UNIVERSIDADE FEDERAL DE LAVRAS

GABRIEL DE ASSIS PEREIRA

DENDROCLIMATOLOGY IN SEASONALLY DRY TROPICAL FORESTS IN THE SÃO FRANCISCO BASIN, BRAZIL.

LAVRAS - MG
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Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Engenharia Florestal, área de concentração em Ciências Florestais.

Dra. Ana Carolina Maioli Campos Barbosa
Orientadora

Dr. David William Stahle
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RESUMO GERAL

Esse trabalho teve como objetivo desenvolver estudos dendroclimatológicos em florestas tropicais sazonalmente secas, na Bacia do Rio São Francisco, Brasil. Foram utilizados discos completos e cilindros do tronco de árvores de *Cedrela fissilis* Vell. Os procedimentos de preparo das amostras, contagem, co-datação e mensuração dos anéis de crescimento foram realizados de acordo com os procedimentos padrões da dendrocronologia. Assim, desenvolvemos duas cronologias de largura de anéis de crescimento, no norte do estado de Minas Gerais, denominadas de Juvenília e Peruaçú, ambas com significativa intercorrelação entre as séries (RBAR) igual a 0.52 e 0.34, respectivamente. Com a cronologia Juvenília, datada de 1961 a 2015, constatamos a forte correlação entre a largura dos anéis de crescimento com precipitação total do período chuvoso (outubro a março), a qual cobriu espacialmente as principais sub-bacias tributárias do rio São Francisco, em algumas áreas a correlação foi superior a r=0.60. A cronologia Peruaçú, datada de 1842 a 2012, permitiu a reconstrução da vazão média mensal do Rio São Francisco no posto de observação de Sobradinho (Bahia), entre os meses de novembro a fevereiro, onde a cronologia Peruaçú explicou 54% da variância no período de calibração (1956-1998). Secas históricas que ocorreram na bacia foram passíveis de identificação na cronologia, como a “Grande Seca” que ocorreu entre os anos de 1875-1879 e a seca de 1932, as quais provocaram grandes ondas migratórias na região do “Polígono das Secas”. Os resultados alcançados mostram o grande potencial para estudos dendrocronológicos na bacia do Rio São Francisco, região vulnerável a eventos severos de seca. As informações geradas nessa pesquisa contribuem para o entendimento do regime hídrico na bacia e fornecem informações para o planejamento do uso múltiplo da água.

Palavras-chave: 1. *Cedrela fissilis*. 2. Dendrocronologia. 3. Polígono das Secas.
4. Reconstrução hidrológica.

ABSTRACT

This work aimed to develop dendroclimatic studies in seasonally dry tropical forests in the São Francisco River Basin, Brazil. Complete cross-sections and cores from *Cedrela fissilis* Vell trees were used to build two ring-width chronologies in the north of the state of Minas Gerais. The procedures for sample preparation, counting, co-dating and measurement of growth rings were made according to standard dendrochronological procedures. The produced chronologies, called Juvenília and Peruaçú, presented significant intercorrelation between the series (RBAR) equal to 0.52 and 0.34, respectively. In the Juvenília chronology, dated from 1961 to 2015, we verified the strong correlation between the tree growth and total precipitation of the wet season (October to March), that spatially covered the main tributary sub-basins of the São Francisco river, in some areas the correlation was higher than r = 0.60. The Peruaçú chronology, dating from 1842 to 2012, was used to reconstruct the average monthly flow of the São Francisco River at the Sobradinho observation station (Bahia state) between November and February, and explained 54% of the variance in the calibration period (1956-1998). Historical droughts that occurred in the basin were identified in the chronology, such as the "Grande Seca" that occurred between 1875-1879 and the 1932 drought, which caused great migratory waves in the "Brazilian Drought Polygon". The results show the great potential for dendrochronological studies in the São Francisco river basin, a region vulnerable to severe drought events. The information generated in this research contributes to the understanding of the water regime in the basin and provides information for planning the multiple use of water.

Keywords: 1. *Cedrela fissilis* 2. Dendroecology. 3. Brazilian Drought Polygon. 4. Hydrologic reconstruction.

SUMÁRIO

PRIMEIRA PARTE

1 INTRODUÇÃO GERAL

Na bacia do São Francisco, o clima desempenha notável influência sobre a população humana e o desenvolvimento econômico. Essa condição de clima e desenvolvimento humano coloca os recursos naturais sob grande pressão antrópica, porém carece de estudos que possam ajudar a compreender a fragilidade ambiental e as principais vulnerabilidades dessas paisagens às mudanças globais.

A construção de cronologias de anéis de crescimento tem um valor inestimável para entender os fenômenos envolvidos na ocorrência de eventos de seca severa na região nos últimos séculos e tem implicação direta em termos sócio-econômico-ambientais. Os dados dendrocronológicos, ao permitirem a reconstrução do clima em períodos pré-instrumentais, poderão fornecer uma nova perspectiva para as discussões climáticas, com ênfase nos processos atmosféricos e oceânicos que condicionam a distribuição espacial e temporal das precipitações pluviométricas sobre a região e as perspectivas de alterações futuras dos padrões de chuvas devido às mudanças climáticas globais. Esse tipo de abordagem tem profundas implicações para a conservação dos ecossistemas, ecologia florestal, fitogeografia e desenvolvimento sustentável na região de estudo onde, até o presente, se desconhecem registros de investigações dendrocronológicas e não existe sequer uma cronologia de anéis de crescimento de árvores disponível para estudos paleoclimáticos

De acordo com a dendrocronologia clássica, com berço nas áreas áridas do Arizona, formações sob pronunciado déficit hídrico sazonal são ideais para construção de cronologias de anéis de crescimento visando reconstruções climáticas de eventos extremos de seca no passado (FRITTS, 1976). Dados paleoclimáticos desta natureza resgatam e completam as lacunas e ausência de dados instrumentais, fornecendo uma perspectiva para a melhor compreensão dos processos atmosféricos e oceânicos que condicionam o crescimento arbóreo e a distribuição espacial e temporal das precipitações sobre a região e tem implicações diretas em termos sócio-econômico-ambientais.

2 REFERENCIAL TEÓRICO

2.1 A árvore como sensor climático-ecológico

Os anéis anuais de árvores constituem-se em um verdadeiro registro bio-geo-cronológico, uma vez que possuem associações fisiológicas diretas com os fatores ambientais (FRITTS, 1976; SCHIPPERS et al., 2015). Esses registros podem ser obtidos para extensas áreas geográficas e assim serem massivamente replicados no espaço e no tempo, constituindo-se em uma rede de dados paleoclimáticos, que auxiliam nos modelos de simulação climática e corroboram com outros registros do holoceno (lagos, cavernas, corais, geleiras, dentre outros) (BETANCOURT; GRISSINO-MAYER; GAO et al., 2016; LIU et al., 2014; BETANCOURT et al., 2002).

A dendrocronologia é a ciência que busca construir cronologias a partir dos anéis de crescimento das árvores (COOK; KIRIUKSTIS, 1989; FRITTS, 1976). A árvore funciona como um sensor climático e através de respostas fisiológicas armazenam essas informações em seus anéis de crescimento, que em certas espécies possuem resolução anual e podem ser datados conforme os anos do calendário (FRITTS, 1976; TOMAZELLO FILHO; BOTOSSO; LISI, 2001). Nas zonas temperadas, a aplicação da dendrocronologia possibilitou o entendimento do paleoclima regional, com a reconstrução de secas continentais, de variações de temperatura e variabilidade das vazões fluviaias (BALLESTEROS-CÁNOVAS et al., 2015; BRIFFA et al., 1992; COOK et al., 1999; STAHLE et al., 2016; STAHLE et al., 2011a; 2011b; STAHLE et al., 2007; STAHLE et al., 2000)

A grande maioria das cronologias foi desenvolvida em florestas temperadas e boreais, enquanto que as formações florestais tropicais, de maior biodiversidade, praticamente não estão representadas no banco internacional de dados de anéis de crescimento (The International Tree-Ring Data Bank - ITRDB, do programa paleoclimático do NOAA). Como consequência, o paleoclima dessas regiões ainda é pouco conhecido, formando uma grande lacuna para a compreensão da vulnerabilidade e fragilidade desses ecossistemas frente às mudanças climáticas globais (BARBOSA et al., 2012; BRIENEN; SCHÖNGART; ZUIDEMA, 2016).

Apesar dos trópicos apresentarem alta diversidade de espécies arbóreas, a maioria não é adequada para a dendrocronologia (COOK; KIRIUKSTIS, 1989). Porém, já foram constatados fenômenos, em regiões tropicais, capazes de induzir a dormência cambial e promover a formação de anéis anuais distintos. São eles, o anaerobismo radicular em planícies alagáveis com pulsos anuais de inundação (BRIENEN; SCHÖNGART ; ZUIDEMA, 2016; SCHÖNGART et al., 2002; SCHÖNGART et al., 2005; WORBES, 1989) e os estresse hídrico causado pelo sazonalidade de chuvas (BRIENEN; SCHÖNGART; ZUIDEMA, 2016; DÜNISCH et al., 2002; STAHLE et al., 1999).

