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THE CLIMATE RESPONSE OF *CEDRELA FISSILIS* ANNUAL RING WIDTH IN THE RIO SÃO FRANCISCO BASIN, BRAZIL

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ABSTRACT

The São Francisco River basin is one of the most drought-prone regions of Brazil. Seasonally dry tropical forests (SDTF) are widely distributed in the basin and we developed a short chronology of *Cedrela fissilis* annual ring widths from SDTF fragments based on 89 cores from 44 trees dating from 1961 to 2015. The average correlation among all radii (RBAR) is 0.52. The tree-ring chronology is correlated with wet season precipitation totals, must strongly and consistently near the beginning of the wet season. The spatial pattern of correlation covers most of the southern portion of the Brazilian Drought Polygon and the sub-basins of the two largest tributaries of the São Francisco River, in some areas exceeding r = 0.60. The chronology is also correlated with total annual discharge of the Rio São Francisco River measured at Barra (r = 0.489; 1961–2015), which is very promising in a country that generates two thirds of its electricity from hydroelectric power plants, particularly if this short chronology can be extended with trees exceeding 150-years old known to still exist in the region.

Keywords: Brazilian Drought Polygon, tropical dendrochronology, seasonally dry tropical forests, *Cedrela fissilis*.

INTRODUCTION

The São Francisco River basin is located in the "Brazilian Drought Polygon," the most drought afflicted region of the country (Liu *et al.* 1994; Hastenrath 2012; Awange *et al.* 2016). This drainage basin is the third largest in Brazil, with an area of 636,477 km^2, and it is home to 15 million inhabitants. This single river accounts for 70% of the total water supply for the "Nordeste" region of Brazil (Ministério do Meio Ambiente 2011; Nobre 2012). The São Francisco River rises in the Canastra Highlands and flows 2696 km to the Atlantic Ocean across a steep moisture gradient (from 1700 mm to 500 mm of mean annual precipitation). *Ca.* 73% of the water supply in the basin comes from the southern region in the state of Minas Gerais (Maneta *et al.* 2009; Nobre 2012).

Economically, the São Francisco basin has played a strategic role in the development of the country. Important hydroelectric plants have been installed in the basin, which contribute to 11.4% of the national energy production (Eletrobras 2015). The production of food in the region is based on irrigation agriculture and accounts for the largest consumption of water in the basin (Maneta *et al.* 2009). A large engineering plan is now under development, which will transfer water out of the basin to arid regions with a high frequency of drought. This intense use of water within and outside of the basin, coupled with strong interannual variations in seasonal precipitation may lead to conflicts of water use during below-normal conditions (Maneta *et al.* 2009).

Past drought in the basin has already caused intense famine that culminated in large population

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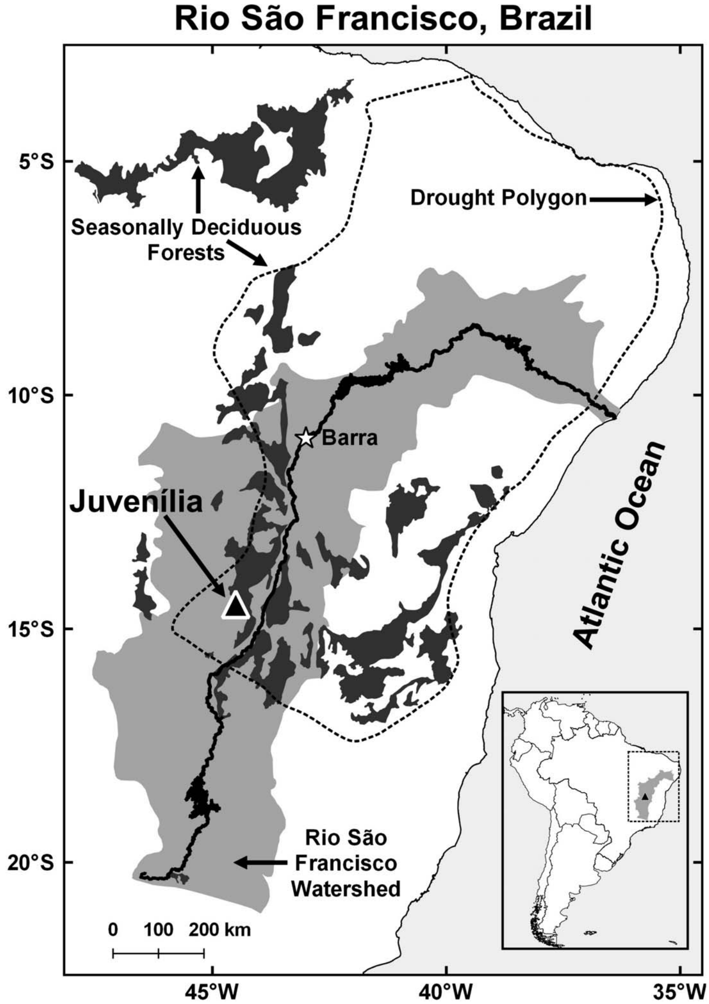

