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SÉRGIO AUGUSTO SANTOS XAVIER

RESPOSTAS DA VEGETAÇÃO DE CERRADO ÀS MUDANÇAS CLIMÁTICAS E ATIVIDADES ANTRÓPICAS NO NORDESTE DO BRASIL DURANTE O HOLOCENO TARDIO

Volume 1

FORTALEZA
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Orientadora: Profª. Drª. Francisca Soares de Araújo (Universidade Federal do Ceará).
Orientadora: Drª. Marie-Pierre Ledru (Universidade de Montpellier).

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BANCA EXAMINADORA

Dr. Yannick Miras
Centre National de la Recherche Scientifique (CNRS)

Profª. Drª. Raquel Franco Cassino
Universidade Federal de Ouro Preto (UFOP)

Prof. Dr. Pierre-Olivier Antoine
Université de Montpellier (UM)

Prof. Dr. Rafael Costa
Universidade Federal do Ceará (UFC)

Drª. Myriam Khodri
Institut de Recherche pour le Développement (IRD)

Profª. Drª. Ingrid Horák-Terra
Universidade Federal do Vale do Jequitinhonha e Mucuri (UFVJM)

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Réponses de la végétation du Cerrado aux changements climatiques et aux impacts humains dans le Nord-est du Brésil au cours de l'Holocène supérieur

Présentée par Sergio XAVIER
Le 10 juillet 2023

Sous la direction de Drª. Marie Pierre LEDRU
et Profª. Drª. Francisca Soares de ARAÚJO

Devant le jury composé de

Dr. Yannick MIRAS, Ingénieur de Recherche, Centre National de la Recherche Scientifique, Paris, France	Rapporteur
Drª. Raquel Franco CASSINO, Professeure, Université Fédérale d'Ouro Preto, Brésil	Rapportrice
Dr. Rafael COSTA, Professeur, Université Fédérale du Ceará, Brésil	Président/Examinateur
Dr. Pierre-Olivier ANTOINE, Professeur, Université de Montpellier, France	Examinateur
Drª. Ingrid HORÁK-TERRA, Professeure, Université Fédérale des Vallées de Jequitinhonha et Mucuri, Brésil	Examinatrice
Drª. Myriam KHODRI, Directrice de Recherche, Institut de Recherche pour le Développement, Paris, France	Examinatrice
Drª. Francisca Soares de ARAUJO, Professeure, Université Fédérale du Ceará, Brésil	Co-directrice de thèse
Drª. Marie-Pierre LEDRU, Directrice de Recherche, Université de Montpellier, France	Directrice de thèse

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PREFÁCIO

Esta tese de doutorado está estruturada em dois volumes. No volume 1 estão presentes: Capítulo I – Introdução Geral que inclui embasamento teórico, objetivos, justificativa, área de estudo e métodos (em português e francês), Capítulo II – artigo publicado na revista *Anthropocene* (Impact Factor 3.9), Capítulo III – artigo submetido na revista *The Holocene* (Impact Factor 3.0). O Capítulo IV consiste em um artigo que será valorizado e aprimorado após a defesa. Os anexos de cada artigo encontram-se no final dos capítulos correspondentes. Ademais, o volume 1 integra os principais resultados, uma discussão geral, conclusão e perspectivas (em português e francês). No volume 2, encontram-se os complementos. O esboço geral da tese é delineado a seguir:

Volume 1

Capítulo I / Chapitre I: Introdução Geral (Introduction Générale)

Capítulo II / Chapitre II: Xavier, S.A.S., Araújo, F.S., Ledru, M-P. (2022). Changes in fire activity and biodiversity in a Northeast Brazilian Cerrado over the last 800 years. *Anthropocene* https://doi.org/10.1016/j.ancene.2022.100356

Capítulo III / Chapitre III: Xavier, S.A.S., Ledru, M-P., Bremond, L., Favier, C., Araújo, F.S. Millennial-scale variability of vegetation and fire activity in a northern Cerrado driven by an east-west rainfall gradient during the Holocene. *The Holocene*, submetido.

Capítulo IV / Chapitre IV: Xavier, S.A.S., Ledru, M-P., Wainer, I., Araújo, F.S. 6000 years of monsoon driven east-west antiphasing of Northeastern Brazil vegetation.

Discussão geral e conclusão (Discussion générale et conclusion)

Perspectivas (Perspectives)

Volume 2

Complementos: histórico escolar, certificados, participação em eventos científicos, resumos, artigos e outras produções científicas que o doutorando é primeiro autor ou coautor, produzidos durante o curso de Doutorado.

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RESUMO

Nas próximas décadas, espera-se que o Cerrado (savana brasileira) sofra mudanças estruturais e tenha suas dinâmicas naturais alteradas devido ao aquecimento global em curso e às pressões antrópicas. Neste contexto, os estudos paleoecológicos permitem a reconstituição das paisagens passadas quando estas foram submetidas a diferentes condições climáticas e outras práticas agrícolas. O objetivo desta tese é estudar e entender as interações entre vegetação, mudanças climáticas e regimes de fogo durante os últimos 6.000 anos no Cerrado do Nordeste do Brasil (NEB). Análises multiproxy (pólen e carvão) foram realizadas em dois testemunhos sedimentares, SAC18 coletado no Parque Nacional de Sete Cidades, Norte do Piauí, e VDD-13 coletado no Parque Nacional da Chapada das Mesas, Sudoeste do Maranhão. Em Sete Cidades, a vegetação aberta dominou de 1200 a 1350 EC. Incêndios naturais ocorreram na transição da fase seca para a úmida por volta de 1350-1400 EC. Então, de 1400 EC em diante, um cerrado arbóreo e uma vereda se expandiram quando a Zona de Convergência Intertropical se deslocou para o sul. Três diferentes práticas de uso da terra foram observadas: ameríndios entre 1400 e 1650 dC, europeus entre 1650 e 1960 dC e políticas de conservação a partir de 1961 dC, que mitigou o desmatamento e os incêndios. Na Chapada das Mesas, a vegetação aberta dominou durante a fase seca de 6.000 a 5.200 anos cal AP, quando a convecção das monções foi enfraquecida. Então, um cerrado lenhoso e uma vereda durante uma fase úmida se expandiram de 5200 para 4300 anos cal AP, quando a umidade das monções aumentou. Quase nenhum incêndio foi observado, o que pode ser atribuído à menor disponibilidade de combustível durante a fase seca e da biomassa úmida durante a fase úmida. Nove amostras estéreis caracterizaram um forte período seco em torno de 4.200 anos cal AP, que durou até 3.600 anos cal AP. A reorganização de táxons resistentes à seca e táxons relacionados à umidade indicaram aumento da umidade para um clima sazonal, com incêndios constantes até 2.600 anos cal AP. Em seguida, cessaram as queimadas e a expansão do cerrado arbóreo, das veredas e da mata ciliar marcaram o início de um período úmido, quando as monções se intensificaram a oeste. Esta reconstituição paleoecológica, com base nos resultados desta tese e outros registros, lança uma nova luz sobre o clima regional do NEB durante os últimos 6.000 anos. Entre 6.000 e 5.200 anos cal AP, uma vegetação aberta no Oeste atestou condições secas causadas pelo enfraquecimento da convecção das monções na bacia amazônica. Entre 5.200 e 4.200 anos cal AP, a expansão do cerrado lenhoso e da floresta amazônica no oeste do NEB e dos táxons de palmeiras e árvores no leste do NEB refletiu taxas de umidade mais altas em toda a região. Após 4.200 anos cal AP, o desenvolvimento da Caatinga no Leste atestou a instalação de um clima seco, enquanto a expansão da floresta amazônica e do Cerrado no Oeste refletiu o fortalecimento das monções. Incêndios naturais ocorreram principalmente no leste do NEB entre 6000-4200 anos cal AP. Desde 3000 anos cal AP, a intensificação das atividades humanas na região é caracterizada por um aumento na atividade de fogo em condições secas e úmidas. Durante os últimos 6.000 anos, a vegetação no Oeste foi mais sensível à variabilidade das monções e no leste mais sensível às mudanças ITCZ e temperatura da superfície do mar (SST). A atividade antrópica no NEB foi mais forte após 3.000 anos cal AP, quando os grupos nativos se espalharam pela região. Consequentemente, a história do regime de fogo no NEB foi uma combinação de dinâmica natural entre vegetação e clima durante o Holoceno médio-tardio e interações homem-ambiente durante o Holoceno tardio. Hoje, as previsões mostram que a mudança das monções para o sul e o aumento da SST podem levar ao esgotamento das chuvas e temperaturas mais altas no NEB, causando redução da cobertura vegetal regional no leste e oeste do NEB e perda de biodiversidade.

Palavras-chave: pólen, carvão vegetal, bioma Cerrado, história do fogo, uso da terra, política de conservação, biodiversidade

RÉSUMÉ

Au cours des prochaines décennies, le Cerrado (les savanes au Brésil) devrait subir des changements structurels et voir sa dynamique naturelle altérée en raison du réchauffement climatique et des pressions anthropiques accrues. Dans ce contexte, les études paléoécologiques permettent la reconstruction des paysages du passé lorsqu'ils étaient soumis à d'autres conditions climatiques et pratiques agricoles. L'objectif de ce travail est d'analyser les interactions entre la végétation, le climat et l'activité des incendies au cours des 6000 dernières années dans le Cerrado du Nord-Est du Brésil (NEB). Des analyses multi-indicateurs (pollen et charbon) ont été réalisées sur deux carottes sédimentaires, SAC18 prélevée dans le Parc National *Sete Cidades* situé au nord de l'état du Piauí et VDD13 prélevée dans le parc national *Chapada das Mesas* dans le sud-ouest de l'état du Maranhão. A Sete Cidades, une végétation ouverte a dominé de 1200 à 1350 CE et des incendies naturels sont observés pendant la transition d'un climat sec vers un climat humide. A partir de 1400 CE, nous observons le développement d'un cerrado arboré et d'un marécage. Trois types d'usage des terres sont mis en évidence : les pratiques amérindiennes entre 1400 et 1650 CE, les pratiques européennes entre 1650 et 1960 CE et la politique de conservation à partir de 1961 CE, qui a mis fin à déforestation et incendies. A Chapada das Mesas, une végétation ouverte caractérise une phase sèche de 6000 à 5200 cal a BP lorsque l'activité de la mousson était plus faible. Puis, entre 5200 et 4300 cal a BP, l'expansion d'un cerrado arboré et du marécage s'accompagne de l'augmentation de l'humidité de la mousson. Les incendies n'ont pas été pas observés et ont été attribués à l'absence de combustible pendant la phase sèche, puis à l'humidité ensuite. La présence de neuf échantillons stériles en pollen caractérise un événement sec entre 4200 et 3600 cal a BP date à laquelle la réorganisation entre les taxons résistants à la sécheresse et les taxons humides indique un climat saisonnier avec de fréquents incendies jusqu'à 2600 cal a BP. Ensuite, les feux se sont arrêtés et l'expansion du cerrado arboré, du marécage et de la forêt galerie caractérise l'intensification de la mousson. Sur la base de ces résultats et d'autres enregistrements, une reconstruction du cadre paléoécologique apporte un éclairage nouveau sur le climat du NEB au cours des derniers 6000 ans. Entre 6000 et 5000 cal a BP, la végétation ouverte à l'ouest caractérise des conditions sèches dues à l'affaiblissement de la mousson sur le bassin amazonien. Entre 5200 et 4200 cal a BP, l'expansion du cerrado arboré et des taxons amazoniens à l'ouest du NEB, des marécages et des taxons arborés à l'est du NEB montrent des taux d'humidité importants sur toute la région. Après 4200 cal a BP, l'expansion de la forêt décidue (Caatinga) à l'est caractérise des conditions sèches alors qu'à l'ouest, l'expansion de la forêt amazonienne et du Cerrado caractérisent le renforcement des précipitations. Depuis 3000 ans l'intensification de l'activité anthropique est marquée par l'augmentation des incendies pendant des conditions sèches ou humides. Au cours des 6000 dernières années, la végétation à l'ouest était plus sensible à la variabilité de la mousson et à l'est plus sensible aux déplacements de la Zone de Convergence Intertropicale. L'histoire des régimes de feu régionaux était une combinaison de dynamiques naturelles entre la végétation et le climat au cours de l'Holocène moyen et récent et des interactions entre l'homme et son environnement au cours de l'Holocène récent. Aujourd'hui les prédictions montrent que le déplacement de la mousson vers le sud et l'augmentation des températures de surface océanique pourraient conduire à une diminution des précipitations et des plus hautes températures sur le NEB, entraînant la réduction de la couverture végétale et la perte de la biodiversité.

