a severe drought that was not El Niño-related but was driven mostly by anomalously warm tropical North Atlantic sea surface temperatures (Marengo et al. 2008a, b; Cox et al. 2008; Tomasella et al. 2010). An event with similar climatological characteristics was recorded in 1963, indicating that events such as the 2005 drought are statistically less frequent than the El Niño-related episodes.

Severe droughts in moist tropical forests provoke large carbon emissions due to increases in forest flammability and tree mortality and the suppression of tree growth (Nepstad et al. 2004; Phillips et al. 2009). For this reason, the ecological impacts of the 1997 drought have been described in terms of the occurrence of widespread vegetation fires (Santilli et al. 2005; Moran et al. 2006), particularly in the Brazilian State of Roraima in northern Amazonia (Barbosa and Fearnside 1999; Shimabukuro et al. 2000). On the other hand, during the 2005 drought, the area most strongly affected by vegetation fires was southwestern Amazonia, which was considered to be the epicenter of the drought (Brown et al. 2006; Aragão et al. 2007; Marengo et al. 2008a). Although drought events lead to an increase in fires in Amazonia, the impacts of droughts have also increased in recent years due to the expansion of anthropogenic land-use changes, which are generally associated with the traditional use of fires for land management (Aragão et al. 2008).

Scientific efforts have been focused on the assessment of how sensitive the Amazonian forest is to severe droughts. Williamson et al. (2000) and Higuchi et al. (2004) reported increased tree mortality rates in 1997 in plots located north of Manaus in central Amazonia, and Phillips et al. (2009) concluded that the 2005 drought accelerated tree mortality over large areas of Amazonia, consequently causing reductions in the forest biomass.

Regarding the human impacts of droughts in Amazonia, the public and the scientific community tend to associate El Niño episodes with droughts in northeastern Brazil (Moran et al. 2006). This is most likely the reason why the impacts of severe droughts on local populations in Amazonia are poorly documented compared with those in semi-arid northeastern Brazil, although Moran et al. (2006) clearly demonstrated the vulnerability of poor Amazonian farmers to the droughts caused by strong El Niño events. There is more detailed information available on the human impacts of the 2005 drought; Brown et al. (2006) estimated that that drought affected more than 400,000 persons and caused over US $50 million in direct economic losses in southwestern Amazonia alone, particularly in the Brazilian state of Acre.

In spite of the existence of a few studies on the ecological and social impacts of both the 1997 and 2005 droughts on the *terra firme* (upland forest, non-flooded) forest environment, comparative studies on the ecological and social impacts of severe droughts on the main stem floodplain are extremely scarce.

The Amazon River floodplain is a complex network that includes the main stem river, permanent lakes of various sizes, large river branches that receive the contributions of major tributaries and small streams that drain riparian areas, and canals that connect floodplain lakes to the main stem and its branches depending on the water level (Richey et al. 2004). The main-stem floodplain is one of the richest ecosystems of the Amazon in terms of both biodiversity and net primary productivity. With a population of approximately 1.1 million (excluding the urban population living on the floodplain near Manaus, the largest city of the Amazon floodplain), the Amazon River floodplain covers an area of approximately 300,000 km^2, equivalent to 5 % of the whole Amazon basin, and is the habitat for approximately 3,000 freshwater fish species, which is equivalent to a quarter of the world's freshwater species (Ribeiro 2007).

Previous studies have indicated that the extensive Amazon floodplains have a strong influence on the hydrological and sediment regimes of the main-stem (Meade et al. 1985; Dunne et al. 1998). A general approximation based on modeling estimated that approximately 30 % of the discharge of the Amazon River is routed through the floodplain along a 2,000-km reach within the Brazilian territory (Richey et al. 1989). Direct measurements that quantify fluxes between the floodplain and the main stem are quite rare. Notable exceptions include the study by Lesack and Melack (1995) that quantified the interactions between Calado Lake (3°15'S, 60°34'W) and the Solimões River in the middle Amazon and a detailed study based on measurements and modeling that was conducted by Maurice-Bourgoin et al. (2007) and Bonnet et al. (2008) to quantify water and sediment exchanges between Curuaí Lake (01°50'S–02°15'S and 55°00'W–56°05'W) and the Amazon River in the lower Amazon basin. Given the high degree of heterogeneity found along the floodplain, interactions between the floodplain lakes and the main-stem are variable in terms of the Amazon River's contribution to the lakes and have been estimated at 70 to 90 % of the water input to Calado Lake (Bonnet et al. 2008) versus only approximately 21 % of the input to Curuaí Lake (Lesack and Melack 1995). However, both of the above studies have consistently shown that the main stem and lake interactions are quite variable over time, are strongly influenced by the local rainfall, and are significantly affected by the interannual climate variability (Lesack and Melack 1995; Bonnet et al. 2008). More importantly, during the low water period (October–November), the only loss of water from either lake occurs through evaporation and seepage into the groundwater (Lesack and Melack 1995; Bonnet et al. 2008). Fluxes are heavily influenced by the local rainfall falling directly onto the lakes or small riparian catchments (Lesack and Melack 1995). Similar results in terms of the exchange of water between the main-stem and the lakes have been described qualitatively by Junk et al. (1983) for Camelão Lake in the Solimões and by Fernandes (1997) for Rei Lake on Careiro Island in the Amazon River, indicating that the hydrological functioning observed at the Calado and Curuaí lakes are fairly uniform all along the Amazon floodplain.

From those studies, it is possible to conclude that the annual hydrological regime of floodplain lakes is dictated not only by the duration and magnitude of river main stem recession but also by the local meteorological drivers of lake water balance, namely precipitation and local evaporation, and marginally by groundwater seepage. The influence of the local meteorological conditions is more important when the floodplain lakes are physically isolated from the main stem (i.e., in low water conditions and during part of the main-stem river's rise), which is the prevailing condition during severe drought events.

The annual flooding pulse is closely linked to the feeding habitats of herbivorous and omnivorous fish (Junk et al. 2007), as the spatial and temporal inundation patterns of the main stem floodplain affect the dynamics of the planktonic and periphytic algae and the phenological development of the tree fruits and seeds (Melack et al. 2009). Moreover, the mobility of the floodplain's local population and their supply of food and medicine depend on the connectedness of the large river branches and floodplain lakes. For this reason, the livelihood strategies of the local floodplain populations are closely linked to the hydrological regime of the main stem (Pinho and Orlove, in review). Therefore, it is clear that the impacts of severe droughts on the main-stem floodplain should not be underestimated, particularly when the floodplain population cannot access the main river by boat due to the drying out of the navigation canals.

The extreme recession of the river in 2005 caused tremendous social, economic and ecological impacts, not only in the *terra firme* environments but also on the main-stem floodplain. News reports, which are not necessarily a trustworthy source of information, categorized the 2005 drought as a "natural disaster" (http://news.mongabay.com/2005/1007-reuters-amazon.html) due to the fish mortality in dried out floodplain lakes and canals and the large number of floodplain inhabitants who became isolated, thereby necessitating large-scale relief operations using helicopters to transport people, food, supplies and medicine (http://www.nytimes.com/2005/12/11/international/americas/11amazon.html?_r=1).

Although the 2005 drought was more severe upstream of the Negro-Solimões confluence compared to the 1997 drought, the situation was the reverse downstream (Tomasella et al. 2010), suggesting that both droughts represent a similar level of severity. Additionally, the perceptions of the local floodplain population, as reported by the press (for instance, http://portalamazonia.globo.com/pscript/noticias/noticias.php?idN=96902), associated both droughts with the "highest rates of fish mortality in the last decade"; therefore, the impacts of both droughts were likely comparable in their intensity.

In this context, the primary objective of this paper is to comparatively assess the hydrological, ecological and human impacts along the main stem river floodplain associated with both the 1997 and 2005 droughts. To achieve this, remote sensing and ground station data were used to quantify the water levels in two representative Amazon floodplain lakes during both droughts. Based on this hydrological assessment and a review of the existing literature, the potential impacts of the droughts on the ecology and the human population of the floodplain were critically analyzed.