Figure 1. The Juvenília study site is located in the São Francisco River basin (grey color) near the southern margin of the Brazilian Drought Polygon (dashed line). The distribution of seasonally dry tropical forest in and near the Drought Polygon is also illustrated, along with the river gage location at Barra.

movements to other regions of Brazil (Magalhães 1993). The interannual variability of deficit rainfall over the study region, the so called "secas," has been the object of public policy prescriptions and scientific research for more than a century (Nobre 2012). Rainfall fluctuations over the Brazilian Nordeste are associated with sea surface temperatures (SSTs) and atmospheric circulation in the tropical Atlantic and equatorial Pacific (*e.g.* Moura and Shukla 1981; Hastenrath 2006, 2012). In fact, an empirical climate prediction model based on ocean-atmospheric conditions and early season moisture levels can explain nearly 60% of the variance in wet season rainfall totals over the Nordeste province (Hastenrath 2012). Tree-ring reconstructions of rainfall could provide additional hydroclimatic data that may be useful for testing empirical prediction models earlier in the 20th Century when observed and modeled SSTs are available, but instrumental rainfall data from the Nordeste are scarce.

Instrumental precipitation and streamflow records are for the most part short, discontinuous, and sparsely distributed in the Drought Polygon. One of the best instrumental precipitation records in the southern portion of the polygon is the Montes Claros Station (ID 83437), which began observations only in 1950, but has major gaps before 1992. Moisture-sensitive tree-ring chronologies might therefore help in understanding the history and causes of precipitation variability in the Drought Polygon. Tree-growth and climate relations have been reported from very moist to very dry environments in the Neotropical region. Rainfall reconstructions were successfully developed in the Amazon Basin (Brienen *et al.* 2012; Lopez *et al.* 2017), and studies with oxygen isotopes indicate the potential to reconstruct Amazon precipitation (Baker *et al.* 2015, 2016). Rainfall seems to be the primary limiting factor for tree growth in the tropics (Brienen *et al.* 2010; Paredes-Villanueva *et al.* 2013; Locosselli *et al.* 2016), and deciduous species that are synchronized with the dry season (Ribeiro and Walter 1998) in some cases form annual rings in some species with potential for dendrochronology.

The objectives of this study were to (1) demonstrate the crossdating of ring-width data from *Cedrela fissilis* in seasonally dry tropical forests in a drought-prone area, (2) develop a replicated ring-width chronology for the study area, (3) investigate the monthly and seasonal rainfall response of the derived chronology, and (4) explore the potential for tree-ring reconstruction of precipitation and Rio São Francisco streamflow once our short 55-year *Cedrela fissilis* chronology can be extended into the pre-instrumental period.

Figure 2. (a) Photograph illustrating a living *Cedrela fissilis* tree in Juvenília site, and (b) a photograph of the annual rings of *Cedrela fissilis* from Juvenília, Brazil.