Mots clé : pollen, charbon, Cerrado, incendie, utilisation des terres, gestion de la conservation, biodiversité.

ABSTRACT

In the upcoming decades, the Cerrado (Brazilian savanna) is expected to undergo structural changes and altered natural dynamics due to the ongoing global warming and human pressures. In this context, palaeoecological studies allow the reconstruction of past landscapes when they were subjected to different climatic conditions and other agricultural practices. The aim of this thesis is to study and understand the interactions between vegetation, climate change and fire regimens during the last 6000 years in the Cerrado of Northeastern Brazil (NEB). Multiproxy analyses (pollen and charcoal) were carried out in two sediment cores, SAC18 was collected in Sete Cidades National Park, North of Piauí State, and core VDD-13 was collected in Chapada das Mesas National Park, Southwest of Maranhão State. At Sete Cidades, open vegetation dominated from 1200 to 1350 CE. Natural fires occurred at the transition from dry to wetter phase around 1350-1400 CE. Then, from 1400 CE onwards, a woody cerrado and palm swamp expanded when the Intertropical Convergence Zone shifted southward. Three different land use practices were observed: Amerindians between 1400 and 1650 CE, Europeans between 1650 and 1960 CE and conservation policy from 1961 CE onwards, which mitigated deforestation and fires. At Chapada das Mesas, open vegetation dominated during a dry phase from 6000 to 5200 cal yr BP, when the monsoon convection was weakened. Then, a woody cerrado and palm swamp during a moister phase expanded from 5200 to 4300 cal yr BP, when the monsoon moisture strengthened. Almost no fire was observed, which can be attributed to the lower fuel availability during the dry phase and the wet biomass during the moister phase. Nine sterile samples characterized a strong dry period around 4200 cal yr BP which lasted until 3600 cal yr BP. Reorganization of dry resistant taxa and moisture related taxa indicated increasing humidity to a seasonal climate, with constant fires until 2600 cal yr BP. Then, fires stopped and the expansion of woody cerrado, palm swamp and gallery forest marked the onset of a wet period, when the monsoon intensified in the west. This palaeoecological reconstruction, based on the results of this thesis and other records, sheds new light on the regional climate of NEB during the last 6000 years. Between 6000 and 5200 cal yr BP, an open vegetation in the western attested dry conditions caused by weakened monsoon convection on the Amazon basin. Between 5200 and 4200 cal yr BP, the expansion of woody cerrado and amazon rainforest taxa on western NEB and palm swamp and tree taxa in eastern NEB, reflected higher moisture rates all over the region. After 4200 cal yr BP, the development of Caatinga in the east attested the installation of a dry climate, while the expansion of the Amazon rainforest and Cerrado in the west reflected the strengthened monsoon. Natural fires occurred mostly in eastern NEB between 6000-4200 cal yr BP. Since 3000 cal yr BP, the intensification of human activities in the region is characterized by an increase in fire activity under dry and wet conditions. During the last 6000 years, the vegetation in the west was more sensitive to the monsoon variability and in the east more sensitive to the ITCZ shifts and Sea Surface Temperature (SST). Anthropogenic activity in NEB was stronger after 3000 cal yr BP, when native groups spread across the region. Consequently, the history of fire regimen in NEB was a combination of natural dynamics between vegetation and climate during the mid-late Holocene and human-environment interactions during the late Holocene. Today predictions show that monsoon shift to the south and SST increase could lead to rainfall depletion and warmer temperatures over NEB, causing reduction of regional vegetation cover in both eastern and western NEB and biodiversity loss.

Keywords: pollen, charcoal, Cerrado biome, fire history, land-use, conservation policy, biodiversity.

SUMÁRIO / SOMMAIRE

1. CHAPITRE I

INTRODUCTION GENERALE

1. INTRODUCTION GENERALE

Les changements climatiques et les modifications de l'utilisation des terres affectent, les modèles, la structure et le fonctionnement de écosystèmes. Parmi ces derniers, les savanes, des écosystèmes secs saisonnièrement qui sont distribués sur les régions tropicales d'Afrique, d'Australie et d'Amérique du Sud, couvrent environ 2,6 millions de km^2, soit 20% de la surface de la terre (Figure I.1) (Olson et al., 2001). La végétation est caractérisée par une couverture arborée clairsemée et une strate herbacée qui varient en composition, densité et structure en fonction du type d'environnement (Hutley and Setterfield, 2008). Les précipitations moyennes annuelles sont de 300 à 2000 mm avec une saison sèche annuelle d'une durée de 2 à 9 mois (Hutley and Setterfield, 2008). Les savanes ont aussi intégré différentes pratiques d'utilisation des terres telles que l'agriculture de subsistance, l'élevage, les terres cultivées, l'exploitation minière, le tourisme et la conservation. La structure et la productivité spatiale des savanes sont directement liées à la durée des saisons sèches et humides, à l'insolation totale annuelle, à la température et aux régimes des incendies (Aleman and Staver, 2018; Durigan, 2020; Moore et al., 2016; Murphy and Bowman, 2012; Sankaran et al., 2005). Elles ont une riche biodiversité et productivité, contribuant à 25% de la séquestration du carbone mondial and hébergent 1/5 de la population mondiale (Moore et al., 2016). Les communautés végétales sont formées d'un mélange d'arbres à feuilles persistantes, décidues et semi-décidues, de buissons, d'herbacées adaptées aux fluctuations annuelles de l'humidité, des nutriments et de l'activité des incendies (Hutley and Setterfield, 2008).

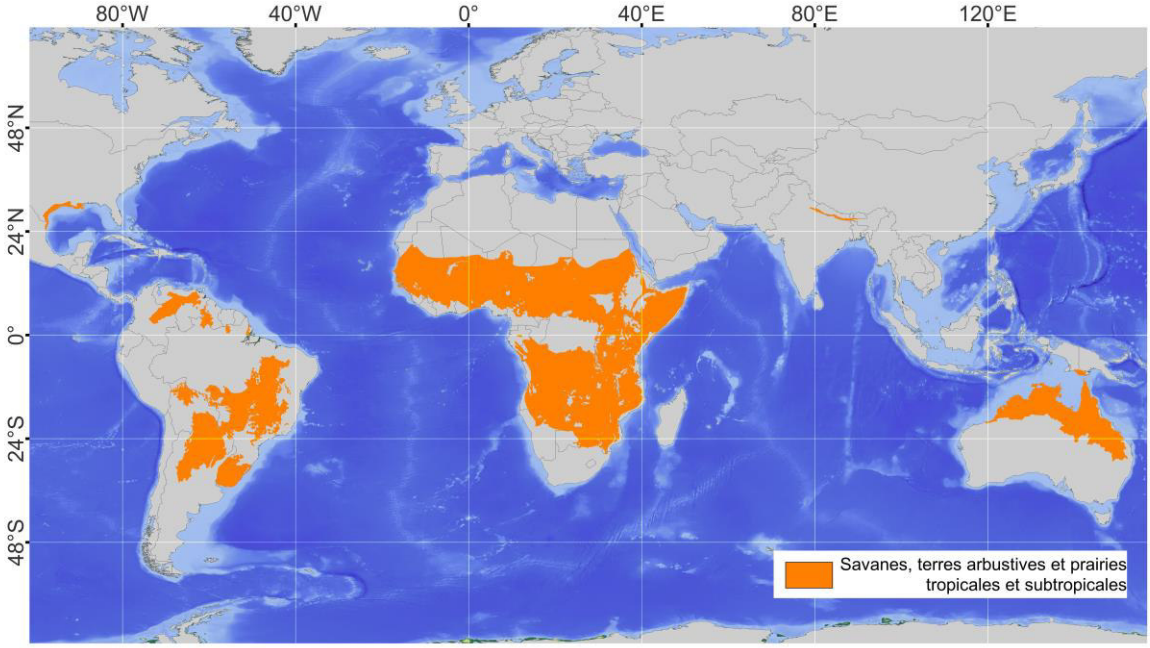

Figure I.1 : Carte de la distribution des savanes tropicales et subtropicales (Olson et al., 2001).

Dans les savanes, les activités anthropiques ont un impact significatif sur les dynamiques de végétation, biodiversité et ressources naturelles (Moura et al., 2019; Pongratz et al., 2008). Le récent développement des pratiques exploiteuses d'utilisation des terres (e ;g., feux anthropiques et déforestation) fait émerger des questions écologiques et socio-économiques au sujet des services écosystémiques associés aux savanes (Moura et al., 2019) tels que la disponibilité de l'eau, le stockage du carbone et les traits fonctionnaux des plantes (Balima et al., 2020; Franco et al., 2014; Spera et al., 2016). Les changements climatiques impactent aussi les dynamiques des savanes responsables de la perte de biodiversité et l'imprédictibilité des incendies (Amorim et al., 2022; Santos et al., 2021). De plus, les aspects historiques et paysagers ont entraîné des variations régionales dans les dynamiques savane-feu (Lehmann et al., 2014; Sluyter and Duvall, 2016).