2 Data and methodology

2.1 Study sites

The eastward-flowing middle and lower Amazon River within the Brazilian territory receives the contributions of major tributaries coming from the northern and southern margins of the main stem. The Amazon River has various names along its main-stem: Marañón before entering Brazilian territory; Solimões from the Brazilian border to the mouth of the Negro river; and the Amazon from the confluence of the Negro and Solimões rivers to the Atlantic Ocean. As noted earlier, all along the Solimões and Amazon River main stems, extensive floodplains that were formed by a complex and entangled system of channels and riparian lakes have developed (Richey et al. 2004).

To assess the hydrological, ecological and human impacts of the 1997 and 2005 droughts on the Amazon floodplain, existing data from three different sites located along the floodplain were used: Mamirauá and Silves, in the middle Amazon Basin, and Curuaí, in the lower Amazon Basin.

Mamirauá is a Sustainable Development Reserve of floodplain forest that covers an area of approximately 11,240 km^2 in the middle Amazon Basin (02°36'S–03°08'S and 67°13'W–64°45'W), delimited by the Solimões, Japurá and Auaiti-Paraná rivers (Ramalho et al. 2009).

Silves (02º50’20” S, 58º12’33”), located at the confluence of Canaçari Lake and the Urubu River, is home to typical Amazonian local fishing communities with traditional ways of living that have been preserved for centuries (Pinho and Orlove, in review).

Finally, Curuaí Lake (01°50’S–02°15’S and 55°00’W–56°05’W) is a complex system of more than 30 interconnected channels, some of them linked to the Amazon River, with a drainage area of approximately 3,800 km^2 (Maurice-Bourgoin et al. 2007). Both lakes are part of the Amazon floodplain ecosystem and are relatively similar in terms of their fluvial geomorphology (Richey et al. 2004)

2.2 Hydrological data

The water level information from the Mamirauá and Curuaí lakes were used to characterize both droughts in the floodplain (Table 1, Fig. 1). These data were compared to the water level behavior in the main stem at the closest river gauging stations of Itapeuá and Óbidos, respectively. The water levels of Mamirauá Lake were collected by the Mamirauá Institute and were extracted from Ramalho et al. (2009), whereas the rest of the hydrological data were obtained from the Brazilian Water Agency ANA database (http://hidroweb.ana.gov.br). The data were quality-controlled following the methodology described in ANEEL (1982). The hydrological data presented in this paper were analyzed according to the water year, which runs from November, when water levels begin to rise, through October of the following year. Therefore, the 1997 drought corresponds to the water year that was recorded from November 1996 to October 1997, and the 2005 drought corresponds to the water year from November 2004 to October 2005. The 1997 drought is generally referred as the 1997–98 event, indicating an El Niño episode that started in 1997 and continued through the first half of 1998 (Kane 1999). However, the minimum water levels in the main stem were

Table 1 Geographical location of the hydrological and meteorological stations used to characterize both droughts

Station	Latitude	Longitude
Floodplain lakes water level stations		
Mamirauá	3°06’55”S	64°47’50”W
Curuaí	2°16.12’S	55°28.84’W
Main stem water level stations		
Itapeuá	4°03’S	63°02’W
Manaus harbor	3°08’12”S	60°01’37”W
Óbidos	1°54’05”S	55°31’07”W
Meteorological stations		
Benjamin constant	4°23’S	70°02’W
Fonte boa	2°32’S	66°10’W
Tefé	3°22’S	64°42’W
Coari	4°05’S	63°08’W
Codajás	3°50’S	62°05’W
Manaus	3°07’S	59°57’W
Itacoatiara	3°08’S	58°26’W
Óbidos	1°55’S	55°31’W
Monte Alegre	2°00’S	54°05’W
Porto De Moz	1°44’S	52°14’W
Macapá	0°03’S	51°07’W

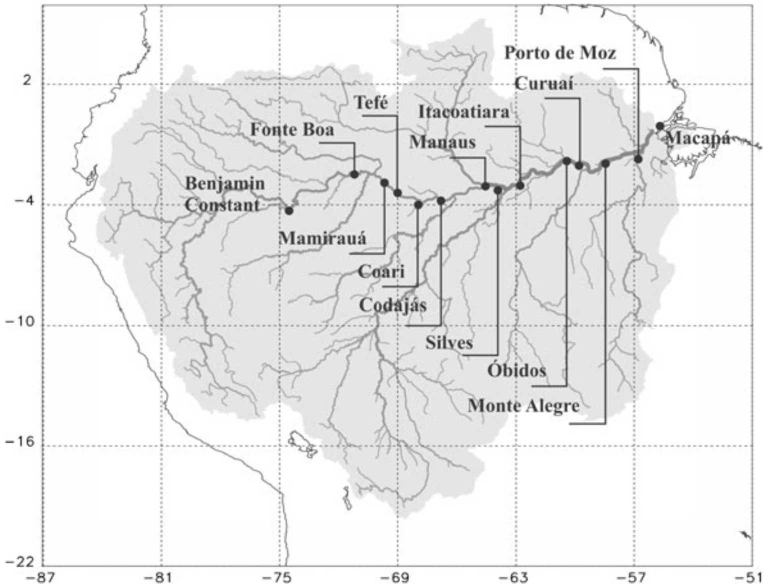

Fig. 1 Main-stem meteorological and hydrological stations

recorded during the low waters of 1997 (Tomasella et al. 2010); consequently, most of the analysis in this paper was focused on the 1996–97 water year.

2.3 Meteorological data

The meteorological data used in this paper were from stations located in the Amazon floodplain and were provided by the Brazilian National Meteorological Service–INMET (Table 1). These data were used to estimate monthly lake evaporation using the Penman-Monteith equation (Allen et al. 1998) for lake evaporation, using an albedo of 0.06 and a surface roughness of 0.0003 m (Cox et al. 1999).

2.4 Remote sensing data processing

Landsat satellite images were extracted from the archives of the INPE's Images Production Division, DGI/INPE (http://www.dgi.inpe.br/siteDgi/). The Amazon floodplain mosaic used in this paper is available through the LBA Data and Information System (www.cptec.inpe.br/lba). Details regarding the development of this mosaic are described in Shimabukuro et al. (2002).

To estimate the surface areas of open water in the floodplain lakes, Landsat images were classified using the region growing segmentation method (Espindola et al. 2006). This approach is a simple region-based image segmentation method that examines the pixels neighboring a set of initial "seed points" and determines whether the pixel neighbors should be added to the region according to a pre-defined set of similarity criteria. The process is iterated in the same manner as general data clustering algorithms. The result is a group of polygons that represent homogeneous areas within the image. In this paper, blue tones in the pixels of the RGB Landsat images were identified as regions occupied by water. The sum of the pixels classified as water represents the total area occupied by open water in the Landsat image. The software used for segmentation was the Geographical Data Mining Analyst (GeoDMA; www.dpi.inpe.br/geodma), which is a plug-in module for the TerraView software (http://www.dpi.inpe.br/terraview).

2.5 Information on ecological and human impacts

Field data on the human impacts of the droughts within the floodplain were collected by Pinho (2007) in the local fishing communities of the municipality of Silves between 2001 and December 2005. This work utilized multiple methodologies that included open-ended and semi-structured questionnaires, surveys, ethnographic data and fish assessments for the floodplain lakes. The ethnographic data were supplemented by water level data for the Urubu River, which was collected by Pinho and Orlove (in review) in 2005 and 2006.

It will be demonstrated in this paper that large-scale official statistical information has several limitations for assessment of ecological impacts in the Amazon ecosystem, especially regarding fishery productivity. Therefore, local communities in the Amazon, such as those described in this paper for the municipality of Silves, are appropriate subjects for assessing the ecological features of the landscape, and for detecting changes in these features when climatic events and their consequent impacts on ecological systems occur. Many of these local communities around the world have developed a sophisticated appreciation for their local ecosystems and the climatic patterns associated with the resulting ecological changes (Green et al. 2010).

