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Amazonian flood impacts on managed Brazilnut stands along Brazil's Madeira River: A sustainable forest management system threatened by climate change

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ABSTRACT

Impact of flooding on tropical forest ecosystems and their management is a little-studied area that is expected to become increasingly important under projected climate change. A demonstration of this was provided by the record-breaking 2014 flood of the Madeira River in Brazil. We assessed factors affecting survival of Brazilnut trees (*Bertholletia excelsa* H.B.K.) under root asphyxia caused by flooding in the Lago do Capanã Grande Extractive Reserve in Manicoré municipality (county), Amazonas state, Brazil. Mortality was surveyed in three Brazilnut groves (*castanhais*) in 680 individual Brazilnut trees of which 357 had been exposed to flooding and 200 had been flooded for at least 83 days, which was the threshold for mortality effects. Trees were georeferenced and measured for DBH and the height above the ground of the flood-water mark. This information, together with topography from satellite data and water levels from hydrographic gauges, allowed calculation of the time each tree was flooded. None of the 323 unflooded trees died. The analysis indicates a relationship between mortality and duration of root asphyxia, killing 17% of the individuals exposed to flooding and 35% of the individuals that were flooded for periods greater than 109 days. Nevertheless, survival exceeded 50% for all flooding durations. The data suggest that larger trees have a greater probability of mortality for any given period of asphyxia. Expected increases in extreme flood events threaten a sustainable forest management system based on harvest of non-timber products.

1. Introduction

Increased flood levels in Amazonian rivers imply impacts on forests and on the human populations that manage them. Quantifying these impacts and identifying their causes are important for any adaptation efforts. In 2014 the Madeira River experienced its largest recorded flood, with the instantaneous streamflow at Porto Velho reaching 66,066 $m^3 s^{-1}$ on 31 March 2014 (Brazil, CPRM, 2014). The Madeira drains parts of Bolivia, Peru and Brazil and ranks among the World's largest rivers despite being a mere tributary of the Amazon River. The 2014 flood had multiple impacts on natural ecosystems and on the human population (Fearnside, 2014, 2015; Vauchel, 2014).

Extreme floods have occurred in the Amazon basin with greater frequency and intensity over the last two decades (Espinoza et al., 2012; Marengo and Espinoza, 2016; Marengo et al., 2011, 2013). These events are generally expected to increase in frequency due to climate change (Arnell and Gosling, 2016; Hirabayashi et al., 2013; Marengo and Espinoza, 2016; Lehmann et al., 2015; Milly et al., 2002; Winsemius et al., 2016). Increased risks are especially high in the western Amazon (Guimberteau et al., 2012, 2013; Ronchail et al., 2006; Sorribas et al., 2016; Zulkafli et al., 2016). In addition to global climate change, ongoing deforestation also increases flood risk (Bradshaw et al., 2007; Coe et al., 2009).

The 2014 Madeira River flood was caused by abnormally high rainfall in the Madeira's Andean tributaries, especially the Beni, Madre de Dios and Mamoré Rivers, with precipitation in December 2013 and January 2014 up to 100% above average, and February 2014 precipitation up to 80% above average (Espinoza et al., 2014; Marengo and Espinoza, 2016). At Manicoré, Amazonas state, Brazil, the Madeira River was above the level of the last great flood (1997) for more than 70 days, and it was above the level of the second-largest previously registered flood (1993) for 97 days. The floodwaters in 2014 reached locations where flooding had never before been recorded, causing forest mortality and serious impacts on the local economy, loss of agricultural

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areas and forest extractivism, death of animals and the loss of houses, forcing the migration of families to higher settlements or to makeshift vessels.

Brazilnut (*Bertholletia excelsa* H.B.K.) is native to the Amazon and is found in all nine states in Brazil's Legal Amazonia region (Rondônia, Acre, Amazonas, Roraima, Pará, Amapá, Tocantins, Maranhão and Mato Grosso), as well as in the other Amazonian countries. The species has multiple uses and has long been widely exploited by traditional peoples, both for its edible seeds and for its excellent quality wood, which is used for building boats and houses despite cutting Brazilnut trees being banned (Decree 1282 of 19 October 1994) (Homma, 2014; Scoles, 2010, 2011; Scoles et al., 2014; Sousa et al., 2014). The nuts represent one of the main extractive export products of Amazonia (Salomão, 2009).

Brazilnut trees are long lived and may even remain productive at ages over 800 years (Salomão, 2009; Zuidema, 2003). Carbon 14 dating indicates an age of 440 ± 60 years for an individual with DBH of 233 cm (Camargo et al., 1994), implying an annual increment in DBH under mature forest conditions of 0.53 cm $year^{-1}$. Young individuals are defined as those with DBH ≤ 50 cm, after which the trees enter the reproductive stage (Sousa et al., 2014; Tonini et al., 2008; Wadt et al., 2005). Like most of the higher plants, Brazilnut trees show a relationship between the age and entry into production in which factors such as the light intensity directly influence reproductive maturity (Scoles, 2010; Guedes et al., 2014; Scoles et al., 2011, 2014).