MATERIALS AND METHODS

The sampling site was a seasonally dry tropical forest fragment located in the middle São Francisco River basin (Figure 1), in the municipality of Juvenília near the northern limit of the Minas Gerais State, Brazil (14.50°S latitude and 44.17°W longitude). The São Francisco River crosses the pronounced moisture gradient from south to north (Figure 1), which is accompanied by a transition zone from *mata atlântica* rain forest, to *cerrado* (Brazilian savannah), into the *caatinga* (xeric shrubland and thorn forest) ecological domain. In northern Minas Gerais this ecotone exhibits great heterogeneity in floristic units, with seasonally dry forests and enclaves of *cerrado* deciduous forests, arboreal *caatinga*, and cristalino's arboreal *caatinga* (Santos *et al.* 2012). The soil types include red latosol and soils of calcareous origin, often with limestone outcrops (Ribeiro and Walter 1998).

According to the Köppen Climate Classification, the climate of the study site is a transition between Aw and Bsh types based on the climatological normal period (1961–1990) from the nearest meteorological station (Cariranha-BA Station, ID:83408). Total annual precipitation is 814 mm and the rainy season is from October to March, when 90.7% of the total annual precipitation typically occurs. The driest months are June, July and August with a three-month precipitation average below 7mm. Monthly mean temperatures range from 22.4°C to 26.4°C with monthly maximum temperatures ranging between 29.8°C and 32.8°C and monthly minimum temperatures between 15.3°C and 21.1°C.

C. fissilis was the target species for this research because of its wide distribution in the

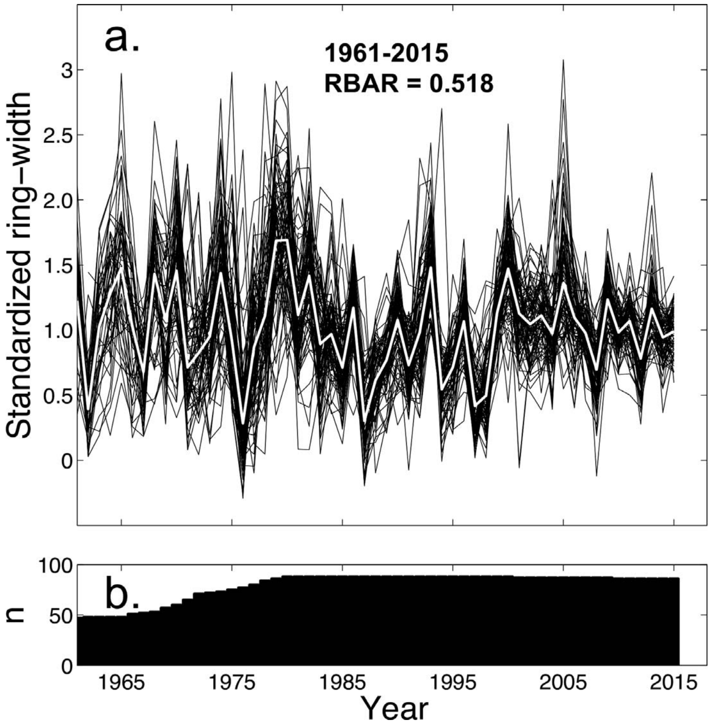

Figure 3. (a) All dated, detrended, and standardized radii of *Cedrela fissilis* from Juvenília are plotted (black) along with the mean index standard chronology (white) from 1961 to 2015. (b) The number of dated radii available each year from 1961to 2015 is also plotted.

seasonally dry tropical forests (SDTFs) in South America (Banda *et al*. 2016), deciduous foliar phenology (Santos and Takaki 2005), and semi-porous ring structure, delimited by marginal parenchyma (Détienne and Jacquet 1983; Marcati *et al.* 2006). In tropical South America, *Cedrela* is a potential genera for dendrochronology (*e.g.* Tomazello *et al.* 2000; Dünisch *et al*. 2002, 2003; Brienen and Zuidema 2005; Dünisch 2005; Brienen *et al*. 2010, 2012). In these forest types, rainfall seasonality synchronizes plant growth and reproduction with soil moisture availability (Murphy and Lugo 1986). Primary productivity and tree growth are controlled by leaf production, which is also conditioned by the amount and timing of rainfall (Jaramillo *et al.* 2011). Leaves of *C. fissilis* are produced during the rainy season, coinciding with the formation of earlywood (Marcati *et al.* 2006). Phenological studies of *C. fissilis* reported the correlation between cambial dormancy and leaf fall during the dry season, and this specific behavior may be related to water economy, leading to a decrease in gas exchange and consequently a decrease in photosynthetic activity (Santos and Takaki 2005; Marcati *et al.* 2006). Under extreme conditions, water stress can cause widespread mortality of trees in seasonally dry forests (Pook *et al.* 1966; Murphy and Lugo 1986).

