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ORIGINAL ARTICLE

Dendrochronological records of a pioneer tree species containing ENSO signal in the *Pantanal*, Brazil

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Abstract

The *Pantanal* is subjected to a monomodal and predictable flood pulse of low amplitude which is the main driver of ecological processes and patterns of biodiversity in one of the largest wetlands in the world. Nevertheless, little is known about how the plant communities of this wetland respond to predicted climate changes. In this paper, we used tree-ring analyses of *Vochysia divergens* Pohl (Vochysiaceae), a light-demanding pioneer species that occurs in periodically or short-term flooded areas in the *Cerrado* and *Pantanal*. We evaluated the influence of precipitation and water level on the growth rates of this species, where it occurs, to determine how local climatic variables (precipitation and water level) influence tree growth and how a large-scale climatic driver in the tropical eastern Pacific (*El Niño* events) could affect both tree growth and local climate in the northern region of the *Pantanal*. The indexed tree-ring chronology of eight individuals had a significant relationship with annual precipitation ($r = 0.22$). Interannual variations of the water level did not affect tree growth. Sea surface temperature anomalies of the *El Niño* 1 + 2 region lead to decreased precipitation in the northern region of the *Pantanal*, resulting in decreased diameter increments of *V. divergens*. Our results demonstrated the dendrochronological potential of *V. divergens* for analyzing climate–growth relationships for developing climate-sensitive proxies for reconstructing past climatic conditions.

Keywords Dendroclimatology · *El Niño* events · Tree ring · *Vochysia divergens*

1 Introduction

The *Pantanal*, located in central South America, is one of the largest wetlands in the word. This region is periodically flooded by the Paraguay River and its tributaries (Junk et al. 2011). Based on hydrological criteria, the *Pantanal* can be classified as a floodplain subject to a monomodal and predictable flood pulse of low amplitude (Junk et al. 2014). This annual oscillation between drought and flood is the main driver of the ecological processes and patterns of biodiversity of such wetlands (Junk et al. 1989). Local differences in the hydrological regime, topography and soil result in a mosaic from unflooded areas to areas with different levels of flooding (Nunes-da-Cunha and Junk 2001; Arieira et al. 2011). Due to the strong influence of the hydrological cycle on the dynamics of the *Pantanal*, these wetlands are considered highly vulnerable to changes in the patterns of temperature and precipitation resulting from climatic change (Erwin 2009; Junk 2013).

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Regional climate changes models for South America predict higher annual temperatures and increase in the frequency of extreme events during the summer (Marengo et al. 2010). In addition, global climate models predict increases in the frequency and magnitude of ENSO (El Niño-Southern Oscillation) activity (Timmermann et al. 1999), which is known to influence interannual variability of the climate of South America. El Niño events lead to anomalous dry conditions over the Amazon region and northeastern Brazil, while at the same time cause strong positive precipitation anomalies in southern Brazil, northeast Argentina and Uruguay (Ropelewski and Halpert 1987; Aceituno 1988). Future climate scenarios could induce changes in the hydrological cycles and precipitation patterns, which may in turn affect the distribution and community composition of tropical species (Esquivel-Muelbert et al. 2017), resulting in an overall decrease in species diversity (Bunker and Carson 2005; Engelbrecht et al. 2007).

The *Pantanal* is subject to multi-annual periods of high floods and pronounced droughts (Junk and Nunes-da-Cunha 2005). During consecutive drought years, the high incidence of fire on vegetation leads to retraction of non-tolerant species and may lead to impacts on plant distribution in the *Pantanal* an increase in fire-adapted species (Coutinho 1977; Nunes-da-Cunha and Junk 2001, 2004; Schöngart et al. 2011; Rocha et al. 2015). Nevertheless, little is known about how the plant communities of these wetlands will respond to climate changes. Understanding the impact of future climate on tropical wetlands requires knowledge about tree age and growth rates and their relationship with climate variability. However, studies of climate–growth relationships based on tree-ring analyses in tropical South America have been concentrated in the Amazon region (Vetter and Botosso 1989; Dünisch et al. 2003; Schöngart et al. 2004, 2005; Brienen and Zuidema 2005). These studies have indicated influences of El Niño events on tree growth in both floodplain (Schöngart et al. 2004, 2005) and non-flooded upland forests (Dünisch et al. 2003; Brienen and Zuidema 2005; Brienen et al. 2012), but in different ways. The external factor controlling the growth rhythm of trees in tropical climates is intra-annual variation of rainfall in non-flooded upland forests (Worbes et al. 2003; Fichtler et al. 2004). On the other hand, the annual occurrence of long-term inundations in floodplain forests results in annual ring formation during high water level due to anaerobic conditions for roots affecting internal water transport of trees leading to leaf shedding (Schöngart et al. 2002; Dezzeo et al. 2003).