Os eventos de inundações e sazonalidade de chuvas, além de promoverem a formação de anéis distintos, ocasionam, em condições de estresse, modificações nas estruturas anatômicas ao longo da vida das árvores (BRAUNING et al., 2016; SCHWEINGRUBER, 2012). Como exemplo, variações no tamanho do vaso em lenho juvenil, formato e número são marcadores para eventos de inundação, estresse por calor ou seca (COPINI, 2015; GONZALEZ; ECKSTEIN, 2003; PRITZKOW et al., 2015; ST GEORGE et al., 2002). Essa sensibilidade dos elementos anatômicos da madeira aos estímulos ambientais possibilita a formação de séries temporais de eventos de estresse na história de vida da árvore, trazendo consigo informações importantes do paleoclima e de relevância para os estudos de mudanças climáticas (CARLQUIST, 2001; GONZALEZ; ECKSTEIN, 2003). Além desses dois principais mecanismos, em manguezais, a variação anual da salinidade das águas também pode induzir a dormência cambial e a formação de camadas de crescimento distintas e anuais (VERHEYDEN et al., 2004; YU et al., 2004).

2.2 A bacia do São Francisco e a região do semi-árido brasileiro

A Bacia do São Francisco é a terceira maior bacia hidrográfica do Brasil e responde por 70% da oferta de água de todo o Nordeste. O Rio São Francisco nasce na Serra da Canastra e percorre 2.696 km pelos estados de Minas Gerais, Bahia, Pernambuco, Alagoas e Sergipe, sendo dividido em 4 sub-bacias: Alto, Médio, Sub-Médio e Baixo São Francisco (BRASIL, 2012). O estado de Minas Gerais contribue com 73% da oferta de água da bacia, ou seja, a maior parte das águas do São Francisco não depende de chuvas caídas no Nordeste, mas no Sudeste.

A distribuição espacial/temporal da pluviometria sobre o Nordeste é fruto de processos atmosféricos oceânicos que causam elevada variabilidade dos totais pluviométricos interanual e intrasazonal. As variações interanuais dos totais pluviométricos sobre a Região Nordeste ocasionam, nos anos de déficit pluviométrico, as chamadas secas, fenômeno recorrente na região e objeto de políticas públicas por mais de um século (BRASIL, 2012; MANETA, et al., 2009).

Na porção sul do Nordeste, que abrange os estados da Bahia, norte de Minas Gerais e Sul do Maranhão e Piauí, a precipitação apresenta quadrimestre mais chuvoso de novembro a fevereiro, com máximos pluviométricos durante dezembro e janeiro. O que determina as chuvas são os movimentos atmosféricos controlados, principalmente, pelas temperaturas superficiais dos oceanos Atlântico Tropical e Pacífico Equatorial. Em função da combinação das condições dos oceanos Atlântico e Pacífico, ocorre grande variabilidade interanual dos totais pluviométricos, resultando em alternância dos anos de seca e de cheias. Estudos dos impactos das mudanças climáticas globais sobre a América do Sul indicam que a região Nordeste do Brasil se encontra dentre as regiões mais vulneráveis às mudanças climáticas, com um quadro de aumento da temperatura do ar e diminuição dos totais anuais de precipitação sobre a região (BRASIL, 2012, MARENGO et al., 2011).

Estudos apontam o risco de agravamento da disponibilidade hídrica para bacias hidrográficas na região do semi-árido brasileiro. De acordo com Montenegro; Ragab (2012) até o final deste século a disponibilidade hídrica superficial e subterrânea pode ser reduzida em 32,91% e 20,58%, respectivamente. Um estudo recente demonstrou que no último século houve o aumento da extensão em área dos eventos de seca em até 3,4% por década (AWANGE; MPELASOKA; GONÇALVES, 2016).

2.3 Florestas sazonalmente secas e o potencial dendrocronológico de *Cedrela fissilis*

O Rio São Francisco atravessa uma região com um pronunciado gradiente de umidade desde a Serra da Canastra seguindo em direção ao semiárido nordestino. Esse gradiente é acompanhado pela variação nas fitofisionomias, formando uma zona de transição dos domínios Mata Atlântica, Cerrado e Caatinga. Esta zona ecotonal é bastante pronunciada na região do norte de Minas Gerais e sul da Bahia, no Médio São Francisco, apresentando grande heterogeneidade das unidades florísticas das Florestas Sazonalmente

Secas, como os enclaves de florestas deciduais do Cerrado, as formações de Caatinga Arbórea e Caatinga Arbórea do Cristalino (SANTOS et al., 2012).

As Florestas Sazonalmente Secas (FSS), também conhecidas localmente como Matas Secas, incluem diversos tipos de formações florestais caracterizadas por diferentes níveis de caducifolia durante a estação seca, variando de sempre verdes, semidecíduas e decíduas (RIBEIRO; WALTER, 1998). No norte de Minas, no limite sul do semiárido brasileiro, são comuns as FSS sobre solos de origem calcária, muitas vezes com afloramentos rochosos típicos (RIBEIRO; WALTER, 1998). Essas formações são promissoras para o desenvolvimento de estudos dendrocronológicos, pois as condições edáficas acentuam o estresse hídrico nas plantas, ampliando a variabilidade interanual do crescimento radial (ANA, 2016).

A espécie arbórea *Cedrela fissilis* é de ocorrência frequente nas FSS do Neotrópico, apresentando todos os requisitos para os estudos dendrocronológicos, incluindo ampla distribuição geográfica, fenologia foliar decidual, anéis de crescimento anatomicamente distintos. Outro comportamento favorável é a tendência da C. fissilis em formar sistema radicular superficial, aumentando a sensibilidade climática do crescimento radial à precipitação e níveis de umidade do solo (BRIENEN et al., 2012).

Análises dendrocronológicas com o gênero Cedrela vem mostrastrando resultados promissores nos neotrópicos. Estudos apontam para a sensibilidade do gênero com variáveis climáticas (BRIENEN; ZUIDEMA, 2005; BRIENEN et al., 2012; DÜNISCH et al., 2002; 2003; DÜNISCH, 2005; TOMAZELLO et al., 2000) e permitiu a reconstrução de chuvas na amazônia oriental (GRANATO-SOUZA et al., 2018) e na cordilheira do Andes (VOLLAND; PUCHA; BRAUNING, 2016), além de um bom proxy para a variabilidade de Oscilação Sul de El Niño (BRIENEN et al., 2012; PUCHA; BRAUNING, 2016).

3 OBJETIVOS E HIPÓTESES

O objetivo deste trabalho foi desenvolver estudos dendroclimatológicos em florestas tropicais sazonalmente secas na bacia do Rio São Francisco.

3.1 Objetivos específicos

I- Investigar a co-datação dos anéis de crescimento da espécie *Cedrela fissilis* em floresta tropical sazonalmente seca.

II- Analisar a resposta do crescimento secundário de *Cedrela fissilis* em relação à sazonalidade de chuvas.

III- Reconstruir a vazão do Rio São Francisco a períodos pré-instrumentais utilizando cronologia de anéis de crescimento de *Cedrela fissilis.*

HIPÓTESES

H1: A região do semi-árido brasileiro, caracterizada pela ocorrência das Florestas Tropicais Sazonalmente Secas, é potencialmente um sítio ideal para o desenvolvimento de estudos dendrocronológicos.

Premissa: Em regiões tropicais, a sazonalidade de chuvas é capaz de induzir a dormência cambial em espécies vegetais (Worbes 1995, 1999; Stahle,1999). Ademais, o estresse hídrico sazonal (uma estação seca e uma estação chuvosa por ano) afeta os processos fisiológicos das árvores levando a caducifolia na estação seca e consequentemente restringindo a assimilação de carbono pela fotossíntese (Frits, 1976; Murphy; Lugo, 1986).

H2: A espécie Cedrela fissilis, de ampla ocorrência geográfica/ecológica no Brasil, responde fortemente à variação da umidade na região de estudo (limite sul do semiárido Brasileiro).

Premissa: O princípio da Lei do Mínimo de Liebig afirma que o crescimento vegetal é reflexo do fator ambiental mais limitante (Liebig, 1841). O limite sul do semi-árido brasileiro apresenta forte sazonalidade de chuvas e com fenômeno de secas recorrentes (Awange et al., 2016; Giannini et al., 2004). A espécie *Cedrela fissilis*, presente nessa região, apresenta fenologia foliar decidual durante o período de estiagem (Marcati et al., 2006) e tendência de formar um sistema radicular superficial (Brienen et al.2012), características as quais lhe proverão sensibilidade do crescimento radial à precipitação e níveis de umidade do solo.

H3: Cronologia de larguras de anéis de crescimento da espécie *Cedrela fissilis* no limite sul do Polígono das Secas é preditora para a reconstrução da vazão do Rio São Francisco.