For this study, 89 cores from 44 trees were extracted with 5- and 12-mm diameter increment borers. The samples were prepared following standard dendrochronological procedures (Stokes and Smiley 1968). Cores were very finely polished and crossdating was identified using the skeleton plot technique (Stokes and Smiley 1968). Ring widths were measured using the LINTAB-TSAPTM measuring device (Rinntech 2017) with a precision of 0.01mm. We used the program COFECHA (Holmes 1983) to verify crossdating and measurement accuracy. Ring-width series were detrended and standardized using an age-dependent spline, and the robust mean index "standard" chronology was computed using the ARSTAN computer program (Cook and Krusic 2005). Total monthly precipitation from Climate Research Unit (CRU) gridded TS3.21 data set was used to analyze the *C. fissilis* response to rainfall. The CRU 0.5° gridded self-calibrating Palmer Drought Severity Index (scPDSI) version 3.25 data were also used to examine the moisture balance signal in the *C. fissilis* chronology. Spatial correlations between wet season monthly rainfall, scPDSI, and the standard ring-width chronology were calculated using the Pearson's correlation coefficient.

RESULTS

Some trees in our collection from Juvenília are over 100 years old and a few are over 150. However, the annual rings are subject to wedging effects in which one or more rings become locally absent, and the ring boundaries themselves can be difficult to identify with confidence on narrow 5- or 12-mm increment cores. The known collection date of the outer ring provides the essential benchmark to begin crossdating in these complex tropical hardwood specimens, but because of wedging and obscure ring definition, crossdating may fail in earlier decades. We have therefore restricted our analyses to the period 1961–2015 when we are certain about the exact dating of the annual rings. Development of 150- to 200-year-long chronologies from the study area should be possible with additional collections, especially with full and partial cross-sections that we are now officially permitted to obtain [native tree species are protected by law in the state of Minas Gerais (Minas Gerais 2004, 2013)]. Note that over half of our available cores extend before 1961.

The 89 dated, detrended, and standardized radii from 44 *C. fissilis* trees collected at Juvenília are plotted in Figure 3 along with the mean index standard chronology and the sample size of radii each year. The very high coherence in ring width growth among trees and radii is clearly apparent, and as a result the mean correlation among all radii is also quite high (RBAR = 0.52; Cook and Krusic 2005). Severe drought years with narrow rings that were valuable for dating these core specimens occurred in 1976, 1987, and 1997. Important wet years with wide rings were 1979 and 2000. The percent of missing rings in all dated radii from 1961 to 2015 was 0.9%, but fully 24.8% of the rings were missing in our specimens for 1997, a clear demonstration of the necessity for careful crossdating of these *C. fissilis* trees from extremely moisture-stressed sites. Some weakening in the time-series coherence among the 89 radii is apparent in Figure 3 before 1985, which we admit may be caused by a few cases to dating error, in spite of our best efforts at crossdating and quality control. If older individuals can be dated and included in the chronology, any potential dating mistakes should become more obvious and can be corrected.

The spatial pattern of correlation between the Juvenília *Cedrela* chronology and wet-season rainfall totals in northeastern Brazil is illustrated in Figure 4. The highest grid point correlation is 0.63 and many exceed $r = 0.50$ across a large portion of the Brazilian Drought Polygon. This includes the transition zone between the Cerrado and Caatinga ecosystems, and the headwaters region of the Rio São Francisco where most of the streamflow originates (Ribeiro and Walter 1998; Pereira *et al*. 2007). The *Cedrela* chronology is also positively correlated with the October–March average scPDSI. The spatial pattern of scPDSI correlation with the tree-ring chronology and the magnitude of correlation (not shown) are both nearly identical with the rainfall signal illustrated in Figure 4.