Les changements climatiques qui se sont produits pendant l'Holocène (~11 700 ans BP jusqu'à aujourd'hui) sont responsables de l'expansion et de la rétraction des savanes, de la formation des mosaïques de végétation et de la répartition des établissements humains dans les tropiques (Bostoen et al., 2015; Cassino et al., 2020; Moraes et al., 2022; Raczka et al., 2013; Rowe et al., 2019; Wurster et al., 2021). Le réchauffement climatique en cours et les pressions anthropiques ont déjà entraîné un déclin de la productivité et de la biodiversité, de la couverture arborée, de l'épuisement du carbone (Balima et al., 2020; Grace et al., 2006) et du recyclage de l'eau dans l'atmosphère (Honda and Durigan, 2016; Spera et al., 2016) dans les savanes d'Australie, d'Afrique et d'Amérique du Sud. En considérant l'histoire des interactions entre l'homme et son environnement sur le long terme, des perspectives plus intégrées concernant les contextes environnementaux et historiques des paysages sont mises en œuvre de nos jours en tant qu'approche alternative pour une utilisation durable des terres des savanes et la gestion de leur conservation (Beale et al., 2013; Eloy et al., 2019; Iriarte et al., 2012; Sangha et al., 2021; Silva, 2014).

1.1. Le biome Cerrado : dynamiques naturelles et impacts humains

Le Cerrado, nom donné aux savanes brésiliennes, représente le 2ème grand biome du pays, s'étendant géographiquement de 2° à 23°S et occupant 23,3% du territoire national (Oliveira and Marquis, 2002; Vieira et al., 2022). Recouvrant les plateaux brésiliens. (*Planalto Central*) (Figure I.2), une partie du Paraguay et de la Bolivie, cet écosystème constitue un *hotspot* de biodiversité mondial qui héberge environ 11000 espèces de plantes parmi lesquelles 4400 sont endémiques (Mendonça et al., 2008). Le Cerrado joue un rôle important sur le recyclage régional de l'eau en rechargeant 8 sur 12 des grands bassins brésiliens et emmagasine jusqu'à 75% du carbone sous la forme de biomasse souterraine (Lahsen et al., 2016). La composition floristique et la structure du Cerrado varient en fonction des propriétés des sols (fertilité, pH, humidité), du climat, de écotones avec les biomes voisins, des perturbations naturelles et anthropiques (Assis et al., 2011; Leite et al., 2018; Ribeiro and Walter, 2008; Sano et al., 2008).

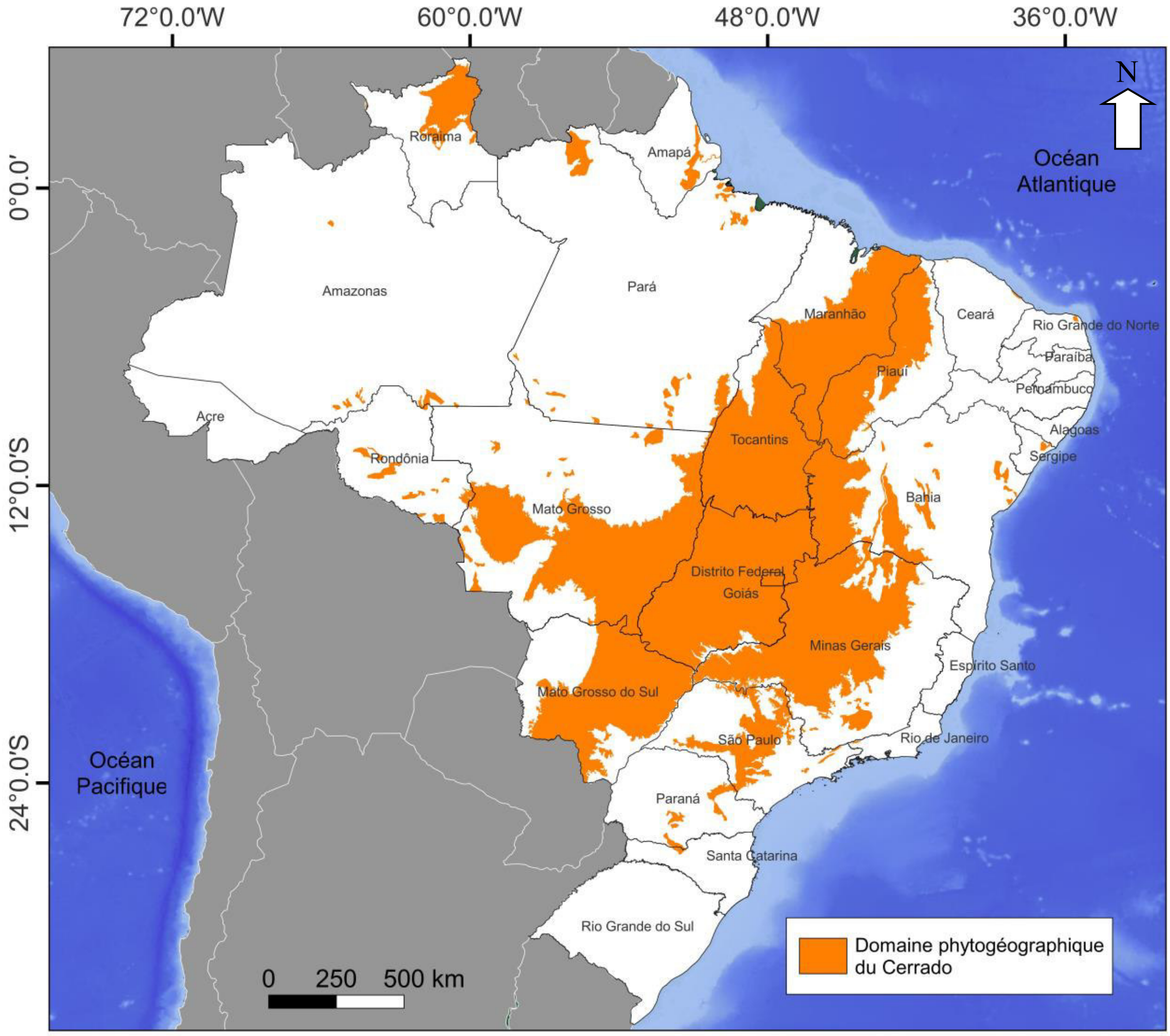

Figure I.2 : Carte de la distribution du Cerrado au Brésil (Vieira et al., 2022).

Du fait de la vaste distribution latitudinale et altitudinale du Cerrado, différents types de climat contrôlent l'hétérogénéité de la végétation, la distribution de la couverture arborée et les variations de la densité des espèces (Felfili et al., 2004; Werneck et al., 2012). Pour ce biome, le feu est un facteur écologique qui se produit naturellement lors du passage de la saison sèche vers la saison humide par la foudre (Ramos-Neto and Pivello, 2000). Les effets de ces incendies varient en fonction du comportement des feux, de l'intensité, de la périodicité, du type de végétation et de l'échelle spatio-temporelle (Gomes et al., 2018). Toutefois, lorsque il est d'origine anthropique le feu affecte la structure de la végétation et la biodiversité et peut être destructif. Les incendies constituent une ressource importante des communautés indigènes natives du cerrado et qui remontent au Pléistocène (Santos, 2013; Silva, 2020). Depuis le début du développement de l'agrobusiness dans les années 1970, les feux d'origine anthropique ont augmenté dans les Cerrados (Cabral et al., 2023), altérant le recyclage de l'eau et l'apport en nutrient qui permettrait le retour de la forêt (Klink et al., 2020).

Actuellement le Cerrado couvre 12 des 26 états brésiliens, en incluant la région centrale et les périphéries (Figure I.2) (Vieira et al., 2022). La végétation est classée en trois groupes avec onze physionomies qui incluent la forêt galerie, la forêt ciliaire, la forêt sèche, le cerradão (un cerrado avec une couverture arborée plus dense) pour le groupe des forêts ; le cerrado *sensu stricto*, le cerrado park, les formations de palmier (*palmeiral*) et les marécages à palmier (*vereda*)pour le groupe des savanes ; les prairies rocheuses (*campo rupestre*), les prairies à buisson (*campo sujo*) pour les groupe des formations herbacées ouvertes (Ribeiro and Walter, 2008). Les physionomies des forêts sont composées principalement d'espèces sensibles au feu ce qui les rend plus vulnérable aux feu que les physionomies de savane ou de prairie (Hoffmann et al., 2012) pour lesquelles le cycle de vie des espèces adaptées au feu sont dépendantes des feux saisonnier (Simon et al., 2009; Souchie et al., 2017). Malgré cela, ces physionomies sont menacées par les feux anthropiques qui augmentent pendant la saison sèche (Gomes et al., 2018; Ramos-Neto and Pivello, 2000).

Dans le cas d'un scenario de réchauffement climatique, le Cerrado serait soumis à des fortes sécheresses prolongées, une augmentation de l'activité des incendies et une diminution des précipitations à la fin de 2100 (IPCC, 2022). Les conséquences d'un climat plus chaud et plus sec seraient une diminution de la couverture arborée, une réduction de la richesse des espèces et une plus grande vulnérabilité envers l'extinction ce qui affecte la distribution spatiale des taxa (Franco et al., 2014; Velazco et al., 2019), des feux plus sévères et plus intenses, la destruction de l'infrastructure socio-économique et la dégradation des services écosystémiques (Bowman et al., 2011). Toutefois, les prédictions des réponses du Cerrado à ces changements sont complexes du fait des interactions sur le long terme entre la végétation hétérogène + les facteurs naturels + l'impact anthropique. La recherche paléoécologique peut être employée pour reconstruire ces dynamiques sur des intervalles de temps allant de la décennie, centenaire, ou millénaire ce qui permet la reconstruction sur des échelles locales et régionales (Chevalier et al., 2020; Ledru et al., 2020).

Les changements climatiques de la transition du Pléistocène vers l'Holocène (~11 700 ans AP), puis de l'Holocène sont responsables de l'expansion et de la rétraction de la couverture arborée du Cerrado et des fluctuations de l'activité des feux (Cassino et al., 2020, 2018). Entre ~10.000 et ~8000 ans AP, l'expansion de sforêts et de smarécages à palmier dans le sud-est du Cerrado montre l'installaiton d'un climat humide (Behling, 2003, 1995; Cassino and Meyer, 2013; Horák-Terra et al., 2015; Ledru, 1993), alors que les sites du nord-est montrent des conditions sèches quelquefois accompagnées d'incendie (Barberi et al., 2000; Cassino et al., 2018; Ferraz-Vicentini and Salgado-Labouriau, 1996). Autour de 7000 ans AP, l'expansion de la forêt galerie, du cerrado arboré et des marécages à palmier dans le nord-ouest montre une augmentation de l'humidité, alors que la prédominance d'un cerrado clairsemé dans le sud-est montre une oscillation entre des épisodes secs et humides, pas nécessairement synchrones entre les sites (BEHLING, 1995; CASSINO et al., 2020, 2018; LEDRU, 1993). A partir de 4000 ans AP, le Cerrado central est devenu plus humide qu'auparavant, marquant l'installation du climat saisonnier qui est observé aujourd'hui. Ces changements sont corrélés aux oscillations de l'activité de la mousson sud-américaine et à la variation de l'insolation (Cassino et al., 2023, 2020; Prado et al., 2013). Bien que les incendies soient plus fréquents pendant les phases sèches, l'activité des feux ne suit pas toujours la même fréquence durant des périodes analogues (Behling, 2003). La relation entre le climat et les feux n'est pas toujours très claire et il est parfois difficile de distinguer s'ils sont d'origine naturelle ou anthropique (Behling, 1995; Pessenda et al., 2010). Ceci montre la complexité entre les paysages du Cerrado, le climat et l'activité humaine, et pointe la nécessité des approches de recherche intégratives pour comprendre ces dynamiques dans les différents contextes spatiotemporels et historiques.

