



DANIELA GRANATO DE SOUZA

**CLIMATE SIGNALS AND RAINFALL RECONSTRUCTION
USING *CEDRELA* TREE-RING CHRONOLOGIES FROM THE
EASTERN AMAZON BASIN**

LAVRAS – MG

2018

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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 ecologia, para a obtenção do título de doutora.

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LAVRAS – MG

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À Deus por sempre se fazer presente em minha vida, iluminando meu caminho, me dando forças pra sempre persistir.

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RESUMO GERAL.

Compreender a complexidade de um dos maiores centros convectivos do mundo, a bacia Amazônica, é um desafio diante de tantas evidências acerca do aumento dos eventos extremos hidroclimáticos nas últimas décadas. Além da megadiversidade da flora e fauna, a Amazônia possui papel significativo na circulação atmosférica e no balanço energético global. Entretanto, a escassez de dados hidroclimáticos instrumentais de longo prazo impede a verificação dessa tendência. Nesse sentido, o resgate de informações climáticas através dos estudos dos anéis de crescimento de árvores, ciência conhecida como dendroclimatologia, tem-se mostrado uma boa ferramenta para reconstruções climáticas. Este trabalho faz parte de um projeto de colaboração internacional entre a Universidade Federal de Lavras (UFLA), University of Arkansas (UARK), Instituto Nacional de Pesquisas da Amazônia (INPA) e Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales (IANIGLA-CONICET), que visa o estudo do clima passado pelo registro das árvores na Bacia Amazônica. Aproximadamente 519 árvores foram amostradas na porção oriental da bacia, por meio de acordos de colaboração com empresas florestais. As espécies-alvo foram os Cedros (*Cedrela fissilis* e *Cedrela odorata*) as quais apresentam comprovado potencial dendroclimatológico nos neotrópicos, como a presença de anéis de crescimento distintos e alta sensibilidade à variabilidade hídrica. O primeiro capítulo apresenta a primeira reconstrução de chuvas para a Amazônia equatorial a partir de uma cronologia de cedros bem datados da Floresta Estadual do Paru, localizada na calha norte do rio Amazonas. O segundo capítulo foca nos esforços para o desenvolvimento de uma rede de novas cronologias de anéis de crescimento de diferentes sítios na Amazônia oriental com a validação da datação e das relações crescimento/clima obtidas pela primeira cronologia. Os dados aqui apresentados trazem novas contribuições acerca da variabilidade hidrológica na porção leste da bacia que pré-datam os dados instrumentais existentes. Frequências interanuais a subdecadais predominam ao longo de toda a extensão de dados reconstruídos (1786-2016), entretanto episódios extremos anteriores às alterações antropogênicas foram identificados pelos anéis de crescimento. As resultantes cronologias expressam as influências das temperaturas da superfície dos mares Atlântico e principalmente Pacífico equatorial na variabilidade de chuvas na Amazônia oriental. Esses resultados mostram que a rede de cronologias de *Cedrela* possui grande potencial para reconstruir a variabilidade hídrica na Amazônia oriental, fornecendo uma perspectiva de longo prazo sobre a ocorrência dos extremos hidroclimáticos e os futuros prognósticos sobre o que se pode esperar desta variabilidade diante do atual cenário de alterações antropogênicas locais e globais.

Palavras-chave: Dendrocronologia tropical, Floresta amazônica, *Cedrela* sp., Reconstrução climática, Sea Surface Temperature, Rede de cronologias.

GENERAL ABSTRACT

Understanding the complexity of one of the world's largest convective centers, the Amazon basin, is a challenge given recent reports regarding the increase of extreme moist and dry events in the last decades. In addition to the mega-diversity of flora and fauna, the Amazon has a significant role in atmospheric circulation and in the global energy balance. However, the lack of long-term instrumental hydroclimatic data prevents this trend from being verified. In this sense, climate information derived from tree-ring analyses, a science known as dendroclimatology, has proved to be a good tool for climate reconstruction. This work is part of an international collaboration project between the Federal University of Lavras (UFPA), the University of Arkansas (UARK), the National Institute of Amazonian Research (INPA) and the Argentinean Institute of Nivology, Glaciology and Environmental Sciences (IANIGLA-CONICET), which aims to apply tree-rings to study the past climate in the Amazon Basin. Wood samples from 519 trees were collected in the eastern portion of the basin thanks to collaboration agreements with legal logging companies. The target species were the Cedros (*Cedrela fissilis* and *Cedrela odorata*), which have proven dendroclimatic potential in the Neotropics due to the presence of distinct annual growth rings and mid-high sensitivity to moisture variability. The first chapter presents the first rainfall reconstruction for the equatorial Amazon using a tree-ring chronology built from well-dated *Cedrela* ring-width time-series from the Paru State Forest, located on the north bank of the Amazon River. The second chapter focuses on the efforts to develop a network of new tree-ring chronologies from different sites in the eastern Amazon with the validation of dating and climate/growth relationships obtained by the first chronology. The data presented here bring new contributions about the hydrological variability in the eastern portion of the basin that predates the existing instrumental data. Interannual and subdecadal frequencies dominate over the entire length of reconstructed data (1786-2016), although extreme episodes prior to anthropogenic changes were identified by growth rings. The resulting chronologies express the influences of the sea surface temperatures of the Atlantic and specially equatorial Pacific on rainfall variability over the eastern Amazon. These results show the potential of a *Cedrela* network of chronologies to reconstruct water variability in the eastern Amazon, providing a long-term perspective on the occurrence of hydroclimatic extremes and future predictions of what can be expected from this variability in the current scenario of local and global anthropogenic changes.

Key words: Tropical dendrochronology, Amazon Forest, *Cedrela* sp., Climatic reconstruction, Sea Surface Temperature, Network of chronologies.

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1. INTRODUÇÃO GERAL

A bacia Amazônica, a maior bacia fluvial do mundo, constitui um complexo sistema hidrofluvial desempenhando importante papel na circulação atmosférica e no balanço energético global (WANG e FU, 2007; HILKER et al., 2014). A sua grande extensão em área, cerca de 7 milhões de km², compreende uma complexa rede de comunicação, descarga fluvial e precipitação, atuando não somente na própria bacia, mas também na formação dos chamados “rios voadores” que se formam pela intensa evapotranspiração da floresta úmida, devolvendo para a atmosfera volumes diários de água semelhantes à vazão diária do grandioso rio Amazonas (NEWELL et al., 1992, NOBRE, 2014).

Mudanças nas temperaturas de superfície dos mares Pacífico e Atlântico (TSMs) combinados a fatores locais como condições de superfície terrestre e transporte de vapor d’água controlam a variabilidade hidroclimática na bacia Amazônica levando a formação periódica de episódios extremos de secas e cheias (VERA et al., 2006; MARENGO e ESPINOZA, 2016). Estas variações são comuns nos trópicos, e pré-datam os registros meteorológicos instrumentais (BUSCH et al., 2008). Entretanto, estudos recentes vem levantando hipóteses sobre um aumento na frequência e intensidade destes episódios em consequência de desmatamentos e mudanças climáticas globais colocando em questão até mesmo a sobrevivência da própria floresta e conseqüentemente todas as complexas interações ligadas à bacia Amazônica (GLOOR et al., 2013; MARENGO e ESPINOZA, 2016).

Por outro lado, a escassez de registros climáticos instrumentais de boa qualidade ou ininterruptos por longos períodos de tempo impedem a compreensão da variação natural dos ciclos hidrológicos, sendo que atualmente menos de 10 estações meteorológicas contribuem com longas extensões de dados (acima de 80 anos) em toda a extensão da bacia Amazônica (GRANATO-SOUZA et al., 2018). Isso aliado à complexa heterogeneidade pluviométrica espacial sobre a região Norte do Brasil dificulta a contextualização dos atuais eventos climáticos extremos diante dos ciclos passados persistindo a dúvida se as mudanças recentes são de fato sem precedentes.

O resgate de registros paleoclimáticos, por sua vez, vem se mostrando cada vez mais necessário pois permite o estudo aprofundado dos processos atmosféricos-ocêânicos que regulam a distribuição espacial e temporal de chuvas sobre a região onde os dados instrumentais são escassos. A construção de redes de cronologias de anéis de crescimento de árvores longevas e bem datadas já vem sendo muito utilizada em regiões de médias latitudes (COOK et al., 2010; STAHLER et al., 2016) e proporcionam a compreensão dos principais

fenômenos envolvidos na ocorrência de eventos extremos nos últimos séculos. Os dados dendrocronológicos, permitem a reconstrução do clima em períodos pré-instrumentais, fornecendo novas perspectivas acerca das discussões climáticas. Possibilitam ainda a validação das previsões de alterações climáticas futuras principalmente devido às mudanças regionais e globais.

1.2 O presente estudo

Este trabalho é parte de um projeto de colaboração internacional entre a Universidade Federal de Lavras (UFLA), University of Arkansas (UARK), Instituto Nacional de Pesquisas da Amazônia (INPA) e Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales (IANIGLA-CONICET), que visa o estudo do clima passado pelo registro das árvores da Bacia Amazônica (NSF 13-576): AMAZONIAN TREE-RING CHRONOLOGIES FOR CLIMATE AND STREAMFLOW RECONSTRUCTION.

Este estudo objetivou a construção de uma rede pioneira de cronologias de anéis de crescimento provenientes de diferentes sítios da Amazônia oriental, confiáveis estatisticamente, e com comprimento suficiente para estender os dados instrumentais preexistentes, de forma a suprir a demanda apresentada. Nesse sentido, os objetivos específicos foram:

- (i) Construção de cronologia(s) de anéis de crescimento de *Cedrela odorata* na porção oriental da bacia Amazônica;
- (ii) Identificação da correlação crescimento-clima para detectar os sinais climáticos contidos nos anéis de crescimento;
- (iii) Reconstrução da variabilidade hidroclimática na Amazônia equatorial na era pré-instrumental;
- (iv) Geração de registros históricos da variabilidade de chuvas da Amazônia oriental a partir dos anéis de crescimento de *Cedrela odorata*.

2. REVISÃO DE LITERATURA

2.1 Principais forçantes climáticas na bacia Amazônica

A região Norte do Brasil caracteriza-se pela ocorrência de marcada heterogeneidade espacial pluviométrica, concentrando seus maiores índices de pluviosidade nas porções ocidental, central e sul da bacia Amazônica (FIGUEIROA e NOBRE, 1990; MARENGO, 2003). Isso ocorre devido à sua grande extensão geográfica, que a torna suscetível a diferentes forçantes climáticas regionais e externas à bacia. Dessa forma, as chuvas da Amazônia estão associadas tanto à intensa atividade convectiva proveniente do Atlântico quanto à precipitação causada pelo aquecimento radioativo da superfície, sendo que a umidade gerada é transportada pelos ventos alísios para dentro da bacia, sendo constantemente renovada para atmosfera através da evapotranspiração de sua floresta úmida, até encontrar os Andes (NOBRE et al., 1991, DA ROCHA et al., 2009). As nuvens formadas pelo aquecimento radioativo da superfície apresentam máximo desenvolvimento ao longo do dia, sendo mais frequentes no verão austral, caracterizando o período de maiores índices pluviométricos ao longo da bacia Amazônica (SALIO et al., 2007).

Outro sistema convectivo que exerce papel fundamental no desenvolvimento e entrada de umidade na bacia Amazônica é a Zona de Convergência Intertropical (ZCIT) que se forma no oceano Atlântico (MARENGO e HASTENRATH, 1993), que se caracteriza por ser uma região de convergência dos ventos alísios de sudeste (vindos do Hemisfério Sul) e os alísios de Nordeste (vindos do Hemisfério Norte), que devido às altas temperaturas e condições de baixa pressão nos trópicos, apresenta intensa atividade convectiva. Esta proporciona a entrada e direcionamento de linhas de instabilidade, fazendo com que essa umidade adentre o continente para oeste, percorrendo a bacia amazônica em toda a sua extensão (KOUSKY, 1980; COHEN et al., 1989; COHEN et al., 1995).

A ZCIT apresenta deslocamento sazonal conforme a temperatura da superfície do oceano Atlântico, alcançando sua posição mais austral ao longo dos meses de fevereiro a abril (verão e outono no Hemisfério Sul) e boreal ao longo dos meses de junho a agosto (inverno no Hemisfério Sul) (HASTENRATH, 1991). A ZCIT é o mais importante sistema convectivo de entrada de umidade para a porção oriental norte da bacia Amazônica (REBOITA et al., 2010). Devido ao movimento de deslocamento sazonal da ZCIT, esta região apresenta os maiores índices pluviométricos no primeiro semestre do ano, sendo maio o mês mais chuvoso. Esse diferenciado regime de chuvas ocorre devido a um atraso na resposta das temperaturas do Atlântico em resposta ao aquecimento solar (demora do aquecimento das águas devido à

capacidade calorífica das águas oceânicas) que faz com que a ZCIT continue se movendo ao sul entre os meses de fevereiro a abril (verão e outono) e portanto ocasionando chuvas intensas nesta porção da bacia enquanto o resto do continente já apresenta redução dos seus níveis (LIEBMANN e MECHOSO, 2010).

Torralba et al. (2015) verificaram que o principal modo regulador das chuvas na porção norte/nordeste da América do Sul e a posição da ZCIT estão associados ao gradiente inter-hemisférico das temperaturas da superfície dos mares Atlântico e Pacífico tropical. Estudos vem reportando as influências das anomalias das TSM dos oceanos Pacífico e Atlântico desde o início do século XX, período no qual se iniciam os registros instrumentais hidrológicos (WANG e FU, 2007; MARENGO e ESPINOZA, 2016). Eventos como El Niño/La Niña atuam reduzindo/intensificando as chuvas na bacia, causando impactos neste rico e complexo ecossistema (HILKER et al., 2014; BACCINI et al., 2017).

Além disso, sabe-se as TSMs do Atlântico possuem papel fundamental na regulação do posicionamento da ZCIT, sendo que o seu dipolo definirá o tempo de permanência austral desta zona convectiva influenciando diretamente na quantidade de umidade que entra na bacia Amazônica (MARENGO e ESPINOZA, 2016). Estudos tem demonstrado as influências diretas das TSMs do Pacífico e Atlântico nas chuvas na bacia Amazônica, atuando tanto isoladamente como através do estabelecimento de teleconexões. Entretanto, a escassez de longas séries de dados instrumentais impede o total esclarecimento destas complexas interações, tornando necessário o resgate de registros históricos através de ferramentas paleoclimáticas.

2.2 Dados climáticos instrumentais na Amazônia

A floresta Amazônica apresenta grande biodiversidade terrestre, estimando-se cerca de 16.000 espécies de árvores nativas em florestas de terras baixas, porém somente 4.000 descritas taxonomicamente (ter STEEGE et al., 2013). Compreendendo cerca de 40% de todas as florestas tropicais do mundo (HUBBELL et al., 2008), estima-se que a floresta Amazônica seja responsável por 14% da produção primária líquida global (ZHAO e RUNNING, 2010). Entretanto a produtividade destas florestas varia ano a ano, principalmente devido à variabilidade de chuvas (MARENGO, 2004). Em anos de secas extremas, tem sido verificada elevada perda de biomassa, como reportado para os anos de 2005 e 2010 (BRIENEN et al., 2015), comprometendo a quantidade de carbono sequestrado pelas florestas amazônicas e acarretando em alterações no balanço energético regional e global (HILKER et al., 2014; BACCINI et al., 2017).

As simulações climáticas de Modelos Globais do CMIP5 (Coupled Model Intercomparison Project Phase 5) estimam um declínio nos índices de precipitação anual sobre a Amazônia para o próximo século, devido, principalmente, a alterações no balanço energético global de origem antropogênica, e às alterações da paisagem em consequência dos desmatamentos ilegais reduzindo a reciclagem de água para a atmosfera e afetando o ciclo hidrológico (FENG e FU, 2013). De fato, Marengo et al. (2011) já relataram uma tendência ao aumento de eventos de secas extremas na parte sul da bacia Amazônica, assim como o aumento do comprimento do período seco em quase um mês para a mesma região a partir de 1970, podendo comprometer irreversivelmente o equilíbrio dessas florestas úmidas.

A variabilidade climática nos trópicos é uma condição normal, que oscila sob diferentes padrões, ocorrendo regimes de altas (anuais e interanuais) e baixas frequências (multi-anuais, decadais e centenais) (MARENGO e ESPINOZA, 2016). Entretanto, estudos recentes têm demonstrado a amplificação dos ciclos hidrológicos ao longo da bacia Amazônica, tornando mais drásticos os eventos de secas e de cheias (MARENGO e ESPINOZA, 2016; LOPEZ et al., 2017). Esses extremos climáticos produzem efeitos desastrosos tanto para a biodiversidade (flora e fauna) nativa, quanto para a população residente, causando notáveis impactos socioeconômicos.

A escassez de registros climáticos instrumentais é realidade para a bacia Amazônica como um todo, sendo que poucas estações meteorológicas possuem dados anteriores a 1930, e somente duas, localizadas em Manaus e Rio Branco, possuem dados que datam do início do século 20. Outro problema a ser considerado é a quantidade de falhas e interrupções na sequência dos dados, o que prejudica bastante a sua utilização para análises climáticas. Grande parte das estações meteorológicas existentes na bacia Amazônica apresenta ao menos 50 anos de dados, mas ainda assim com falhas de pelo menos 10% de dados faltantes (MARENGO, 2004). Entretanto pode-se considerar mínima a área de cobertura desses dados, o que inviabiliza a sua extrapolação para o desenvolvimento de estudos climáticos ao longo de toda a extensão da bacia Amazônica. Importante ressaltar que nenhuma das estações meteorológicas com série longa de observações estão localizadas na Amazônia oriental, evidenciando a necessidade do desenvolvimento de reconstruções climáticas para essa região.