Premissa: Cronologia de larguras de anéis de crescimento de *Cedrela fissilis* respondem fortemente a variação anual de chuvas (Pereira et al., 2018) e os padrões de descarga do Rio São Francisco são determinados principalmente pela precipitação e sua variabilidade (Maneta et al., 2009). Assim, por relação indireta o crescimento secundário anual de *Cedrela fissilis* poderá ser correlacionado com a vazão do Rio São Francisco.

4 CONSIDERAÇÕES GERAIS

Os resultados gerados com essa pesquisa demonstram o potencial para o desenvolvimento da ciência da dendrocronologia no Brasil, principalmente na região do semi-árido, que ainda se encontra incipiente.

O primeiro artigo apresenta uma cronologia curta de largura de anéis de crescimento da espécie *Cedrela fissilis* (1961-2015), contudo com uma elevada intercorrelação das séries, equiparada com espécies de clima temperado, berço da dendrocronologia (St George, 2014), bem como uma elevada correlação climática. Essa cronologia foi denominada de “Cronologia Juvenília”. Foi possível perceber o cuidado que deve-se ter com a amostragem com baquetas, mesmo em ambiente favorável para estudos dendrocronológicos. É necessária a obtenção do máximo de amostras possíveis (raios por árvore e número de indivíduos) para a construção de uma cronologia confiável. Observamos a presença de indivíduos centenários amostrados, porém o campo restrito de visibilidade das baquetas dificultou a co-datação de qualidade anterior ao ano de 1961, devido principalmente à presença de canais de resiníferos, anéis muito estreitos e confluentes.

Com os resultados promissores da pesquisa, uma autorização foi solicitada junto ao Instituto Estadual de Florestas do Estado de Minas Gerais para o corte de alguns indivíduos de *Cedrela fissilis* (amostragem destrutiva), a fim de obter discos do tronco para ampliar o campo de visualização dos anéis e por fim validar a datação das amostras da Cronologia Juvenília e permitir a datação das demais baquetas da primeira coleta

Assim, a Cronologia Juvenília foi estendida do ano 1882 até 2017, totalizando 136 anos, a mesma foi depositada no International Tree-Ring Data Bank (NOAA, 2018) sob o código BRA002. Salientamos ainda que essa é a primeira cronologia de anéis de crescimento do semi-árido brasileiro a fazer parte desse banco de dados paleoclimáticos.

O segundo artigo demonstra o potencial da cronologia da largura de anéis de *Cedrela fissilis* para a reconstrução da Vazão do Rio São Francisco. Foi desenvolvida uma outra cronologia, denominada “Cronologia Peruaçú”, datando de 1842 a 2012. Os resultados apontam satisfatoriamente a “Cronologia

Peruaçu” como preditora da vazão do Rio São Francisco, onde foi possível estimar a vazão a períodos pré-instrumentais. As informações geradas são inéditas no Brasil, sendo o primeiro estudo com anéis de crescimento para a reconstrução hidrológica de um rio. Os dados auxiliaram no entendimento do regime hídrico dessa importante bacia hidrográfica, onde a economia é altamente sensível às flutuações de chuvas (Maneta et al., 2019) e os dados das estações meteorológicas e hidrológicas são curtas e descontínuas.

As perspectivas futuras para o desenvolvimento da dendrocronologia na bacia do São Francisco serão a construção de novas cronologias ao longo da bacia, seguindo as formações de Florestas Tropicais Sazonalmente Secas, a fim de construir uma rede de dados paleoclimáticos de qualidade. Também pretende-se construir cronologias com isótopos estáveis de oxigênio, as quais poderão trazer informações ainda mais acuradas do regime pluvial da região.

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SEGUNDA PARTE - ARTIGOS

ARTIGO 1 - THE CLIMATE RESPONSE OF *Cedrela fissilis* ANNUAL RING WIDTH IN THE RIO SÃO FRANCISCO BASIN, BRAZIL

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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 width 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 could prove valuable in a country that generates two thirds of its electricity from hydroelectric power plants, if this short chronology can be extended with trees over 150-years old that are known to still exist on a limited basis in the region.

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

1 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 km², 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 2,696 km to the Atlantic Ocean across a steep moisture gradient (from 1700 mm to 500 mm of mean annual precipitation). Approximately 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 is the largest water consumption activity in the basin (Maneta et al. 2009). A large engineering plan is now under development that 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 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 understand 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 successful 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; Baker et al. 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 1) to demonstrate the cross-dating of ring-width data from Cedrela fissilis in seasonally dry tropical forests in a drought-prone area, 2) to develop a replicated ring-width chronology for the study area, 3) to investigate the monthly and seasonal rainfall response of the derived chronology, and 4) to explore the potential for tree-ring reconstruction of precipitation and Rio São Francisco streamflow once our short 55-year Cedrela fissilis can be extended into the pre-instrumental period.

2 Material 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) that 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).

Using 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.

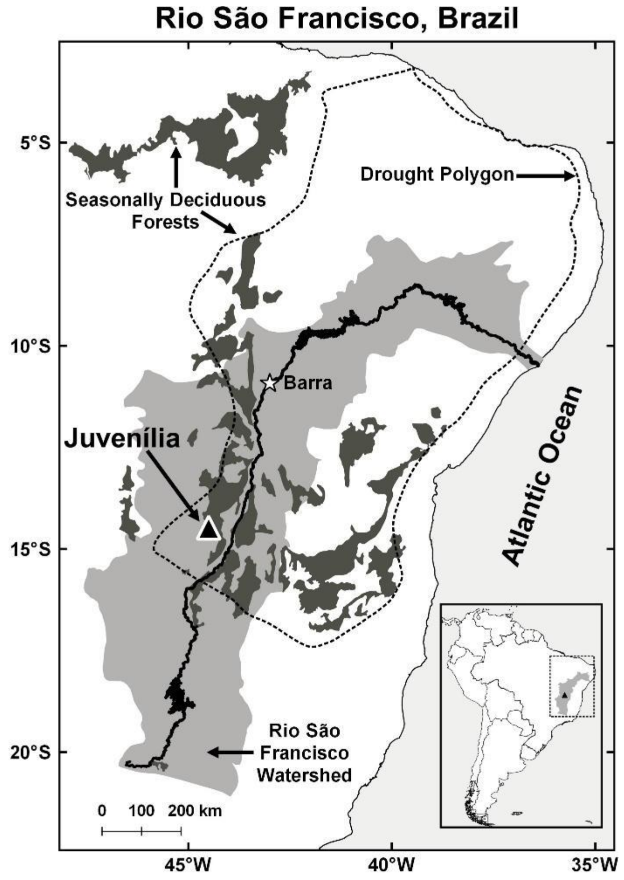

Figure 1. The Juvenília study site is located in the São Francisco River basin (grey color) near the southern margin of the Brazilian Drought Polygon (dashed line). The distribution of seasonally dry tropical forest in and near the Drought Polygon is also illustrated, along with the river gage location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

C. fissilis was the target species for this research (Figure 2) due to its wide distribution in the 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).

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

For this study, 89 cores from 44 trees were extracted with 5 and 12mm 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.

3 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 where 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 due to wedging and obscure ring definition, crossdating can begin to 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 which 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 due in 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 will 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 show) are both nearly identical with the rainfall signal ilustred in Figure 4.

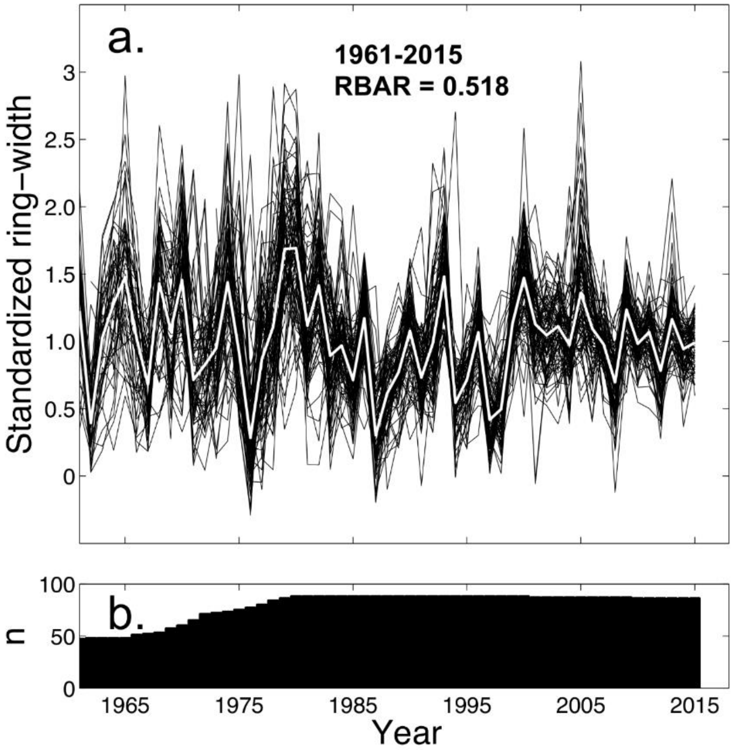

Figure 3. (a) All dated, detrended, and standardized radii of Cedrela fissilis from Juvenília are plotted (black) along with the mean index standard chronology (white) from 1961 to 2015. (b) The number of dated radii available each year from 1961to 2015 is also plotted.