In this paper, we used tree-ring analyses of *Vochysia divergens* Pohl (Vochysiaceae), a light-demanding pioneer tree species widespread in *Cerrado* and *Pantanal* of central Brazil, where it occurs in periodically flooded or short-term flooded areas (Nunes-da-Cunha and Junk 2004; Arieira and Nunes-da-Cunha 2012) to describe how local climatic variables, such as precipitation and water level, influence variation in tree growth of this species, and how a large-scale climatic driver of the tropical eastern Pacific (El Niño events) could affect both tree growth and local climate.

2 Materials and methods

Study species and sample collection—*Vochysia divergens* Pohl is a light-demanding pioneer tree species found mostly in Goiás, Mato Grosso and Mato Grosso do Sul states of Brazil, including the *Pantanal* region (Faßenacht 1998). It possesses a great ability to invade natural and artificial pastures of the *Pantanal*, developing almost monospecific stands on non-flooded or short-term flooded sites locally called *Cambarazais* (Pott 1982; Arieira and Nunes-da-Cunha 2012). The species is characterized by a brevi-deciduous functional ecotype (Borchert 1994) remaining leafless for a short period with leaf shedding normally occurring between April and July at the beginning of the dry season (Nunes-da-Cunha and Junk 2004). This leads to the formation of annual tree rings evidenced by cambial wounding, radiocarbon dating (Ishii 1998) and monitoring of diameter growth by dendrometers (Machado et al. 2015; Sallo et al. 2017). The wood is frequently used for joinery, plywood and cellulose by the local population, while its bark is used for medicinal purposes (Pott and Pott 1994).

Field study was carried out in the northern region of the *Pantanal* in the Brazilian state of Mato Grosso located in the center of South America (16–22°S, 55–58°W) (Fig. 1a). The natural vegetation consists of stands dominated by *V. divergens* situated next to the Cuiabá River (Fig. 1b) at the northern limit of the Ecological Station SESC *Pantanal* RPPN (Private Natural Heritage Reserve) (Arieira and Nunes-da-Cunha 2012). The climate of this region is dominated by distinct seasonality with a rainy season from October to April and a dry season from May to September. Mean monthly temperature varies between 23 °C in the dry season and 26 °C in the rainy season (Hasenack et al. 2003). The flood pattern in the northern region of the *Pantanal* is strongly influenced by regional precipitation, with maximum flood levels occurring during January and February in synchrony with the rainy season (Nunes-da-Cunha and Junk 2001).

For dendrochronological records, we used 28 entire stem disks of *V. divergens* at diameter at breast height obtained from trees harvested in 2005 for the construction of a highway in the region (Fig. 2a). The surfaces of the samples were carefully polished with sand paper of decreasing grain size to 600 to improve visibility of tree rings