Local ecological knowledge is still highly valued by these communities today (Pinho 2007; Orlove and Tosteson 1999; Taddei 2009; Green et al. 2010), as it is used to direct their daily livelihood strategies as well as to inform many seasonally-dependant cultural events (Green et al. 2010). In recent years, the local observations have been recognized by scientists as a vital source of environmental data for regions where few historic records exist (Green et al. 2010). This is the case for the Amazonian ecosystems and specifically for the assessment of the impacts of the 1997 and 2005 droughts on the fishing communities. Thus, the seasonal change observations made by the local people have the potential to fill gaps in the climate data for the tropical Amazonia region and could also serve to inform culturally appropriate adaptation strategies (Pinho and Orlove, in review).

3 Results and discussion

3.1 Hydrological analysis of the 1997 and 2005 droughts in floodplain lakes

Tomasella et al. (2010) showed that discharge anomalies along the main stem during the 1997 drought were, by and large, controlled by a below-the-mean discharge from the northern tributaries; whereas in the 2005 drought, below-the-mean discharges were driven by the southern tributaries. Because most of the water contributions from the northern tributaries come from the Negro River, the water levels in the Amazon main-stem were lower downstream of the Negro-Solimões confluence in 1997 compared to 2005. Upstream of that confluence, the situation was exactly the opposite; that is, water levels were lower in the 2005 drought.

Because the hydrological functioning of the floodplain lakes depends on local meteorological conditions during periods of low water, it is important to assess whether the impacts of the 2005 drought were more intense in the floodplain lakes compared to those of 1997, regardless of the discharges observed in the main stem. Figure 2 presents the daily water

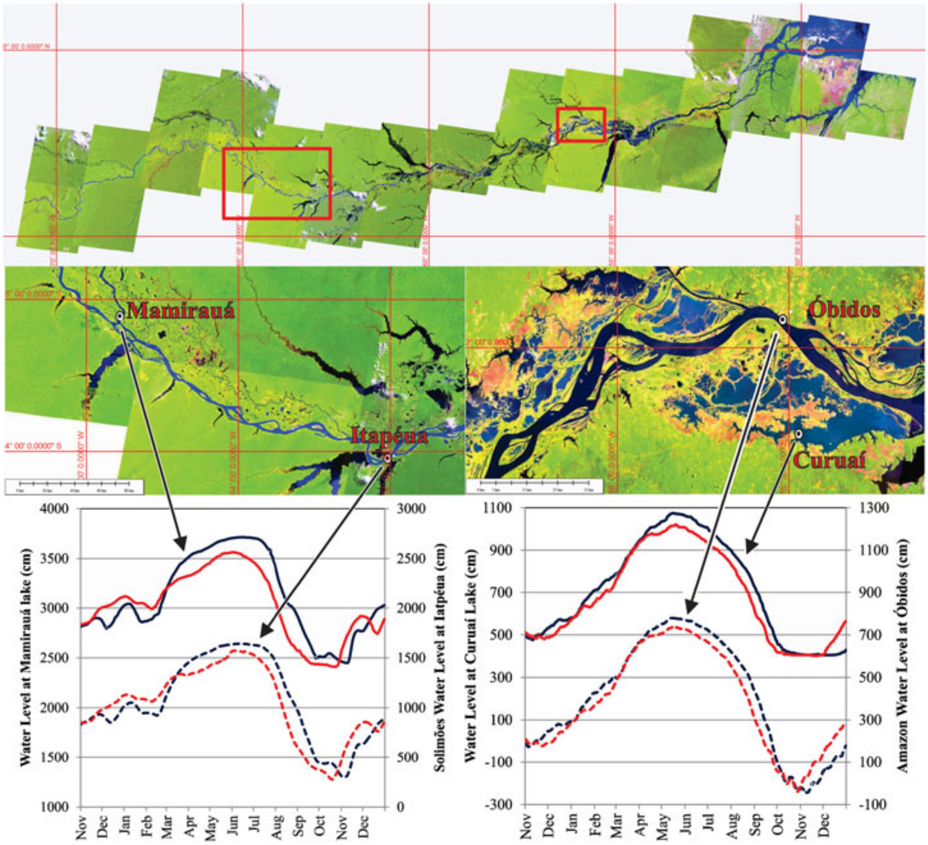

Fig. 2 Landsat mosaic showing the Amazon floodplain (*top*); close-ups of two spots of the floodplain area, with *white circles* indicating the locations of the stations in Mamirauá and Curuaí lakes and the nearby main stem gauging stations, Itapeuá and Óbidos (*middle*); the *blue lines* correspond to daily variations in water level from November 1996 to December 1997, whereas the *red lines* correspond to November 2004 through December 2005; *continuous lines* indicate the water levels of the floodplain lakes and the *dotted lines* are the water levels of the main stem (*bottom* graphs)

levels (above the arbitrary zero of the rules) for the 1997 and 2005 droughts for the two lakes along the floodplain and in the nearby main stem gauging stations: Mamirauá, located in the middle Amazon close to the station of Itapéua, and Curuaí, located in the lower Amazon close to the station of Óbidos. As mentioned previously, the data are shown dating from the beginning of the water year, that is, November 1996 and November 2004, for the droughts of 1997 and 2005, respectively.

A comparison of the water levels in the main stem and in the floodplain of the middle Amazon during both droughts revealed that the minimum water level recorded at Itapéua in 1997 was 40 cm higher than the minimum recorded in 2005. In Mamirauá Lake, the situation was similar: the minimum water level in 1997 was 21 cm higher than the minimum recorded in 2005. An analysis of the water levels in the lower Amazon, on the other hand, indicates that the minimum recorded at the Óbidos station during 1997 was 5 cm lower than in 2005, implying that a more critical hydrological drought occurred in 1997 (Tomasella et al. 2010). Surprisingly, the annual minimum water level at Curuaí Lake was slightly higher (3 cm) in 1997 compared to 2005.

The last result is corroborated by a sequence of Landsat images from a region in the vicinity of Óbidos (mosaic of the images: path 228, row 61 and path 228, row 62); these images were previously processed using the TerraView plugin GeoDMA to highlight the surface area of open water, which characterizes the situations of the floodplain lakes on almost equivalent dates in late 1997 and in late 2005, close to the time when the water levels were the lowest. The gray arrows in Fig. 3 indicate the differences between the episodes. A comparison of the images from September confirmed that the water levels at the floodplain lakes dropped earlier during the 2005 drought, as shown by Tomasella et al. (2010). Although the situation in the floodplain looks fairly similar for both years in October, subtle differences can be observed for both years, suggesting that the floodplain lakes were drier in 2005 compared to 1997.