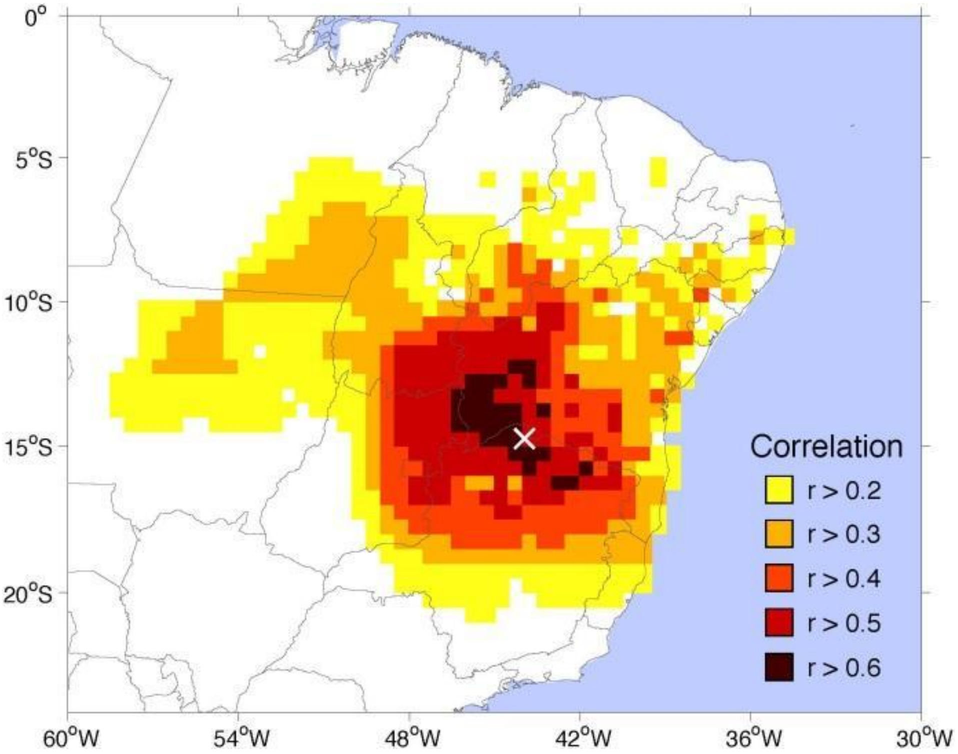

Figure 4. The spatial correlation of the Juvenília standard ring-width chronology (x) with the 0.5° CRU TS3.21 gridded rainfall totals for the wet season (October-March) for the period 1961-2012 is illustrated. Correlations above $r = 0.3$ are significant at $p < 0.05$ and the highest single grid point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

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 approximately 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 due to 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.

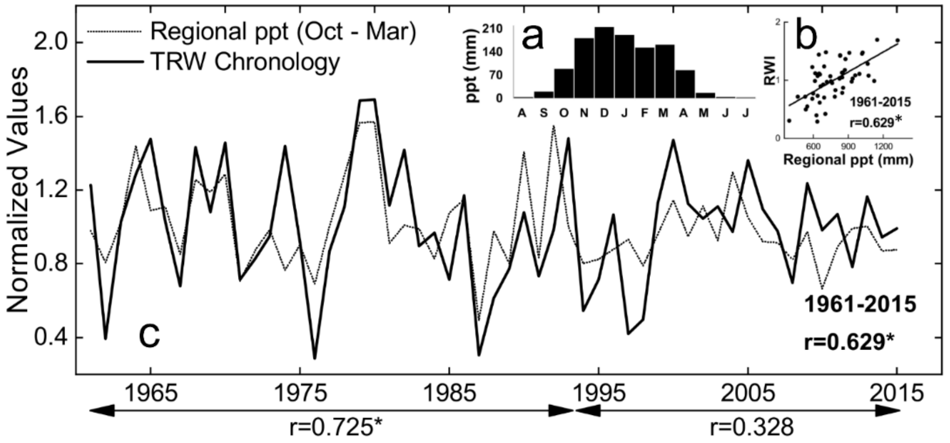

Figure 5. a) The average monthly precipitation for the study area is plotted for 1961-2015 (11-16°S, 42-48°W; CRU TS4.01) along with (b) the scatter plot comparing the chronology and wet season rainfall totals for the period 1961-2015. c) The time series of the Juvenilia chronology is plotted with regional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

However, these analyses are based on the nearest available instrumental rainfall stations closest to the Juvenília site 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).

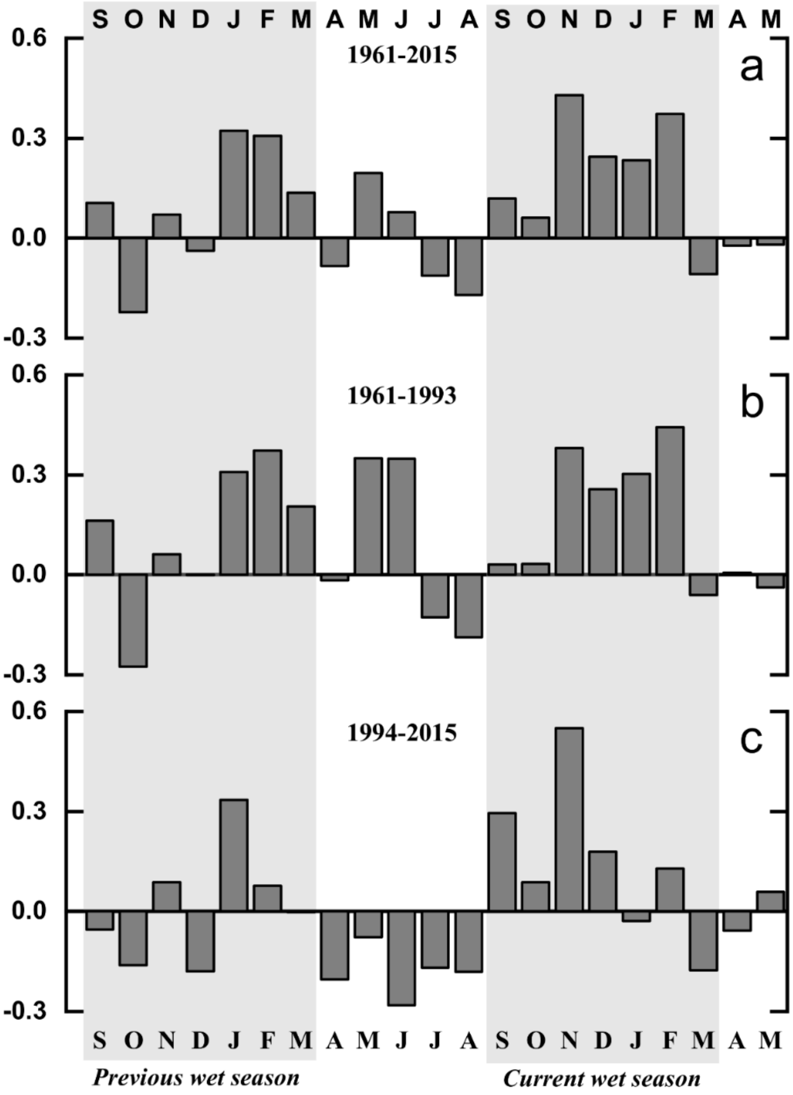

Figure 6. Correlation values between the Juvenilia chronology and monthly precipitation for three time periods (a) = 1961-2015, (b) = 1961-1993, and (c) = 1994-2015. Areas in gray represent the current and previous wet seasons.

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). However, the correlation disapears 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 due to 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 therfore provide useful information on natural flows in both the pre-instrumental period and during the most recent decades of streamflow manipulation.