The regional average (11–16°S and 42–48°W) of wet season (October–March) CRU TS4.01 rainfall totals is well correlated with the Juvenília tree-ring chronology from 1961–2015, using both time series and scatter plots (Figure 5). The single Juvenília *Cedrela* chronology can explain *ca*. 40% of the variance in wet season rainfall over a large portion of the Drought Polygon (the Pearson correlation coefficient squared). However, the correlation between wet season rainfall and tree growth is much higher from 1961–1993, and is weaker and not significant from 1994–2015 (Figure 5). This change in the full wet-season rainfall correlation after 1993 appears to be caused by a shift in response to rainfall near the start of the wet season (Figure 6 a–c). The tree-ring chronology is significantly correlated ($p < 0.01$) with November rainfall totals from 1994–2015, but not during other months of the wet season (Figure 6c). Figure 6 therefore suggests that the rainfall response of *Cedrela fissilis* in northern Minas Gerais may shift from a full to early wet season signal on decadal timescales. However, these analyses are based on the nearest available instrumental rainfall stations closest to the Juvenília site

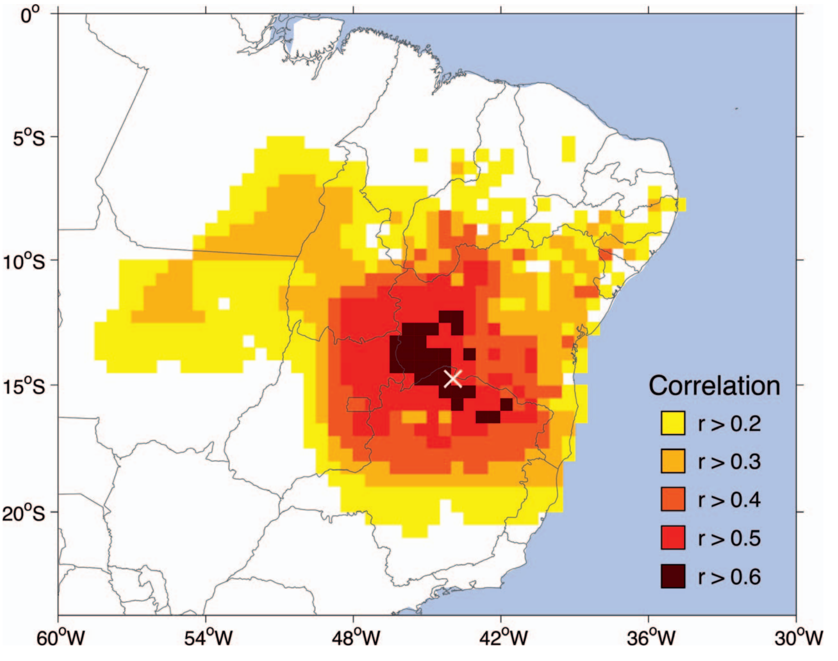

Figure 4. The spatial correlation of the Juvenília standard ring-width chronology (x) with the 0.5°CRU TS3.21 gridded rainfall totals for the wet season (October–March) for the period 1961–2012 is illustrated. Correlations above $r = 0.3$ are significant at $p < 0.05$ and the highest single grid point correlation is $r = 0.63$.

in the CRU data set, which are actually not close at all. They are 160, 250 and 360 km from Juvenília (*i.e.* Bom Jesus da Lapa, Bahia; Montes Claros, Minas Gerais; and Lençóis, Bahia, respectively).

The Juvenília *Cedrela* chronology is also significantly correlated with total annual discharge in the Rio São Francisco recorded at Barra from 1961–2015 ($r = 0.489$; $p < 0.001$) (Figure 7).