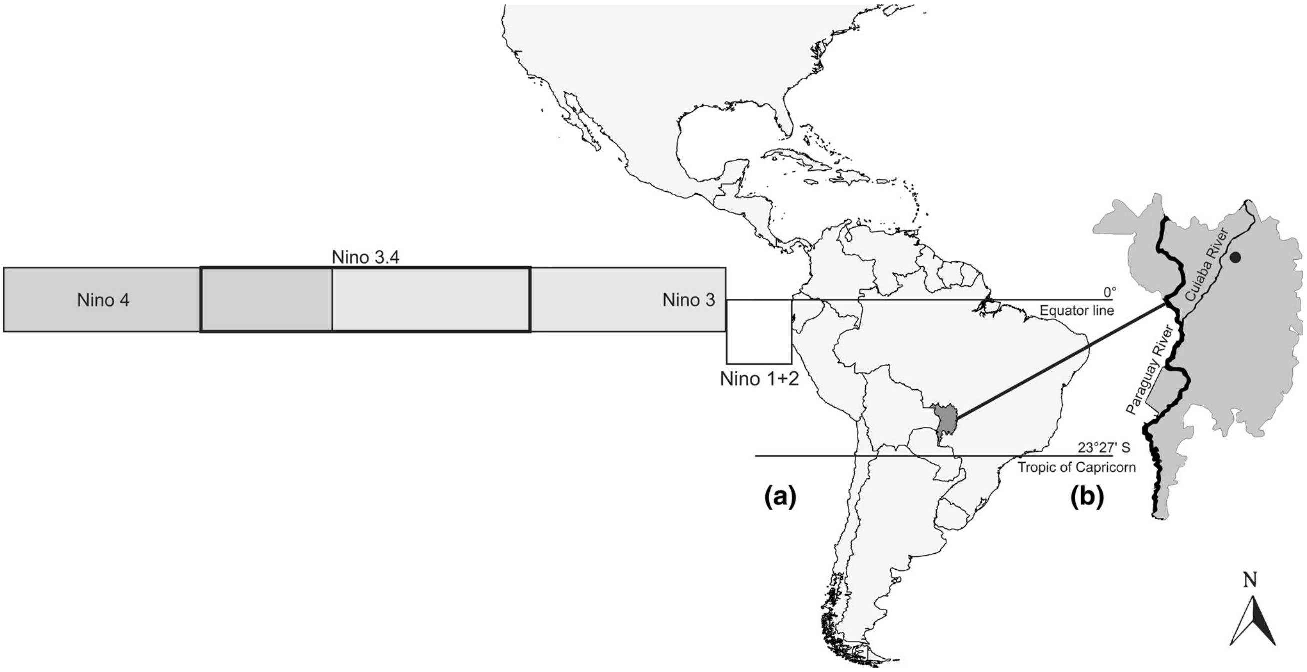

Fig. 1 **a** *El Niño* regions in the tropical eastern Pacific and the *Pantanal* region in South America. **b** Overview of study site indicated by the circle

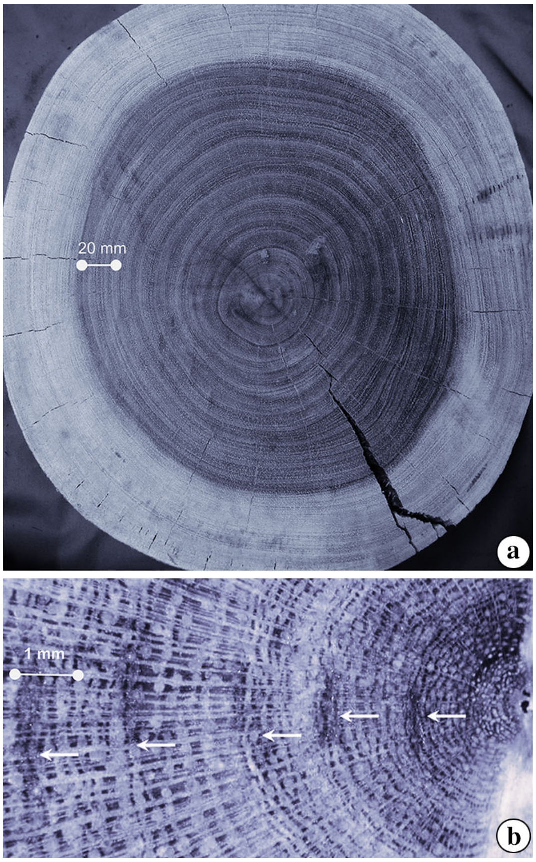

Fig. 2 **a** Stem disk of *Vochysia divergens* Pohl (Vochysiaceae). **b** Distinct growth rings of *V. divergens*. Tree rings are characterized by alternating tissues of fibers and parenchyma. Arrows indicate ring boundaries

(Schöngart et al. 2004). Wood anatomical structure characterized by periodical patterns of parenchyma and fiber tissue was used to identify the limits of growth zones and to determine tree age by ring counting (Fig. 2b). Ring widths were measured along two to three radii with a digital measuring device (LINTAB) to the nearest 0.01 mm in association with TSAP-win software (*Time series analyses and presentation*, Rintech, Heidelberg, Germany). All analyses were carried out at the Dendroecological Laboratory of the National Institute for Amazonian Research (INPA), Manaus, Amazonas state.