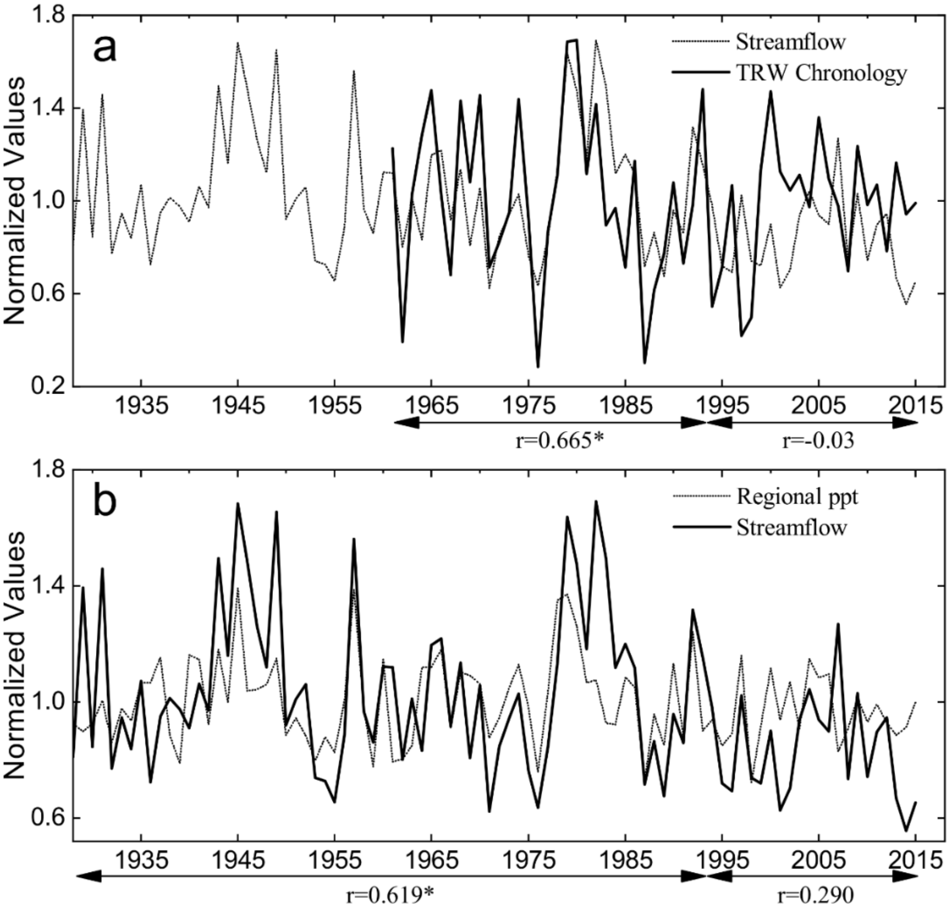

Figure 7. a) The time series of the Juvenilia chronology is plotted with average annual streamflow of the São Francisco River measured in Barra. b) Total annual precipitation for the study area (11-16°S, 42-48°W; CRU TS4.01) is plotted with annual streamflow at Barra from 1928-2015. Note the decline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

4 Discussion and Conclusions

A better understanding of the long-term moisture variability in the Rio São Francisco basin and 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 report on the negative impact of climate change on species growth and studies aimed at understanding these connections are needed, because these forests formations are important in storing carbon (Brienen et al. 2010; Jaramillo et al. 2003; 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.

Acknowledgments

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ARTIGO II - A TREE-RING RECONSTRUCTION OF THE SÃO FRANCISCO RIVER STREAMFLOW IN TROPICAL SOUTH AMERICA

(Artigo a ser submetido no periódico *Journal of Hydrology*)

A Tree-ring Reconstruction of the São Francisco River Streamflow in Tropical South America

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Abstract

The São Francisco River crosses the most drought-prone region of Brazil and regional economic dynamics are dependent on the water availability in the basin. Sensitive tree-ring chronology of *Cedrela fissilis* from seasonally dry forests was used to reconstruct the São Francisco river discharge from 1842 to 2015. The regression model explains 54% of the variance (R^2adj) of pNovember-February São Francisco discharge. Historical droughts of the 19th, 20th and 21st centuries were detected by the reconstruction model. The outflow of the year 2015 was the lowest of the series. The results point to the increase of maximum temperature, irrigated plantations and deforestation of the cerrado (Brazilian Savanna) areas are probable factors that are causing alteration in the water regime in recent years in the basin. This tree-ring reconstruction provides important information on streamflow variability of São Francisco River, where hydrological records are often short and discontinuous.

Keywords: Climate changes, Tropical droughts, Cerrado desforestation, *Cedrela fissilis*.

1 Introduction

The São Francisco River, locally called the National Integration River or just ‘Velho Chico’, that means ‘old Francisco’, has a huge basin that is exclusive to the Brazilian territory and includes seven states. Since the 1960s, the São Francisco river has been increasingly subjected to a series of development projects such as mining activities, deforestation, population supply for urban and rural areas, irrigation and indiscriminate use of agrochemicals for food production, hydroelectric energy production, navigation, fishing and aquaculture, among other activities, compromising water quality and quantity, thus generating a threat to water and biological resources (Codevasf, 2016; Ibama, 2005).

About 16 million people live in the São Francisco basin and many native species depend on these waters. More than 3,000 km^2 of cultivated area are irrigated by the São Francisco River, and six major hydroelectric plants produce about 10,400 MW (Codevasf, 2016). The transposition of its waters is already running and deviates part of the mainstream to supply mainly agriculture and small urban populations from the semiarid dry lands of the ‘Nordeste’ (Ab’sáber, 2006).

The basin is mosaicked by at least three biomes and many ecological units. This diversity of environments, fauna and flora species is unique but is not always considered. The seasonal flooding allows the connection of the main stream with adjacent lagoons, renewing the resources to its fishes (Pompeu and Godinho, 2006). It is known the importance of the environment heterogeneity to fauna and even the reginal heritage on the speleology, archeology and paleontology (Silva et al., 2006). Still, little attention has been given to the Brazilian Northeast environmental questions when compared to Amazonia (Prance, 2006).

The São Francisco basin is subdivided into four physiographic regions, where a big portion (the medium and sub-medium parts) is inside the semi-arid, also called the “Brazilian Drought Polygon”, first delimited in 1946 but many times reshaped (Christofidis, 2017). Several of the driest years are unhappily remembered for the suffering faced by the entire region, many people and animals just starved and reservoirs lowered to almost total (Ab’sáber, 2006, Hastenrath, 2012).

The streamflow is a key aspect to understand the hole basin mechanism because it reflects precipitation and additional factors, including its river heads. Just 19 of its 36 tributaries are perennial in São Francisco Basin, and the main tributaries correspond to almost 46.3% of the total area but contribute to 81% of its flow in the period after the reservoirs implementation (Pereira et al., 2007). But there are almost no long-term record of streamflow in the basin (Pereira et al., 2018), compromising the understanding of its historical behaviour and other key information needed to support planning and management of the basin and to predict future scenarios.

Tree-ring chronologies can be used to reconstruct rivers streamflow but until now just few reconstructions were done in South America (Ferrero et al., 2015, Herrera and Del Valle, 2011, Lopez et al., 2017). Tree rainfall reconstructions were performed in the Amazon Basin (Brienen et al. 2012, Lopez et al. 2017, Granato-Souza et al., 2018) while oxygen isotopes indicate a good possibility to reconstruct precipitation in the Amazon (Baker et al. 2015; Baker et al. 2016).

Once the *Cedrela fissilis* tree species from the São Francisco River Basin has confirmed potential to allow tree-ring studies (Pereira et al., 2018), in this work we aimed to reconstruct the discharge of the São Francisco River to pre-instrumental periods using dendrochronology.

2 Study Area

The São Francisco river basin is located in the northeastern portion of South America and covers an area of 636,437 km² (Figure 1). The main channel has the extension of 2,696 km, between the coordinates 21 ° S and 7 ° S of latitude, it flows through a gradient of humidity (from 1700 mm to 500 mm of mean annual precipitation) and by different type of vegetation (Seasonal Forest Semidecidual, deciduals, savannas (Cerrado) and xeric shurb-lands (Caatinga). In the basin, economic activities are closely linked to water resources, both for electricity generation, irrigated agriculture, urban and industrial supply, navigation and fishing production (Eletrobras, 2005, Maneta et al., 2009) and due to the strong seasonality of rainfall can directly affect these activities.

The interannual rainfall seasonality in the middle San Francisco, study site, is a consequence of the SST (sea surface temperature) variability of the tropical Pacific Ocean and the Atlantic. The anomalies in the SST of these oceans are associated with changes in the circulation of the atmosphere and, consequently, the interannual fluctuations in the precipitation in the region (Marengo, 2011).

3 Data

3.1 Streamflow and Climate Data

The São Francisco River monthly discharge data was obtained from the National Operator of the Brazilian Electric System (ONS). The observation point for this study was in the Sobradinho Reservoir (9° 35'S, 40 ° 50'W, drainage area 498,968km2), the data simulate the natural flow of the river from 1931 to 2015, where the effects of the operation of the reservoirs are removed existing upstream and incorporating the flows related to the net evaporation in the reservoirs and the consumptive uses of the water in the basin (ONS, 2016). The average annual flow rate in Sobradinho is 2,606.2m3.s-1 and the São Francisco River hydrological regime shows a well-defined seasonality, with a mean flow rate of 64% lower in the dry winter months (July-September) compared to the other months of the year (October-June) (Figure 2). This seasonal variation is due to the performance of the Intertropical Convergence Zone (ITCZ), the most important rainfall system in the region (Ferreira and Mello, 2015). Variability which results in strong extremes in flow with the minimum recorded of $226.6m^{3}.s^{-1}$ and maximum of $15,676.0\ m^{3}.s^{-1}$.