A visual analysis of the Landsat images has limitations, as such images do not reflect the most critical conditions during the two droughts. According to the water level data from Curuaí Lake, the minimum water levels during both drought episodes were recorded several

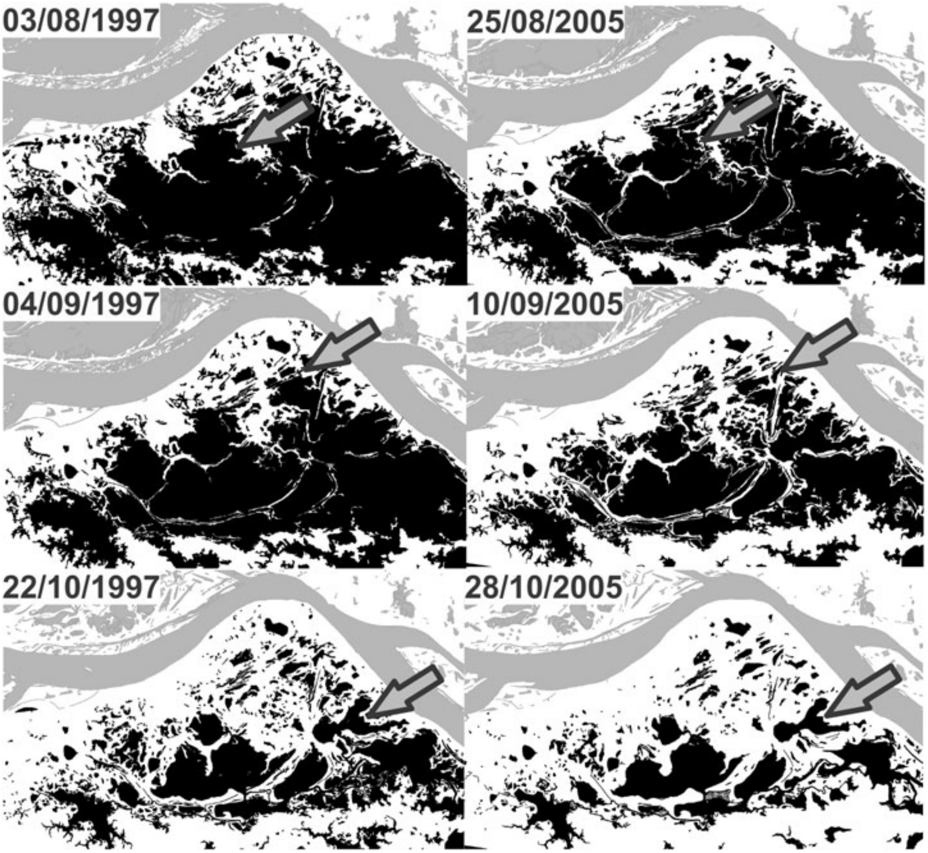

Fig. 3 Compositions of Landsat 5 images of the Curuaí floodplain (path 228, row 61 and path 228, row 62), classified using the TerraView plug-in GeoDMA, comparing the droughts of 1997 and 2005. The *gray arrows* highlight the differences between the two events

days after the Landsat images of Fig. 3 were captured. Daily records indicate that the water level of Curuaí Lake dropped 7 cm between the Landsat image date (22 October 1997) and the date when the minimum lake water level was recorded (27 November 1997); whereas the difference in the water level fall was only 3 cm between the Landsat image date (28 October 2005) and the date when the minimum lake water level was recorded for Curuaí Lake (17 November 2005).

To assess the most critical conditions in both droughts, the open surface water estimations made using the plugin GeoDMA for each Landsat image in Fig. 3 were related to Curuaí Lake water level data for the corresponding dates. Assuming that the morphometric changes in the bottom topography of Curuaí Lake between 1997 and 2005 were not significant, the set of the open surface area and water level data at Curuaí Lake was used to build a polynomial relationship, shown in Fig. 4, using a methodology similar to Bonnet et al. (2008). Knowing that the minimum water level recorded at the Curuaí station was 402 cm in 2005 and 405 cm in 1997, it is possible to estimate that the minimum flooded area for Curuaí Lake was 446 km^2 in 2005–approximately 6.5 km^2 smaller than the minimum flooded area in 1997.

The most likely explanation for the fact that water levels in the floodplain lakes were lower during 2005 compared to 1997, in spite to the fact that the opposite occurred in the main stem, is related to the local meteorological conditions. As demonstrated by previous studies, the influence of the local meteorological conditions is maximized when the interaction between the lakes and the main-stem is severed because the water depletion in the floodplain lakes under such conditions is primarily controlled by evaporation, local rainfall (and the consequent runoff from small local streams), and the marginal influence of groundwater seepage. This can easily be observed by comparing the behavior of the water levels of the main stem and the floodplain lakes over time, as shown in Fig. 2, which shows that the water levels in both lakes remain almost parallel to the main stem levels most of the time. However, during the peak of the low water period, the recession in the lakes became almost flat while the water levels continued to drop steadily in the main stem. Figure 2 indicates that, in both lakes, this condition is verified from late September through mid-December. For this reason, the comparison of the local meteorological conditions, specifically evaporation and rainfall, during both of the drought events was restricted to data collected in October and November.

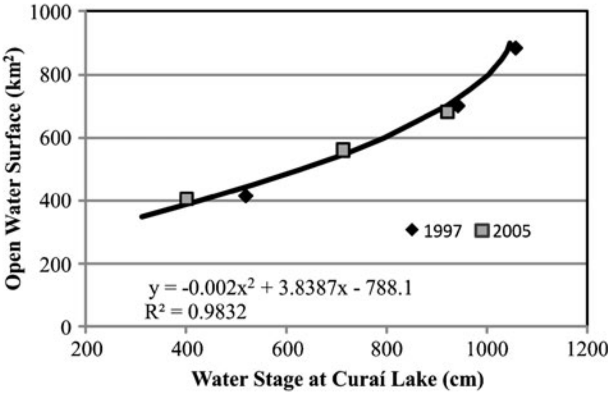

Fig. 4 The relationship between the surface area of open water at Curuaí Lake and the water level at the Curuaí station

The meteorological data from the Tefé station, the closest to Mamirauá Lake, indicated that the total rainfall during October–November 1997 was 278.3 mm compared to 276.0 mm for the same period in 2005, which is a statistically similar value. The evaporation estimations, which were calculated using the Penman-Monteith equation for free water surface, indicate that the total evaporation was 344.8 mm in October–November 1997 compared to 391.1 mm in October–November 2005, which led to a more drastic lake depletion during the 2005 drought.

In the case of the Óbidos meteorological station, located close to Curuaí Lake, the total rainfall was 191 mm for the period of October and November 1997 versus 125.1 mm during the same months in 2005. Penman-Monteith estimations indicate that the evaporation rates were higher during 2005: the total evaporation in October–November 1997 was 388.6 mm versus 437.5 mm in October–November 2005.

In conclusion, these results suggest that, in Mamirauá Lake, the 2005 drought was more intense than the event of 1997 because the minimum water levels in the main stem dropped faster in 2005, thereby interrupting the connection between the main-stem and the lake earlier in the dry season. During this period, the evaporation rates are estimated to have been higher in 2005, promoting a more rapid depletion of the lake water levels.

Regarding Curuaí Lake, although the minimum water level in the main stem was lower during the 1997 drought in comparison to the 2005 drought, the minimum water level of the lake was more critical in 2005. The cause of this pattern is the local meteorological conditions during the period when the lake was disconnected from the main stem (October through November). The rainfall was lower in that period during 2005; consequently, the recharge rate from the surface runoff was lower, which combined with higher evaporation rates in that year.

Given the scarcity of the floodplain lake data and the heterogeneity of the Amazon floodplain ecosystem, it is not possible to conclude that the hydrological behavior of the entire Amazon floodplain can be extrapolated from the information derived from two lakes. Moreover, the Landsat 5 images available for the drought of 1997 are generally more compromised by cloud cover, preventing a cloud-free analysis such as that shown in Fig. 3. However, it is possible to make inferences on a wider scale using the data from the meteorological stations located on or in the vicinity of the main stem floodplain. Figure 5 shows the total evaporation rates and rainfall values for October and November 1997 and 2005 along the main stem floodplain. An analysis of Fig. 5 reveals that the total rainfall, in general, was higher in 1997 than 2005 (except in Manaus, Monte Alegre and Porto de Moz, where rainfall was marginally lower in 1997) while in Benjamin Constant rainfall in 2005 was three times greater than the amount recorded during 1997. Regarding evaporation, Fig. 5 indicates that the total evaporation rates during October–November were higher in 2005 compared to 1997, with the only exception being at the Monte Alegre station, where the rates were marginally higher during 1997. Therefore, it is possible to conclude that, in most of the main stem floodplain, the rainfall was generally higher and evaporation lower during October–November 1997 compared to the same months in 2005. As mentioned previously, both of these factors reduce the water level replenishment and favor the depletion of floodplain lakes.