Brazilnut is a species that is characteristic of the unflooded uplands (*terra firme*) and is typically not found in *várzea* (floodplain in rivers with "white" or muddy water) or in *igapó* (black-water floodplain) (Fernandes and Alencar, 1993; Scoles, 2010, 2011; Scoles and Gribel, 2015; Scoles et al., 2014; Tonini et al., 2014; Wadt and Kainer, 2009). Flooding stress interferes with photosynthesis in four of ten *terra firme* species that have been studied (dos Santos Júnior et al., 2013, 2015), but data are lacking on Brazilnut. There is a general lack of studies on responses of trees to anoxic stress under flooding.

The present study evaluates the survival of Brazilnut trees, relating mortality to duration of inundation and DBH. The study examines the impact of the 2014 Madeira River flood in an "extractive reserve," which is a type of federal conservation unit that allows extraction of non-timber forest products by local populations (e.g., Fearnside, 1989).

2. Materials and methods

2.1. Study area

The study was carried out in the Lago do Capanã Grande Extractive Reserve, which is located in the municipality (county) of Manicoré (Fig. 1). This reserve is part of a mosaic of federal lands that also includes the Matupiri Agro-Extractive Settlement Project (PAE) and the Capanã Indigenous Land (Supplementary Material, Fig. S-1).

The reserve was created by Decree on 3 June 2004 (IBAMA Process n° 02001001183/2003-57), covering an area of 304,146 ha. It is bounded to the north by the Amapá River, to the south by the Campanã stream, to the east by the Madeira River and on the west by Highway BR-319 (Fig. S-1). The reserve is home to 127 families divided into seven communities: Ponto do Campo, Santa Civita, Nossa Senhora de Fátima, Jutaí, São Raimundo, São Sebastião and Bom que Dói (Miranda et al., 2004).

Brazilnuts are the main non-timber forest product (NTFP) extracted in the reserve, but other products include rubber (*Hevea brasiliensis* Willd.), açai (*Euterpe oleracea* Mart.) and various species of vines ("*cipós*") (Brazil, ICMBio, 2013). This extraction is complemented by small-scale agriculture based on annual crops like manioc (cassava) and watermelon (Miranda et al., 2004; Brazil, ICMBio, 2009a,b, 2013). NTFP extraction, in addition to being the mainstay of the local economy, has an important role in maintaining the culture of Lago do Capanã Grande communities (Fig. S-2) (Miranda et al., 2004; Brazil, ICMBio, 2009a, 2013). Our survey of mortality was conducted in three Brazilnut groves (*castanhais*) in the reserve.

Miranda et al. (2004) conducted forest inventories in the reserve and found a high density of Brazilnut trees: up to 48 individuals per hectare, of which 26 were adults with diameter at breast height (DBH, measured 1.3 m above the ground) greater than 50 cm and 22 were young trees (DBH < 50 cm). These densities are higher than in other areas that have been surveyed in Acre, Pará and Rondônia (Miranda et al., 2004).

2.2. Determination of the duration of root asphyxia

To calculate the period of time (days) that each individual was under root asphyxia we used the height of the high-water mark on the trunk of the tree, together with river-stage data from the Hidroweb fluviometric system (Brazil, ANA, 2014). River-stage data were used from the station at Manicoré, Amazonas (station 15,700,000) for 2013 and 2014 as well as over the past 50 years. A total of 680 individual Brazilnut trees were surveyed, of which 357 had been exposed to flooding in the 2014 flood (Table S-1).

The daily record of the river level in centimeters defines the variable "y." The river level reached a maximum on 19 April 2014 (y_{max}). This variable was associated with the variable "x," also measured in centimeters: the mark of the maximum water depth, taking the ground at the base of the tree as the reference level. This permitted identifying the starting and ending day of root asphyxia conditions from the daily records in the Hidroweb system. The "z" value was identified using Eq. (1)

$$z = y_{max} - x \tag{1}$$

where

"z" is the elevation of the ground at the location of the tree (m above mean sea level),

"y" is the maximum level of the river (m above mean sea level), and

"x" is the maximum height of the water-level mark on the trunk of the tree (measured from the ground at the base of the tree (m above mean sea level).

From the estimate of "z" one can infer the number of days that the individual was under asphyxia. For example, if the maximum river level was 28.88 m above mean sea level and the high-water mark on the trunk of the tree was 4.00 m above the ground, this means that this individual went into a condition of asphyxia when the river had a level of 24.88 m (the "z" level). The dates of beginning and ending asphyxia can therefore be determined from the Hidroweb data. We established a relationship between river level (m) and the duration of root asphyxia.

2.3. Relation between mortality and the age of the individuals

The Brazilnut trees were classified into 10-cm DBH intervals. The relationship between mortality and age (indicated by DBH) of individuals was assessed by logistic regression. Determination of the status of individuals as live or dead was based on symptoms indicating lack of physiological activity: individuals without foliage and with necrotic stems, dry twigs and with evidence of attack by termites.

2.4. Topographic analysis of the Madeira River flood

The geographic locations of the Brazilnut trees (Fig. S-3) were determined in the latitude/longitude coordinate system and *datum* WGS 84 using a GPS (global positioning system). For each tree, status as live or dead was recorded and the DBH and height of the water mark on the trunk were determined with a tape measure. The sample was composed of trees along the trails established by the Brazilnut gatherers for harvesting the nuts.

Geographical analysis was based on the information gathered in the field (georeferenced individuals) and from Shuttle Radar Topography