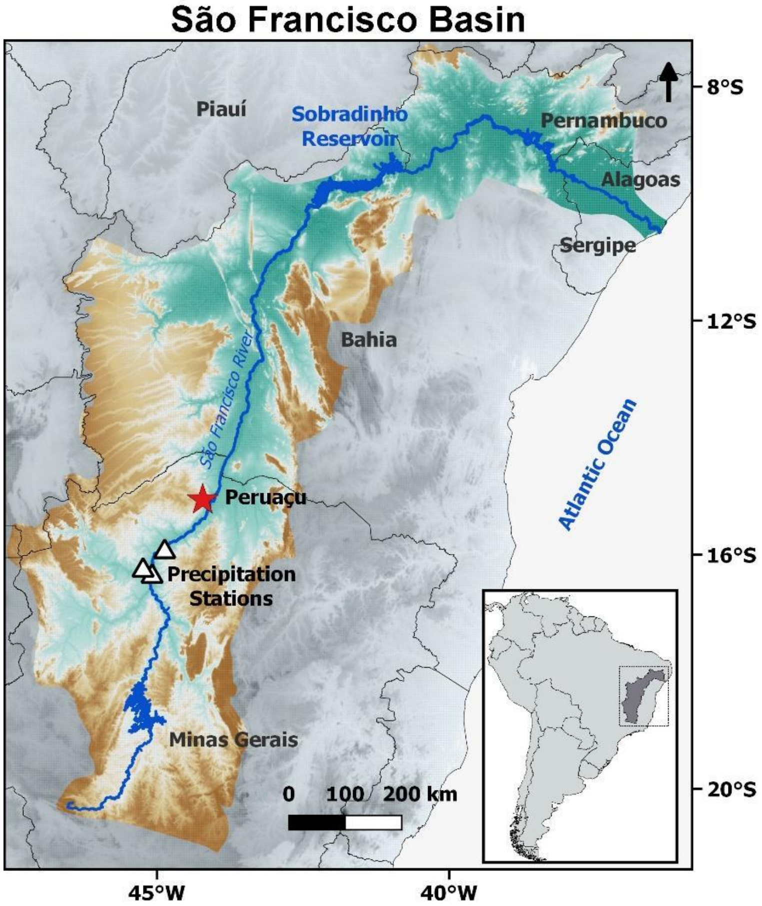

Figure 1. The Peruaçú site (red star) is located in the São Francisco River basin (terrain map). The locations of the precipitation stations are indicated (white symbols) and the river gage is located at Sobradinho Reservoir.

Precipitation data were obtained from stations operated by the National Water Agency, three stations were selected (figure 1), São Francisco, São Romão e Barra do Escuro. The criteria used to choose these stations were because they had at least 60 years of data and did not present gaps (Barra do Escuro station presented missing data only for the years 1995 and 1996). After the selection of these three stations, the average of the monthly precipitation values was made.

The other climatic variables were obtained from the Gridded Climate Research Unit (CRU) (selected region 15-18 ° S, 42-45 ° W) for self-calibrate Palmer Drought Severity Index (scPDSI) (CRU 0.5 ° gridded version 3.25) and Maximum Temperature (CRU 0.5 ° gridded TS 4.01-land).

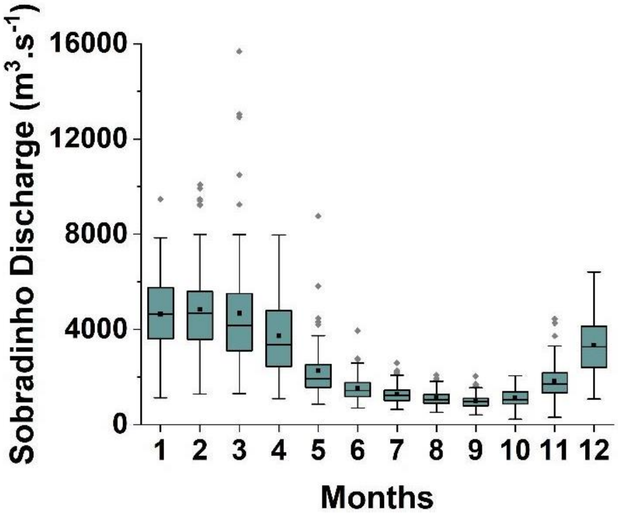

Figure 2. Box-plot diagram showing monthly hydrograph of Sobradinho Reservoir discharge over the period 1931-2015. The diagram represents the range 0.25 - 0.75 percentile (blue box), range with 1.5IQR (vertical line), mean (black symbol), median (horizontal line) and outliers (grey symbols).

3.2 Tree-Ring Data

The chronology was developed with the species *Cedrela fissilis*, which was named Peruaçú Chronology. Samples were collected around the Cavernas do Peruaçú National Park (15°S latitude and 44°W longitude) in the northern state of Minas Gerais. We sampled full cross-sections and cores from 24 living and dead trees. The samples were polished according to standard dedrochronological procedures (Stokes and Smiley, 1968). Then, 53 radii from 24 trees were crossdated using the skeleton-plot technique (Stokes and Smiley, 1968). The width of the dated ring series were measured using the Velmex Tree Ring Measuring System, with 0.001mm precision. We used the program COFECHA (Holmes, 1983) to verify crossdating and measurement accuracy. Ring-width series were detrended and standardized using the ARSTAN computer program (Cook and Krusic, 2005). The raw ring width data were power transformed, and an age-dependent spline was used to remove nonclimatic effects on tree secundary growth and to standardize the mean and variance of each individual ring width time series (Cookand and Peters, 1981, Melvin et al., 2007).

4 Analyses

To verify the relationship between *Cedrela fissilis* growth and the São Francisco river discharge, correlations analysis was calculated using the Peruaçú chronology and Sobradinho monthly streamflow data. Following the methodology suggest by Blasing et al. (1984), several monthly and seasonal combinations were tested, thus allowing to determine the strongest correlation.

The reconstruction of São Francisco river discharge was developed using leave-one-out method of Blasing et al. (1981). Bivariate regression model was developed between the Juvenilia Chronology (predictor) and Sobradinho monthly average streamflow from previous November to current February (predicant). The calibration period was from 1956 to 1998 and two validations periods were used: 1939-1955 and 1999-2012. To evaluate the quality of the fit between observed and predicted discharge values, we used the proportion of variance explained by the regression and the first-order autocorrelation of the residual regression (Durbin-Watson test).

In the validation of the model, we analyzed the Pearson correlation together and the coefficient of efficiency (CE). To estimate the uncertainty of the reconstruction we calculated the root mean square error of validation (RMSEv) (Weisberg, 2005). Singular spectrum analysis (SSA) (Ghil et al., 2002) was performed to identify important frequency components in the 173-yr reconstruction. Subsequently, other reconstructions were done using Peruaçú Chronology as predictor for precipitation, scPDSI and Maximum Temperature. In addition, precipitation, scPDSI and Maximum Temperature as predictors for flow.

We did historical research of the reports in bibliography, newspapers and literary books of the important drought and flood events that devastated the region of the Brazilian drought polygon, in order to validate historically our reconstruction of the flow of the São Francisco River.

5 Results

The Peruaçú Chronology is dated from 1842 to 2012 and the average correlation among all radii (RBAR) is 0.365. For the analyses the residual chronology was used.

The seasonal flow from previous November to February is most highly correlated with the Peruaçú Chronology, the Pearson correlation is 0.57 in the period from 1939 to 2012. The Peruaçú Chronology explained 54% of the variance in the São Francisco River discharge (pNovember – February) measured in Sobradinho gage (Figure 3a). According to Durbin–Watson tests, the residuals of the regression models are not significantly autocorrelated.

We used two validation periods (1939-1955 and 1999-2012), in the 1939-1955 period the model validated well, with positive coefficient of efficiency (CE) and Pearson correlation is 0.54, indicating predictive skill. In the 1999-2012 validation period the Pearson correlation is 0.54, but the CE is negative, indicating difference between the average of the observed and estimated discharge. It is observed in figure 3a that the estimated discharge by the Peruaçú Chronology is overestimated in relation to that observed.

Thus, we evaluated the ability of three more predictors to reconstruct the flow of the São Francisco River, precipitation (pOctober-February), self-calibrate Palmer Drought Severe Index - scPDSI (pDezember-January) and maximum temperature (pOctober-February). The seasons of these variables were defined as having sufficient correlation for the reconstruction of the São Francisco River flow and later predicted by Peruaçú Chronology.

For the three predictors (precipitation, scPDSI and maximum temperature), figures 3b, 3c, 3d, we used the period 1956-1998 for calibration and two periods for verification (1939-1955 and 1999-2012), except for precipitation that had only one verification period because the data from the selected stations start at 1956. The precipitation and scPDSI predictors explained 49% and 52% of the São Francisco River discharge variance, respectively, and the models did not present autocorrelation of the residues by the Darbin-Watson test. When analyzing the 1999-2015 verification period, these two variables presented the same behavior observed in the Peruaçú Chronology, presenting a good correlation, but the CE was negative. For the verification period of 1939-1955, the model with scPDSI as predictor presented skills with Person Correlation equal to 0.81 and CE positive.

Figure 3d shows the period of calibration and validation of the maximum temperature as a predictor, we can see its increase in the region, from 1939 to 2015. This variable in the calibration period (1956-1999) explained 17%

of the variance and had a different behavior in the verification periods, with the Pearson correlation increasing, r = 0.17 (1939-1955) for r = 0.56 (1999-2015) and the CE value was negative in the

first period and positive in the second. Thus, we can verify the increase of the influence of the maximum temperature in the discharge of the São Francisco River.