2.3 Potencial da dendrocronologia para estudos climáticos na Amazônia

Os estudos dendrocronológicos na Amazônia tiveram início há mais de 20 anos abordando principalmente a identificação de espécies com anéis de crescimento visíveis (SCHÖNGART et al., 2010; PAROLIN e WORBES, 2000; SCHÖNGART et al., 2017). Hoje

estima-se que cerca de 220 espécies possuam anéis de crescimento de formação anual em florestas neotropicais (SCHÖNGART et al., 2005; SCHÖNGART et al., 2010), sendo que na Amazônia os estudos aplicados estão concentrados na região Central (DÜNISCH et al., 2003; SCHÖNGART, 2008; SCHÖNGART et al., 2010) e porção sul da bacia (LOPEZ et al., 2017; ROSA et al., 2017).

O desenvolvimento de longas cronologias de anéis de crescimento de árvores nas florestas bem preservadas da bacia Amazônica e que possuam exemplares de espécies longevas e com potencial dendrocronológico é uma valiosa ferramenta para a extensão dos dados instrumentais que datam apenas da metade do século 20. Assim será possível a investigação das influências a longo prazo dos principais moduladores do clima na região (forçantes oceânico-atmosféricas), possibilitando a verificação da real existência de aumento das tendências dos extremos hidroclimáticos na bacia Amazônica. Apesar da comprovação do potencial de aplicação da dendrocronologia em florestas tropicais (STAHLE et al., 1999; DÜNISCH et al., 2002; SCHÖNGART et al., 2002, 2005; LOPEZ e VILLALBA, 2011), muitas espécies não apresentam crescimento anual que é registrado em camadas de crescimento distintas (BRÄUNING et al., 2009; LOPEZ e VILLALBA, 2011).

A complexidade existente nos ecossistemas tropicais (interações ecológicas, competição por luz e nutrientes, etc), bem como a ausência de sazonalidade climática acentuada faz com que muitas espécies tropicais não apresentem sincronismo no seu crescimento, característica básica necessária ao desenvolvimento de estudos dendroclimáticos (SPEER, 2010). Além disso, a anatomia dos anéis de crescimento da grande diversidade de espécies tropicais nativas aliada às condições ecológicas de sítio propicia a formação de defeitos e anomalias que prejudicam a identificação dos seus limites (flutuações de densidade e formação de canais de resina produzindo falsos anéis, anéis casados, micro-anéis, etc) (DÜNISCH et al., 2002; LOPEZ e VILLALBA, 2016).

Estes fatores mostram que, em muitos casos, amostras obtidas com a utilização de trados de incremento podem ser insuficientes para a construção das primeiras cronologias regionais, corretamente datadas e temporalmente extensas, tornando necessária a obtenção de amostras com grande área de observação, tais como discos completos e parciais dos troncos das árvores (STAHLE et al., 1999). Entretanto recentes esforços tem sido identificados na busca de amostras de espécies tropicais que atendam às necessidades dendrocronológicas, e no desenvolvimento de cronologias corretamente datadas ao longo da bacia Amazônica (SCHÖNGART et al., 2005; LOPEZ e VILLALBA, 2011; SCHÖNGART et al., 2015; LOPEZ et al., 2017).

As cronologias de anéis de crescimento corretamente datadas são, portanto, essenciais para os estudos climáticos. Uma vez desenvolvidas, podem ser utilizadas para outras aplicações dendrocronológicas, como estudos ecológicos e de dinâmica florestal (BRIENEN e ZUIDEMA, 2006; SCHÖNGART, 2010; ROSA et al., 2017), de produção florestal e modelagem da biomassa (CINTRA et al., 2013), modelagem de crescimento para suporte ao manejo sustentável de espécies nativas (SCHÖNGART, 2008; MIRANDA et al., 2018; ROSA et al., 2017) e ainda a investigação das tendências de crescimento diante das atuais alterações no ciclo global de carbono (SCHÖNGART et al., 2011; GROENENDIJK et al., 2015) as quais contribuem enormemente para a compreensão da futura distribuição e manutenção da biodiversidade nos trópicos.

Os laboratórios de dendrocronologia tem de lidar com dificuldades como a falta de recursos humanos que tenham disponibilidade de permanecer longos períodos em campo, a escassez de recursos financeiros para a realização das viagens, coletas de campo e o transporte desse material ao laboratório de origem, e ainda a dificuldade em acessar áreas remotas e bem preservadas em meio à complexa floresta Amazônica. E ainda, a falta de compartilhamento dos dados de cronologias brasileiras na plataforma internacional de paleoclima do NOAA impede o acesso dos registros climáticos nos anéis de crescimento de cronologias desenvolvidas nos trópicos (Figura 1). Nesse sentido se faz cada vez mais necessária a intensificação dos estudos dendrocronológicos que busquem desenvolver cronologias centenárias de anéis de crescimento com sensibilidade climática suficiente para gerar reconstruções climáticas confiáveis.

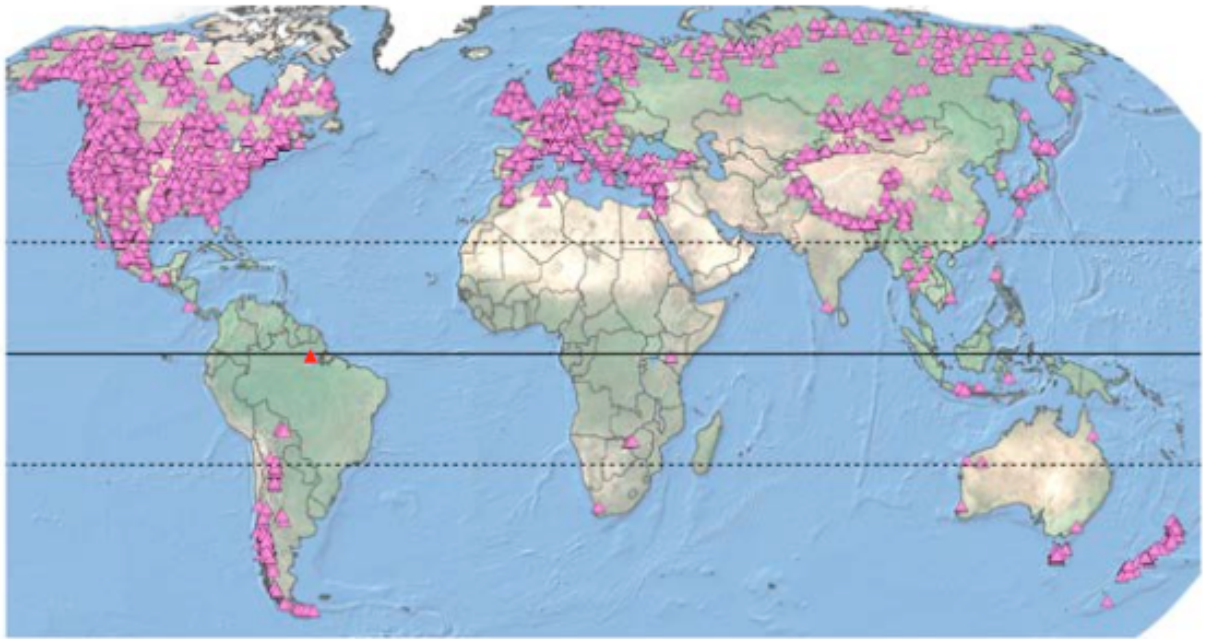


Figura 1. Todas as cronologias de anéis de crescimento disponíveis na base de dados internacional do NOAA (*International Tree-Ring Database*) estão identificadas (triângulos). A primeira cronologia da Amazônia equatorial foi desenvolvida durante a execução deste estudo (triângulo vermelho).

2.4 Amostragens oportunistas e o potencial da *Cedrela* sp. para estudos dendrocronológicos na Amazônia

Uma das maiores dificuldades em se estudar e desenvolver estudos em dendrocronologia de florestas tropicais é a obtenção de amostras apropriadas para a completa visualização dos anéis de crescimento. Estudos prévios já documentaram a ocorrência de problemas anatômicos na formação dos anéis de crescimento em espécies provenientes de ambientes tropicais (anéis falsos, casados, ausentes, canais de resina) (DÜNISCH et al., 2002; LOPEZ e VILLALBA, 2016) que prejudicam ou impedem o processo de co-datação das amostras tanto dentro de uma mesma árvore, quanto entre árvores diferentes. Nesse caso, estudos dendrocronológicos já comprovaram a efetividade da amostragem de discos completos ou de secções radiais, que permitem a ampliação do campo de visão para a análise dos anéis de crescimento destas espécies (STAHLE et al., 1999).

Nesse sentido, os projetos de concessão de florestas públicas que vem se desenvolvendo no estado do Pará, região considerada nordeste da Bacia Amazônica, viabilizam aos concessionários a exploração comercial de espécies nativas desde que submetidas a um plano de manejo florestal sustentável (LEI 11.284/2006). Estas áreas possibilitam a obtenção de amostras destrutivas de espécies comerciais e que sejam promissoras para a dendrocronologia. As amostras destrutivas podem ser obtidas durante as

operações de derrubada, diretamente dos pátios das empresas florestais onde as toras são estocadas após a derrubada das árvores selecionadas, ou também pode ser feito um resgate na floresta após o manejo visitando os tocos e remanescentes deixados na floresta. A amostragem destrutiva permite a obtenção de amostras de secções transversais completas (discos, bolachas) e parciais, que são ideais para os estudos dos anéis. Para árvores que não serão derrubadas, pode-se fazer a retirada de amostras radiais sem comprometer muito a árvore. Esse procedimento deve ser realizado apenas mediante autorização ambiental.

As espécies *Cedrela fissilis* e *C. odorata* (Meliaceae) ocorrem naturalmente nas florestas amazônicas orientais, sendo consideradas espécies-modelo para estudos dendrocronológicos por apresentarem anéis de crescimento anatomicamente distintos, e na maioria dos casos de formação anual (DÜNISCH et al., 2002; BRIENEN et al., 2012). Essa periodicidade anual é devida ao seu sistema radicular superficial, o que aumenta sua sensibilidade climática de crescimento radial à precipitação e níveis de umidade do solo (KUNERT et al., 2010; BRIENEN et al., 2012; SCHWENDENMANN et al., 2015). Portanto, a formação dos anéis de crescimento destas espécies está diretamente relacionada com a sazonalidade das chuvas, apresentando período de dormência durante a estação seca (MARCATI et al., 2006). Diversos trabalhos tem apresentado as respostas climáticas registradas nos anéis de crescimento de *Cedrela* sp., tornando-a uma espécie chave para o desenvolvimento de estudos dendroclimáticos na América do Sul (DÜNISCH et al., 2002; BRIENEN e ZUIDEMA, 2005; BRIENEN et al., 2012).

3. CONSIDERAÇÕES GERAIS

Compreender a variabilidade climática em uma das mais importantes bacias hidrográficas do mundo é um desafio para os pesquisadores. As atuais previsões de aumento de extremos climáticos e redução e alteração dos padrões de distribuição de chuvas na Amazônia tornam necessário o conhecimento mais aprofundado das dinâmicas que influenciam a região. Infelizmente não existem dados instrumentais que possibilitem a confirmação de que os atuais eventos não possuem precedentes históricos.

O primeiro artigo apresenta a primeira cronologia de anéis de crescimento do Brasil (BRA001, GRANATO-SOUZA et al., 2018) a integrar a base de dados paleoclimáticos do NOAA (*International Tree-Ring Data Bank – ITRDB*), podendo ser considerado um importante marco para a geração de registros geocronológicos na bacia Amazônica. A base de dados do ITRDB representa o maior arquivo mundial de dados de anéis de crescimento e é rigorosamente administrada pela equipe de paleoclimatologia do Centro Nacional para Informações Ambientais (NCEI) e pelo Sistema Mundial de Dados para Paleoclimatologia. A inclusão dos dados aqui apresentados representa o livre acesso para que sejam utilizados para diversos fins científicos, sem que essas informações sejam perdidas em laboratórios. Ademais, serve como incentivo para que os demais pesquisadores nacionais promovam o compartilhamento dos respectivos dados paleoclimáticos.

O segundo artigo representa a primeira iniciativa de construção de uma rede de cronologias de *Cedrela*, ainda que em sua fase inicial, mas que já demonstra uma melhor acurácia e sensibilidade aos fatores climáticos regionais e de larga escala que regulam a variabilidade climática na Amazônia oriental.

Como perspectivas futuras, a continuidade do desenvolvimento de cronologias de anéis de crescimento de *Cedrela* na região e a adição sistemática destes dados ao ITRDB permitirá a médio e longo prazos uma melhor contextualização da dinâmica hidroclimática na Bacia Amazônica, bem como uma discussão mais sólida sobre os atuais eventos extremos (grandes secas e cheias), ampliando o entendimento sobre variabilidade natural e/ou antrópica nas mudanças climáticas. Redes de cronologias de anéis de crescimento já tem contribuído para esse fim em diversas partes do globo, permitindo a construção de atlas de secas regionais e continentais: América do Norte (North American Drought Atlas – NADA; COOK et al., 2009), México (Mexican Drought Atlas – MXDA; STAHL et al., 2016), Ásia (Monsoon Asia Drought Atlas – MADA; COOK et al., 2010).

Além da aplicação dos anéis de crescimento para estudos climáticos (dendroclimatologia), tema que trata essa tese, a base de dados gerada já tem contribuído para o desenvolvimento de outras pesquisas, que podem agora explorar uma vasta coleção de amostras datadas para estudar os aspectos ecológicos da *Cedrela odorata*, calibração da curva radiocarbono e análise de isótopos estáveis, todos esses trabalhos se encontram em andamento.

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SEGUNDA PARTE

ARTIGO 1**TREE RINGS AND RAINFALL IN THE EQUATORIAL AMAZON**

Esse manuscrito está publicado na revista *Climate Dynamics*:

Daniela Granato-Souza, David W. Stahle, Ana Carolina Barbosa, Song Feng, Max C. A. Torbenson, Gabriel de Assis Pereira, Jochen Schöngart, João Paulo Barbosa, Daniel Griffin (2018) Tree rings and rainfall in the equatorial Amazon. *Climate Dynamics*. Doi: 10.1007/s00382-018-4227-y.

Abstract

The Amazon basin is a global center of hydroclimatic variability and biodiversity, but there are only eight instrumental rainfall stations with continuous records longer than 80 years in the entire basin, an area nearly the size of the coterminous US. The first long moisture-sensitive tree-ring chronology has been developed in the eastern equatorial Amazon of Brazil based on dendrochronological analysis of *Cedrela* cross sections cut during sustainable logging operations near the Rio Paru. The Rio Paru chronology dates from 1786 to 2016 and is significantly correlated with instrumental precipitation observations from 1939 to 2016. The strength and spatial scale of the precipitation signal vary during the instrumental period, but the Rio Paru chronology has been used to develop a preliminary reconstruction of February to November rainfall totals from 1786 to 2016. The reconstruction is related to SSTs in the Atlantic and especially the tropical Pacific, similar to the stronger pattern of association computed for the instrumental rainfall data from the eastern Amazon. The tree-ring data estimate extended drought and wet episodes in the mid- to late-nineteenth century, providing a valuable, long-term perspective on the moisture changes expected to emerge over the Amazon in the coming century due to deforestation and anthropogenic climate change.

Keywords: Equatorial Amazon · *Cedrela* · Tree rings · Precipitation · Sea surface temperature · ENSO

1 Introduction

The Amazon basin is one of the largest centers of deep atmospheric convection on earth and it plays a major role in the general circulation of the atmosphere and the global energy balance (Crutzen 1987; Wang and Fu 2007; Hilker et al. 2014). The hydroclimatology of the Amazon basin may be changing because drought and wetness extremes have both increased in frequency over portions of the basin since 1960 (Lewis et al. 2011; Gloor et al. 2013; Marengo and Espinoza 2016). This apparent amplification of the hydrologic cycle over the Amazon has been hypothesized to arise from both natural and anthropogenic factors, including interactions between deforestation and climate over the Amazon (Gentry and Lopez-Parodi 1980; Costa et al. 2003; Callede et al. 2004; Chagnon and Bras 2005; Khanna et al. 2017), anthropogenic alterations to global climate (IPCC 2013; Nobre et al. 2016), increased water vapor transport from the warmer tropical North Atlantic (Gloor et al. 2013), decadal sea surface temperature (SST) changes in the Pacific (Gloor et al. 2015), or it may simply be due to the large natural variability of Amazonian hydroclimate. Just how unprecedented these recent moisture extremes might be in the context of natural climate variability is impossible to determine from the short, sparse, and frequently interrupted instrumental precipitation and stream flow records for Amazonia.

The longest continuous precipitation measurements in the entire 7.5×10^6 km² drainage basin of the Amazon River begin in 1892 at Rio Branco in the western Amazon and in 1901 at Manaus, Brazil (based on the stations included in the CRU TS4.00 gridded precipitation data set; Harris et al. 2014). The longest hydrological observation in the Amazon is the stage height record of the Rio Negro at Manaus that began continuous measurements in 1903 (Richey et al. 1989). However, only eight instrumental rainfall records longer than 80 years with less than 10% missing values are available for the entire basin, an area nearly the size of the coterminous US. Very high-resolution precipitation proxies will be necessary to extend the instrumental record in the Amazon in order to evaluate the apparent amplification of moisture extremes in the context of natural climatic variability during the late Holocene.