1.2. Le Nord-est du Brésil

1.2.1. Contexte climatique

La région est caractérisée par un climat tropical chaud et semi-aride avec des précipitations interannuelles saisonnières. Dans le nord du Nord-est brésilien (Nordeste ou NEB),le pic de la saison des pluies est observé de février à mai (4-5 mois), induit par la zone de convergence inter tropicale (ZCIT) (Marengo et al., 2017). Dans l'ouest et le sud-ouest du NEB, la saison des pluies est observée de octobre à mars (5-6 mois), modulée par les flux d'humidité amazonien apporté par le système de mousson sud-américaine (SASM) (Figure I.3) (Nascimento, 2014). La précipitation moyenne annuelle est entre 400 et 1800 mm (Figure I.3) (INMET, 2023; Silva et al., 2012) mais une grande partie de la région centrale et orientale ne reçoit que 300 à 800 mm de précipitation annuelle de février à mai (Marengo et al., 2020). D'autre part, plus de 2000 mm de précipitation annuelle sont enregistrées dans le nord-ouest, où la saison des pluies es observée de janvier à juillet (7 mois) (INMET, 2023). La température moyenne annuelle varie entre 23° et 28°C (Fig. I.3). La température moyenne minimale n'arrive jamais en dessous de 20°C. et la température moyenne maximale ne dépasse pas 32°C (INMET, 2023). La variabilité interannuelle des précipitations est influencée par les anomalies des températures de surface océanique (SST) dans l'Océan Atlantique et Pacifique (Marengo et al., 2017). Actuellement, la région est soumise à des épisodes récurrents de sécheresse qui s'intensifient lors des événements El Niño dans l'Océan Pacifique ou une combinaison des deux (Marengo et al., 2020, 2017).

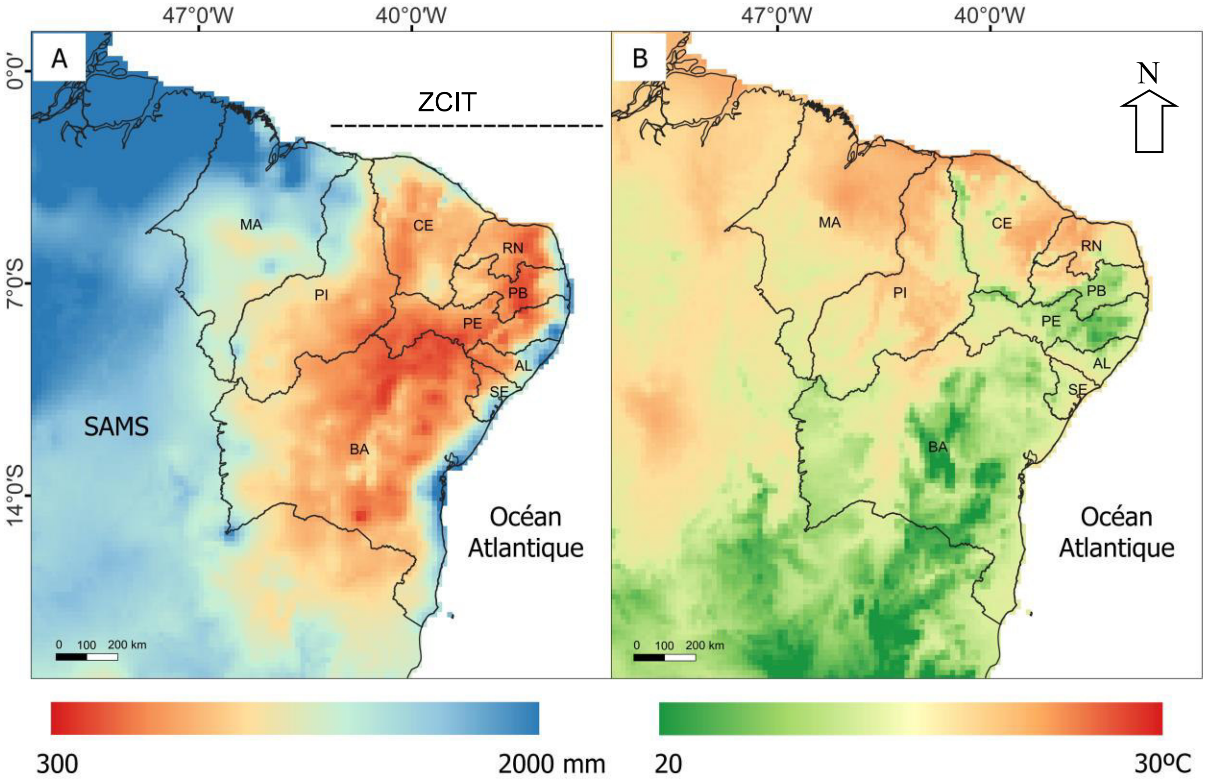

Figure I.3 : a) Précipitation moyenne annuelle montrant l'influence de la ZCIT (février -mai) dans le NEB et de la SASM (octobre-mars) dans l'ouest et le sud-ouest du NEB. b) température moyenne annuelle (source: FICK; HIJMANS, 2017).

La position de la ZCIT et la force de convection de la SASM ont oscillé sur des échelles séculaires à millénaires du fait de la variabilité thermale de l'Océan Atlantique et des cycles de l'insolation. Pendant le début de l'Holocène (~11700 ans à ~8200 ans AP), le NEB a enregistré des conditions plus humides associées à la faible insolation de l'hémisphère sud et à au déplacement de la ZCIT vers le Sud (Cruz et al., 2009; Utida et al., 2020). Cette situation est anti-corrélée avec un climat plus sec sur les Andes tropicales, l'ouest amazonien et le sud-est du Brésil (Seltzer et al., 2000; van Breukelen et al., 2008; Wang et al., 2007). Les tendances plus humides dans le NEB sont observées jusqu'à environ 5000 ans AP (Utida et al., 2020) alors que l'ouest et le centre et le sud du Brésil étaient soumis à un climat instable (Cheng et al., 2013; Gorenstein et al., 2022). Une plus faible insolation et des anomalies de température de surface de l'Océan Atlantique ont affaibli l'activité de la SASM et entraîné des oscillations de la Zone de Convergence de l'Atlantique Sud (ZCAS) qui a causé la sécheresse de l'Holocène moyen sur toute la partie orientale de l'Amérique du Sud, sauf le NEB (Prado et al., 2013; Utida et al., 2020). Puis, à partir de 4200 ans AP, les précipitations régionales ont diminué abruptement (Cruz et al., 2009; Utida et al., 2020) alors que la mousson était renforcée sur l'ouest amazonien et le sud-est du Brésil (van Breukelen et al., 2008) en réponse à l'augmentation de l'insolation et des températures de surface océanique de l'Atlantique tropical (Chiessi et al., 2021). Ces changements se sont reflétés sur les contractions latitudinales de la ZCIT (Vásquez P et al., 2022) et le renforcement de l'activité de la SASM, qui ont contribué à l'aridification du Nordeste après 4000 ans AP, et à l'installation du climat actuel (Chiessi et al., 2021).

1.2.2. Végétation et activité des feux

Le NEB est formée de 4 biomes : la forêt Amazonienne située sur la partie nord-ouest, la forêt Atlantique le long de la côte orientale, la Caatinga à l'est et au centre et le Cerrado dans la région ouest-sud-ouest (Figure I.4). La distribution spatiale de chaque domaine phytogéographique est fortement influencée par la variabilité des précipitations. Par exemple, la région de la forêt amazonienne reçoit des précipitations moyennes annuelles de 1800 mm, la saison des pluies est observée de janvier à juillet (7 mois) et les températures moyennes annuelles sont entre 25° et 27°C. (INMET, 2023). Entre janvier et mai, la précipitation est maintenue par la ZCIT et de mai à juillet par le flux est-amazonien (Nascimento, 2014). La longue saison sèche et l'humidité constante permet le développement d'une forêt à feuilles persistantes. Du fait du fort taux d'humidité, les incendies naturels sont rares (Hardesty et al., 2005).

La Caatinga est une forêt sèche caractérisée par une végétation décidue épineuse clairsemée avec des arbustes et des buissons adaptés aux conditions semi-arides du climat avec une saison sèche de janvier à mai (3-5 mois) (NIMER, 1989), une température moyenne annuelle de 28°C et une précipitation moyenne annuelle entre 400 et 800 mm (INMET, 2023). Le pic de la saison des pluies entre février et mai correspond à la position sud de l'ITCZ (Marengo et al., 2017) avec une variabilité interannuelle importante et des sécheresses récurrentes (Velloso et al., 2002). Les 10 genres les plus communément observés dans la Caatinga sont *Croton* (Euphorbiaceae), *Mimosa* (Fabaceae), *Ipomoea* (Convolvulaceae), *Chamaecrista* (Fabaceae), *Erythroxylum* (Erythroxylaceae), *Senna* (Fabaceae), *Cyperus* (Cyperaceae), *Eugenia* (Myrtaceae), *Sida* (Malvaceae) et *Evolvulus* (Convolvulaceae) (Moro et al., 2014). Les feux naturels ssont rares du fait de la faible fréquence de la foudre et de la végétation arborée sans tapis graminéen qui empêchent la propagation des feux (Pivello et al., 2021).

Le Cerrado comprend des forêts humide et sèche, des savanes boisées, des marécages et des prairies herbacées. Le climat est tropical saisonnier avec une saison des pluies d'octobre à mars (5-6 mois), une température moyenne annuelle de 22° à 27°C et une précipitation moyenne annuelle de 1000 à 1800 mm (Silva et al., 2008). Sa localisation entre la Caatinga sèche et l'Amazonie humide (Castro et al., 1998) et les latitudes 2° à 15°S entraîne une variabilité importante sur le début et la durée de la saison des pluies et sur les moyennes de température (Castro and Martins, 1999). Dans le nord, la saison des pluies correspond à la position sud de l'ITCZ entre février et mars (5-6 mois) tandis que dans le sud-ouest elle est modulée par la phase mature de la SASM, d'octobre à mars (5-6 mois). Toutefois , la durée de la saison des pluies peut être raccourcie à 4 mois pendant les années sèches dans les régions du Cerrado localisées au sud des états du Maranhão et du Piauí (Silva et al., 2008). Dans ces régions, la température moyenne minimale est entre 21° et 23°C, et maximale entre 31° et 33°C (Silva et al., 2008). Les incendies naturels sont communs pendant la transition de la saison sèche vers humide, du fait de la forte fréquence des orages et de la foudre et de la présence permanente de matière inflammable, le tapis graminéen (Gomes et al., 2018).