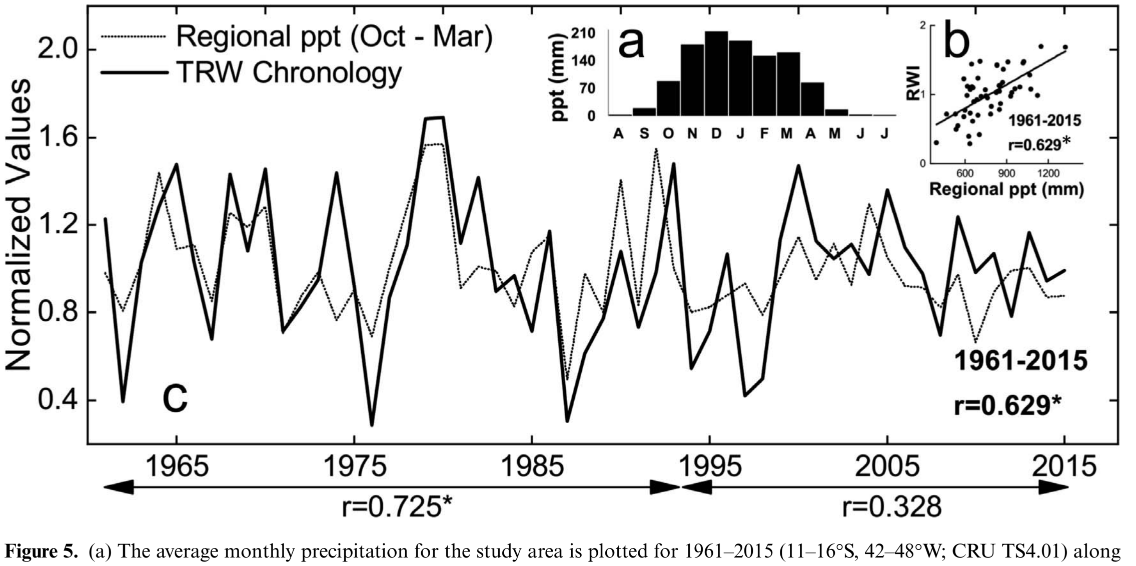

Figure 5. (a) The average monthly precipitation for the study area is plotted for 1961–2015 (11–16°S, 42–48°W; CRU TS4.01) along with (b) the scatter plot comparing the chronology and wet season rainfall totals for the period 1961–2015. (c) The time series of the Juvenilia chronology is plotted with regional wet season precipitation totals (October–March) for the period 1961–2015. (* = correlation that is significant, $p < 0.05$).