The analyses of the mean climatic fields and temperature anomaly fields provided by CPTEC and INMET suggest that during October–November 1997, temperatures were approximately 1–2 °C warmer than during October–November 2005. The primary differences in 1997 (as compared to 2005) were identified as stronger winds, lower relative humidity and relatively warmer maximum and minimum air temperatures. It is possible that at the regional level in western Amazonia, the relatively clear skies in 2005 may have

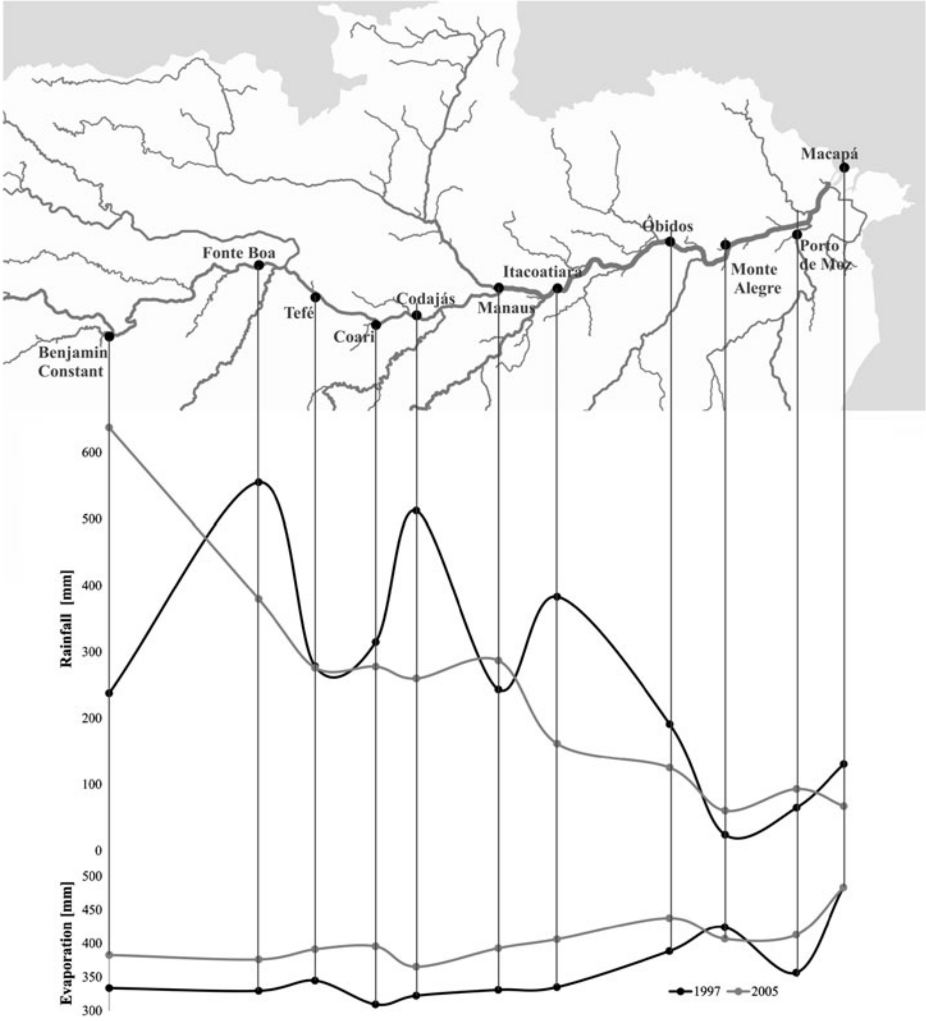

Fig. 5 Comparison of accumulated rainfall and evaporation in October–November of 1997 and 2005 along the main-stem floodplain

favored more solar radiation reaching the water's surface, favoring the more intense evaporation of the lakes. This indicates a strong dominant effect of the energy term from the Penman equation compared to the aerodynamic term, and it is also consistent with the observed evaporation values.

Finally, although the evaporation estimations are based on the measurements from meteorological stations that are relatively close to the main-stem (less than 5 km away), it is clear that the observed data reflect micro-meteorological conditions that are similar to, but not the same as, those of the floodplain lakes. Moreover, the evaporation estimations produced using the Penman-Monteith approach do not consider other effects, such as water heat storage, that influence the evaporation rates of open water surfaces. Therefore, the provided evaporation estimations should be considered a crude approximation of a complex process. However, and more importantly than the exact evaporation rates, the differences in the evaporation rates between the two drought events are a clear indication of drier local climate conditions in 2005 than in 1997 along most of the main-stem floodplain.

Although the water levels in the main stem were lower during the 1997 event downstream of the Solimões–Negro confluence (Tomasella et al. 2010), the ground data suggest that lower rainfall and higher evaporation rates in the critical months of 2005 counterbalanced the effects of the more intense drop in the water levels in the main stem in 1997 and were responsible for a stronger depletion of the floodplain lakes than those verified for 1997.

3.2 Ecological impacts on the floodplain forests

Most of the research on the floodplain forests has generally been conducted under climatologically normal conditions, limiting the identification of the critical ecological mechanisms of floodplain species during severe droughts (Parolin et al. 2010).

In spite of these limitations, the extended inundation of the floodplain areas results in the formation of annual rings in older trees in the Amazon floodplain (Schöngart et al. 2002) that can be used as proxies for the hydrological conditions in the main-stem. A dendrometric study conducted by Schöngart et al. (2004) for *Piranhea trifoliate* (Euphorbiaceae), which is a widespread species in the whitewater floodplains (*várzeas*) of the Solimões and Amazon rivers, demonstrated a significant correlation between the El Niño events and the width of tree rings.

Piranhea trifoliate is a brevi-deciduous tree species that sheds its leaves during flooding and begins to flush at the end of the high water season (August in central Amazonia). The growth in trunk diameter occurs primarily during the non-flooded period. At the beginning of the high water season, the diameter increments rapidly decline to zero (Schöngart et al. 2004). Therefore, the El Niño events, which are primarily associated with low rainfall in Amazonia, result in lower than normal main-stem river discharges and, consequently, a longer vegetation period for several floodplain species and wider tree rings (Schöngart et al. 2004).

Schöngart et al. (2004) conducted a detailed analysis of the relationships between tree ring width and several hydrological characteristics of the flood pulses recorded at Manaus Harbor for the period of 1903–1999. Among all of the hydrological characteristics of the annual flood wave that were analyzed, the variable with the most significant correlation with ring width was the duration of the non-flooded period, which approximately defines the duration of the vegetation period of *Piranhea trifoliate*. The duration of the non-flooded period, as defined by Schöngart et al. (2004), corresponds to the number of days when main-stem water levels remained below a certain threshold value, which is 2,438 cm in the case of the water level records at Manaus Harbor.

Another strong line of evidence for the relationship between tree ring widths and the duration of the non-flooded period is provided by another dendrochronology study (Schöngart et al. 2005) focused on *Macrolobium acaciifolium* (Fabaceae), a dominant, brevi-deciduous legume tree species occurring at low elevations in either the nutrient-poor black-water (*igapó*) or the nutrient-rich white-water floodplain forests (*várzeas*) of the Amazon. Although this species exhibits significantly lower mean radial increments in the *igapó* compared with the same species located in the *várzea* (because of lower nutrient availability), the ring widths in both floodplain forests were, again, significantly correlated with the duration of the non-flooded period and showed increases in wood growth associated with the El Niño events (Schöngart et al. 2005). This clearly indicates that *Macrolobium acaciifolium* of the blackwater and whitewater floodplain forests exhibit similar ecological responses.

Unfortunately, dendrometric data are not available for the 2005 drought; therefore, it is not possible to use direct measurements to assess which of the two droughts was related to more vigorous tree growth in several floodplains. However, indirect evidence can be derived from the knowledge that the duration of the non-flooded period is significantly correlated with tree growth.