Annual precipitation data comprising the period 1912–2004 were obtained from the data bank at the National Institute of Meteorology–INMET (http://www.inmet.gov.br), and the maximum water level data for Cuiabá River for the period 1933–2004 were acquired from the National Agency of Waters–ANA (http://portalsnirh.ana.gov.br/). Records of sea surface temperature (SST) indices of El Niño events during the period of 1950–2005, including El Niño 1 + 2, El Niño 3, El Niño 4 and El Niño 3.4 regions of the Tropical Pacific Basin, were obtained from the Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST) through the KNMI Climate Explorer tool. The ENSO (*El Niño*-Southern Oscillation) events were demarcated by 5-month running means of SST anomalies in the *El Niño* region exceeding + 0.4 °C for six or more consecutive months (Trenberth 1997).

Tree-ring analyses – For climate–growth analyses was initially visually and statistically verified each pair of increment curves cross-dated for building a mean chronology based on tree-ring series of all individuals (Pilcher 1990). We used the Student's T value (Baillie and Pilcher 1973) and the percentage of parallel run (ppr) indicating the year-to-year concordance in the fluctuation curve pairs within an overlapping interval (Schweingruber 1988) to evaluate cross-dated curves. To remove long-term growth trends related to the increasing age and size of the trees, or even due to changes in the surrounding forest causing affects to competition structure (Fritts 1976), a 5-year moving average was used to convert raw tree-ring curves into growth indices. This procedure results in normally distributed data, which is an elementary condition for correlation with climate variables (Cook and Briffa 1990).

To assess how local climate variables could influence tree growth, we correlated the indexed ring-width chronology of *V. divergens* with annual precipitation and water level of the Cuiabá River. Since climatic conditions have influence on radial tree growth for several months before ring formation (Fritts 1976), we included both climate data from the previous and current growing seasons in this analysis. To determine which *El Niño* region of Tropical Pacific Ocean modulated tree growth, we correlated the indexed ring-width chronology of *V. divergens* with the large-scale climatic driver of the *El Niño* 1 + 2, *El Niño* 3, *El Niño* 4 and *El Niño* 3.4 regions. Therefore, we calculated 3-month averages from July to September of the previous year (JAS-1) to April–June of the following year (AMJ + 1) to identify which season influenced tree growth. Statistical analyses were executed with STATISTICA program (Statsoft, Tulsa, OK, USA).

3 Results

Vochysia divergens Pohl formed distinct tree rings of annual nature providing a confident determination of tree age and increment rates. From ring-width time series of trees older than 40 years ($n = 8$), we established a mean chronology comprising almost 100 years for the period 1909–2005 (Fig. 3). Statistically significant correlations between tree growth indices and annual precipitation are presented in Fig. 4. Similarities were indicated by the percentage of parallel run of 66.5%, a Student's T value of 2.8 and correlation coefficient with $r = 0.22$ ($P < 0.05$). No significant correlation was detected between the chronology of *V. divergens* and the maximum water level of Cuiabá River.

Precipitation patterns of the northern region of the *Pantanal* correlated significantly only with SST anomalies of the *El Niño* region 1 + 2 (Fig. 5) including the period of 1950–2005. There was a positive correlation with the previous year, indicating a maximum during October–December (OND-1) ($r = 0.41$, $P < 0.01$). During the current year, annual rainfall in the northern region of the *Pantanal* was negatively correlated with *El Niño* events showing again a maximum during the period October–December (OND) ($r = -0.39$, $P < 0.01$). Tree growth of *V. divergens* correlated negatively only with SST anomalies of the *El Niño* region 1 + 2 (Fig. 5), and it occurred throughout the entire current year ($P < 0.05$).

4 Discussion

The results found a positive correlation between the ring-width index of *V. divergens* and the regional precipitation regime indicating the annual nature of the rings for this species in the northern region of the *Pantanal*. Diameter growth of this species in the same region monitored by dendrometer bands indicated a cambial dormancy during the dry season (July–September) due to strong stem water deficit (Sallo et al. 2017) leading to leaf shedding and flowering in this period (Machado et al. 2015). In parallel, studies have described the occurrence of annual tree rings