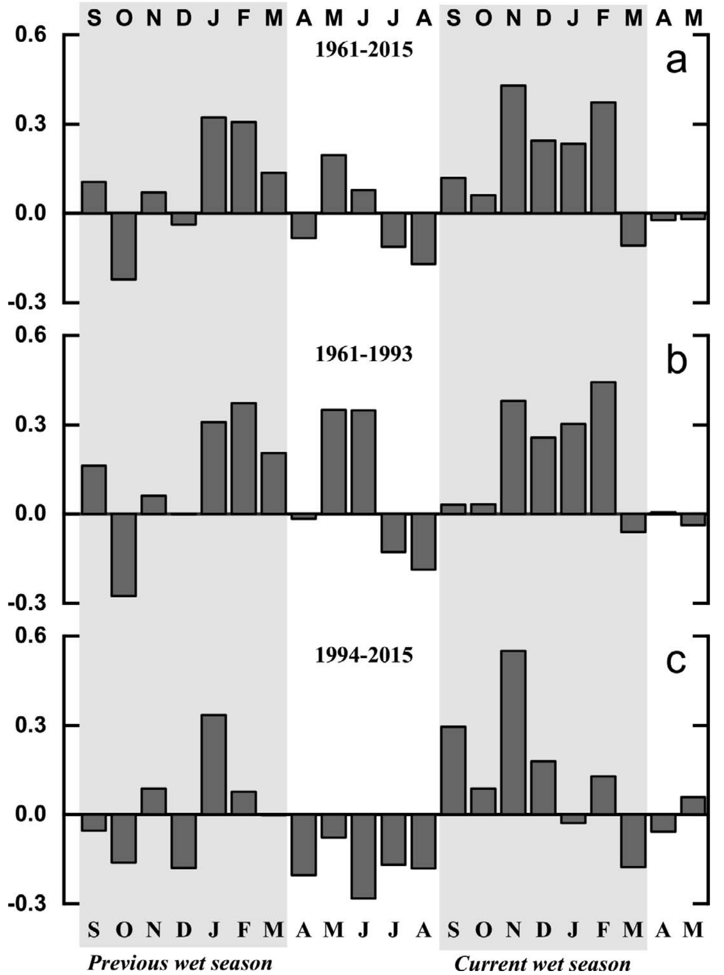

Figure 6. Correlation values between the Juvenilia chronology and monthly precipitation for three time periods (a) = 1961–2015, (b) = 1961–1993, and (c) = 1994–2015. Areas in gray represent the current and previous wet seasons.

However, the correlation disappears after 1993 (r = 0.665 for 1961–1993, but r = −0.03 for 1994–2015), which might reflect the shift from a full wet-season response to just a November rainfall signal in the Juvenília *Cedrela* chronology (Figure 6). November rainfall represents only some 16% of the annual average total precipitation in the study region (Figures 4 and 5) whereas Rio São Francisco annual discharge integrates precipitation throughout the wet season. We also suspect that the stream gage at Barra has been impacted by human activity, mainly from the increase in the area of irrigated crops (Maneta *et al.* 2009). This inference may be supported by the correlation between regional precipitation and streamflow recorded at Barra, which declines from r = 0.619 to r = 0.290 before and after 1993 (Figure 7). A high-quality tree-ring reconstruction of São Francisco discharge, based on several precipitation-senstive chronologies in and near the drainage basin, might therefore provide useful information on natural flows in both the pre-instrumental period and during the most recent decades of streamflow manipulation.

DISCUSSION AND CONCLUSIONS

A better understanding of the long-term moisture variability in the Rio São Francisco basin and