As mentioned previously, the water year begins in November in the main-stem, when the river water levels begin to rise in response to the onset of the wet season. The water levels reach their maximum by the middle of the following year and then recede to a minimum by the end of October or the beginning of November. The so-called flooded period, when the water levels are above 2,438 cm at Manaus Harbor, according to the definition of Schöngart et al. (2004), normally occurs between March and August. Then, the non-flooded period begins and normally extends through March of the following year. Therefore, the definition of the non-flooded period depends not only on the hydrological characteristics of the annual flood pulse but also on the timing and intensity of the next rainy season.

Figure 6 presents the daily water levels at Manaus Harbor for the 1997 and 2005 droughts. In both cases, the levels are shown through the end of the following May (i.e., May 1998 and May 2006 for the 1997 and 2005 droughts, respectively). The horizontal line indicates the water level of 2,438 cm above which the floodplain is considered flooded. The descending vertical arrows indicate the beginning and end of the flooded and non-flooded periods for the 1997 drought, and the ascending arrows correspond to the same periods for the 2005 event. Figure 6 clearly indicates that the flooded season began on almost the same dates for both events. The duration of the 1997 flooded season was slightly longer than that of 2005, whereas the duration of the non-flooded period in 1997 was much longer. The water levels at Manaus Harbor indicate that the non-flooded period in 1997 was 242 days compared to 184 days in 2005. Based on the statistics of Schöngart et al. (2004) for the period of 1903–1999 at Manaus Harbor, the 1997 drought is classified as a typical El Niño year, whereas the 2005 event is not. The longer duration of the non-flooded period for the 1997 drought is not surprising considering the evolution of the El Niño event of 1997–98

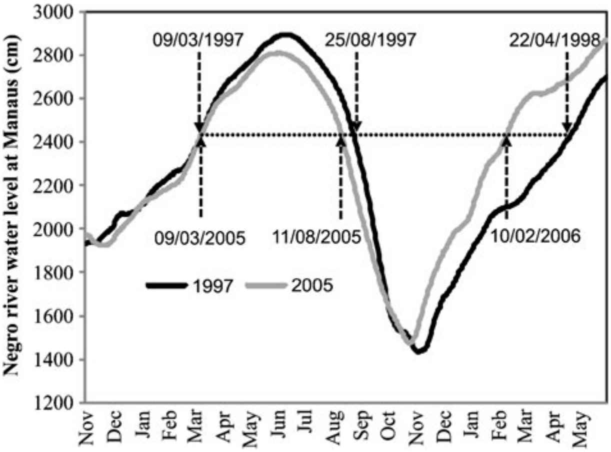

Fig. 6 Comparison of daily water levels of the Negro River at the port of Manaus from November 1996 to May 1998 and from November 2004 to May 2006. The *horizontal line* defines the main-stem water level that defines the occurrence of flooding in the floodplain. *Vertical descending arrows* signal the beginning and end of the flooded and non-flooded periods during the 1997 drought, and the *ascending arrows* define the same periods for 2005

(Kane 1999), in which the mature phase of the event was observed by October 1997 and faded away by March 1998.

Based on the assessment of the non-flooded periods for both droughts, it is hypothesized that for species with ecological mechanisms similar to *Piranhea trifoliate*, stem growth rates during the 1997 drought were higher than during the 2005 drought, which resulted in increased biomass in 1997.

The floodplain forests possess relatively high species richness (approximately 1,000 species), and many species have developed a variety of survival strategies that make them highly tolerant to waterlogging and submergence (Parolin et al. 2004). It may thus be argued that drawing conclusions on the impact of drought events on floodplain forests based on the ecological responses of a few species has serious limitations. However, a detailed study by Schöngart et al. (2002) based on the dendrometric measurements for nine different floodplain species, including not only brevi-decidous species but also evergreen, semi-deciduous and stem-succulent trees, conclusively determined that all trees have high stem increment rates during the low water period. The diameter growth of all species begins immediately after the flushing of new leaves close to the end of the flooded period and peaks at the beginning of the non-flooded period. Therefore, it is clear that the behavior of *Piranhea trifoliate* can be extended to many floodplain tree species (Schöngart et al. 2004).

In addition, Schöngart et al. (2002) observed a strong decline in diameter growth at the end of the dry season related to decreases in water content, occasionally to the permanent wilting point. Because the vegetation period during the 1997 drought was longer than during the 2005 event, it is possible that an extended low water period in the dry season could have been associated with greater soil water deficits to a point that compromised tree growth during the non-flooded period. However, Fig. 5 indicates that during the peak of the dry season, rainfall was higher and evaporation was lower in most of the floodplain during the 1997 drought compared to 2005, which reduces the chances of severe soil moisture deficits and favors the hypothesis of higher tree growth rates during 1997.

3.3 Ecological impacts on fish productivity and mortality rates

Many fish species in the Amazon undergo seasonal lateral migrations in response to water level fluctuations (Fernandes 1997), and migration patterns usually have two seasonal peaks. The first peak occurs at the beginning of the flooding (from December to January), when the water invades the floodplain lakes, mixing the nutrient-poor black waters of the small local catchments with the white and nutrient-rich main-stem waters. During this period, many fish species migrate to the floodplain lakes to feed on the fruits produced by the flooded forests (Goulding 1980; Junk 1989; Smith 1981; Junk et al. 2007). It follows that the fishery potential of the Amazon River system is directly related to floodplain area and to the magnitude and duration of the floodplain's inundation (Welcomme 1990; Bayley 1989; Petrere 1989).

The second migration peak occurs as the water is receding (August–September), when the currents are moving from the lakes to the main stem (Junk et al. 1983; Fernandes 1997). As the water levels recede, the connection between the lakes and the main stem is severed by aquatic macrophytes and woody matter that is transported by the flood (Junk et al. 1983; Fernandes 1997), and many fishes are trapped in the lakes. In this situation, the floodplain lakes are physically isolated from the main-stem, and oxygen concentrations within the lakes and communication canals drop (Junk et al. 1983) because of the large quantities of organic material and detritus from the flood that are available for decomposition (Fernandes 1997; Castello 2008).

The interannual climate variability affects the ecological and freshwater dynamics of the Amazon Basin, altering the net carbon flux to the atmosphere, river discharges and the seasonal inundation of the floodplain (Foley et al. 2002). Because extreme droughts are usually associated with high water periods of shorter duration and a smaller-than-normal inundated area, extreme events can disrupt the migrations of several fish species to the floodplain lakes and reduce the accessibility of the food in the flooded forests. Additionally, the connections between the main stem and the lakes along the floodplain are interrupted earlier and for a longer period than in normal years; consequently, large populations of fish that are trapped in the lakes eventually die of hypoxia or predation. This is why low water levels are associated with higher fish mortality (Welcomme 1979; Junk et al. 1983).

Regarding the effects of droughts on fish production, Melack et al. (2009) recognized difficulties in identifying relationships between the maximum total flooded area and the total annual fish yield, as markets in Amazonia tend to commercialize fish of varying sizes, ages and trophic levels. However, when adult fish and trophic levels are analyzed separately, significant relationships between fish yield and flooding area emerged. The relationships presented by Melack et al. (2009) indicated that the links between the total flooded area and fish productivity had short time lags (0–1 years) for small species of lower trophic levels and longer time lags (3–5 years) for fish species at higher trophic levels. The existence of lagged relationships between annual flooding and fish yield, as well as the absence of long-term standardized fish yield measurements in Amazonia, makes it extremely difficult to assess the impact of severe droughts on fish yields on an annual basis similar to the analyses presented in this paper.