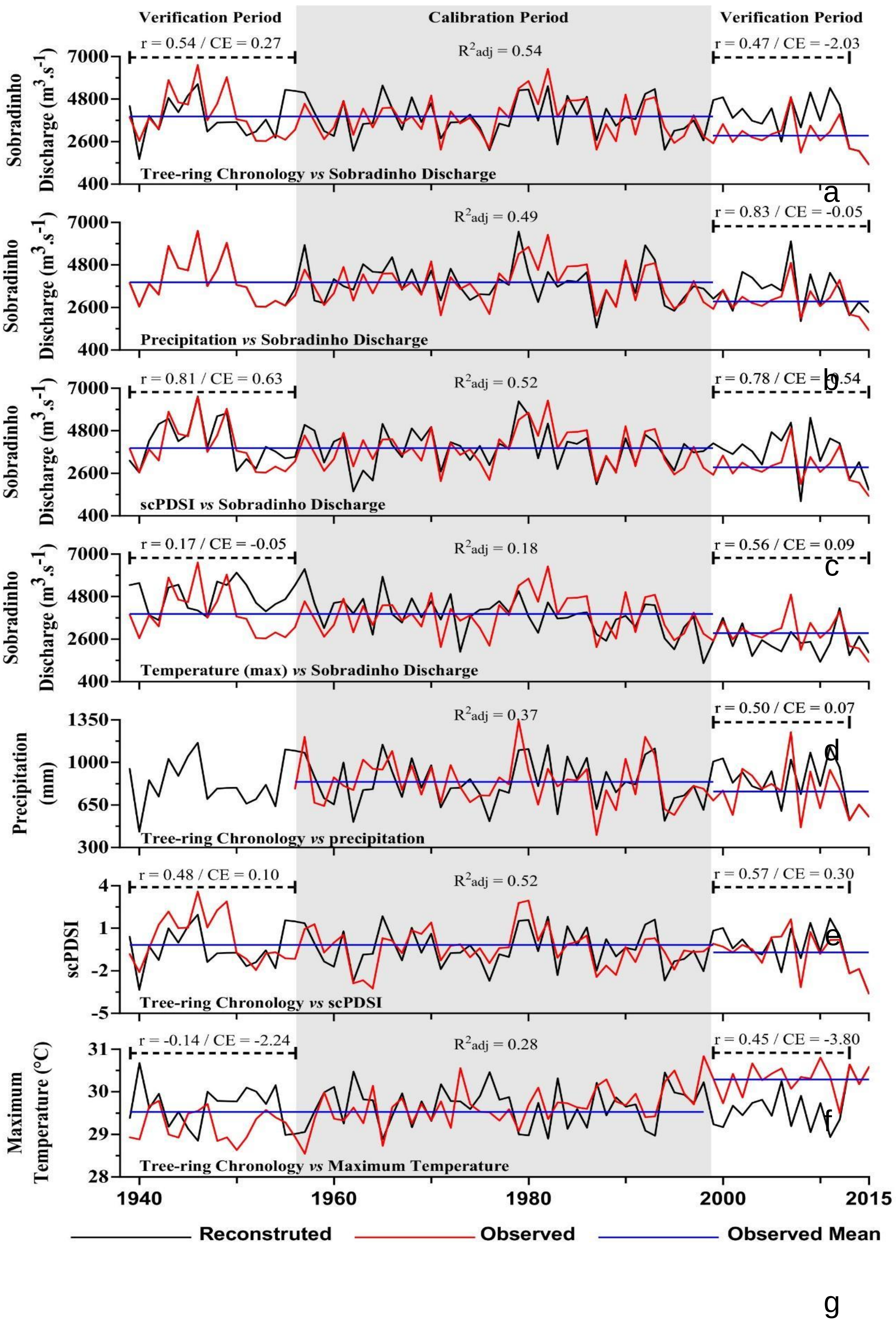
Verification Period
Calibration Period
Verification Period
r = 0.54 / CE = 0.27
R^2_{adj} = 0.54
r = 0.47 / CE = -2.03
Sobradinho Discharge ($m^3.s^{-1}$)
7000
4800
2600
400
Tree-ring Chronology vs Sobradinho Discharge
a
R^2_{adj} = 0.49
r = 0.83 / CE = -0.05
Precipitation vs Sobradinho Discharge
b
r = 0.81 / CE = 0.63
R^2_{adj} = 0.52
r = 0.78 / CE = 0.54
scPDSI vs Sobradinho Discharge
c
r = 0.17 / CE = -0.05
R^2_{adj} = 0.18
r = 0.56 / CE = 0.09
Temperature (max) vs Sobradinho Discharge
d
Precipitation (mm)
1350
1000
650
300
R^2_{adj} = 0.37
r = 0.50 / CE = 0.07
Tree-ring Chronology vs precipitation
e
scPDSI
4
1
-2
-5
r = 0.48 / CE = 0.10
R^2_{adj} = 0.52
r = 0.57 / CE = 0.30
Tree-ring Chronology vs scPDSI
f
Maximum Temperature (°C)
31
30
29
28
r = -0.14 / CE = -2.24
R^2_{adj} = 0.28
r = 0.45 / CE = -3.80
Tree-ring Chronology vs Maximum Temperature
1940
1960
1980
2000
2015
Reconstruted
Observed
Observed Mean
g

Figure 3 Comparison between observed variables (red line) and reconstructed variables (black line). Calibration and verification results are indicated, the 1956-1998 calibration period was used for all reconstructions and two verification periods (1939-1955 and 1999-2015) were used, except in situations with precipitation data (just one validation period 1999-2015) and Tree-ring chronology (validation periods 1939-1955 and 1999-2012). (R^2adj = coefficient of determination adjusted for loss of degrees of freedom; r = Pearson correlation coefficient squared; CE = coefficient of efficiency). The Durbin-Watson test for autocorrelation of residuals is not significant for all calibrations.

We also analyzed Peruaçú Chronology ability to predict precipitation (pOctober-February), self-calibrate Palmer Drought Severe Index - scPDSI (pDezember-January) and Maximum Temperature (p pOctober-February). For the variables precipitation (pOctober-February) and scPDSI (pDezember-January), the Peruaçu Chronology explained 0.37 and 0.52 of their variances, respectively, and the models presented skill in all periods of verification, with positive values of coefficient of efficiency (figures 3e and 3f).

For the maximum temperature, the Peruaçú Chronology did not obtain good indicators as a predictor because CE values were negative in both verification periods, mainly for the period 1999-2012, where the model underestimated the maximum temperature (figure 7g).

The full tree-ring reconstruction is plotted from 1842 to 2015 (Figure 4) and estimates the São Francisco discharge for the past 174 years. The significant decadal waveform was identified in the time series by singular spectrum analysis (SSA) (Figure 4). The worst single year in the entire reconstruction was for 2015. According to the reconstruction, periods of relatively low discharge occurred in 1875–1879, 1912-1915, 1939–1940, 1962-1964, 1976–1978, 1994-1998 and 2013–2015.

In addition, a research was made in newspapers and literary books in order to find reports of important historical droughts in the region of the São Francisco Basin and in the Brazilian drought polygon in pre-instrumental periods, aiming to validate the chronology historically.

The droughts of 1875-1879 and 1915 were reported in classics of the Brazilian literature, in the famous books “Os Sertões” (Cunha, 1902) e “O Quinze” (Queiroz, 1930). The drought of 1875-1879 is known as the "Grande Seca" and triggered the migratory wave of northeasterners to the Amazon region and other regions of Brazil (De Nys, 2016). Estimates indicate that only in the state of Ceará, 500,000 people died (more than 50% of the population at that time) due to the consequences of drought (Smith, 2012). The droughts of 1915 and 1932 reached a huge portion of northeastern Brazil and are known as the "Human Corrals Droughts", because the government-built shelters for the drought flagellates, in order to prevent them from wandering the streets of the capitals cities (Neves et al., 1995; Correio do Amanhã, 1932).