Moisture sensitive tree-ring chronologies provide excellent seasonal and annual proxies of precipitation in the middle latitudes (e.g., Fritts 1966; Villalba et al. 1998; Griffin et al. 2013), but have been very difficult to develop in the moist tropics due to the scarcity of native tree species with clear annual growth rings that can be exactly dated to their calendar year of formation. However, annual tree-ring chronologies have recently been developed in the western Amazon basin (Bräuning et al. 2009; Lopez and Villalba 2011; Paredes-

Villanueva et al. 2016), and a well dated and replicated tree-ring reconstruction of wet season rainfall totals was reported by López et al. (2017) for the headwaters of the Madeira River in the southern Amazon basin. These chronologies were based on the dendrochronological crossdating of ring width time series, but Baker et al. (2015) demonstrate that oxygen isotope measurements on the growth rings can enhance crossdating of selected tropical species in the western Amazon. In this paper we describe the development of the first exactly dated and well-replicated ring-width chronology in the eastern equatorial Amazon basin of Brazil. We document the precipitation signal in this tree-ring chronology, use the chronology to estimate precipitation variability over the eastern Amazon for the past 231 years, and examine the large-scale climate dynamics involved in the inter-annual variability of instrumental and reconstructed precipitation over this sector of Amazonia.

2 Background to the tree ring collections

An estimated 16,000 tree species may be native to the low-land forests of the Amazon (ter Steege et al. 2013), but only 6727 have been described taxonomically (Cardoso et al. 2017). A small fraction of the known tree species (227) are actually found widely across the basin and represent $\pm 50\%$ of the 390 billion individual trees estimated to be present in the lowland Amazon (ter Steege et al. 2013). This includes *Cedrela odorata*, which has been found in 96 of the study plots tabulated by ter Steege et al. (2016). A few of these “hyperdominant” species form annual growth rings (Schöngart et al. 2017) and may be suitable for the development of a geographic network of climate sensitive tree-ring chronologies as has been possible in the mid-to high-latitudes of the Northern and Southern Hemisphere (e.g., Meko et al. 1993; Cook et al. 1999; Villalba et al. 2012).

We have collaborated with logging companies and Norte Energia, the large energy conglomerate responsible for the construction of the Belo Monte hydroelectric project on the Rio Xingu to obtain cross-sections for tree ring analysis (Fig. 1). These companies have legal authority for sustainable forestry or full deforestation in construction zones. With the cooperation of the owners of these firms, their managers, and employees we were able to cut full and partial cross-sections from recently felled trees. As part of this collaboration, all tree-ring specimens collected under the auspices of Norte Energia, CEMAL, and other firms have been cataloged and permanently stored in the archives of the Tree Ring Laboratories at the Federal University of Lavras and the National Institute for Amazonian Research (INPA) where they are available for further scientific research.

Eastern Equatorial Amazon

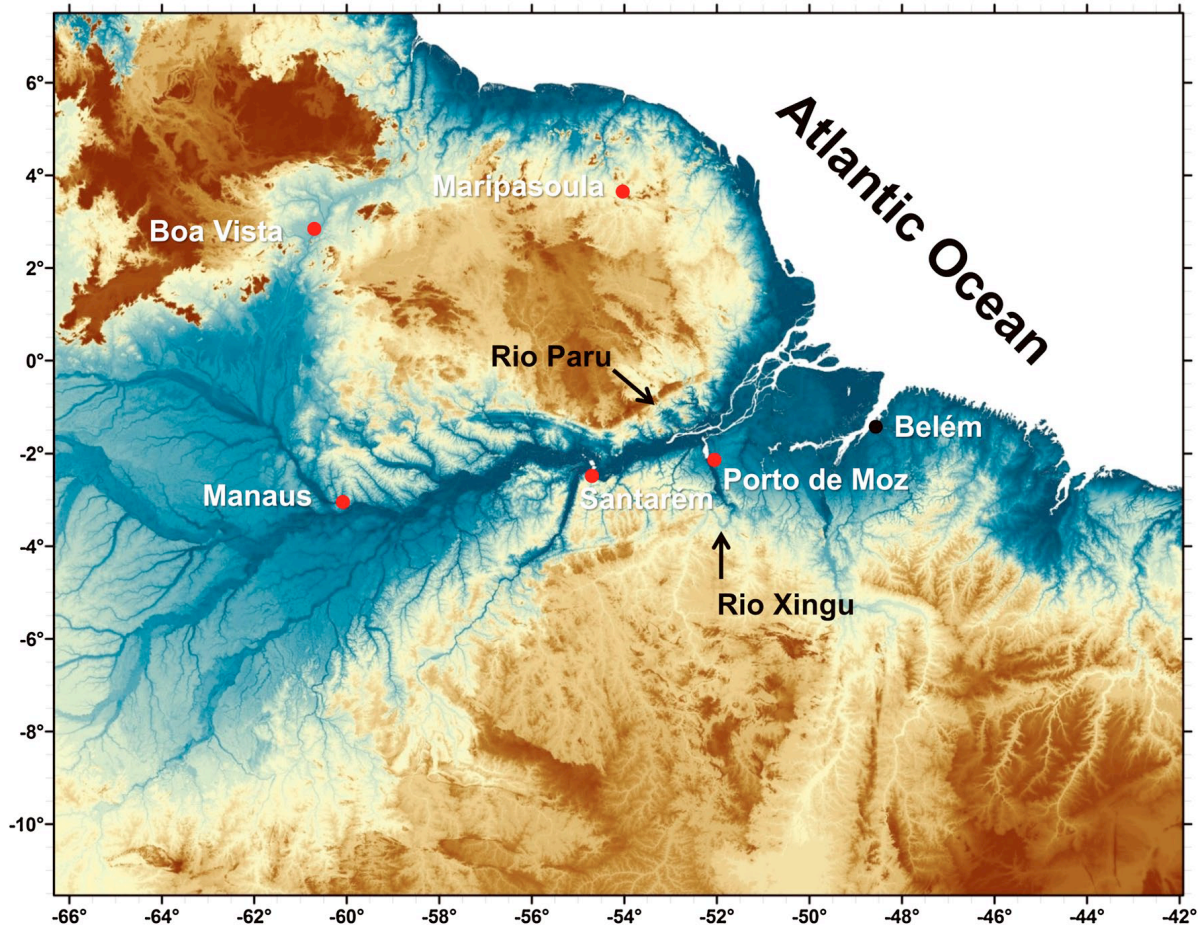


Fig. 1 The tree-ring collection sites on the Rio Paru and Rio Xingu are located on this terrain map of the eastern Amazon River basin. The *Cedrela* specimens were collected just west of the Rio Paru and near the southern escarpment of the Guiana Highlands at 200 m elevation. The locations of the weather recording stations included in these analyses are also indicated (red symbols).

Chainsaw operators employed by our collaborating firms cut all of these research cross sections. To facilitate these collections we developed a guide in Portuguese to explain the procedures for cutting specimens for tree-ring analysis. This guide is illustrated in Fig. 2 and highlights where the samples should be cut on the felled trees. Some specimens were obtained in the forest where the trees were actually felled, but many were collected at log yards (pátios) where recently cut logs were stored prior to shipment (Fig. 3). Only general provenience (± 10 km) is known for the specimens obtained from the pátios.

Our target species were *Bertholletia excelsa* (Lecythidaceae), *Cedrela fissilis* and *Cedrela odorata* (Meliaceae), and *Macrolobium acaciifolium* (Fabaceae), all of which have wide distributions in the Amazon. *Bertholletia excelsa*, the Brazil nut tree, is a protected and socioeconomically important tree species that is not harvested by our collaborating logging companies. However, hundreds of *Bertholletia* had to be cut during the construction of the

Belo Monte project. We collected cross-sections from 212 *B. excelsa* trees from the Rio Xingu region, which is believed to be the largest collection of *Bertholletia* cross sections currently available. *Macrolobium acaciifolium* is a dominant floodplain species with low economic value and thus far we have collected cores and cross-sections from over 200 *Macrolobium* trees the eastern Amazon on the Rio Tapajós and Rio Xingu.

Cedrela fissilis and *C. odorata* are both native in the eastern Amazon and in some cases these species have clear and unambiguous annual rings useful for tree-ring dating elsewhere in the basin (Dünisch et al. 2002; Brienen et al. 2012). Cross-sections from 47 legally harvested *Cedrela* sp. were obtained from an old growth State-owned forest near the Rio Paru (Fig. 1) that has been recently opened to sustainable timber production and 45 were collected from the Belo Monte project on the Rio Xingu. It is not possible to identify the species of *Cedrela* from the wood anatomy alone, but we believe that *C. odorata* dominates our collections from the Rio Paru because it is the only species of *Cedrela* cited in the forest inventory of CEMAL, the operator of the forest concession on the Rio Paru. The analyses reported below are all based on *Cedrela* from the Rio Paru in the eastern equatorial Amazon.

ESTUDO DOS ANÉIS DE ÁRVORES: RECONSTRUINDO O CLIMA

GUIA DE AMOSTRAGEM

1 O QUE CORTAR?

Amostras do tronco de árvores de **CEDRO** (*Cedrela odorata* e *Cedrela fissilis*).

Para cada sítio (área com um raio de 10 km), são necessárias em torno de 100 amostras.

Se na área a espécie for abundante, dar preferência para as maiores e mais velhas, mas também algumas menores.
*proporção de aproximadamente 80% grandes e 20% médias)

2 COMO CORTAR?

Corte uma seção transversal no final da primeira tora
*** não na base/toco**

Tentar cortar duas faces paralelas:

- ✓ Espessura das amostras: 5-6 cm
- ✓ Largura do corte radial: 20-25 cm
- ✓ Cortes de pizza e radial: mais de uma amostra, preferencialmente.

"CORTE DISCO" (disco completo)

"CORTE PIZZA" (1/4 - 1/8 disco)

"CORTE RADIAL" corte retangular

O CORTE IDEAL
Primeira e melhor opção

*** INCLUIR A MEDULA E CASCA**
Tentar incluir o anel central, albúmeno e último anel formado abaixo da casca

Identificar a amostra:

- Código de identificação da empresa
- Data de abate da árvore
- Se a árvore já está morta, indicar "morta"
- Código da espécie (CEOD, CEFI ou CESP*)

* CEOD: *C. odorata* CEFI: *C. fissilis* CESP: *Cedrela sp.*

3 ONDE CORTAR A AMOSTRA?

1. Selecione região de forma a evitar cicatrizes, canais de resinas, crescimento anômalo (nem sempre possível)
2. Se a medula não estiver no centro, selecione região de maior crescimento
3. Árvores sólidas ou com pouco oco podem ser amostradas
4. Árvores muito ocas não devem ser amostradas.

4 COMO GUARDAR?

Armazenar as amostras dispostas verticalmente em local seco e ventilado (para evitar empenamento).

Deixar espaço para circulação do ar entre as amostras.

UFPA INSTITUTO FEDERAL DE PAULISTA

INPA INSTITUTO NACIONAL DE PESQUISAS DA AMAZÔNIA

UNIVERSITY OF ARKANSAS

NSF

Fig. 2 This is the Portuguese language guide to the collection of thin cross-sections from tropical trees felled during construction projects or under legal and sustainable logging concessions.



Fig. 3 A typical collection of tropical hardwood logs felled during construction of the Belo Monte hydroelectric project on the Rio Xingu. All felled trees were cataloged, identified to species and prepared for sale. Hundreds of hardwood cross-sections were obtained from these logs with the assistance of Norte Energia, and are preserved in the Tree-Ring Laboratory at the Federal University of Lavras, Brazil.

3 Data and methods

3.1 Sample preparation and tree-ring analysis

Cross-sections were dried and highly polished to reveal the minute cellular anatomy of the annual rings. Most tropical hardwoods have complex xylem anatomy, but previous research has proven that annual rings can be formed in *Cedrela* (Brienen and Zuidema 2005; Paredes-Villanueva et al. 2016). In some *Cedrela* stands, the symmetry of the concentric growth rings can be distorted by competition among trees for light, insect attack (Dünisch et al. 2002), and senescence (Lopez and Villalba 2016). But the well-formed concentric growth rings in the *Cedrela* sections from the Rio Paru site are exceptionally clear (Fig. 4) and the time series patterns were easily matched among trees.



Fig. 4 This polished cross-section illustrates the clear annual growth rings on a *Cedrela* sp. cross-section cut during a legal operation near the Rio Paru (this portion of the specimen dates from 1785 (pith) to 1856, decades noted with white marks). The annual growth rings of this species are readily distinguished by semi-ring porosity and marginal parenchyma. The micro ring at 1833 is locally absent and difficult to see in this image.

The annual growth rings of the Rio Paru *Cedrela* were crossdated using skeleton plots and visual dating under the microscope (Douglass 1941; Stokes and Smiley 1996). The dated ring widths were measured to a precision of 0.001 mm and the derived time series were submitted to dating and measurement quality control with the computer program COFECHA (Holmes 1983). The correctly dated series were carefully detrended and standardized by fitting cubic smoothing splines to remove non-synchronous and likely non-climatic multi-decadal to centennial growth trends using the program ARSTAN (Cook 1985; Cook and Krusic 2005). The derived tree-ring indices were computed by dividing the measured ring-width value for each year by the value of the fitted curve for the same year (ratios). The final robust mean index standard chronology was obtained by averaging all ring width index series on a year-by-year basis (Cook 1985; Cook and Krusic 2005). These detrending and standardization procedures were designed to maximize the high- to medium-frequency (e.g., interannual to decadal) coherence between the tree-ring time series because the lower frequency variance in these relatively short records does not strongly synchronize among trees and may arise primarily from age trend and stand dynamics in these closed forest environments. A series of statistics were computed with the ARSTAN program to describe the internal consistency of the individual ring width series and of the derived standard

chronology [e.g., mean sensitivity, mean correlation among all series (RBAR; Cook and Pederson 2011), and the expressed population signal (EPS; Wigley et al. 1984)].

Note that the “Schulman Shift” was not applied to the dating of the Rio Paru chronology. This means that tree growth occurring in the 2016 calendar year was assigned to 2016 and not 2015 as it would have been using the “shift” which has been the Southern Hemisphere standard since Schulman’s pioneering tree-ring research in the 1950s (Schulman 1956). Based on limited observations and informant information, most annual radial growth in *Cedrela* trees at Rio Paru appears to take place during the wet season (February-July; see also Wagner et al. 2014), so it seems reasonable to assign annual dating to the rings during the year in which they are largely formed in these near equatorial forests.

3.2 Growth-climate analyses

The Rio Paru *Cedrela* chronology was correlated spatially with monthly precipitation totals in the Climatic Research Unit (CRU) TS4.00 0.5° gridded data set from 1900 to 2015 (Harris et al. 2014) and in the Global Precipitation Climatology Centre (GPCC) V7 0.5° data set from 1901-present (Becker et al. 2013; Schneider et al. 2017), maximum and minimum temperatures (HadCRUTS4.01; Harris et al. 2014), and the Palmer Drought Severity Index (CRUscP- DSI3.25; van der Schrier et al. 2013) to identify the strongest monthly or seasonal climate signals. An experimental reconstruction of February–November precipitation totals was developed using the point-by-point regression (PPR) method of Cook et al. (1999, 2010) to calibrate the standardized ring width chronology from the Rio Paru with a four-station average of instrumental precipitation data from the eastern Amazon extracted from the CRU TS4.00 data set (i.e., Porto de Moz, Santarem, Manaus, and Boa Vista). The tree-ring chronology was calibrated from 1939 to 1970 with normalized February–November total precipitation using a bivariate regression model. The derived reconstruction was then validated against just a 20-year period 1971–1990 because the data available for Porto de Moz and Santarem in the CRU TS4.00 compilation end in 1990. To estimate the uncertainty of the tree-ring estimates each year, semi-parametric 90% prediction intervals described by Cook et al. (2013) and based on both standard least squares theory (Seber and Lee 2003; Olive 2007) and the maximum entropy bootstrap method (Vinod 2006) used to randomly rearrange the predictor and predictand were computed for each year of the reconstruction. Additional climate analyses were performed using station precipitation data for Maripasoula, French Guiana (CRU TS4.00, Harris et al. 2014), the COBE Sea Surface Temperature data set (Ishii et al. 2005), and NCEP/NCAR reanalysis data (Kalnay et al. 1996). These analyses were

computed using the unfiltered instrumental and reconstructed time series, and with filtered versions emphasizing interannual to subdecadal and decadal to multidecadal components of the rainfall series isolated with a nine-point binomial filter.

4 Results

We analyzed the annual growth rings on cross sections from 47 trees cut near the Rio Paru with dendrochronology. A total of 56 dated and measured radii from 27 separate trees were used to construct a fully replicated chronology that dates from 1786 to 2016 (RBAR 0.246; Fig. 5). Many of the trees that were not included in the chronology are in fact datable with dendrochronology, but they were either young trees with short time series or suffered other irregularities in growth and were excluded from these analyses. A second chronology was also developed from a subset of the 10 oldest and most highly cross-correlated trees (27 total radii; RBAR 0.319; Fig. 5). Both dated tree ring data sets are highly correlated ($r = 0.91$ from 1786 to 2016, $r = 0.90$ from 1901 to 2016), but the most internally coherent chronology from the ten best trees has a stronger correlation with monthly precipitation values and is used in all subsequent climate comparisons and reconstructions.