La composition floristique du Cerrado du NEB est différente de celle de la région centrale (Vieira et al., 2022). Dans le NEB, les 10 genres les plus communs sont *Qualea* (Vochysiaceae), *Byrsonima* (Malpighiaceae), *Anacardium* (Anacardiaceae), *Bowdichia* (Fabaceae), *Annona* (Annonaceae), *Caryocar* (Caryocaraceae), *Dimorphandra* (Fabaceae), *Hymenaea* (Fabaceae), *Stryphnodendron* (Fabaceae) et *Curatella* (Dilleniaceae) (Vieira et al., 2019). Dans la région centrale du Brésil, les 10 genres les plus communs sont *Paepalanthus* (Eriocaulaceae), *Mimosa* (Fabaceae), *Chamaecrista* (Fabaceae), *Myrcia* (Myrtaceae), *Hyptis* (Convolvulaceae), *Vellozia* (Velloziaceae), *Croton* (Euphorbiaceae), *Syngonanthus* (Eriocaulaceae), *Xyris* (Xyridaceae) et *Paspalum* (Poaceae) (Mendonça et al., 2008). Ainsi, le Cerrado du NEB est classé comme une province périphérique avec des assemblages d'espèces végétales différents de ceux de la région centrale (Françoso et al., 2019; Ratter et al., 2003; Vieira et al., 2019). Ce provincialisme est attribué à une dispersion géographique, à la variabilité climatique de la région et au mélange des espèces en provenance à la fois de l'Amazonie et de la Caatinga (Castro and Martins, 1999; Vieira et al., 2019).

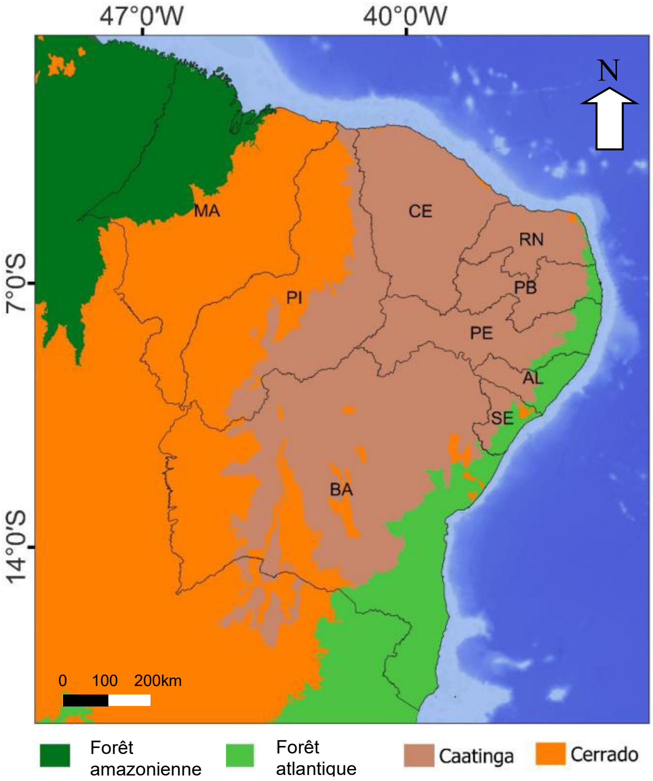

Figure I.4 : Carte des domaines phytogéographiques du NEB (Vieira et al., 2022).

Les changements climatiques passés du NEB ont conduit à des modifications de la distribution des domaines phytogéographiques au cours de l'Holocène. De ~6000 ans AP dans l'ouest du NEB, la réorganisation des taxa amazoniens et du Cerrado était causé par l'alternance des conditions sèches et humides de l'Holocène ancien et moyen (Ledru et al., 2006; Moraes et al., 2022, 2021). Dans l'est du NEB, la prédominance de la forêt semi-décidue, décidue et à feuilles persistantes, Cerrado et Caatinga étaient influencée par les oscillations d'un transect humide est-ouest au cours de l'Holocène moyen et récent (Montade et al., 2014; Moraes et al., 2020; Oliveira et al., 1999). Autour de 4200 ans AP, les taxa arborés amazoniens ont progressivement augmenté pendant une phase climatique humide à l'ouest alors que la végétation de la Caatinga s'est développée pendant une phase climatique sèche à l'est (Moraes et al., 2020; Oliveira et al., 1999). Les forêts décidues, semi-décidues et à feuilles persistantes forment des refuges isolés dans les montagnes au milieu de la Caatinga.

A partir de 6000 ans AP, une faible fréquence des incendies est observée dans la plupart des régions (Moraes et al., 2022, 2021; Oliveira et al., 1999; Pessenda et al., 2010). Pendant l'Holocène moyen et récent, l'activité des feux a progressivement augmenté à l'est du NEB (Pessenda et al., 2010) mais pas dans la partie ouest (Ledru et al., 2006; Moraes et al., 2022, 2021). Ceci a changé au cours de l'Holocène récent lorsqu'une intense activité des feux est observée dans toute la région. Ces incendies sont liés à différentes sources. Dans la région sèche du NEB, les incendies ont été attribués au changement climatique (Oliveira et al., 1999) et à la présence de l'Homme (Moraes et al., 2020) tandis que dans l'ouest humide NEB ils étaient liés seulement à l'activité anthropique (Moraes et al., 2022, 2021). De plus, les incendies de l'Holocène récent peuvent aussi être une combinaison des deux facteurs climat-activité humaine (Pessenda et al., 2010).

1.2.3. Occupation humaine

Le NEB est la région sèche la plus peuplée de l'hémisphère sud et la deuxième du Brésil avec 55 millions d'habitants (IBGE, 2023). Elle était occupée avant l'arrivée des Européens vers 1500 AD (Dantas et al., 1992; Medeiros, 2002; Prado Jr, 2011). Les sites archéologiques remontent au Paléolihique (~50.000 ans AP) (Martin, 2013) et incluent plusieurs sites du patrimoine mondial de l'humanité de l'UNESCO, avec le géoparc Seridó du Ruio Grande do Norte, le géoparc Araripe dans le Ceará et le parc national de la Serra da Capivara dans le Piauí. Des foyers, de l'industrie lithique et des peintures et gravures rupestres ont été retrouvés à travers le Cerrado et la Caatinga (Bueno and Dias, 2015; Etchevarne, 2000; Guidon et al., 1994; Martin, 2013).

En dépit de la richesse archéologique, les données archéologiques et paléoécologiques éparpillées empêchent de comprendre les dynamiques régionaux homme-environnement (Araujo et al., 2006, 2005), également aggravée par l'absence de datations archéologiques pour l'Holocène moyen. Toutefois, des inférences locales ont été faites concernant la répartition des groupes humains, en les reliant aux changements paysagers, culturels et climatiques. Au cours de l'Holocène ancien et moyen, des groupes de chasseur-cueilleurs vivaient dans les abris sous roche et les espaces ouverts lorsqu'un climat plus humide prédominait dans le NEB (Laroche and Silva Laroche, 1987; Martin, 2013; Melo, 2007). L'industrie lithique et les peintures rupe de tradition similaire sont aussi retrouvées dans la région centrale mettant en évidence un large réseau culturel (Bueno and Isnardis, 2018).

Après l'aridification de la région vers 4200 ans AP, l'Holocène récent montre la prédominance de potiers et une agriculture à proximité des rivières et des prairies humides. Ils sont attribués aux traditions Jê et Tupiguarani anciennes, des groupes amérindiens qui ont vécu dans la Caatinga et le Cerrado (Martin, 2013; Perota, 1987; Souza et al., 2020). L'utilisation des terres par ces groupes amérindiens consistaient en peu d'incendies et pas de déforestation. Toutefois ces pratiques ont changé pendant le dernier millénaire, principalement après 1492 AD (Koch et al., 2019) pendant l'époque coloniale brésilienne pour l'extraction du bois, l'élevage et les activités agricoles (Moura et al., 2019; Sluyter and Duvall, 2016). Actuellement, la région affronte une dégradation de l'environnement accentuée et une perte des ressources naturelles dues à la combinaison de sécheresses aggravées et de la forte pression anthropique (Silva et al., 2023).

1.3. Objectifs et justificatifs

Le NEB est un vaste territoire avec une densité de la population hétérogène, différents systèmes climatiques et une végétation hétérogène qui est soumise à une utilisation des terres intensives depuis des décennies. La variabilité des précipitations, la forte évapotranspiration, la forte insolation et la dégradation des terres rendent la région vulnérable au réchauffement climatique (IPCC, 2022; Marengo et al., 2017). Les épisodes de sécheresse enregistrés depuis le 16è siècle ont augmenté en intensité et fréquence, devenant plus fréquent dans les 30 dernières années (Marengo et al., 2017). Les projections montrent une diminution des précipitations de 54% sur la région avec un réchauffement de 4°C en 2100 CE (Figure I.5) (Marengo et al., 2020) qui se traduira par des saisons sèches plus longues et des épisodes de sécheresse extrêmes en même temps que la dégradation des terres accélèrera le processus de la désertification en cours (MARENGO et al., 2016; VIEIRA et al., 2015). Ceci affectera à la fois les écosystèmes et le bien-être de la population dans un scenario de diminution des ressources et de dégradation des actifs naturels (Marengo et al., 2016).

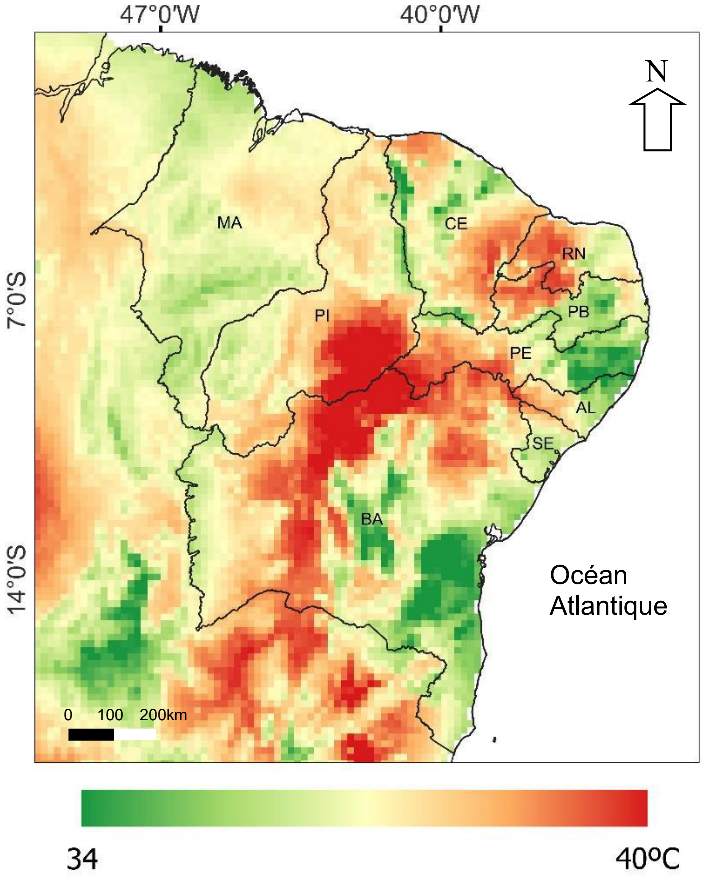

Figure I.5 : Projection future de la température maximale moyenne mensuelle (°C) à NEB d'ici 2080-2100 (source : CMIP6, 2021).