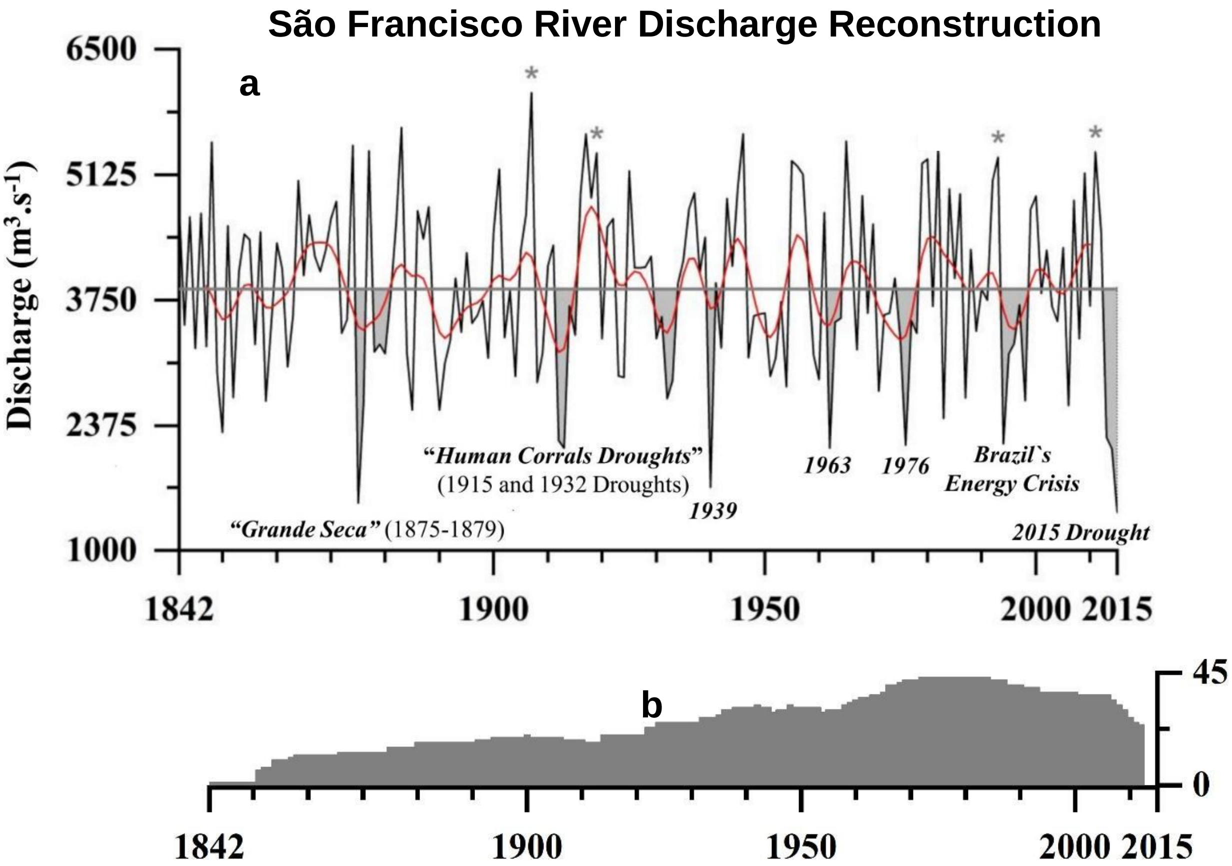

Figure 4. (a) The annual tree-ring reconstructed São Francisco river streamflow (pNovember – February average) is plotted from 1842-2015. The singular spectrum analysis waveforms for decadal component is illustrated by red line. Historical events of droughts are indicated and São Francisco floods events in past documents are represented by the symbol *. **(b)** The number of dated radii available each year from 1842 to 2012 is also plotted. The root mean square error of validation (RMSEv) is 1055.3$m^3.s^{-1}$.

The same research was done for historical floods of the São Francisco River, the largest one recorded in the reconstruction was for the year 1906 and in news of that time they report the phenomenon in the city of Penedo (Alagoas), mouth of the São Francisco River, where there were expropriation of several housing and crops lost (Figura 5) (O Malho, 1906).

Another interesting point to be observed in figure 4 is the set of four successive years of droughts from 1994 to 1998, which culminated with Brazil's energy crisis in 1999 and 2000. Situation generated by the fact that much of the energy generated in the country comes from hydropower plants and the system is sensitive to rainfall variability (Eletrobras, 2015, Maneta et al., 2009)

Figure 5. In the left, Image belonging to the “Secca de 1877-78” collection, depicting the drought of 1877-78 in the state of Ceará (Source: Côrrea, J. A., 1878). In the right, São Francisco flood of 1906 in Penedo – Alagoas. (Source: O Malho, 1906).

6 Discussion and Conclusions

Since the time of colonization, the São Francisco River basin has played an important role for the occupation of the interior of the Brazilian territory. And today with 15 million inhabitants, with an economy strictly dependent on rainfall variations and recurrent drought events, the paleoclimatic data of the region is important to improve the understanding of long trends related to regional climate dynamics.

In this contribution, we developed a pioneer research in Brazil and especially for the "Brazilian Drought Polygon", where we used a moisture sensitive ring-width chronology for river's discharge reconstruction. Our time-series reconstructed 174 years of São Francisco river discharge from previous November to February, precisely in the rainy season and period of more variability in the discharge (Maneta et al., 2009).

The use of composite chronologies is desirable for climate reconstructions, because improves the quality of the records and facilitates the capture of common climatic signals at a regional spatial scale (Ferrero et al., 2015, Villalba et al., 2012). Our reconstruction was based on a single chronology, the "Peruaçú Chronology", that explains 54% of the variance of the discharge of the São Francisco River in the Sobradinho gauge. This result is similar to river's reconstructions in South America (Ferrero et al., 2015; Lara and Villalba, 2008, Herrera and Del Valle, 2011).

In the 1999-2012 verification period of the model for the reconstruction of São Francisco River Discharge (predicant) using the Peruaçú Chronology (predictor), the equation overestimated the discharge rate. The same behavior was observed using precipitation and scPDSI as predictors. This situation indicates that other factors are influencing the São Francisco river discharge, which is falling below what is estimated by the models. Two probable factors occurring in the basin may be altering the water regime, the increase of temperature and the alteration of the soil cover.

When using the predicted maximum temperature, it is observed the increase of its influence in the estimation of the discharge over the time. The estimated flow correlation with that observed in the 1939-1955 verification period is 0.17 and increased to 0.56 in the 1999-2015 validation period. According to Marengo (2012), annual average temperature of the São Francisco basin has been increasing in recent years and by the end of the century can rise by at least 3.8 ° C. The increasing temperature, regardless of precipitation, would be enough to cause greater evaporation of the lakes, dams, reservoirs and increased evapotranspiration of plants (Marengo, 2011).

In addition to this factor, the increase of irrigated areas and the change of the soil cover in the basin, when replacing the native vegetation with crops and pasture could potentially alter the regional hydrology (Maneta et al., 2009, Oliveira et al., 2005; Silva et al., 2006). The main areas of recharge of the basin are in the cerrado domain (Brazilian savanna), this type of vegetation is known as "upside down forest", due to its characteristic deep root system that pumps deep table water to the atmosphere contributing significantly to the water balance of the ecosystem. The agriculture land-use of the cerrado is a relatively recent, with more than 50% of the native vegetation removed during the last 40 years (Klink and Moreira, 2002, Oliveira et al., 2005).

The Peruacú Chronology was sensitive in capturing drought events, which reflected in the flow of the São Francisco River. In the region, drought events are mainly related to the events of El Niño Southern Oscillation (ENSO) (Marengo, 2011). In our reconstruction we can identify key years of low river discharge of the São Francisco, coinciding with El Niño years: 1875-1879 ("Grande Seca"), 1915 and 1932 ("Humam Corrals Droughts"), 1994-1998 ("Brazil's Energy Crisis"), and 2014-2015 ("2015 Drought"). Atmospheric and oceanic circulation of the Tropical Atlantic also plays a key role in climate variability in the semi-arid region (Hastenrath, 1984, Giannini et al., 2004). Thus, some dry or wet years in the Brazilian Northeast do not depend on the phases of the ENSO and are more linked to the actions of the Tropical Atlantic. An El Niño year can be rainy and a La Niña year can be dry (Kayano and Andreoli, 2006), as examples the years of 1963 and 1976, both years of drought in the reconstruction during La Niña years.

A strong El Nino event occurred in the late 1870s and generate the so-called "Grande Seca" (1875-1879 Drought) in northeast of Brazil. This event was contemporaneous with prolonged droughts in India, China, Egypt, Morocco, Ethiopia, Southern Africa, Colombia, and Venezuela (1875-1878), which became known as the "Global Famine" (Davis 2001; Singh et al. 2018). It is estimated that around 50 million people died in these regions, only in Brazil it is estimated that the number of fatalities reached 2 million (Davis, 2001). It was the most severe global hunger crisis in the last 150 years (Hasell and Roser, 2017; Singh et al., 2018). This humanitarian disaster was a combination of climatic events on Tropical Pacific, Indian Ocean and North Atlantic (Singh et al., 2018).

The lowest flow observed in our series was 2015 (2015 Drought), which was the result of a series of dry years since 2012, culminating in a strong El Nino event in 2015 (L'Heureux, 2016). During this period, the reservoirs in the São Francisco River reached critical levels, compromising the generation of electric energy and several municipalities passed through water shortages for human supply (De Nys, 2016).

It's notorious the recurrence of droughts in the São Francisco River basin and our reconstruction was robust to show these events. Knowledge of past events of high and low flows are important for the management of water resources. The flow database used for the hydroelectric planning in the basin goes until the 1930s, our time series with annual resolution doubled the perception about the hydrological variability of the São Francisco River until the mid-nineteenth century. The use of tree-ring chronologies has enormous potential for hydrological studies in the São Francisco River Basin, the Peruaçú Chronology is just a first step for the construction of a network of chronologies to be used in the knowledge of the paleoclimate of the third largest basin of Brazil.

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