Pinho and Orlove (in review) evaluated the impact of the interannual climate variability on the catches of two commercial fish species: Tambaqui (*Colossoma macropomum)* and Pirarucu (*Arapaima gigas)*. Silves, like several other areas of the Amazon floodplain, shows clear signs of the overfishing of highly economically valuable species, which is related to the technological changes that enable more efficient fishing combined with an increased number of vessels and fishermen (Pinho et al. 2012). This makes a statistical assessment of the changes in fishery productivity in relation to extreme climate events impossible to disentangle from the impacts of overfishing. Therefore, the available statistics are not suitable for assessing the impacts of the 1997 and 2005 droughts on fish productivity or mortality rates, and indirect indicators must be used.

Data from Pinho and Orlove (in review) indicated that the extreme drought in 2005 led to an increase in poaching in Silves. This was the result of two different factors: (i) the lower the water level of the floodplain lakes became, the more vulnerable commercial fish species in the floodplain lakes became and (ii) the greater depletion of oxygen levels in the floodplain lakes during extreme droughts led to the increased lateral migration of large fish species to the main river system, where they became accessible to large-scale commercial fishing operations. It is important to note that this process affected even protected lakes where local community regulations involving fishing are more strictly enforced. In fact, from a total of 300 individual fishermen interviewed, 92 % stated that the major threat to the protection of fish species and floodplain lakes during extreme droughts is the intensification of poachers and commercial fisheries in the area (Pinho and Orlove, in review).

With regard to the fish mortality rates, one indirect indicator is the prevailing meteorological conditions at the peak of the droughts. Large fish mortality rates during periods of low water levels are clearly related to episodes of hypoxia (Welcomme 1979) in the floodplain lakes. As indicated previously, the severity of the 2005 drought was equal or greater in the Curuaí and Mamirauá lakes compared to the 1997 drought. Figure 5 indicates that in many areas of the floodplain, evaporation was higher at the peak of the dry season in 2005 than in 1997 due to higher solar radiation and air temperatures (data not shown), combined with lower rainfall levels. It is well known that higher solar radiation and temperatures favor the decomposition of vegetation debris in the floodplain lakes, increase water temperature, and reduce the solubility of oxygen in the water, consequently resulting in higher fish mortality. Based on this assumption, the most likely hypothesis is that the drought of 2005 was associated with higher fish mortality rates. Unfortunately, there is no experimental data available with which to prove (or disprove) this hypothesis.

3.4 Human impacts of droughts on the floodplain: a perspective from Silves, central Brazilian Amazon

The floodplain communities (*caboclos*) of the Amazon Basin define four seasons according to the main-stem hydrological regime: the rising of waters, the flood period, the receding of waters, and the dry season (Orlove 2003). All of the economic activities of the floodplain communities, including fisheries, agriculture and timber extraction, are directly associated with the fluctuations of the river's water level. Because economic activities are dictated by the hydrological regime of the main stem, it is clear that the interannual climate variability impacts the livelihoods of local populations (Schongart and Junk 2007).

In the Silves community, as in other floodplain areas, fishing is conducted throughout the year, but occurs more intensely during the low water season when the fish stocks are trapped in the floodplain lakes (Chernela et al. 2002). Fishing is the primary economic activity of the *caboclos*. Because fish species are spread across the seasonally flooded forest during the high water season, the fish catch is drastically reduced during floods. Given the seasonal variation in the fish catch, local communities depend on other economic activities for subsistence, such as agriculture (manioc cultivation), hunting and cattle rearing.

Agriculture in the floodplain is practiced during the dry season when larger areas of the floodplain are available for cultivation. As the duration of the low water period is approximately 6 months, the dry period lasts long enough to allow the crops to mature (Junk 2000).

For most floodplain communities, the primary economic activity during the high water season is timber extraction. During this period, accessing upland areas of the floodplain forests is relatively easy, and the communication canals of the floodplain are hydrologically active and can be used for the transportation of logs (Padoch and Pinedo-Vasquez 1991). Harvesting begins in the central Amazonia floodplains in March/April, when river levels are still rising in the main stem. By June/July, when the flooded area is at its annual maximum, the cut logs are skidded (Albernaz and Ayres 1999). During the dry years when the water levels during the high water season are below normal, large areas of the floodplain are not flooded. In these situations, harvested logs cannot be skidded and eventually become rotten, resulting in serious economic losses for local communities (Schongart and Junk 2007). This clearly demonstrates that the varying duration of the flooded phase has strong impacts on the economic activities, and thus on the economic situation, of the floodplain communities.

The riverine population of Silves is aware of the adaptive strategies developed by major fish species in open water and lakes, as well as how these strategies are affected by hydrological droughts. The dry season is the best time for fishing (Pinho and Orlove, in review) because the water volumes of the floodplain lakes are at their annual minimums, thus the population densities of commercial fish, such as pirarucu *(Arapaima gigas)*, are higher (Castello 2008). As described by Pinho and Orlove (in review), the local communities in Silves have developed strategies to maintain the stock sizes of commercial fish species, creating protected lakes where capture is restricted and improving the quality of the flood-forest surrounding those lakes.

The local fishery communities of Silves have developed strategies for coping with extreme hydrological events by adapting their livelihoods and economic activities accordingly. They can describe and remember with a surprising level of detail extreme events such as those related to El Niño and La Niña events, which are associated with interannual climate anomalies, and even short-lived hydrological events, such as *repiquetes*, a false beginning of the rising water season, and meteorological events, such as *friagens*, or cold surges (Pinho and Orlove, in review). This is why qualitative assessments of the impacts of severe droughts on the Amazon floodplain communities, which are traditionally linked to the river's hydrological regime, are crucially important for understanding the human dimensions of these extreme events.

The accuracy of the local fishermen's perceptions regarding extreme hydrological and climate events is acute and quite unlike the perceptions of *terra firme* local communities of eastern Amazonia that have been described by Brondizio and Moran (2008) in an area close to Santarem (Pará State). When Brondizio and Moran (2008) surveyed the impacts of environmental and climate change on local communities, the majority of the people surveyed were unable to remember extreme climate events beyond 3 years. The differing perceptions of the communities are likely to be related to the traditional knowledge acquired by the floodplain communities of Silves, who are long-term residents of the floodplain. In contrast, the communities surveyed by Brondizio and Moran (2008) have been receiving migrants from other areas of Brazil with different cultural backgrounds as a consequence of economic drives related to the expansion of agriculture in eastern Amazonia.

The severity of a hydrological drought is usually perceived by the local populations of Silves based on the rate at which the water level falls as well as some ecological parameters observed in floodplain trees (e.g., phenology, etc.). The experimental rule is based on the overnight drop in the water level: if levels drop more than 4 fingers (approximately 10 cm), it is an indication that the hydrological drought will be severe. The faster the water level drops, the longer the dry season is likely to be. As simple as this sounds, Tomasella et al. (2010) showed that severe hydrological droughts are, in fact, associated with rapid river recessions. Therefore, severe droughts are anticipated by the *caboclos* based on the water levels at critical periods during the beginning of the recession and the rate of the drop in the water level. In 2005, for instance, the local population realized the severity of the drought before it became global news based on their observations that "the lake dried out very quickly" (Pinho and Orlove, in review).

Although the communities' livelihood strategies proved to be successful in normal years, it is quite clear that severe droughts have the potential to cause serious disruptions in those strategies. For instance, the local community related that during the 2005 drought, commercial fish species such as the pirarucu, which is a species highly tolerant of low levels of oxygen (Castello 2008), left the protected lakes as the water level receded dramatically, and those that remained in the lakes died, mostly from hypoxia, during that drought (Pinho and Orlove, in review).

From the perspective of the local community in Silves, the 1997 drought was as severe as the 2005 event in terms of fish catches and mortality. The majority of community members perceived the 2005 event as less harsh in terms of the river recession compared to 1997. The reason for this perception, according to the local community, was that the water levels dropped faster and the low water period lasted longer during the 1997 drought (Pinho 2007).