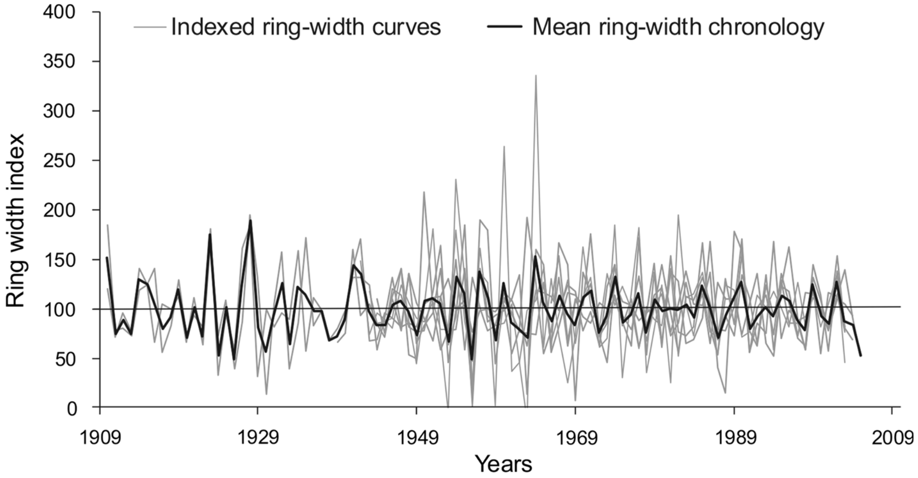

Fig. 3 Synchronized individual tree-ring time series of eight trees of *V. divergens* (gray curves) averaged to a mean curve (chronology) (black curve)

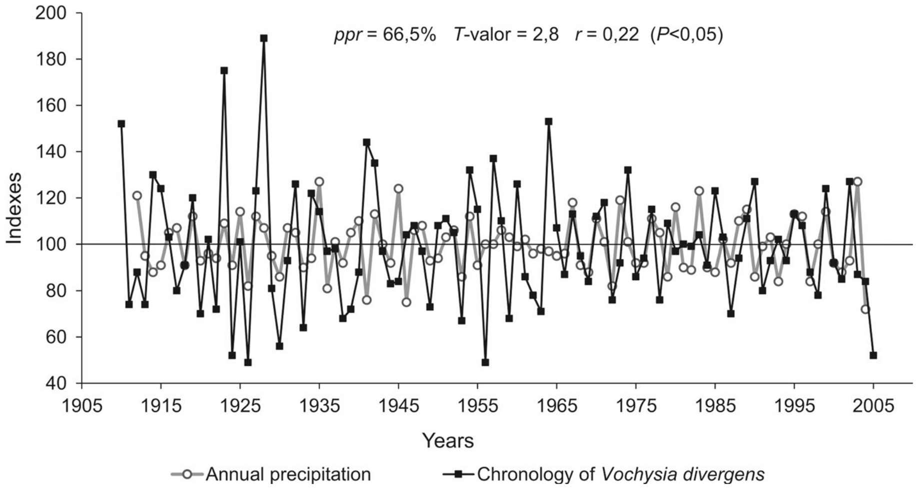

Fig. 4 Relationship between indexed ring-width chronology and annual precipitation of Cuiabá, northern region of the *Pantanal*. The curves are significantly correlated as indicated by a percentage of parallel runs of 66.5%, Student's *T* value of 2.8 and correlation coefficient with $r = 0.22$ ($P < 0.05$)