Dans ce contexte, l'objectif principal de ce travail est de reconstruire les réponses de la végétation du Cerrado au changement climatique de l'Holocène moyen et récent dans le NEB afin de comprendre les interactions entre le climat, l'Homme et la végétation et le futur impact du réchauffement climatique et de la pression anthropique actuels sur ces écosystèmes. Pour cette recherche nous avons utilisé les grains de pollen et les macro-charbons déposés dans les sédiments de marécages en tant qu'indicateurs de l'environnement et du climat. Les trois articles de cette thèse contribuent à atteindre cet objectif de façon complémentaire. Chaque article avec sa propre spécificité est décrit selon :

Article 1. Chapitre II : Changes in fire activity and biodiversity in a Northeast Brazilian Cerrado over the last 800 years.

Objectif: Décrire comment les modifications de l'occupation humaine et du climat ont affecté un écotone Cerrado-Caatinga pendant le dernier millénaire.

Article 2. Chapitre III : Millennial-scale variability of vegetation and fire activity in a

northern Cerrado driven by an east-west rainfall gradient during the Holocene.
Objectif: Analyser les réponse de la végétation et des incendies d'un Cerrado de l'ouest du NEB à la variabilité de la précipitation au cours des 6000 dernières années avec un focus sur les dynamiques à long terme d'une aire de transition entre l'humidité amazonienne et le domaine semi-aride.

Article 3. Chapitre IV : 6000 years of monsoon driven east-west antiphasing of Northeastern Brazil vegetation.
Objectif: Evaluer la dynamique des incendies et de la végétation ainsi que les impacts anthropiques sur les paysages du NEB au cours de l'Holocène. Cet article présente une synthèse de toutes les études paléoécologiques (pollen et charbon) réalisées dans la région et analyse les réponses de la végétation le long de deux transects spatio-temporels, l'un est-ouest et l'autre nord-sud.

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1.4. Zones d'étude

Notre recherche a été menée dans deux unités de conservation : le parc national « Sete Cidades » dans le nord du Piauí (article 1) et le parc national de « Chapada das Mesas » dans le sud-ouest du Maranhão (article 2) (Figure I.6). Respectivement créées par des décrets fédéraux en 1961 et 2005, ce sont des zones protégées avec une gestion correspondant à catégorie II de l' International Union for Conservation of Nature (IUCN) (Dudley, 2008). Les carottages ont été prélevés en septembre 2013 dans un marécage à palmier situé à proximité du parc « Chapada das Mesas » et en juin 2018 dans une dépression humide avec un marécage à palmier à proximité du parc « Sete Cidades ». Une description détaillée de chaque site est présentée dans les articles 1 et 2.

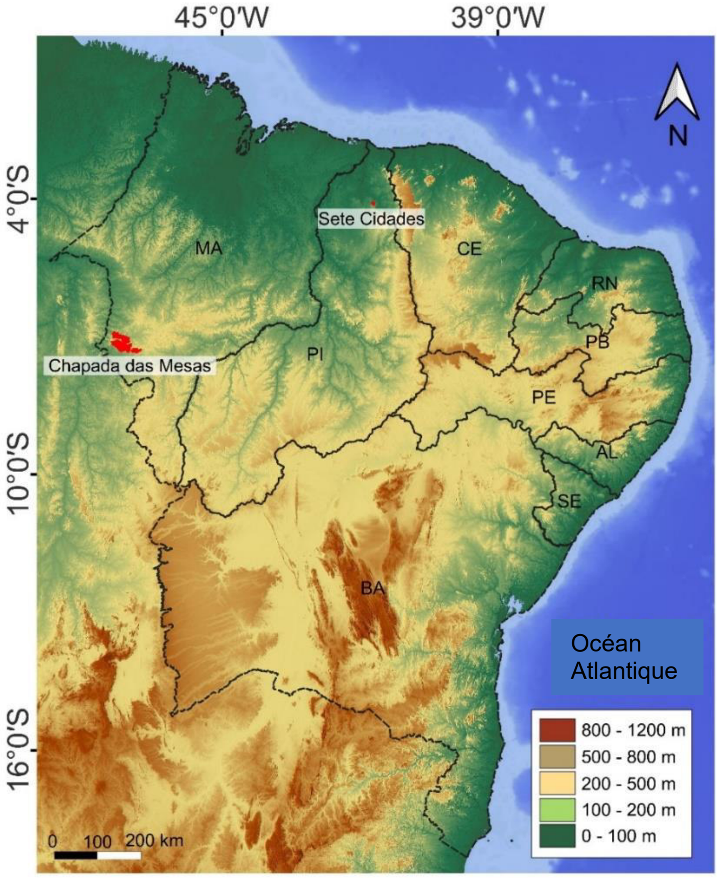

Fig. I.6 : Carte hypsométrique du Nordeste avec le relief montrant la localisation des parcs nationaux « Sete Cidades » et « Chapada das Mesas ».

1.5. Méthodes

Deux indicateurs principaux, les grains de pollen et les macro-charbons déposés dans les carottes sédimentaires prélevées dans des surfaces humides en permanence, ont été utilisés pour reconstruire la végétation et l'activité des feux du passé. Pour chaque séquence sédimentaire, un modèle d'âge basé sur les datations radiocarbone a été défini. Les modèles d'âge ont été construits à l'aide du Rbacon package sur RStudio (Blaauw and Christen, 2011). En outre, une analyse granulométrique a été réalisée pour l'article 1. La granulométrie consiste à déterminer la répartition des particules primaires dans le sédiment : argile, limon et sable (Wentworth, 1922). Les approches statistiques et modélisation des données (analyse en composantes principales, taux de variation paléoenvironnementales, indice pollinique, positionnement multidimensionnel non-métrique et fonctions orthogonales empiriques) ont été menées sur RStudio. Le choix des méthodes est détaillé dans les articles 1, 2 et 3.

Les échantillons destinés à l'analyse palynologique ont été prélevés à 1 cm d'intervalle pour les deux carottes. L'extraction des pollens a été réalisée dans le laboatoire de palynologie de l'Institut des Sciences de l'Evolution de Montpellier (ISEM) en utilisant une combinaison de techniques standard (Faegri and Iversen, 1989) et d'un protocole sans acide (Santos and Ledru, 2021) décrite ci-dessous. Dans un tube Falcon 50 ml, deux tablettes d'un marqueur exotique *Lycopodium clavatum* (18,407 spores per tablet) ont été dissoutes dans 10 ml d'eau distillée. Ensuite 0,5 cm^3 d'échantillon ont été déposés dans chaque tube et homogénéisés avec un mixer vortex. Le tube a été centrifugé pendant 4 mn à 3000 tours/mn et le surnageant éliminé. Une solution à 10% d'hydroxyde de potassium a été ajoutée pour laver le contenu pollinique des acides fulviques et humiques dans un bain-marie à 80°C pendant 6 mn en remuant la péparation. Une autre centrifugation à 3000 tours/mn permet de jeter le surnageant. Cette étape avec de l'hydroxyde de potassium suivie d'une centrifugation a été répétée plusieurs fois pour chaque échantillon jusqu'au nettoyage complet du résidu. Celui-ci est ensuite rincé deux fois à l'eau distillée.

Les tubes sont ensuite retournés et séchés sur une surface plane pendant 60 mn. Une solution de chlorure de zinc (densité 1,9 $g.cm^3$) est ajoutée aux tubes, homogénéisé avec le mixer vortex, centrifugé à 1000 tours par mn. Afin de laisser flotter les grains de pollen en surface. Le surnageant est transféré dans un bécher de 100 ml avec 10 ml d'eau distillée afin de laver le Chlorure de Zinc. Le mélange est versé dans un nouveau tube Falcon, centrifugé à 3000 tours par mn pendant 4 mn et le surnageant est éliminé. Cette étape est répétée deux fois afin d'éliminer toute trace de chlorure de zinc. Le résidu est ensuite traité avec une solution de 10 ml d'hydroxyde de potassium et de métaphosphate de sodium, mélangé au mixer vortex et chauffé au bain-marie à 80°C pendant 30 mn en remuant. Ensuite, les tubes ont été centrifugés à 3000 tours par minute, le surnageant éliminé et une nouvelle centrifugation avec de l'eau distillée est effectuée. Certains échantillons présentant des fortes teneurs en silicate qui pouvaient masquer les grains de pollen ont été traités avec 5 ml d'acide fluorhydrique pendant 1 h. Les tubes son centrifugés à 3000 tours par mn, le surnageant est éliminé et 10 ml d'eau distillée a été ajoutée puis le tube de nouveau centrifugé. Cette étape est répétée deux fois afin d'éliminer la totalité de l'acide fluorhydrique. Le résidu de pollen est transféré dans des tubes Eppendorf de 2 ml, le surnageant éliminé et une solution à 80% de glycérine déposée sur chaque résidu dans une proportion 1 :1. Le protocole sans acide permet une meilleure concentration du résidu de pollen, tout en facilitant un traitement éventuel à l'acide fluorhydrique en petites quantités (seulement 5 ml par échantillon).

Un total minimum de 300 grains de pollen terrestres a été compté pour chaque échantillon. Les grains de pollen ont été identifiés en utilisant la collection de référence de l'ISEM, des atlas de pollen publiés sur le Cerrado (Cassino and Meyer, 2011; Colinvaux et al., 1999; Lorente et al., 2017; Salgado-Labouriau, 1973) et d'autres biomes et des bases de données en ligne. (Bush and Weng, 2007; Martin and Harvey, 2017). Les comptages des grains de pollen ont été réalisés au Laboratório de Ecologia e Anatomia Funcional (LEAF), at the Universidade Federal do Ceará (UFC) and at Laboratoire de Palynologie of ISEM at the Université de Montpellier.