Additional evidence of the reliability of the observations of the local community are shown in the hydrological data. Daily records of the level of the Urubu River at Silves, collected by Pinho and Orlove (in review) in 2005, showed a high correlation with the water level records for the Negro river at Manaus Harbor (data not shown).

In this context, the data in Fig. 6 indicate that the non-flooded period lasted longer in 1997 than in 2005 and that the minimum water levels were lower, which supports the testimonies of the local community.

4 Perception and adaptation

As expected, the response to extreme events in the Amazon Basin revealed a high degree of complexity. The Amazon ecosystems have adapted to cope with interannual climate variability. Although extreme drought events are rare, this study showed that not all of the ecological impacts should be considered negative.

The comparative analysis of impacts on the water levels in the floodplain lakes for two different sites for both droughts (1997 and 2005) indicated that the 2005 drought was equal or greater in severity in terms of lake water depletion at the peak of the dry season, when the lakes are physically isolated from the main stem. The reason for this was not related to main stem water levels, but rather to local meteorological conditions: in most of the floodplain, the rainfall was higher and the lake evaporation lower in October–November 1997 compared to October–November 2005.

From the ecological viewpoint, for the floodplain tree species whose vegetation period is defined by the duration of the non-flooded period, the hydrological data suggest that the growth of most of the tree floodplain species was more vigorous during the drought of 1997. However, this conclusion should be considered cautiously in the case of seedlings and juveniles of certain species, which appear to be more sensitive to dry periods (Parolin et al. 2010).

Observations during the drought of 2005 and descriptions of the impacts of the 1997 drought in the Silves communities showed clear signals of overfishing and exacerbated competition among fishermen. Fishing was facilitated in the floodplain lakes by lower-than-normal water levels and by the migration of large stocks of commercial species from local community-managed floodplain lakes to the main river system, where they were available to large-scale commercial fisheries.

Regarding the potential impacts of both droughts on fish mortality rates, we hypothesized that the 2005 drought was more severe than the 1997 drought because the prevailing meteorological conditions favored the occurrence of hypoxia in the isolated floodplain lakes at the peak of the dry season. Unfortunately, there are no experimental data with which to confirm this hypothesis.

Because local fishing communities lack technological assets, such as storage capacity and cooling systems, and easy access to markets, it is clear that fish mortality and over-catching during severe droughts disrupted the local economies in the intermediate term. The absence of an appropriate response from the government at such a time made the socio-economic impacts associated with both droughts even more pronounced.

Because of these disruptions, the testimonies of local riverine dwellers of the small town of Silves in central Amazonia indicate that residents have clear memories of both events as the “worst in the last decade”, with profound impacts on the livelihood of fishery communities (Pinho and Orlove, in review). Therefore, it is possible to conclude that, according to the perceptions of Silves’ local communities, both drought events were equally severe, regardless of the differences in magnitude and duration between the events as indicated by hydrological or ecological indicators. This conclusion is based on the fact that the primary economic activity of the Silves community is fishing, but this is generally the case for most of the river floodplain populations (Ribeiro 2007).

Although these results cannot be generalized to the entire Amazon floodplain, documenting local observations of environmental change is crucial for assessing the climate impacts in Amazonia (Pinho 2007; Pinho and Orlove in review), particularly for the impacts on fish catch, as the available official series are limited due to the lack of standardized fish yield measurements (Melack et al. 2009) and the effects of technological changes and overfishing (Pinho and Orlove, in review).

It is also clear that the current understanding of fishery dynamics in the Amazon is still far from being sufficient to inform coherent policy strategies to safeguard fish species and to improve the adaptive strategies of local communities facing extreme events driven by global environmental changes. In this regard, the local knowledge of local ecosystem changes may be used to validate model simulations to increase confidence in future climate projections, in addition to providing information for historical climate reconstructions (Green et al. 2010).

Worldwide news broadcasts by the press labeled the 2005 drought as “the most severe in the last 105 years”. Moreover, the database of the Brazilian National Civil Defense (http://www.defesacivil.gov.br/situacao/municipios.asp) indicates that 62 municipalities, 38 of them located in the main stem floodplain, declared public calamity during the 2005 drought. This was clearly not the case during the 1997 episode, when emergency was declared in the 62 municipalities of the Northern Hemisphere State of Roraima by March 1998 only as a consequence of the generalized fires. Therefore, it is clear that governmental action during the 1997 drought was in response to the emergency created by forest fires, whereas the government response during the 2005 episode addressed not only uncontrolled forest fires but also impacts on the local population related to the severe drop in the water level in the main-stem floodplain.

It is important to mention that, until July 1999, the declaration by the Brazilian Federal Government of the state of public calamities by municipalities in Brazil was not regulated. After 1999, the National Council of Civil Defense of Brazil established criteria to assess damages and conditions and to create restrictions and procedures for declaring public calamity in the national territory (http://www.defesacivil.gov.br/situacao/index.asp). Therefore, the lack of a legal framework and criteria could have been a serious obstacle during the 1997 drought in the assessment of the true situation of main-stem municipalities by local, State, and Federal authorities with almost no background experience in facing severe droughts compared to, for instance, the municipalities of the drought-prone semi-arid northeast of Brazil. This was not the case during the 2005 drought, when official criteria and conditions for declaring public calamity were in effect.

Boyd (2008) suggested that the disaster response during the 2005 drought was successful because of the availability of real-time satellite imagery and the meteorological data corroborated by on-the-ground information, both integrated in user-friendly analysis software, which ultimately convinced authorities at all governmental levels to take immediate action.

It may be argued that the meteorological information is not widely available to local Amazon communities living in remote areas. Moreover, the information from meteorological services is considered irrelevant for the communities’ day-to-day activities (Lemos et al. 2002; Pinho and Orlove in review). For fishing communities of the Amazon, for instance, information related to climate change, or to weather and climate forecasts, has been considered too complex and meaningless from a practical perspective (Pfaff et al. 1999; Costa 2006). Additionally, climate information is considered too coarse (usually for the Amazon region as a whole or at the state level, rather than local information) and ineffective in motivating changes in the behavior of local populations (Brondizio and Moran 2008). The effectiveness of disseminating climate information at different levels and to different groups is also challenged by its scale and resolution, its perceived relevance, differences in knowledge systems, differences in the language and terminology and the legitimacy and credibility of the institutions involved in the process (Brondizio and Moran 2008).

Despite these perceptions of the local population about the usefulness of scientific information, the availability of novel technology, such as free, near-real-time satellite information and decision-making software, has created new networks of knowledge that have not only improved governance during extreme events (Boyd 2008) but have also increased the level of awareness of the population, facilitated wide-spread dissemination in the press, and facilitated a more active role for environmental organizations. These governance mechanisms proved to be successful in triggering governmental action during the 2005 drought (Brown et al. 2006; Boyd 2008).

It is also clear that the networks of knowledge created during the 2005 drought (Boyd 2008) were not in place during the 1997 drought, when the availability of near-real-time satellite information, ground data and internet communications were much more restricted. This is why most of the impacts of the 1997 drought on the floodplain were not well known to those living outside the Amazon, notwithstanding that this event was as severe as the 2005 drought from the viewpoint of the local communities of Silves (Pinho 2007). Additionally, as is common for major El Niño-triggered droughts in Brazil, most of the public attention was focused on the poorer regions of semi-arid northeast Brazil, which was affected by a severe drought in April 1998 (Kane 1999).

Finally, it is apparent that the Amazon ecosystems are adapted to cope with extreme climate events, and the ecosystems recover relatively quickly (Williamson et al. 2000). However, events such as those of 1997 and 2005 have relatively low frequency. As climate change scenarios suggest an increase in the frequency of extreme events in the Amazon Basin (Cox et al. 2008) and considering that more intense droughts are likely to affect the Amazon floodplain forest at both the species and community levels (Parolin et al. 2010), it is not possible to conclude that the floodplain ecosystems will be able to adapt to extreme events in the same way under such scenarios (Nobre and Borma 2009).

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