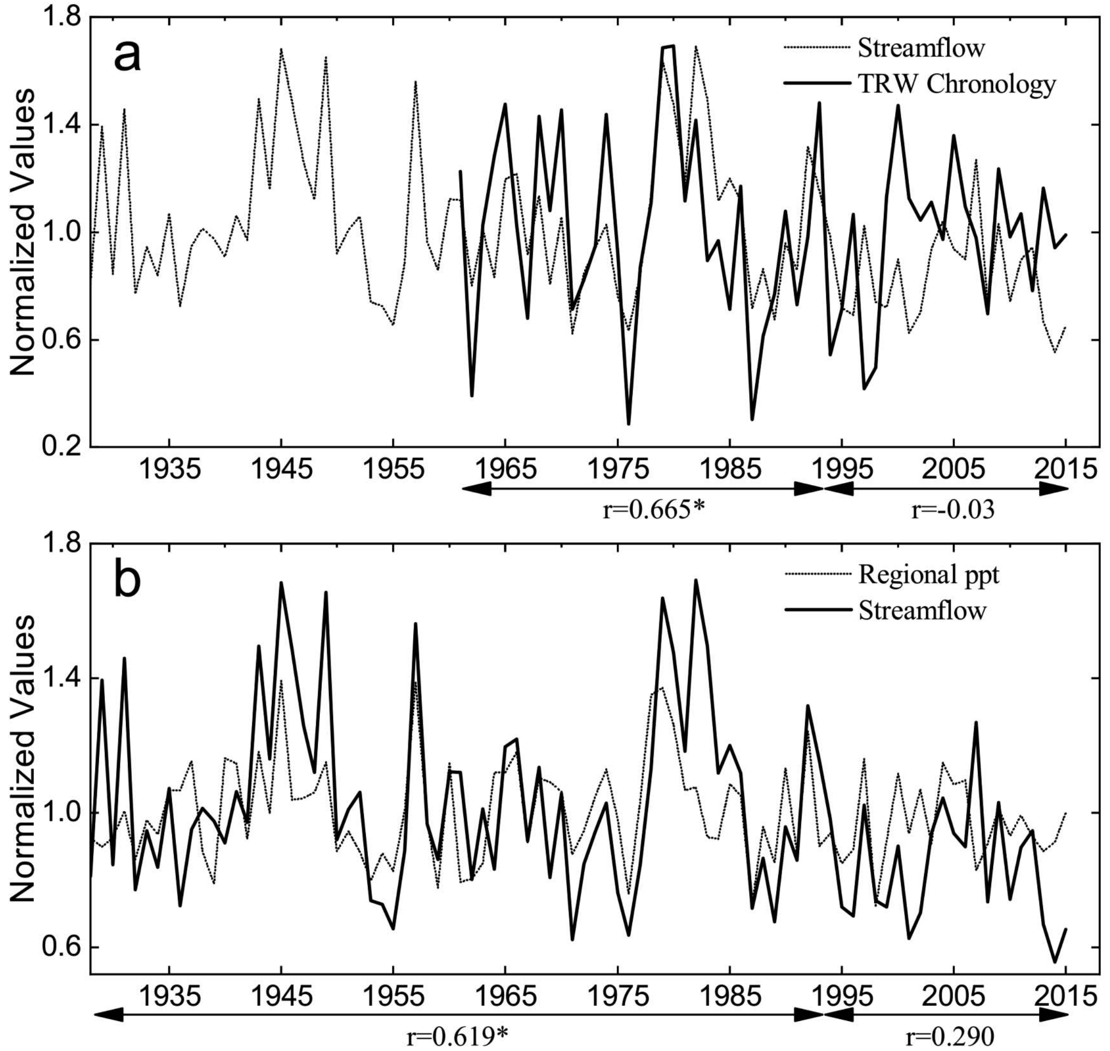

Figure 7. (a) The time series of the Juvenilia chronology is plotted with average annual streamflow of the São Francisco River measured in Barra. (b) Total annual precipitation for the study area (11–16°S, 42–48°W; CRU TS4.01) is plotted with annual streamflow at Barra from 1928–2015. Note the decline in correlation between streamflow and both rainfall and tree growth after 1993 (* = correlation that is significant, $p < 0.05$).

Brazilian Drought Polygon will be important because 15 million people live in the basin, and the regional economy is very sensitive to rainfall fluctuations (Maneta *et al.* 2009; Awange *et al.* 2016). The available meteorological and hydrological records for this region are often short and discontinuous (Agência Nacional das Águas 2017). No annually-resolved paleoclimate data are currently available for either the São Francisco basin or the Brazilian Drought Polygon, but tree-ring chronologies from *C. fissilis* and possibly other tree species native to the region may contribute to our understanding of hydroclimate variability in this drought-prone region of Brazil.

The *C. fissilis* chronology from Juvenília is only 55 years long (1961–2015), but it does have excellent internal crossdating and a strong rainfall signal. The influence of rainfall on tree growth has been reported for other species in seasonally dry tropical forests of South America (Brienen *et al.*

2010; Locosselli *et al.* 2016; Paredes-Villanueva *et al.* 2013; Worbes 1999). Understanding the relationship between climate and tree growth in seasonally dry tropical forests is important in the face of anthropogenic climate change (Brienen *et al.* 2010; Locosselli *et al.* 2016). Future scenarios predict the reduction of rainfall and soil moisture in the Caatinga region (Bates *et al.* 2008), where water availability is the main limiting factor for tree growth (Murphy and Lugo 1986; Pennington *et al.* 2006). Studies in seasonally dry tropical forests reveal the negative impact of climate change on species growth, and studies aimed at understanding these connections are needed because these forests are important in storing carbon (Jaramillo *et al.* 2003; Brienen *et al.* 2010; Locosselli *et al.* 2016).

Uncut old-growth *C. fissilis* forests still exist in portions of the Drought Polygon, in spite of heavy anthropogenic impacts in the region. If additional tree-ring cores and cross-sections can be obtained, it should be possible to develop rainfall and possibly streamflow reconstructions covering the past 150 to 200 years. The chronology developed during this research will be contributed to the International Tree-Ring Data Bank and to "*Cedrelanet*", a collaboration among scientists working to develop a network of tree-ring chronologies derived from *Cedrela* species in tropical South America, which was formed during the 68th Brazilian National Congress of Botany in 2017.

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