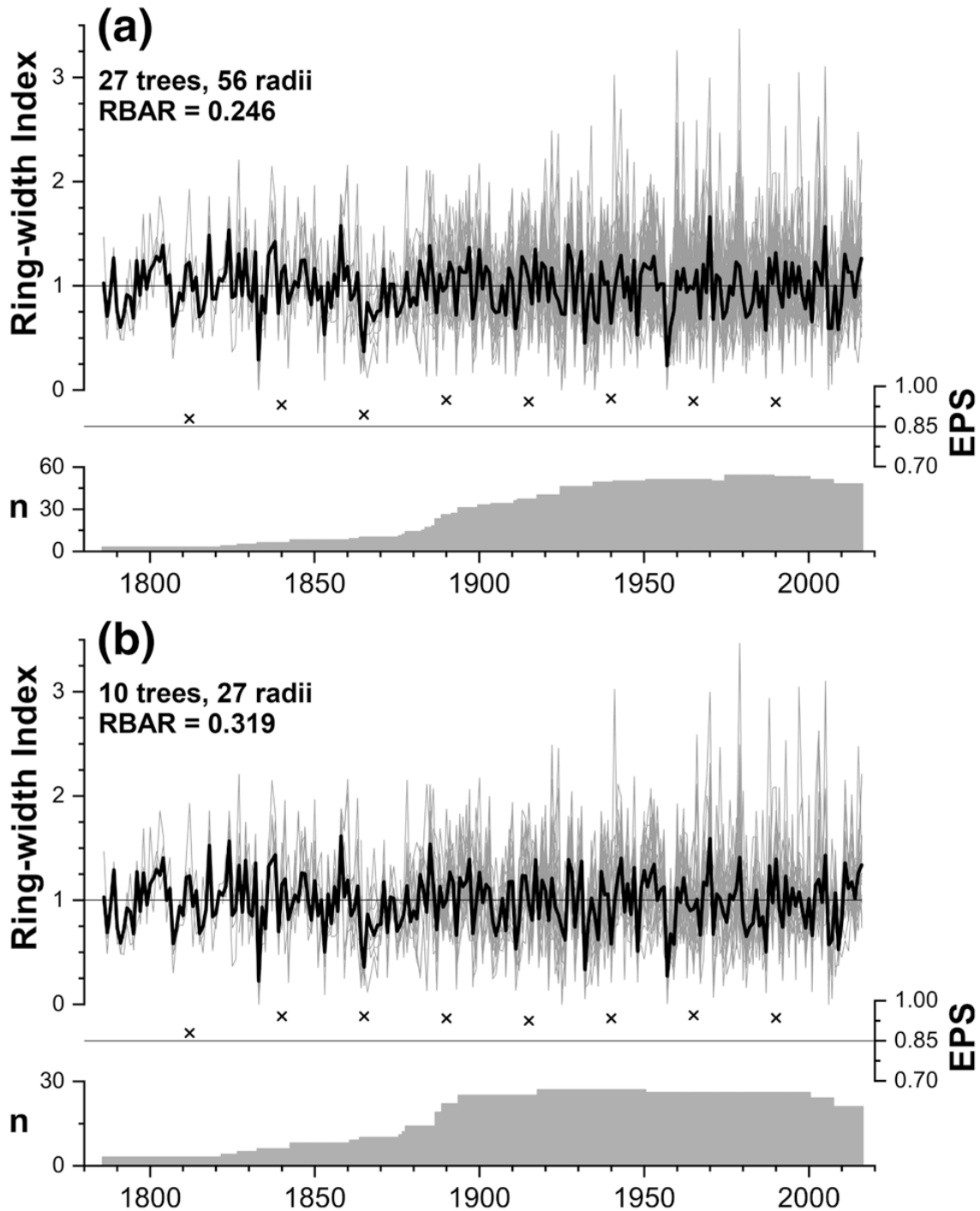


Fig. 5 a The 56 tree-ring dated and measured radii from 27 *Cedrela* trees obtained from the Rio Paru are plotted as detrended, standardized and autoregressively modeled white noise residuals (gray time series). The mean index residual chronology is also plotted (black), both for the fully replicated set of 56 radii and **b** a subset of the 27 radii from 10 trees that are longest and most strongly correlated among all component radii (i.e., RBAR 0.246 and 0.319, respectively). Both data sets pass the 0.85 EPS threshold test for all 50-year subperiods (overlapping 25 years). The changing sample size of dated radii is plotted below each panel.

Exploratory analyses using both the CRU and GPCC gridded precipitation data sets indicated that the Rio Paru *Cedrela* ring-width chronology is positively correlated with monthly instrumental precipitation observations available from the eastern Amazon during

most months of the calendar year for the period 1939–2015 when the observations are most complete. However, the strength and spatial scale of the correlations seem to have shifted over this interval (Fig. 6a–d). The period with the strongest and most widespread precipitation signal is 1939–1970 when the chronology was correlated with February–November rainfall over the eastern equatorial Amazon and into Venezuela and Columbia (Fig. 6a). From 1971 to 2015 the area of significant positive precipitation correlation is restricted to the extreme eastern Amazon and Guiana Highlands (Fig. 6b). The near-annual February–November precipitation totals appear to be most highly correlated with the tree-ring chronology (Fig. 6a, b), but the chronology is also significantly correlated with March–May rainfall totals during the heart of the wet season in the vicinity of the Rio Paru during both subperiods of the instrumental era (Fig. 6c, d). The Rio Paru chronology was also correlated with gridded temperature and PDSI for the Amazon basin, but the results were much weaker than for precipitation, likely due in part to the very limited number of long temperature records from the region.

Rio Paru Chronology Spatial Correlation with Rainfall

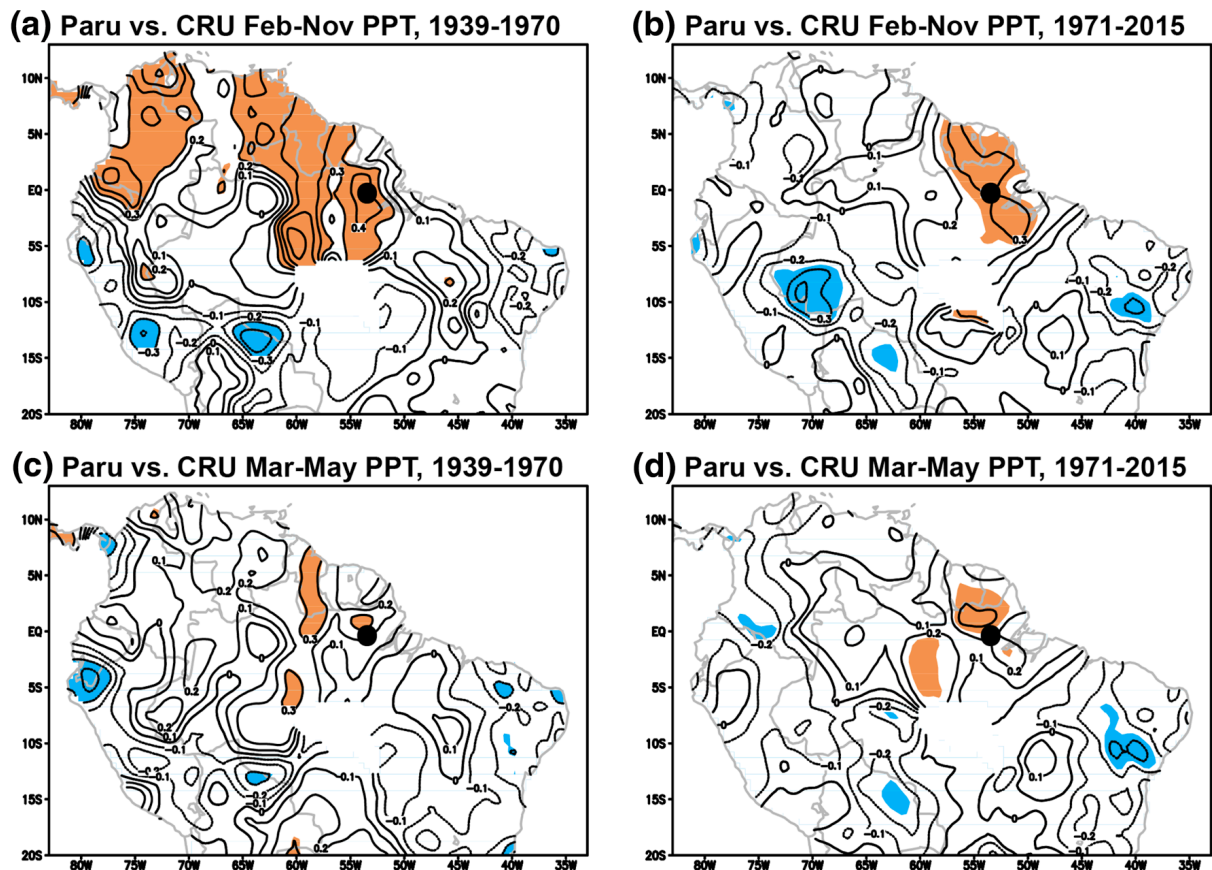


Fig. 6 The spatial pattern of correlation computed between the standard chronology from the Rio Paru and CRU TS 4.00 0.5° gridded February–November total precipitation is illustrated for 1939–1970 (a), and 1971–1990 (b).

The Rio Paru chronology (black dot) is also correlated with CRU 3-month precipitation totals during the heart of the wet season (March–May) for both subperiods, 1939–1970 (c) and 1971–2015 (d; significant positive correlations shaded orange, negative in blue, $p < 0.10$). A data void area is located near 10°S and 55°W.

The Rio Paru site is located less than one degree south of the equator where it may be affected by the two leading modes of rainfall variability in northeastern South America. Empirical orthogonal function (eof) analysis of GPCP wet season (MAM) precipitation totals from 1939 to 2013 identifies a dipole in rainfall variability north and south of the equator that represents 23.8% of the precipitation variance (eof1, Fig. 7a; see also Torralba et al. 2015). The second mode of variance (eof2) highlights variability largely confined to the eastern and central equatorial Amazon River sector, which is the mode that would tend to be represented by the four-station precipitation average that straddles the equator (i.e., Porto de Moz, Santarem, Manaus, and Boa Vista; Figs. 1, 7b). The changes in the spatial pattern of correlation between the tree-ring data and rainfall (Fig. 6) might be due in part to temporal variations in the influence of these modes of rainfall variability (e.g., Torralba et al. 2015).

In spite of the changes in strength and spatial pattern of precipitation correlation (Fig. 6), rainfall variability appears to be the primary climate signal reflected by the coherent ring width variability in the Rio Paru chronology. This is supported by the significant positive correlations in Fig. 6a–d, by the correlation with select wet season rainfall totals [e.g., MAM at Maripasoula, French Guiana ($r = 0.37$; $p < 0.01$, 1961–2016)], and by the significant positive correlation between the Rio Paru chronology and annual maximum river levels for the Rio Negro at Manaus during the full common interval of 1903–2015 ($r = 0.25$; $p < 0.01$). It is also possible to calibrate and validate the Rio Paru chronology with February–November precipitation totals observed in the eastern equatorial Amazon during the 1939–1990 period.

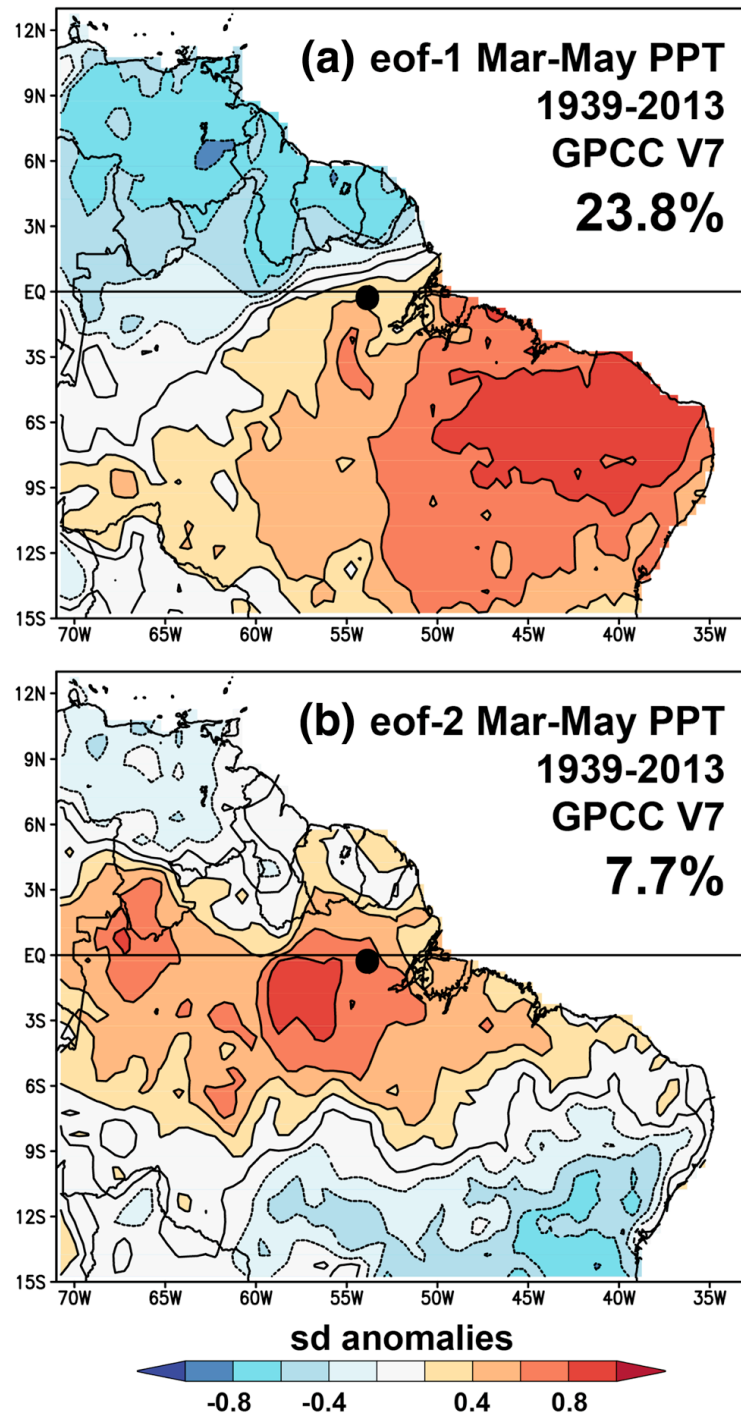


Fig. 7 The spatial anomaly patterns associated with the two leading modes of precipitation variability in northeastern South America are mapped [eof1 (a) and eof2 (b)] based on GPCC March–May precipitation totals, 1939–2013 (similar results were observed for 10-month February–November precipitation totals and using the CRU TS4.00 precipitation data). The percent variance represented by each mode is listed and the location of the Rio Paru tree-ring chronology is noted on both maps (black dot). The eofs were computed using the KNMI Climate Explorer (<https://climexp.knmi.nl>).

To define the optimal season and region for this preliminary tree-ring reconstruction of precipitation, a regional average of the four longest monthly precipitation stations in the eastern Amazon was computed using Porto de Moz, Santarem, Manaus, and Boa Vista, which

are largely complete from 1939 to 1990 (a few missing monthly values were replaced in the station observations with monthly means). The Rio Paru tree-ring chronology is positively correlated with precipitation during most months of the year concurrent with growth (Fig. 8). The highest correlations were calculated for February and March, which is the beginning of the wet season (generally February to July) in this region of the eastern Amazon (e.g., Torralba et al. 2015). The driest months of the year generally include August and September, but the tree-ring chronology remains positively correlated with monthly totals for the 10-month extending from February through November (Fig. 8).

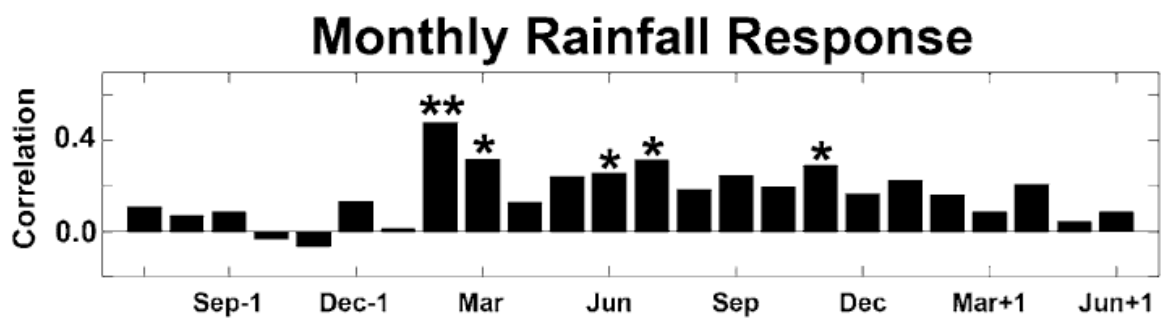


Fig. 8 The monthly values for the four-station regional precipitation average were correlated with the Rio Paru standard chronology from 1939 to 1990 to identify the monthly precipitation totals most important to the radial growth of *Cedrela* from the Rio Paru for a 24-month period including 6 months prior to (-1) and following (+1) the year concurrent with growth. Significant correlations are noted with asterisks (* $p < 0.05$, ** $p < 0.01$); the highest single monthly correlation is February, $r = 0.49$).