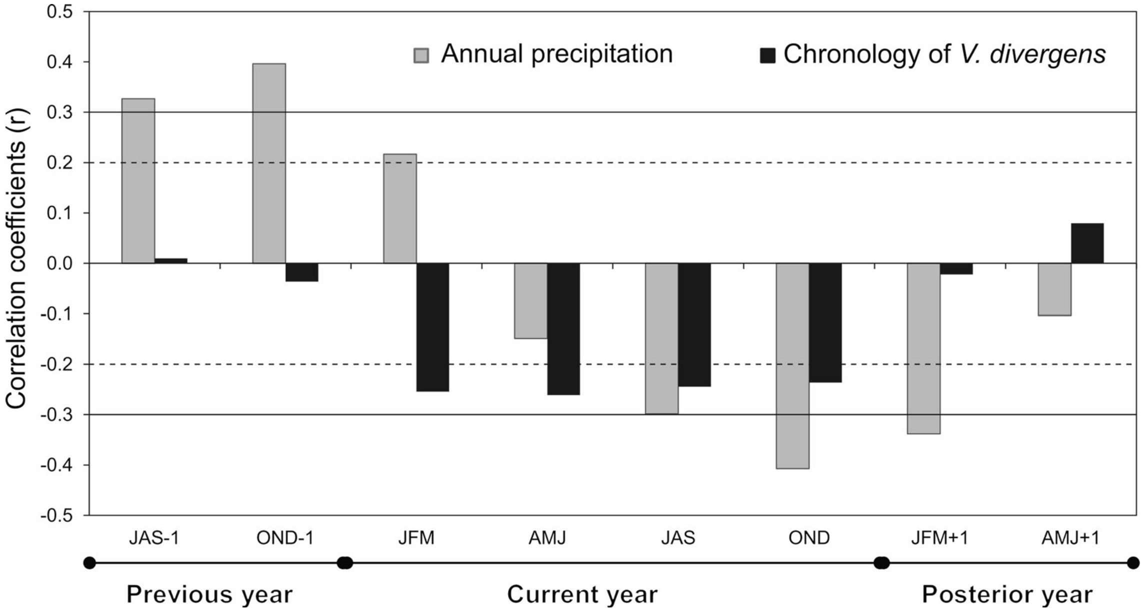

Fig. 5 Relationship of SST anomalies of the *El Niño* region 1 + 2 (sums of 3 months July–September JAS, October–December OND, January–March JFM, April–June AMJ) comprising a 24-month period with annual precipitation of Cuiabá (gray bars) and ring-width indices of the chronology of *V. divergens* (black bars) for the period 1950–2001. Dashed line indicates $P < 0.05$, and the continuous line indicates $P < 0.01$

by radiocarbon dating and cambial wounding (windows of Mariaux) for this and other species in the southern region of the *Pantanal* (Ishii 1998). This author also verified stem-growth periodicity by dendrometric bands and indicated decreasing cambial activity during the dry season, when deciduous species change their leaves. Other studies in the southern region of the *Pantanal* have indicated annual tree rings for 27 species among deciduous and brevi-deciduous functional ecotypes, and positive correlations between precipitation data and ring-width of *Handroanthus heptaphyllus* (Vell.) Mattos (Bignoniaceae) and *Anadenanthera colubrina* var. *cebil* (Griseb.) Altschul. (Fabaceae) (Mattos 1999).

Ishii (1998) emphasized that two climatic factors control the growth rhythm of arboreal species in the *Pantanal*: flooding of areas at lower elevations lasting up to 6 mo y^{-1} and seasonal precipitation at sites with no or short inundations. At low elevation sites, the factor that triggers tree growth is annual flooding, which induces anaerobic conditions in root space hindering water uptake by the fine roots, leading to leaf fall and reduced tree growth (Schöngart et al. 2002). At higher elevations, the dry season causes a reduced soil water potential, resulting in drought stress for trees and consequently leaf fall and reduced tree growth (Borchert 1999). Our results exhibited a significant relationship of tree growth only with annual precipitation, but there was no correlation between ring width and flood patterns. Cambial activity of *V. divergens* in the study region occurs from October to May (Machado et al. 2015; Sallo et al. 2017) mainly during the rainy season. Likewise, slight differences in topography, short periods of flooding and specific adaptations to flood conditions likely explain why trees of *V. divergens* only respond to differences in precipitation patterns and experience no influence on growth from water level.

Tree growth of *V. divergens* responded negatively to ENSO episodes only for the *El Niño* region 1 + 2, and there was no relationship between growth and water level of Cuiabá River. Similarly, in floodplain forests next to our studied site in the northern region of the *Pantanal*, tree growth of two species was also found to have been influenced by *El Niño* events, but in different ways. *Tabebuia aurea* (Manso) Benth. & Hook (Bignoniaceae), which occurs in non-flooded areas, exhibited positive correlations with annual precipitation and *El Niño* events, while *H. heptaphyllus,* which occupies periodically flooded areas, exhibited no correlation with precipitation and negative correlations with *El Niño* episodes (Leite 2012). In this case, slight differences in topography caused by the existence of non-flooded earth mounds (locally named “murundus”) surrounded by grass-covered floodplains (Oliveira-Filho 1992) likely explain the differences in the impact of *El Niño* events on tree growth of these two species.