Les échantillons pour les analyses des charbons sédimentaires ont été prélevés à 1-cm d'intervalle pour les articles 1 et 2, préparés au laboratoire de sédimentologie de l'ISEM en utilisant un protocole classique (Stevenson and Haberle, 2005) décrit ci-dessous. Les échantillons sont placés dans des tubes en plastique, traités avec de l'hypochlorite de sodium et de l'hydroxyde de potassium dissous dans 10 ml d'eau distillée afin de nettoyer le contenu organique et séparer les particules de charbon. Les tubes sont ensuite remués constamment pendant 24 heures sur un plateau automatique. Ensuite, le contenu des tubes est tamisé à 160µm et lavé sous un robinet d'eau afin d'éliminer les résidus chimiques et le sédiment. The lavage a été effectué sous un jet d'eau modéré avec des mouvements circulaires et réguliers pour ne pas endommager les particules. Le résidu est transféré dans une boîte de Petri de 10 cm de diamètre. Tous les fragments de charbon ont été quantifiés (nombre de particules) et mesurés (largeur, longueur et surface) à l'aide d'un stéréomicroscope et du logiciel WinSeedle. Les comptages des charbons ont été réalisés à l'ISEM.

1.6. Principaux résultats

Changes in fire activity and biodiversity in a Northeast Brazilian Cerrado over the last 800 years

L'étude multiproxy (pollen, charbon, granulométrie) d'une carotte sédimentaire du parc national « Sete Cidades » a montré des changements dans la composition floristique et le structure du Cerrado pendant des épisodes humides et secs associés à des modifications de l'activité des feux pendant les derniers 800 ans. La période sèche de 1200 à 1350 CE est caractérisée par la dominance des taxa résistant à la sécheresse (e.g. *Curatella, Cuphea*) liée l'anomalie climatique médiévale observée dans l'hémisphère nord de 950 à 1250 CE. L'absence d'incendie est attribuée à l'absence d'occupation humaine sur cette période. A partir de 1400 CE, un intervalle plus humide correspondant au petit âge de la glace dans l'hémisphère nord entre 1400 et 170 CE est caractérisé par l'expansion des palmiers (*Mauritia* *flexuosa*) et des taxa indicateurs d'humidité (e.g. Myrtaceae, *Spatiphyllum*). L'augmentation du dépôt de sable est attribuée à des conditions de dépôt érosives. Une légère augmentation des incendies caractérise la transition d'une période sèche vers une période plus humide, suivi de feux permanents jusqu'à 1650 CE. Cette période est interprétée comme le retour des groupes amérindiens dans la région après l'augmentation de l'humidité et où les pratiques d'usage des terres consistaient en peu de feu et pas de déforestation. Un saut dans les incendies est observé après 1650 CE caractérisé par des feux intenses et de pics de charbon attribué à la déforestation. Nous avons relié ce changement à l'arrivée des Européens dans le nord de l'état du Piauí où ils ont pratiqué des déforestations intenses. Les feux se sont arrêtés après la création du parc « Sete Cidades » en 1961 CE avec pour conséquence l'expansion des taxa arborés du Cerrado. (e.g., *Byrsonima, Caryocar*, *Mimosa*). Ce travail a montré que le couplage des analyses multiproxy et des archives historiques constitue une approche très fiable pour la reconstruction des changements climatiques et des pratiques d'usage des terres sur le long terme, renforçant les informations manquantes sur les documents historiques. Il a montré également l'importance d'intégrer l'histoire des paysages à la mise en place des plans de gestion et conservation de l'environnement.

Millennial-scale variability of vegetation and fire activity in a northern Cerrado driven by an east-west rainfall gradient during the Holocene

L'enregistrement des grains de pollen et des charbons à haute résolution montre une alternance de changements dans la végétation pendant des phases humides et sèches de l'Holocène récent. Entre 6000 et 5200 ans AP, une végétation ouverte composée d'herbacées Asteraceae, *Acalypha, Scoparia* et du taxon arboré *Protium* dominait la région de la Chapada das Mesas pendant des conditions relativement sèches sans incendie. Cette période est liée à une mousson plus faible qu'aujourd'hui enregistrée dans le centre du Brésil. A partir de 5200 ans AP un cerrado boisé avec *Guazuma, Casearia, Alchornea* et le palmier de marécage (*Mauritia flexuosa*) s'est étendu pendant une période plus humide et peu d'incendie, synchrone avec le renforcement de la mousson dans le centre et le nord-est du Brésil. Entre 4300 et 3800 ans calibrés AP, neuf échantillons stériles ont été attribués à un épisode de sécheresse qui a provoqué l'oxydation du contenu pollinique. Les conditions sèches ont continué jusqu'à 3500 ans calibrés AP lorsque les taxa résistants à la sécheresse *Byrsonima, Dimorphandra* ont été remplacés par Melastomataceae et Myrtaceae avec l'augmentation progressive des taux d'humidité dans la région. La forte combustion de la biomasse observée pendant cet intervalle est liée à l'installation d'un climat saisonnier, favorable aux incendies dans le Cerrado. A partir de 2600 ans cal AP, l'expansion de la forêt galerie, du marécage et du cerrado arboré caractérisent l'augmentation de l'humidité sans combustion de la biomasse. Un changement dans les taxa arborés et les. Fréquences des incendies est observé à 270 ans cal AP, lié à l'activité anthropique dans la Chapada das Mesas en l'absence de changement climatique notoire sur cet intervalle. La végétation du Cerrado du nord montre une grande sensibilité aux oscillations des précipitations de la mousson depuis l'Holocène moyen et pendant l'Holocène récent comme dans le centre du Brésil.

6000 years of monsoon driven east-west antiphasing of Northeastern Brazil vegetation

Une meilleure compréhension des changements paléoécologiques régionaux repose sur des ensembles de données de haute qualité. Nous avons intégré nos résultats (article 1 et 2) à six autres enregistrements palynologiques and trois enregistrements de charbon du Nordeste brésilien qui montrent une variabilité environnementale au cours des 6000 dernières années. Nous discutons de leur évolution vers la signature spatiale des changements climatiques et la présence anthropique dans toute la région. Des schémas similaires de réponse de la végétation aux changements climatiques sont observés entre. 6000 et 4200 ans cal AP. Une alternance des taxons du Cerrado, de la Caatinga et de la forêt amazonienne lors des oscillations d'un transect pluviométrique est-ouest à travers la région, avec une intensité variable de quelques sites dans le nord-ouest NEB est observée. Après 4200 ans cal AP, un événement sec marque l'installation de l'aridification régionale observée sur de nombreux sites. Dans l'ouest du NEB, la faible préservation des grains de pollen de la Chapada das Mesas est attribuée à des conditions de dépôt oxydantes pendant un climat plus sec. Dans l'est du NEB, la faible préservation des grains de pollen suivi de l'expansion de la forêt sèche de la Caatinga a été observée dans l'enregistrement de la vallée d'Icatu. Sur les reliefs, cet événement sec a aussi entraîné le remplacement de la forêt ombrophile humide par une forêt semi-décidue pendant 750 ans. Inversement, les taxons de la forêt amazonienne et le Cerrado arboré se sont étendus vers l'ouest, en suivant le flux d'humidité de l'Amazonie et le renforcement de la mousson dans le Brésil central. Aucune présence humaine n'est attestée dans la région avant 3000 ans cal AP lorsque les activités humaines se sont intensifiées dans la région. Des incendies anthropiques intenses ont été enregistrés pendant des conditions climatiques sèches à l'est et des conditions climatiques humides à l'ouest, variant en intensité et en modèles en fonction des aspects historiques de chaque site. Pendant un climat sec à l'est du NEB, des changements dans la combustion sont attribués aux pratiques indigènes suivis de la présence européenne pendant l'époque coloniale. Pendant un climat humide à nord-ouest du NEB, des amérindiens ont pratiqué des feux sur la côte. En dépit de l'augmentation du nombre d'enregistrements paléoécologiques dans la région au cours de la dernière décennie, davantage d'études sont nécessaire pour élargir la distribution spatiale des ensembles de données et améliorer la précision du cadre régional.

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1. CAPÍTULO I

INTRODUÇÃO GERAL

1. INTRODUÇÃO GERAL

As mudanças climáticas e de uso da terra afetam significativamente os padrões, a estrutura e o funcionamento dos ecossistemas. Entre eles, as savanas, ecossistemas secos sazonais que se estendem pelas regiões tropicais e subtropicais da África, Austrália e América do Sul, cobrindo cerca de 27,6 milhões de km², 20% da superfície terrestre (Figura I.1) (OLSON et al., 2001). A vegetação é caracterizada por uma cobertura arbórea esparsa e um estrato herbáceo variando em composição, densidade e estrutura dependendo do tipo de ambiente (HUTLEY; SETTERFIELD, 2008). A precipitação varia de 300 a 2.000 mm, com estação seca anual durando de 2 a 9 meses (HUTLEY; SETTERFIELD, 2008). As savanas também incorporam diferentes práticas de uso da terra, como agricultura de subsistência, pecuária, lavouras, mineração, turismo e conservação. A estrutura espacial e a produtividade da savana estão diretamente ligadas à duração das estações seca e úmida, insolação anual total, temperatura e regimes de fogo (ALEMAN; STAVER, 2018; DURIGAN, 2020; MOORE et al., 2016; MURPHY; BOWMAN, 2012; SANKARAN et al., 2005). Apresentam rica biodiversidade e produtividade, contribuindo com 25% do sequestro global de carbono terrestre e sustentando 1/5 da população global (MOORE et al., 2016). Essas comunidades vegetais são uma mistura de espécies lenhosas perenes, decíduas e semidecíduas, arbustos, ervas e gramíneas adaptadas às variações anuais no teor de umidade, disponibilidade de nutrientes e atividade do fogo (HUTLEY; SETTERFIELD, 2008).

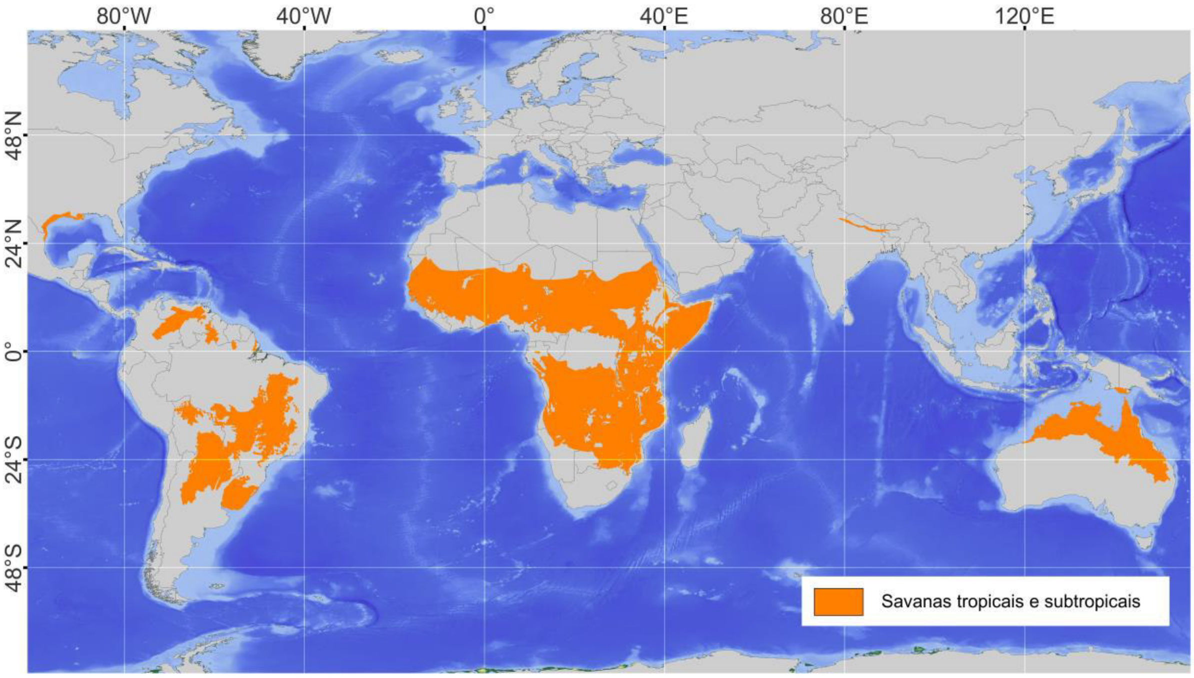

Figura I.1. Mapa da distribuição atual das savanas tropicais e subtropicais (OLSON et al., 2001).