The correlation of the tree-ring chronology with 10-month total precipitation (February–November) for the four-station average from 1939 to 1990 is strong enough to develop an experimental tree-ring reconstruction of precipitation for the equatorial Amazon (note that the regional precipitation average was computed from the normalized station totals). The chronology explains 37% of the instrumental precipitation variance during the 1939–1970 calibration period (adjusted $R^2 = 0.375$; no lead or lag versions of the tree-ring chronology were selected as predictors; Fig. 9), and the cross validation reduction of error computed for the same interval is $CVRE = 0.356$. The reconstruction compares reasonably well with the independent instrumental precipitation data during the short 1971–1990 validation interval. For the period 1971–1990, the Pearson R^2 is 0.275, the RE is 0.288, and the coefficient of efficiency (CE) is 0.273 (Cook et al. 1999). The two worst 4-year droughts in the instrumental record occurred from 1957 to 1960 and 1980–1983 and were also the worst 4-year periods of tree growth/inferred precipitation during the instrumental period from 1939 to 1990 (Fig. 9).

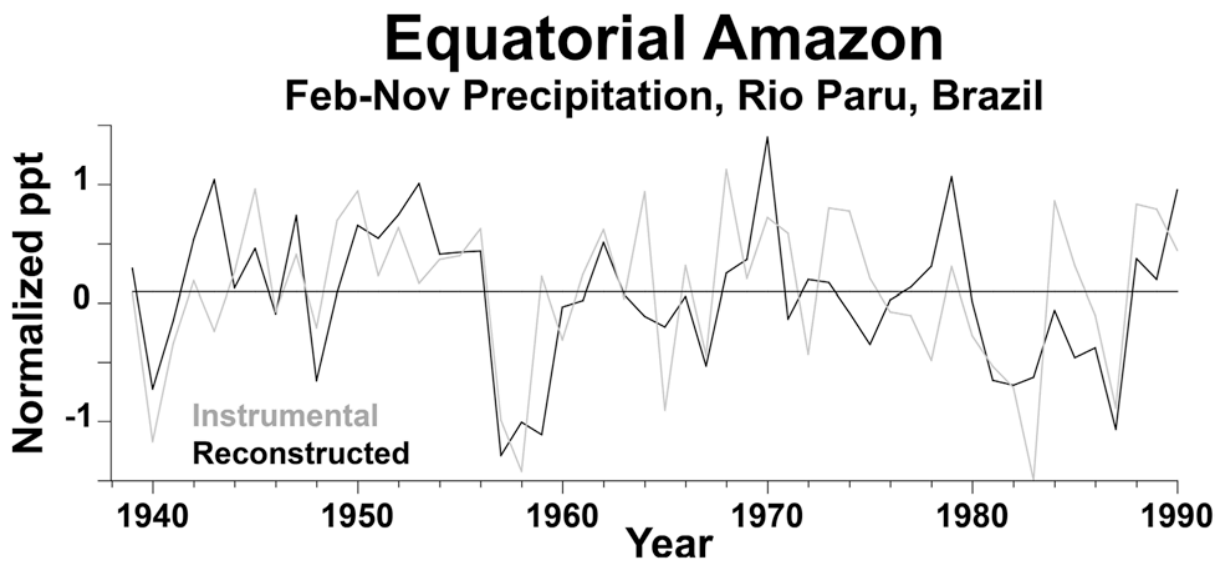


Fig.9 The instrumental (gray) and reconstructed (black) February- November precipitation totals for the eastern equatorial Amazon are plotted together from 1939 to 1990. The tree-ring chronology was calibrated with instrumental precipitation from 1939 to 1970 (RSQ- adj = 0.375) and validated from 1971 to 1990 (Pearson R = 0.275).

The full reconstruction is plotted from 1786 to 2016 (Fig. 10) and estimates interesting moisture variability over the eastern equatorial Amazon for the past 230 years. The reconstruction is dominated by interannual and sub-decadal variability, not unlike the instrumental precipitation totals for the eastern Amazon study area (Fig. 9). But the reconstruction also provides preliminary evidence for a decade-long regime of dryness in the mid-nineteenth century (Fig. 10). The worst single year in the entire reconstruction was for 1865, which occurred during seven straight years of reconstructed dryness (1864–1970), part of an 18-year period (1864–1881) of prolonged dryness when only 2 years were above average. This apparent drought regime predates the continuous instrumental measurements of precipitation and streamflow in Amazonia, but earlier discontinuous hydroclimate measurements and documentary information might be found from the mid-nineteenth century to provide some historical validation of this reconstructed dry interval (e.g., monthly precipitation totals for Manaus are available from 1870 to 1874 in CRU TS4.00).

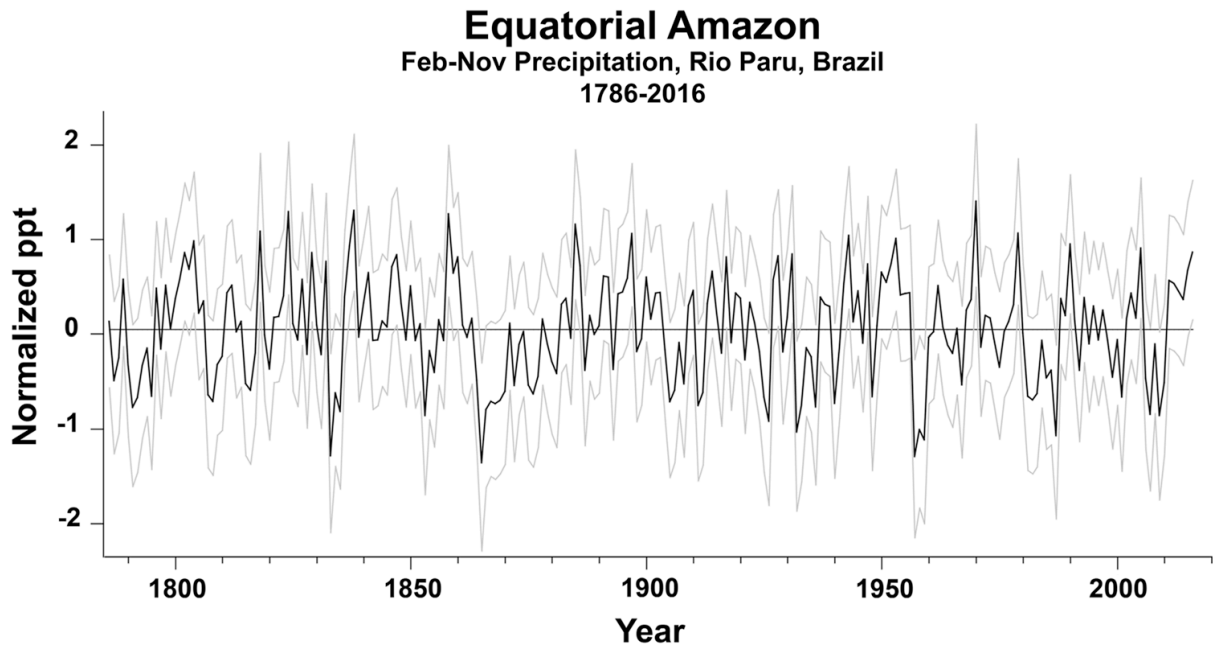


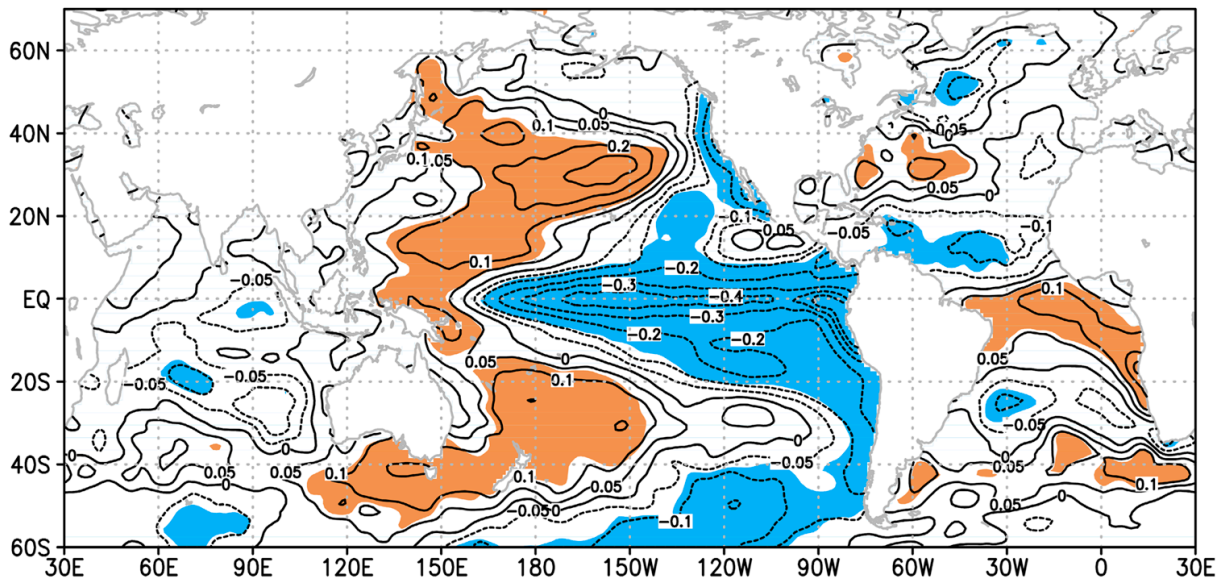
Fig. 10 The tree-ring estimated February–November precipitation totals are plotted from 1786 to 2016 along with 0.05 and 0.95 semi-parametric prediction intervals. Note the 7-year episode of below mean estimates in the 1980s, six of which were below average in the instrumental data (Fig. 9). A more prolonged dry interval is estimated to have persisted over the Rio Paru sector in the mid-nineteenth Century.

Two extended wet episodes are also indicated in the new reconstruction. The mid-twentieth century wet period extended in the reconstruction from 1942 to 1956 and was interrupted by only two dry years (Figs. 9, 10). Rainfall was also above average during this interval in the four-station regional average (Fig. 9). A second regime of elevated rainfall was estimated for the late nineteenth century (1882–1903; Fig. 10) and historical information would again be valuable for testing the validity of this pluvial.

When the observed and proxy rainfall data (February–November) for the eastern Amazon are regressed on gridded sea surface temperatures (averaged for February–April), similar global scale patterns associated with the El Niño/Southern Oscillation (ENSO) are identified in both time series during the 1939–1990 common period (Fig. 11). A 9-point binomial filter was used to remove decadal and longer variability from both the instrumental and reconstructed time series prior to regression with the SST data. The SST patterns associated with the reconstruction are weaker than those observed for the instrumental rainfall data, but both time series are related with cold conditions in the eastern equatorial Pacific and with a gradient of SST anomalies in the South Atlantic (Fig. 11). A very similar pattern of SST association is observed when the regression is based on instrumental precipitation data averaged only for February–April during the heart of the wet season (1939–1990).

The similarity of SST signals in the observed and reconstructed rainfall data provides further support for the proxy climate value of the *Cedrela* chronology from the Rio Paru. The Pacific SST signal in the reconstruction does weaken during the 1991–2016 period, and the signal in the tropical North Atlantic strengthens (not shown). But a regression of the rainfall reconstruction on the COBE SSTs from 1881 to 2016 is very similar to the global SST patterns illustrated in Fig. 11b.

(a) Instrumental 4-Station PPT (Feb–Nov), 1939–1990



(b) Reconstructed 4-Station PPT (Feb–Nov), 1939–1990

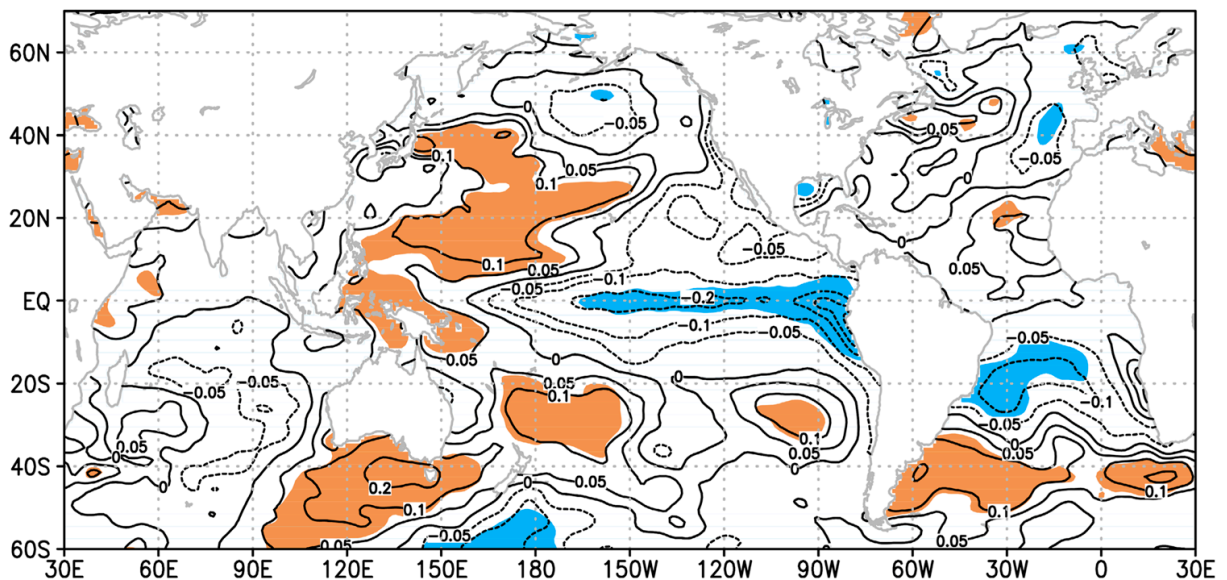


Fig. 11 The instrumental (a) and the reconstructed February–November precipitation totals (b) for the four-station average from the eastern Amazon were regressed on the gridded COBE SSTs averaged for February–April for the 1939–1990 period. The two precipitation series were first filtered to emphasize interannual to subdecadal variability. Note the similar patterns of SST variability in both the instrumental and reconstructed rainfall series, especially in the cold tongue region of the tropical Pacific. Significant positive and negative

relationships are colored orange and blue, respectively ($p < 0.10$). Similar results were obtained using the Kaplan and NOAA gridded SST data sets.

5 Discussion and conclusions

The Rio Paru *Cedrela* collections have provided one of the longest equatorial ($\pm 5^\circ$ N–S) tree-ring chronologies in the world, based on tree-ring data that have been contributed to the NOAA Paleoclimatology Program. These outstanding *Cedrela* trees have well formed concentric growth rings that are obvious and are among the best we have yet found in tropical rainforests. The master dating chronology developed from the Rio Paru has very good chronology statistics reflecting strong internal coherence among the component trees and radii. We are confident that every annual ring on all trees has been exactly dated to the true calendar year of formation. However, this hypothesis can be tested with every new *Cedrela* tree-ring sample dated in the eastern Amazon climate province. Because of the excellent time control provided by the Rio Paru chronology, and the clear definition of the annual growth rings in *Cedrela* from this area, development of additional *Cedrela* chronologies and testing of the hypothesis of exact dating control will now be much easier and perhaps even possible with 12 mm diameter increment cores that can be extracted non-destructively in large numbers from living *Cedrela* in protected forests.

The Rio Paru *Cedrela* chronology is correlated with precipitation, especially February and March rainfall totals at the beginning of the wet season. The ring width correlation with monthly rainfall totals appears to extend to the end of the dry season, which is rarely completely dry in this region. These late dry season correlations improve the overall correlation of Rio Paru tree growth with precipitation, and if real they may be the combined result of soil moisture recharge, lower evapotranspiration demand, or autocorrelation in monthly precipitation totals.

The changes in the strength, spatial scale, and possibly the seasonality of the tree-ring correlation with rainfall are difficult to explain and may be related to some unknown non-climatic factors affecting tree growth at our moist closed-canopy collection site, the lack of long nearby rainfall recording stations, or to spatial and temporal discontinuities in the instrumental precipitation data. For example, the Porto de Moz and Santarem records included in the CRU TS4.00 data set both end in 1990, and several precipitation stations begin observations in Brazil, French Guiana, and Surinam after 1960 (e.g., Maripasoula, French Guiana). In fact, none of the eight Brazilian stations in the CRU TS4.00 data set that have at

least 80 years of observations are located in the eastern Amazon Basin (Manaus is the closest long rainfall station to the Rio Paru site, and they are separated by 800 km).

The apparent changes in the tree growth-climate signal might also arise in part from differences in the regional and large-scale climate influences on tree growth at the Rio Paru. Changes in the two leading modes of precipitation variability, including variability in the position of the Inter-tropical Convergence Zone (ITCZ), may have impacted the reconstructed rainfall record from the Rio Paru. Torralba et al. (2015) demonstrate that the leading mode of rainfall variability in northeast South America (eof1) and the position of the ITCZ are associated with the inter-hemispheric SST gradient in the tropical Atlantic and with tropical Pacific SSTs, but that the combined influence of these SST patterns on the dipole in wet season rainfall totals increased after 1970. An increase in the SST gradient from the tropical to subpolar North Atlantic has also been hypothesized due to SST warming in the tropics and SST cooling in the north due to ice melt, and may have led to a northward shift in the ITCZ resulting in a drier southeastern Amazon (e.g., Malhi et al. 2008; Hilker et al. 2014). The weakening of the climate signal in the tree-ring data after 1990 might also arise simply from random variability, and the only long term solution will be the development of a well-replicated network of tree-ring chronologies in the eastern Amazon, something that is now much more likely given the high-quality crossdating observed in the new master chronology from the Rio Paru.