The impact of the SST anomalies on tree growth by changing precipitation and/or hydrological regimes has been confirmed by several other studies in tropical regions. Berlage (1931) was the first to relate precipitation regime with ring-width indices studying *Tectona grandis* L. f. (Verbenaceae) in Java, Indonesia, and observed a cyclic behavior in the over 400-year-old tree-ring chronology, which decades later was associated with the occurrence of ENSO events (Jacoby and D’Arrigo 1990). In the Amazon region, observed decreased flows of the Negro River are associated with years of *El Niño* events (Richey et al. 1989; Marengo et al. 1998), which lead to increases in the terrestrial phase of the annual flood pulse and extend the growing period in the associated floodplains (Schöngart and Junk 2007). In turn, studies have related *El Niño* episodes with observed increases in tree growth rates of *Piranhea trifoliata* Baill. (Picrodendraceae), *Macrolobium acaciifolium* (Benth.) Benth. (Fabaceae) and *Calophyllum brasiliense* Cambess. (Calophyllaceae) (Schöngart et al. 2004, 2005; Rosa 2013). The opposite was found for *terra firme* (non-flooded areas) where tree growth negatively responds to SST anomalies at Equatorial Pacific as a consequence of reduced precipitation (Vetter and Botosso 1989), and for trees of *Calophyllum brasiliense* in flooded areas of the southern coast of Brazil, where episodes of *El Niño* cause increases in local precipitation (Rosa 2013).

In southern Africa, Fichtler et al. (2004) related ring-width indices of two tree species with *El Niño* events, finding them to lead to decreased increment growth rates, while in western tropical Africa ring-width tree chronologies were related not with ENSO events, but with SST anomalies in the Guinean Gulf (Schöngart et al. 2006). Other dendroclimatological studies have indicated the influence of the tropical Atlantic on tree growth of tropical trees. Strong positive correlations between growth and SST anomalies were found in the north tropical Atlantic during the first half of the year, while in the Pacific it was a negative relationship and during reduced precipitation during the second half of the year (Brienen et al. 2010). Along the southern coast of Brazil, tree growth of *C. brasiliense* responded positively to SST anomalies in the south tropical Atlantic (Rosa 2013), and the same was found for trees of *T. aurea* in non-flooded areas of the northern region of the *Pantanal* (Leite 2012).

The *Pantanal* is a wetland subject to multi-year periods of high floods and pronounced droughts, and association with natural wild fire has a great impact on the fauna and flora of this region (Junk et al. 2006). Studies have indicated that tree growth of *V. divergens* is sensitive to interannual rainfall variability and also responds to decadal rainfall variability, retreating during dry periods and invading open areas during wet episodes (Nunes-da-Cunha and Junk 2004). Changes in the amplitude and duration of this roughly climate cycle would change the pattern of precipitation and the hydrological cycle of the region, modifying the natural occurrence of fire and consequently the pattern of distribution of the species and biodiversity in the region of the *Pantanal*. Besides, the results indicated that *El Niño* events have impacted both the pattern of precipitation and tree growth of *V. divergens* in the northern region of the *Pantanal*. Increases in frequency and magnitude of ENSO (El Niño-Southern Oscillation) activity predicted for the future climate (Timmermann et al. 1999) could also exert severe impacts on tree growth of the species in this wetland.

The evidence that tree growth of *V. divergens* responds to ENSO underlines the importance and potential of dendroclimatological studies in the *Pantanal* region. More studies should be focused not only on the influence of ENSO events, but also on the impact of SST anomalies of the tropical Atlantic and decadal oscillations such as the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO) on tree growth of woody species of the *Pantanal*. Dendroclimatological studies are fundamental for understanding the impacts of climate on forest dynamics and enable the possibility for climatic reconstruction of the precipitation and hydrological regimes of tropical regions where long-term data are not available (Jacoby and D'Arrigo 1990; Schöngart et al. 2004, 2006; Therrell et al. 2006). In the present study, we only cross-dated eight individuals with diameters of 30–80 cm and maximum ages of 44–107 years, which is insufficient to reconstruct climatic data.

The present study reports for the first time the influence of a large-scale climatic driver on tree growth in the *Pantanal* region. This is an important step toward understanding how tree growth in the *Pantanal* region may behave in the face of predicted climate changes. However, more dendroclimatic studies comprising different ecotypes, habitats and macroregions of the *Pantanal* are necessary for a better understanding of the diversity of the relationships between climate and tree growth and to identify tree species with the potential for climate reconstruction in this large wetland for at least 200 years.

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Author's contribution CFF contributed to sample acquisition, analysis and interpretation of dendrochronological data and writing; CNC was involved in research supervisor, contributed to conception and design and manuscript revision; WJJ, SAR and EP contributed to evaluate and performed the manuscript edition; JS contributed to conception and design, performed data analysis and evaluated the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

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