In spite of changes in strength and spatial scale, the Rio Paru chronology is significantly correlated with rainfall throughout the instrumental era (1939–2016), and the derived reconstruction is correlated with SSTs in the Pacific and Atlantic similar to the instrumental rainfall data from the eastern Amazon. The preliminary rainfall reconstruction is dominated by notable inter-annual to sub-decadal drought and wet episodes. The reconstruction indicates a decadal dry spell in the mid-nineteenth century and long wet episodes in the late 19th and mid-twentieth century, in spite of the detrending applied to the relatively short forest interior tree-ring time series. The reconstructed mid-nineteenth century drought appears to be as persistent and prolonged as any recorded over the eastern equatorial Amazon during the instrumental era. The implications of this apparent mid-nineteenth century drought are important because it occurred prior to major anthropogenic climate forcing at the regional and global scale, and droughts of the last 20 years are known to have severely impacted forest productivity in Amazonia, resulting in the transient release of carbon dioxide to the atmosphere (Hilker et al. 2014). The true magnitude and persistence of the mid-nineteenth century drought and other decadal precipitation regimes inferred from the *Cedrela*

chronology need to be tested with additional historical and proxy data. The Rio Paru chronology and the recently developed *Centrolobium* chronologies from the southern Amazon Basin (López et al. 2017) both demonstrate that ring-width chronologies from selected native tree species can be used to reconstruct inter-annual and decadal variability of rainfall and provide a valuable perspective on the limited instrumental observations in Amazonia.

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Compliance with ethical standards

Conflict of interest: The authors declare that they have no conflict of interest.

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ARTIGO 2**TREE-RING DATING OF *Cedrela odorata* FROM THE EASTERN AMAZON BASIN
OF BRAZIL**

Esse manuscrito será submetido à revista *Global Change Biology*, posteriormente a esta defesa, e ainda não apresenta lista de autores, sendo apresentado a esta banca da seguinte forma:

Abstract

The recent tree-ring reconstruction of the long-term moisture variability in the eastern Amazon (1786-2016) is now confirmed by the addition of a second well dated ring-width chronology from the second site at the Paru State Forest. Both chronologies, rio Paru A and B, were built with native *Cedrela odorata* trees and are highly correlated showing strong coherence under high frequency components of their time series. The second *Cedrela* chronology is reported here for the first time (1759-2016) and shows the same climate-growth relationship of the February-November precipitation signal, consistent to previous rio Paru A chronology, and similar spatial correlation patterns with regional precipitation. Both chronologies are related to SSTs, especially in the tropical Pacific, and reproduce the association pattern observed between SSTs and the instrumental precipitation data from the eastern Amazon. The rio Paru B chronology reports a stronger and more stable SSTs signal over time and brings a great breakthrough to the already described climatic signal of the first chronology. Furthermore, preliminary analysis with additional *Cedrela* collections from the eastern Amazon shows the great potential of these ring-width datasets to expand the first network of *Cedrela* chronologies in this region and may successfully reproduce the moisture variability extending back to the pre-instrumental era of the meteorological data helping to fill the gaps needed for a better understanding of the ongoing climate changes.

Keywords: Eastern Amazon, *Cedrela* chronologies Network, High frequency components, SSTs, ENSO

1 INTRODUCTION

The Amazon basin is the largest drainage basin in the world, representing an area of $7.5 \times 10^6 \text{ km}^2$ (Barthem et al., 2004). Atmospheric moisture transport from the tropical Atlantic Ocean during austral summer plays an important role in precipitation totals over the Amazon basin (Marengo, 2006; Drumond et al., 2014). The humid forest then returns massive amounts of moisture to the atmosphere through evapotranspiration from the estimated 390 billion individual trees (ter Steege et al., 2013), which represents a volume of water comparable to the mean flow of the Amazon River itself (Newell et al., 1992; Nobre, 2014). These so called “flying rivers” not only guarantee the maintenance of the Amazon forest biodiversity, but they also contribute to atmospheric moisture transport to southcentral Brazil, the most agriculturally productive and developed region of the country (Marengo & Soares, 2004; Nobre, 2014).

Changes in the Equatorial Pacific and Atlantic sea surface temperatures (SSTs) influence annual rainfall variability in the Amazon basin (Vera et al., 2006; Yoon & Zeng, 2010; Marengo et al., 2013; Marengo & Espinoza, 2016), and appear to be the main drivers of the recent wet and dry extremes observed since the beginning of the 19th century (Gloor et al., 2013; Gloor et al., 2015; Marengo & Espinoza, 2016). The frequency of these events varies depending on particular conditions in both oceans, but their combined influence is reported to be stronger since 1970 (Torralba et al., 2015). The inter-hemispheric SST gradient in tropical Atlantic results in the southward displacement of the intertropical convergence zone (ITCZ; Ronchail et al., 2002). The ITCZ then contributes large amounts of rain to the northern and northeastern coastal areas in South America (Guimarães et al., 2017) and helps to intensify the South American monsoon system (SAMS; Vuille et al., 2012), the most important system controlling rainfall variability in South America, including the Amazon basin (Jones & Carvalho, 2013; Guimarães et al., 2017).

Extreme wet and dry episodes are common in the tropics, and may have increased in the last decades over the Amazon Basin (Marengo & Espinoza, 2016). The primary cause of recent drought and wetness extremes over the Amazon appears to be Pacific and Atlantic SSTs anomalies (Marengo & Espinoza, 2016), but anthropogenic changes at regional and global scales may also be involved (Gloor et al., 2013). The lack of long meteorological observations makes it difficult to answer the important question of how unprecedented these extreme events in the Amazon might be. Only eight meteorological stations in all of

Amazonia have rainfall records that are longer than 80 years with fewer than 10% missing data (Granato-Souza et al., 2018).

Moisture sensitive tree-ring chronologies can provide reliable climatic reconstructions and have been widely and successfully applied in the middle latitudes (Fritts 2001; Villalba et al., 1998; Stahle et al., 2011; 2016). Dendrochronological studies have shown promising results with a few native tropical species (Worbes, 1984; 1985; Villalba et al., 1985; Détienné et al., 1989), and efforts are now underway to describe hydroclimatic variability over the Amazon basin through the study of annual growth rings (Bräuning et al., 2009; Lopez & Villalba, 2011; López et al., 2017; Granato-Souza et al., 2018). The development of a dendrochronological network is an important step to address the spatio-temporal complexity of the climate patterns regulating rainfall frequency and intensity over the Amazon basin (Sorí et al., 2018).

A well-dated moisture sensitive tree-ring chronology based on *Cedrela odorata* from the Rio Paru State Forest in the eastern Amazon has been recently reported (Granato-Souza et al., 2018). The first rainfall reconstruction for the eastern Amazon was based on this chronology and it revealed regional and large-scale influences on precipitation variability, as well as changes in the frequency of the dry and wet episodes predating the instrumental era. However, this Rio Paru chronology is the only annually resolved climate proxy for the recent past in the eastern Amazon and it needs to be validated with additional collections to confirm the crossdating and climate signal. This paper reports on recent efforts to validate the Rio Paru chronology and build a network of *Cedrela* chronologies in the eastern Amazon. We describe tree-ring collections of *Cedrela odorata* from five different sites in the eastern Amazon basin and report a well-dated and replicated chronology for a new site near the Rio Paru that substantiates our previous chronology. We then use correlation analysis with gridded monthly precipitation data from the Amazon and with global sea surface temperature (SST) data to document the climate response of these two Rio Paru chronologies. We also describe the potential to develop additional *Cedrela* chronologies at other locations in the eastern Amazon.

2 MATERIALS AND METHODS

2.1 Target species and sampling

This project concentrated on the collection of cross sections of *Cedrela* sp. from logging concessions and construction sites in the eastern Amazon. The various species of *Cedrela* are well-known for their dendrochronological potential in Neotropical environments, including the forests of the Amazon (Dünisch et al., 2002; Brienen et al., 2012), mostly because of their moisture sensitive behavior under seasonal conditions (Kunert et al., 2010; Granato-Souza et al., 2018; Pereira et al., 2018), the presence of distinct annual growth rings (Brienen & Zuidema, 2005; Paredes-Villanueva et al., 2016) and their widespread distribution across the lowland Amazon (terSteege et al., 2016). To develop a spatial network of *Cedrela* chronologies in the Amazon basin we arranged collaboration agreements with the owners and employees of legal logging companies (e.g., CEMAL, RRX FLORESTAL), construction firms (e.g., Norte Energia, the company responsible for the construction and operation of the Belo Monte hydroelectric project on the Rio Xingu), and the Environmental and Sustainability Agency in the state of Para (SEMAS). Full and partial cross-sections of *Cedrela odorata* were donated from public forests and legally cleared areas in the state of Para for growth ring analyses. A few *Cedrela fissilis* may also be included in some of the collections obtained from already cut trees, especially from the Belo Monte Project area on the Rio Xingu. In some cases plunge cuts were also obtained from living *Cedrela odorata* trees with the chain saw. All tree-ring specimens have been cataloged and permanently stored in the archives of the Tree Ring Laboratory of the Federal University of Lavras where they are available for further scientific research.

Only full and partial cross-sections were used in this study because tropical hardwoods often have complex xylem anatomy and anatomical anomalies such as missing rings, false rings, resin bands, and distorted growth rings (Dünisch et al., 2002; Lopez & Villalba, 2016) that greatly complicate the analysis of narrow core samples. Increment cores often do not provide sufficient surface area to reliably identify annual rings (Stahle et al., 1999) and build well-dated chronologies. All cross sections were dried and highly polished to reveal a clear surface and the minute cellular anatomy of the annual rings. *Cedrela* sp. usually presents distinct annual growth rings, marked by semi-porous structure, delimited by marginal parenchyma (Dünisch et al., 2002; Brienen & Zuidema 2005).

2.2 Tree ring analyses

Most of our collections were obtained from logging operations so we relied on informant information to identify the exact cutting date of the trees. In most cases, this was the same year we collected the cross sections. But because we sampled hundreds of logs and the cutting date on some of them has been forgotten even by the crews who felled the trees. This added to the difficulty of crossdating at the Altamira National Forest, Monte Alegre, and the Rio Xingu, but the felling dates for the Rio Paru collections are known with certainty. Individual time series were crossdated using skeleton plots and visual dating under the microscope (Douglass, 1941; Stokes & Smiley, 1996). The “Schulman Shift” (Schulman, 1956) was not applied to the dated samples from Rio Paru sites, because the wet season typically begins in February in this area and the Rio Paru tree-ring chronologies respond most strongly to precipitation during the current calendar year (February to November, see Granato-Souza et al., 2018). However, the Schulman Shift was applied to the dated samples from the Altamira site because the wet season typically begins in October and concludes in April, so in this case it is reasonable to follow the Southern Hemisphere convention and assign the calendar date to the year when trees begin growth (i.e., the Schulman Shift).

Dated ring-widths were measured using the LINTAB-TSAPTM measuring device (Rinntech, 2017) with a precision of 0.01mm. The dating and measurement accuracy of the derived time series were checked by the program COFECHA (Holmes, 1983). Dated time series were detrended and standardized with an age-dependent spline to remove any non-synchronous and non-climatic trends (multi-decadal to centennial) using the program ARSTAN (Cook, 1985; Cook & Krusic, 2005). Each measured annual ring-width was divided by the respective value of the fitted curve, producing the derived tree-ring indices (ratios). Then all ring-width index series were averaged on a year-by-year basis producing the final mean index chronology (Cook, 1985; Cook & Krusic, 2005). Several statistics computed with the program ARSTAN were used to describe the internal consistency of the ring width series and the final mean index chronology, including mean sensitivity, the mean correlation between series (RBAR; Cook & Pederson, 2011) and the expressed population signal (EPS; Wigley et al., 1984).

These chronology development procedures maximized the high to medium frequency (e.g., interannual to decadal) variance between the time series because the lower frequencies do not seem to synchronize among trees. The short length of the time series complicates the identification of low frequency tree growth and climate variance. In fact, the low frequency variability in these relatively young *Cedrela* series may largely reflect age trend and stand

dynamics (e.g., Granato-Souza et al., 2018). For this reason, all final mean index chronologies were further filtered with a nine-point binomial weighting scheme to remove decadal and longer variance from the chronologies and emphasize just the interannual to subdecadal variance in the time series.

2.3 Growth-climate analyses

Correlation analyses between the two chronologies from the Rio Paru and gridded monthly precipitation data were computed in order to define the strength and seasonality of the climate signal of these tree-ring time series (the coordinates of the extracted precipitation data are 5°N to 5°S, 48 to 60°W). Monthly precipitation totals were obtained from the Climatic Research Unit (CRU) TS4.00 0.5° gridded data set from 1901 to 2016 (Harris et al., 2014). Unfortunately, these gridded precipitation data are based on very few station observations before 1939 (Marengo, 2004; Fontalvo-Garcia et al., 2015; Lopez et al., 2017). As a result, we focus our analyses with the CRU precipitation data from 1939 to 2016, but also report the results for the full period in common to both the precipitation and tree-ring data.

Spatial correlations between the derived chronologies, the regional precipitation data, and global SSTs were computed to identify possible large-scale ocean-atmospheric teleconnections to precipitation and tree growth over the eastern Amazon. Data to test the presence of teleconnections were obtained from Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST) (Rayner et al., 2003). Spatial correlations were carried out with KNMI Climate Explorer (Trouet & Van Oldenborgh, 2013).

3 RESULTS

Over 300 cross sections of *Cedrela* have been acquired from five locations in the eastern Amazon. The sites are mapped in Figure 1 and the location information and specimen data are summarized in Table 1. The best results thus far have been obtained from the two collections sites near the Rio Paru. The analyses of the Rio Paru Sites A and B will be described first, followed by the results for the collections from the Altamira National Forest, Monte Alegre, and the Rio Xingu.

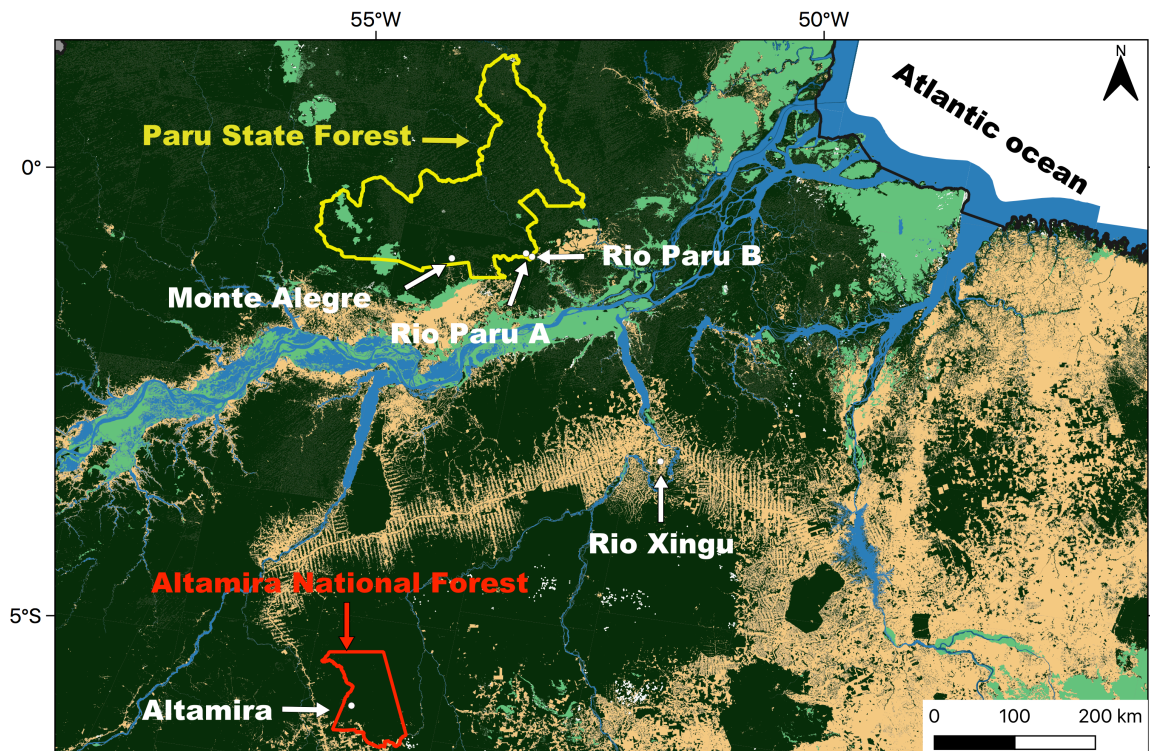


FIGURE 1 The tree-ring collection sites are located on this land cover map of the Brazilian Amazon River basin. The *Cedrela* specimens were collected in three different sites at the Paru State Forest, north of the Amazon River and near the southern escarpment of the Guiana Highlands, and two different sites south of the Amazon River, at the Altamira National Forest and Rio Xingu. The land cover areas with forest (dark green), non forested vegetation (light green), deforestation (beige) and the hydrography are shown (blue) (updated data by: <http://mapbiomas.org/>).

TABLE 1 Geographic information and specimen data for the five *Cedrela* collections from the eastern Amazon.

Site Name	Forest type	Latitude	Longitude	ntion	Cross-sections
Rio Paru A	Terra firme dense forest	0°57'S	53°19'W	175	47
Rio Paru B	Terra firme dense forest	0°59'S	53°15'W	90	95
Monte Alegre	Terra firme dense forest	1°00'S	54°09'W	328	41
Altamira	Terra firme dense/open forest	6°00'S	55°16'W	298	79
Rio Xingu	Terra firme dense/open forest	3°17'S	51°49'W	97	45

3.1 Paru State Forest chronologies

Cross-sections from 47 legally harvested *C. odorata* were obtained from the first site at Rio Paru State Forest (Rio Paru Site A) in January of 2017. These specimens from Rio Paru Site A were used to develop the first climate sensitive tree-ring chronology for the eastern Amazon (Granato-Souza et al., 2018). An additional 95 cross sections were collected from a second site in the same forest concession that was 10 km southeast of Rio Paru A and 80 m lower on elevation, referred to as Rio Paru B, in an effort to validate the tree-ring chronology first developed at Site A. Well-formed concentric growth rings were found for both of the sites from the Rio Paru. A fully replicated chronology dating from 1786 to 2016 was developed based on 56 radii from 27 different trees from Paru A (Figure 2a). At Site B near the Rio Paru a chronology dating from 1759-2016 was developed based on 120 radii from 60 trees (Figure 3a).

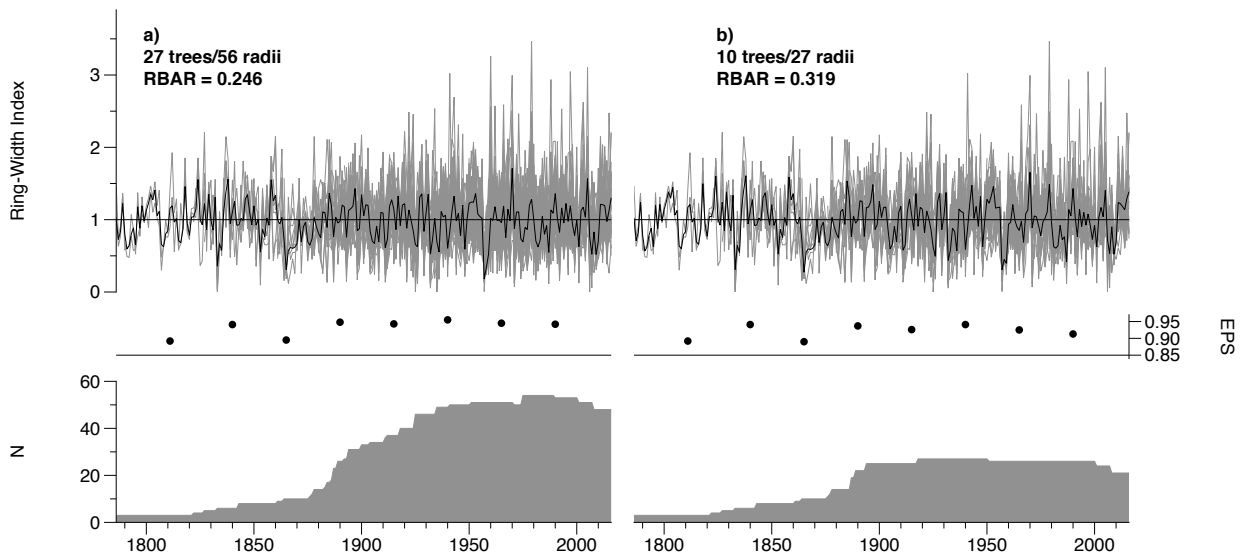


FIGURE 2 Dated, detrended, and standardized radii of *Cedrela odorata* (gray time series) obtained from the first site at the Paru State Forest, Paru A, are plotted along with the mean index standard chronology (black) from 1786 to 2016. The EPS values and the sample depth for each year are also plotted. (a) The 56 radii from 27 trees and (b) a subset of the 27 radii from 10 trees that is longest and most strongly correlated. Both data sets pass the 0.85 EPS threshold test.

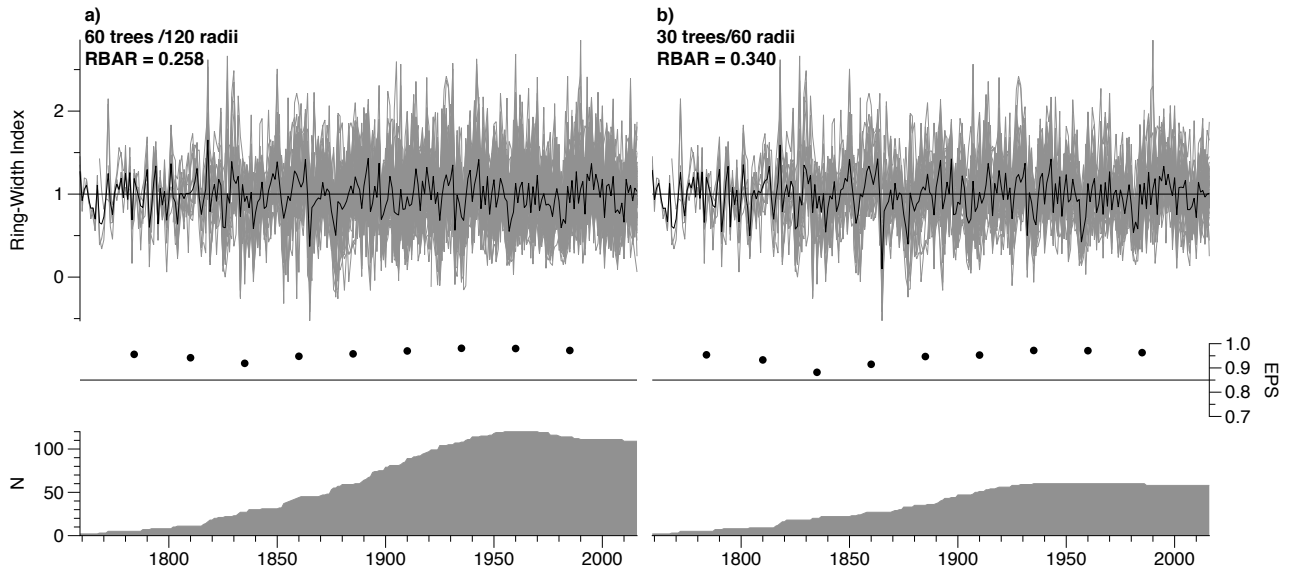


FIGURE 3 Dated, detrended, and standardized radii of *Cedrela odorata* (gray time series) obtained from the second site at the Paru State Forest, Paru B, are plotted along with the mean index standard chronology (black) from 1759 to 2016. The EPS values and the sample depth for each year are also plotted. (a) The 120 radii from 60 trees and (b) a subset of the 60 radii from 30 trees that is longest and most strongly correlated. Both data sets pass the 0.85 EPS threshold test.

The fully replicated chronologies from Rio Paru Sites A and B are well correlated internally and between the two sites (Table 2). Nevertheless, Granato-Souza et al. (2018) found that the best correlated subset of trees and radii from Rio Paru Site A actually had the strongest correlation with regional and large-scale climate data (i.e., 27 radii from 10 trees). Therefore, the most internally consistent subset of trees and radii from Site B was also identified using correlation analysis to investigate the climate signal, in this case using 60 radii from the 30 oldest and best cross-correlated trees (Figure 3b).

TABLE 2 Statistical parameters of the Rio Paru standard chronologies from the eastern Amazon basin.

Site	Time span	Trees/Radii	Mean sensitivity	Mean EPS	Mean RBAR
Rio Paru A	1786-2016	27/56	0.376	0.932	0.246
Rio Paru B	1759-2016	60/120	0.422	0.958	0.258

Note that 60% of the total collected samples of each site were of sufficient quality to be used to the development of the chronologies. Most of the remaining 40% could also be dated with dendrochronology, but some were either short or were collected from stumps near the root collar which degraded the common growth pattern, and thus were excluded from further analyses. Despite the presence of good correlation among all dated trees at Paru A and

B, the subsets based on the oldest and best cross-correlated trees provided chronologies that have the strongest climate signal at both sites.

3.2 Correlation between Rio Paru A and B

The chronologies from Rio Paru A and B were correlated in an attempt to confirm the dating analysis of Granato-Souza et al (2018) based only on the single chronology from Paru A (Table 3). The residual chronologies computed with ARSTAN were used in this analysis, along with filtered versions of both chronologies that emphasize the high frequency (HF) and low frequency (LF) variance of each series. A 9-point binomial filter was used to process the chronologies (Granato-Souza et al., 2018). The correlation coefficients computed between the residual chronologies are slightly higher than the standard versions of these chronologies (not shown). These results indicate that all types of chronologies from Rio Paru A and B are significantly correlated, but the 9-point filtered versions have the highest correlations. These results confirm the original dating of the Rio Paru A chronology with the new record from Rio Paru B. The results also indicate that the two chronologies are most strongly related in the high frequency interannual to subdecadal time scales, suggesting that the lower frequency components of both chronologies may be governed by age trend and or stand dynamics. These frequency-based correlation results are supported by coherency analysis which indicates significant coherence between Sites A and B at high frequencies, but no significant coherence at the lowest frequencies (Figure 4). A comparison between the unfiltered and filtered versions of the Rio Paru A and B chronologies, and also the resulted regional Rio Paru chronology is shown in figure 5.

TABLE 3 Pearson correlation matrix between all the versions of the Rio Paru chronologies over 1786-2016. The 9-point filtered versions (HF) and the low frequency components (LF) of both chronologies were also tested to check the synchronism among interannual to subdecadal and decadal to centennial periodicity over both ring width datasets.

Chronologies	Rio Paru A	Rio Paru B	Rio Paru A HF	Rio Paru B HF	Rio Paru A LF
Rio Paru B	0.63	-			
Rio Paru A HF	0.90	0.62	-		
Rio Paru B HF	0.59	0.91	0.68	-	
Rio Paru A LF	0.63	0.31	0.22	0.11	-
Rio Paru B LF	0.35	0.61	0.14	0.21	0.51

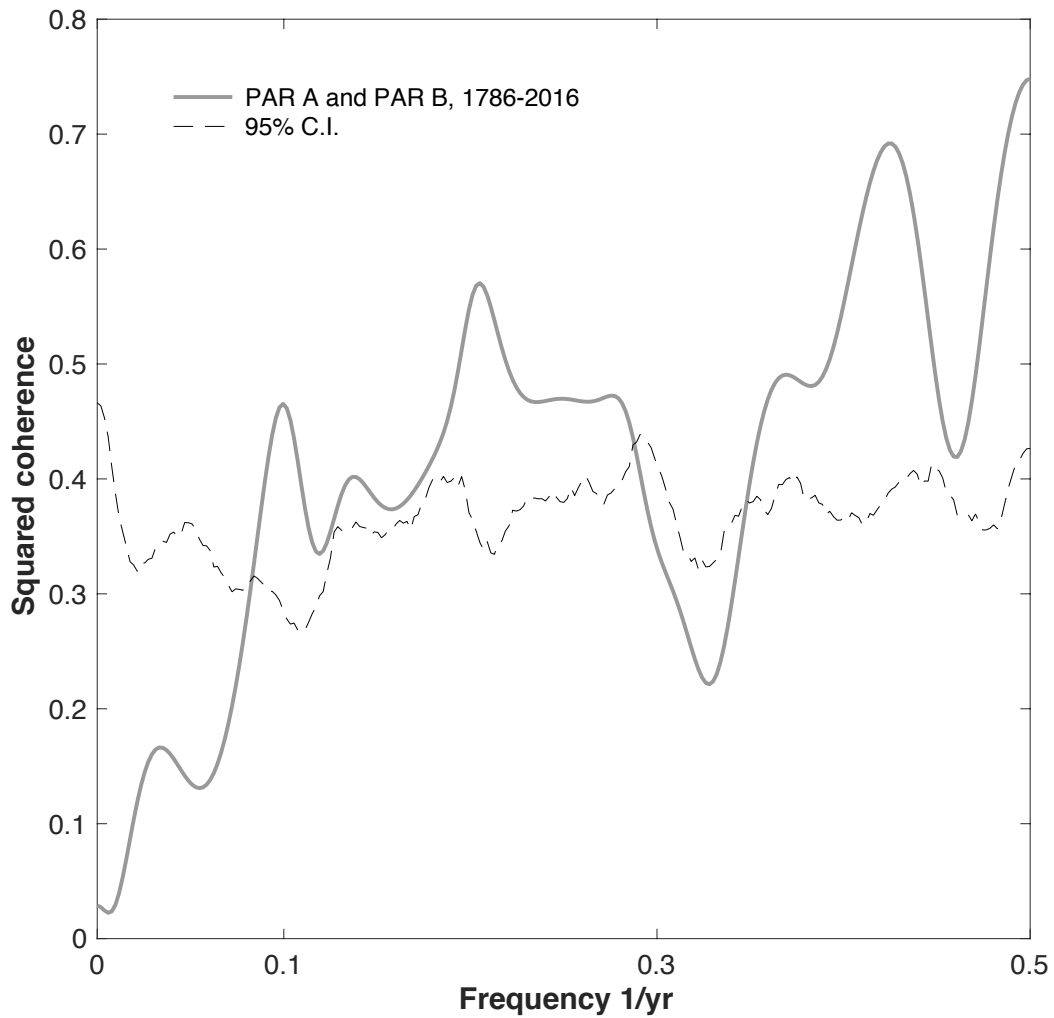


FIGURE 4 Spectral coherence analysis between the Rio Paru A and B standard chronologies performed over 1786-2016. Significant coherence under 2-10 years periodicity and no coherence between both chronologies under low frequencies. The 95% confidence level is estimated through 10,000 runs of Monte Carlo simulations.

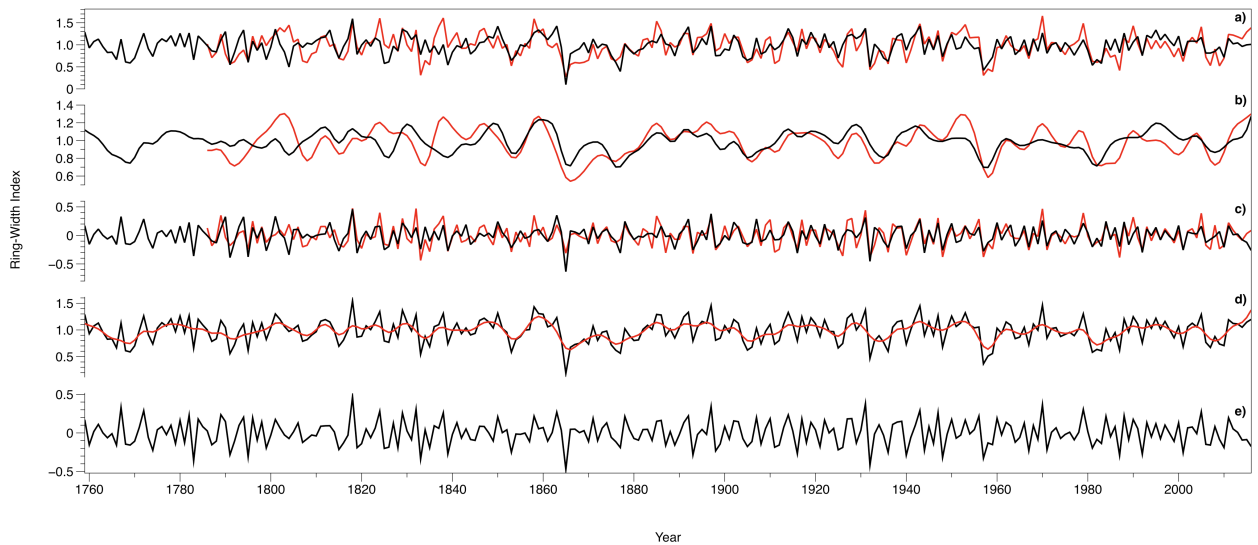


FIGURE 5 Comparisons between the filtered and unfiltered standard versions of the Rio Paru chronologies over 1786-2016. (a) Rio Paru A and B chronologies; (b) Low frequency components; (c) High frequency components; (d) Regional Rio Paru (black line) and its smoothed version (red line); (e) High frequency components of the Regional Rio Paru chronology. Rio Paru A and Rio Paru B are indicated by red line and black line on a, b and c.

3.3 Climate-Growth relationship of Rio Paru chronologies

Correlation analyses between the new Rio Paru Site B chronology and the CRU gridded precipitation data (1939-2016) confirmed previous results described in Granato-Souza et al. (2018) for Rio Paru Site A. Both chronologies from Site A and B, and a regional average of these two series, are positively correlated with precipitation during most months of the calendar year, starting in February and extending through November (Figure 6a, b, c). Spatially, the Rio Paru A and B chronologies show similar widespread positive correlations with Feb-Nov precipitation totals over the eastern Amazon and Guiana highlands for the 1939-2016 period (Figure 7). Small differences between the chronologies include a stronger correlation over the extreme eastern Amazon and Guiana highlands for Site A, and a more westward distribution of the signal for Site B (Figure 7a, b). The Regional Rio Paru chronology reinforces the spatial patterns of both chronologies, with a somewhat stronger regional precipitation signal overall (Figure 7c).

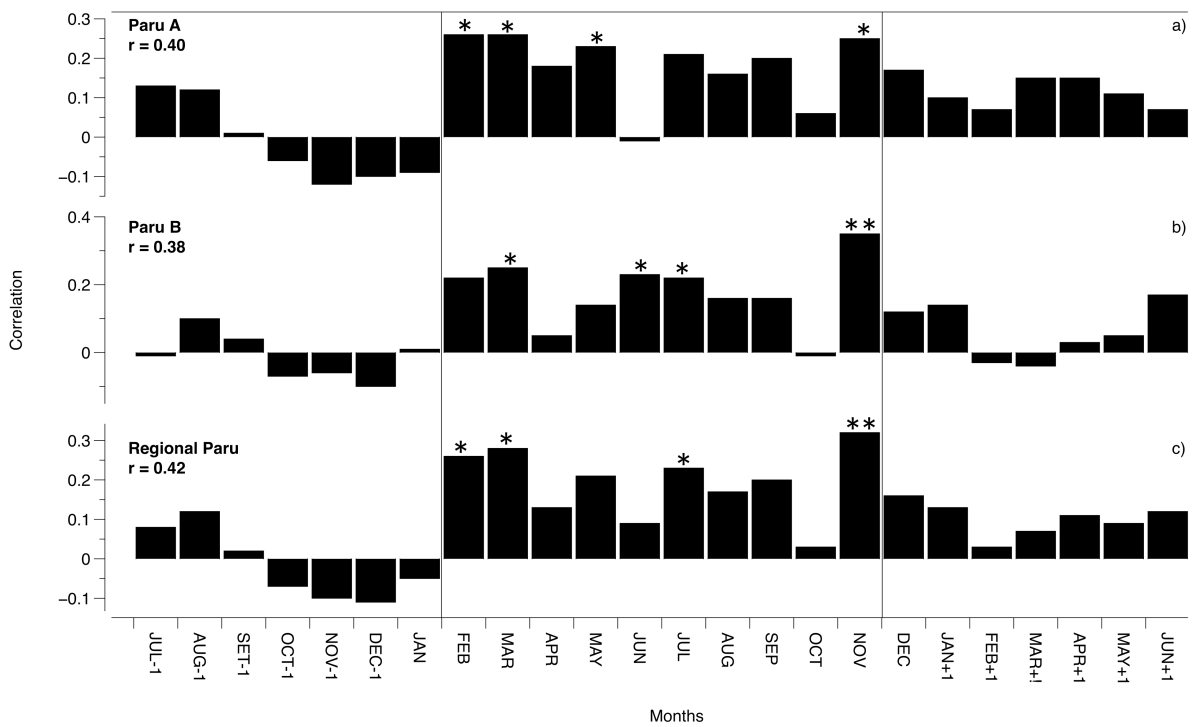


FIGURE 6 The monthly values for the CRU TS4.00 gridded precipitation (5N5S and 60-48W) were correlated with the Rio Paru standard chronologies from 1939 to 2016 to identify the monthly precipitation totals most important to the radial growth of *Cedrela* from the Rio Paru for a 24-month period including 6 months prior to (-1) and following (+1) the year concurrent with growth. (a) Rio Paru A chronology; (b) Rio Paru B chronology; (c) Regional Rio Paru chronology. Significant correlations are noted with asterisks (* $p < 0.05$, ** $p < 0.01$; the Feb-Nov correlation values are indicated in the figure).

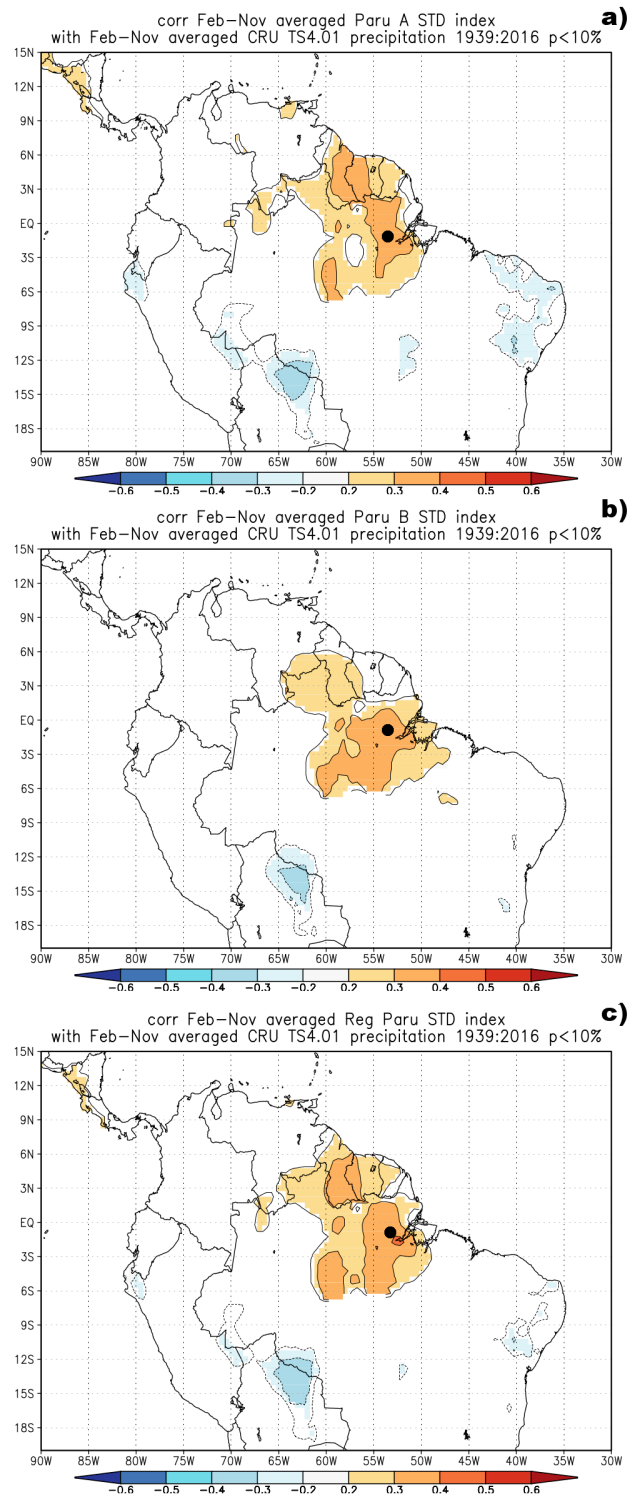


FIGURE 7 The spatial pattern of correlation computed between the (a) Rio Paru A, (b) Rio Paru B and (c) Regional Rio Paru standard chronologies from Paru State Forest (black dots) and CRU TS 4.00 0.5° gridded February–November total precipitation is illustrated for 1939–2016.

3.4 Teleconnections between Rio Paru chronologies and SST's

Spatial correlations between the Rio Paru A and B chronologies and the gridded SSTs (averaged for February-April) confirm the signal previously described for the Rio Paru A chronology (Granato-Souza et al., 2018). The 9-point binomial filter was used to remove decadal and longer variability from both the instrumental precipitation data and the Rio Paru chronologies prior to these comparisons with SST data. Weak negative correlations with the SST's anomalies in the eastern equatorial Pacific are observed in both ring width datasets during the entire instrumental era from 1870-2016, but the SST signal is stronger in these two chronologies after 1939. Granato-Souza et al. (2018) detected a February-November SST signal consistent with the precipitation data from 1939-1990 and it is perhaps slightly stronger for just February-April (Figure 8a). This seasonalization of the SST's does not cross the typical boreal spring transition season that is part of the climatology of ENSO. However both February-April and February-November SST signals in Rio Paru A chronology weaken after 1990 (Figure 8b). The Rio Paru B chronology is stably correlated with the SST's in the eastern equatorial Pacific in the full overlap from 1939-2016, and it does not weaken dramatically after 1990 (Figure 8c). The February-April SST's correlation in both Rio Paru chronologies is also strongly present in the instrumental PPT data for the eastern Amazon (Figure 8d). The Regional Rio Paru chronology shows the same patterns associated with the El Niño/Southern Oscillation (ENSO) as the Rio Paru B chronology (not shown).

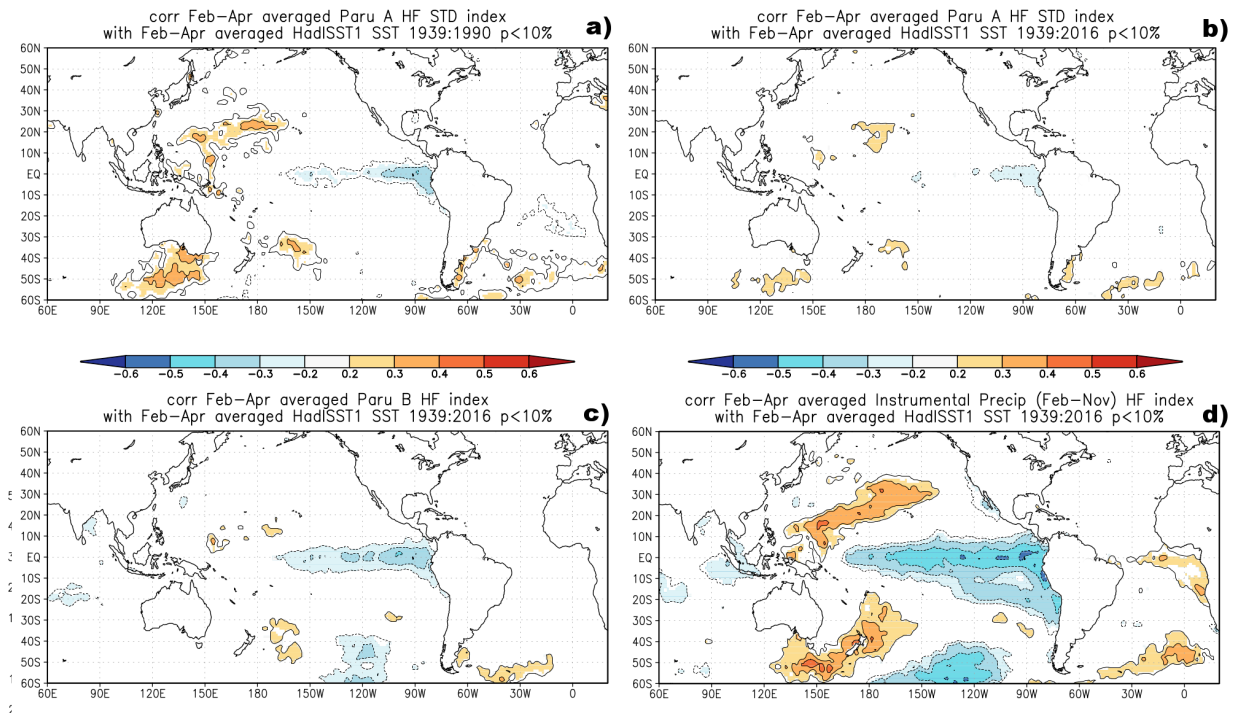


FIGURE 8 The filtered versions of the Rio Paru A standard chronology during 1939-1990 (a) and 1939-2016 (b), the Rio Paru B standard chronology during 1939-2016 (c) and the instrumental February–November precipitation totals (5N5S and 60–48W) (d) were correlated with the gridded CRU SSTs averaged for February–April. Similar relationships are observed to the instrumental precipitation and the Rio Paru chronologies. The series were first filtered to emphasize interannual to subdecadal variability. Significant negative relationships are colored blue ($p < 0.10$).

3.5 *Cedrela* chronology development at Altamira, Monte Alegre, and Rio Xingu

Cross-sections were obtained from 79 *C. odorata* logs legally cut from the Altamira National Forest, located approximately 500 km to the southwest of the Rio Paru sites. The crossdating among these specimens is very strong and a chronology based on 80 radii from 44 different trees has been developed for the Altamira National Forest. Unfortunately, the exact cutting date of these logs is not well known. We have tentatively assigned the absolute dating of the Altamira chronology to 1878-2009 (Figure 9), based on the weak correlation with the Rio Paru Site B chronology at this calendar dating position ($r = 0.40$, based on the high frequency components and best replicated subperiod of the two chronologies, $5_{\text{trees}}/12_{\text{radii}}$ and $30_{\text{trees}}/60_{\text{radii}}$ for Altamira and Rio Paru B respectively during 1944-2009). There is no doubt about the internal crossdating among the trees and radii at Altamira, as can be documented with the computer program COFECHA and by the strong average correlation among the component specimens computed with ARSTAN (RBAR = 0.233). Nevertheless, additional

collections from living trees in the Altamira National Forest will be required to firmly document the true calendar year dating of this collection. Once the exact dating is confirmed, the climate response of the Altamira chronology can be investigated.

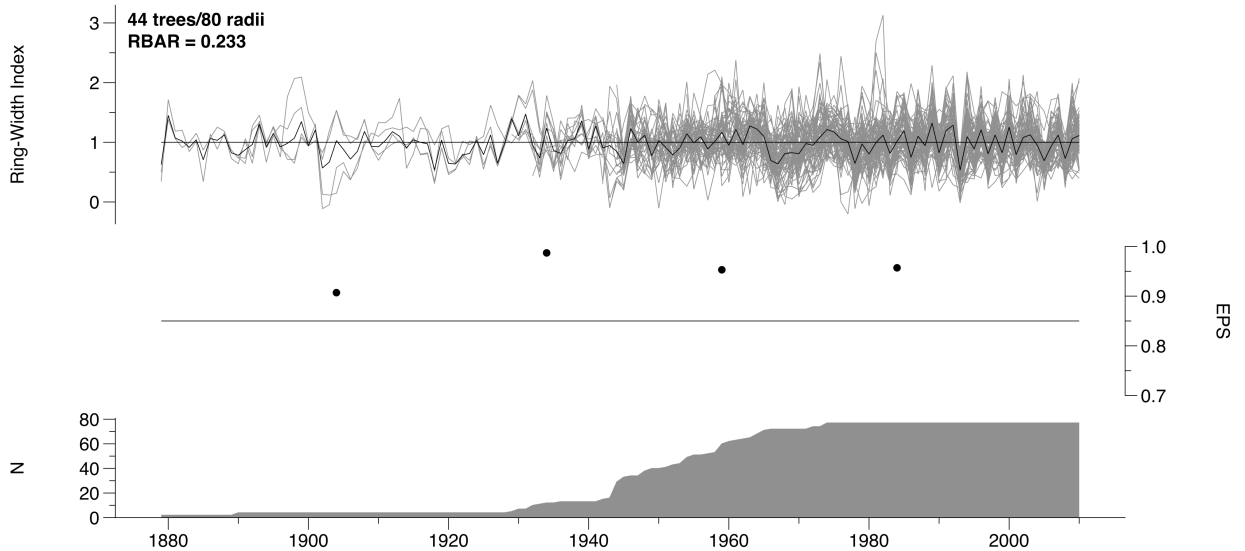


FIGURE 9 Provisional dated, detrended, and standardized radii of *Cedrela odorata* (gray time series) obtained from the Altamira National Forest are plotted along with the mean index standard chronology (black) from 1880 to 2009. The EPS values and the sample depth for each year are also plotted.

Cross-sections and plunge cuts were obtained from 41 *C. odorata* near Monte Alegre, a site that is also in the Rio Paru State Forest, but located approximately 90 km west of Rio Paru Sites A and B. A few very old *Cedrela odorata* trees were found at the Monte Alegre site, one of which is estimated to have at least 400 annual rings. If confirmed with dendrochronology, this would be the oldest *Cedrela* yet reported. Unfortunately, the complex and suppressed growth rings observed in the available collections from Monte Alegre could not be successfully crossdated. Additional collections from this promising site will be required to resolve the dating at Monte Alegre, which has great potential to provide an exceptionally long *Cedrela* chronology.

Suppressed growth and other wood anatomical anomalies were observed in most *Cedrela* cross sections from the Rio Xingu collection site (these collections may include both *C. odorata* and *C. fissilis*). These anomalies included eccentric growth, resin bands, ring wedging, and what appear to be false intra-annual parenchyma bands. The 45 Rio Xingu cross sections came from an area of forest that may have previously suffered human impacts. The

species inventory of the trees removed for construction of the Belo Monte project indicates that the felled trees are dominated by species with low quality wood, suggesting that the area had been high degraded in the past. This high grading may have included canopy dominant *Cedrela*, because the relatively few *Cedrela* cut during construction of the Belo Monte project and available for our sampling appear to have been suppressed understory trees.

4 DISCUSSION AND CONCLUSIONS

The first tree-ring chronology developed for the eastern Amazon Basin at Rio Paru Site A has been used to reconstruct rainfall over the region from 1786-2016 (Granato-Souza et al., 2018). This reconstruction has provided new information on natural climate variability in a region with relatively short instrumental observations. The new chronology from Rio Paru Site B extends from 1759-2016 and provides important confirmation of the dating and climate response of Rio Paru Site A. The trees from both Rio Paru sites have clear and concentric annual growth rings. The dated ring width series from both sites are highly cross correlated, both internally and between the two sites, in spite of the fact that they grew in different locations within the complex humid forests of the eastern Amazon. Rio Paru Site A and B are both well correlated with regional rainfall totals and with sea surface temperatures in the eastern equatorial Pacific. This SST correlation in the Rio Paru chronologies is weaker than the correlation computed for instrumental precipitation data from the eastern Amazon, but like the instrumental precipitation data the correlation with SST is negative and largely restricted to the cold tongue region of the eastern Pacific. Furthermore, the SST response of the new Rio Paru B chronology is stronger and more stable over time compared to the patterns found for the Rio Paru A chronology. The weakening of the climate signal after the 1990 in the chronology from Rio Paru A was reported by Granato-Souza et al. (2018) and might be related to site-specific factors or might arise simply from random variability in the tree growth and climate relationship. The strong crossdating and stable climate signal are important contributions from the second Rio Paru chronology. Based on both chronologies from the Rio Paru, we conclude that a fraction of *Cedrela* growth in the eastern Amazon is sensitive to both the inter-annual variability of regional rainfall and the influence of large-scale ocean-atmospheric forcing from the equatorial Pacific.

The new Rio Paru chronologies are also promising first steps to the construction of a well-replicated network of exactly dated tree-ring chronologies in the equatorial Amazon. The preliminary analysis of *Cedrela* cross sections from the Altamira National Forest indicates that it should be possible to expand the network of chronologies in the tropical forests of this

region. This developing network of rainfall sensitive tree-ring chronologies could help place observed hydroclimate variability into a longer historical perspective, including the recent extreme droughts and floods over the Amazon (Gloor et al., 2013; Marengo et al., 2013; Marengo & Espinoza, 2016).

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