Nas savanas, as atividades antrópicas têm um impacto significativo na dinâmica da vegetação, biodiversidade e recursos naturais (MOURA et al., 2019; PONGRATZ et al., 2008). O recente aumento de práticas exploratórias de uso da terra (por exemplo, incêndios antrópicos e desmatamento), levanta questões ecológicas e socioeconômicas sobre os serviços ecossistêmicos associados às savanas (MOURA et al., 2019), como disponibilidade de água, armazenamento de carbono e características funcionais das plantas (BALIMA et al., 2020; FRANCO et al., 2014; SPERA et al., 2016). As mudanças climáticas também impactam a dinâmica das savanas, responsáveis pela perda de biodiversidade e imprevisibilidade do comportamento do fogo (AMORIM et al., 2022; SANTOS et al., 2021). Além disso, aspectos históricos e paisagísticos levam a diferentes variações regionais na dinâmica savanas-clima-fogo (LEHMANN et al., 2014; SLUYTER; DUVALL, 2016).

As mudanças climáticas que ocorreram durante o Holoceno (~11.700 anos AP até o presente) são responsáveis pela expansão e retração de savanas, criação de mosaicos de vegetação e distribuição de assentamentos humanos nos trópicos (BOSTOEN et al., 2015; CASSINO et al., 2020; MORAES et al., 2022; RACZKA et al., 2013; ROWE et al., 2019; WURSTER et al., 2021). O aquecimento global em curso e as pressões antrópicas já levam ao declínio da produtividade e da biodiversidade, perda da cobertura vegetal, esgotamento do carbono (BALIMA et al., 2020; GRACE et al., 2006) e diminuição da água reciclada para a atmosfera (HONDA; DURIGAN, 2016; SPERA et al., 2016) em savanas australianas, africanas e sul-americanas. Considerando a longa história das interações homem-ambiente, perspectivas mais integradas que consideram os contextos ambientais e históricos das paisagens são implementadas atualmente, como abordagem alternativa para o uso sustentável da terra nas savanas e gestão de conservação (BEALE et al., 2013; ELOY et al., 2019; IRIARTE et al., 2012; SANGHA et al., 2021; SILVA, 2014).

1.1. O Bioma Cerrado: dinâmica natural e impactos antrópicos

O Cerrado é o segundo maior bioma do país, estendendo-se geograficamente de 2º a 23º S e ocupando 23,3% do território nacional (OLIVEIRA; MARQUIS, 2002; VIEIRA et al., 2022). Abrangendo o planalto central brasileiro (Figura I.2), algumas partes do Paraguai e da Bolívia, esse ecossistema é um hotspot global de biodiversidade que abriga cerca de 11.000 espécies de plantas, das quais 4.400 são endêmicas (MENDONÇA et al., 2008). Desempenha um papel importante no ciclo regional da água, reabastece 8 das 12 bacias hidrográficas brasileiras e armazena até 75% do carbono como biomassa subterrânea (LAHSEN; BUSTAMANTE; DALLA-NORA, 2016). A florística e a estrutura do Cerrado variam sob diferentes propriedades do solo (fertilidade, pH, teor de umidade), padrões climáticos, ecótonos com outros biomas, distúrbios naturais e antrópicos (ASSIS et al., 2011; LEITE et al., 2018; RIBEIRO; WALTER, 2008; SANO et al., 2008).

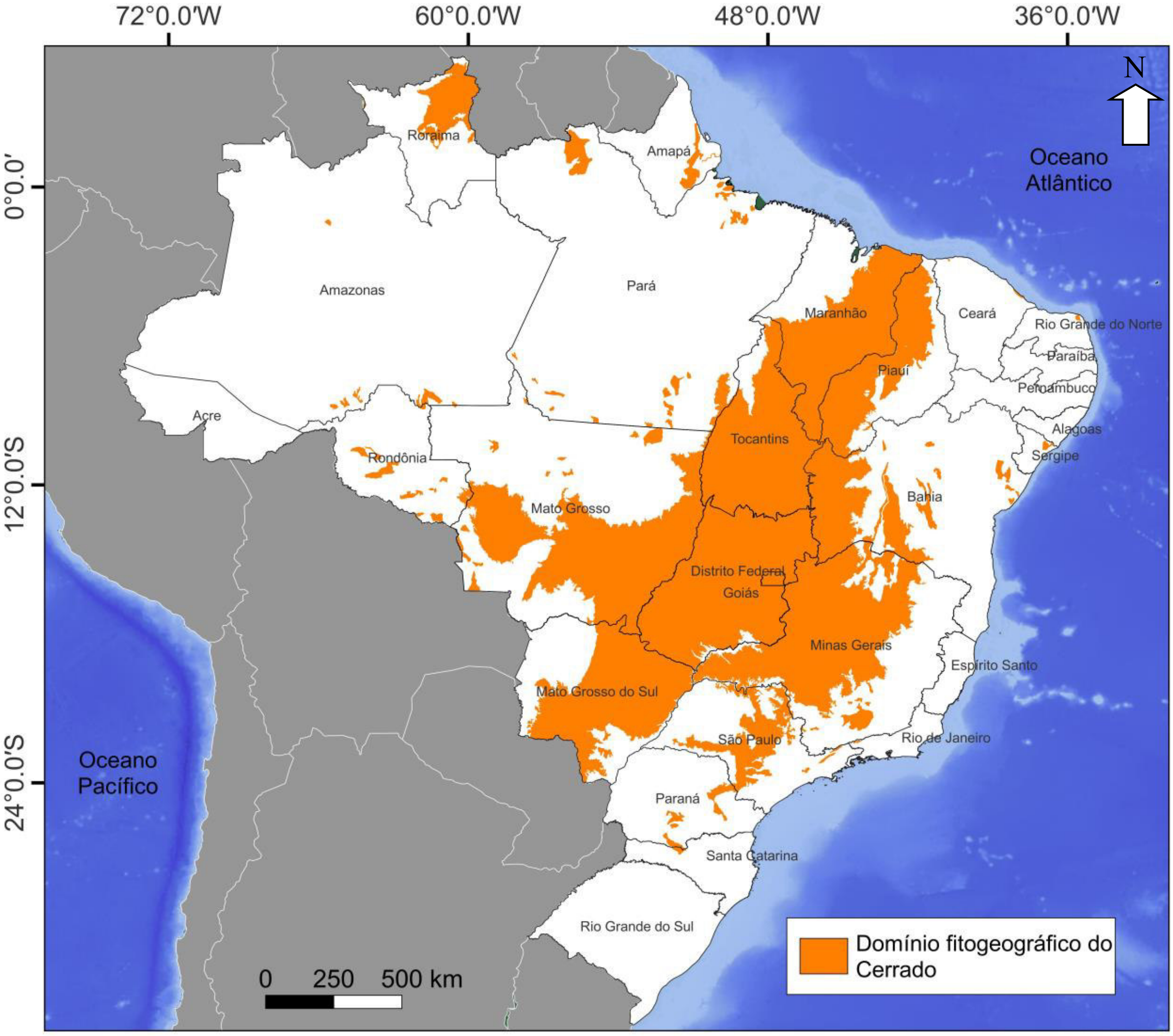

Figura I.2. Mapa da distribuição atual do Cerrado no Brasil (VIEIRA et al., 2022).

Devido à larga amplitude latitudinal e altitudinal da distribuição do Cerrado, diferentes padrões climáticos controlam a heterogeneidade da vegetação, distribuição da cobertura arbórea e variações na densidade de espécies (FELFILI et al., 2004; WERNECK et al., 2012). Nesse bioma, o fogo é um fator ecológico que ocorre naturalmente durante a transição da estação seca para a chuvosa por meio de descargas elétricas atmosféricas (RAMOS-NETO; PIVELLO, 2000). Os efeitos dessas queimadas variam dependendo do comportamento do fogo, intensidade, periodicidade, tipo de vegetação e escala espaço-temporal (GOMES; MIRANDA; BUSTAMANTE, 2018). No entanto, quando causadas pelo homem, a frequência natural das queimadas pode ser interrompida, o que afeta a estrutura da vegetação e a biodiversidade. O fogo tem sido um importante recurso cultural das comunidades humanas nativas do Cerrado desde o Pleistoceno/Holoceno até o presente (SANTOS, 2013; SILVA, 2020). Desde o início da expansão do agronegócio na década de 1970, as queimadas antrópicas vêm aumentando nas paisagens do Cerrado (CABRAL; SAUER; SHANKLAND, 2023), alterando o ciclo da água e o fornecimento de nutrientes que permitem a recuperação da floresta (KLINK et al., 2020).

Atualmente, o Cerrado cobre 12 dos 26 estados brasileiros, incluindo a região central e áreas marginais (Figura I.2) (VIEIRA et al., 2022). A vegetação é classificada em três formações com 11 fisionomias que incluem floresta de galeria, mata ciliar, mata seca, cerradão (formações florestais); cerrado *sensu stricto*, parque cerrado, palmeiral e vereda (formações savânicas); e campo rupestre, campo sujo e campo limpo (formações campestres) (RIBEIRO; WALTER, 2008). As formações florestais são compostas em sua maioria por espécies sensíveis ao fogo, o que as torna mais vulneráveis às queimadas do que as formações savânicas e campestres (HOFFMANN et al., 2012), cujas espécies adaptadas ao fogo dependem de queimadas sazonais para seu ciclo de vida (SIMON et al., 2009; SOUCHIE et al., 2017). Apesar disso, essas formações são ameaçadas por queimadas antrópicas com maior frequência durante a estação seca (GOMES; MIRANDA; BUSTAMANTE, 2018; RAMOS-NETO; PIVELLO, 2000).

Em um cenário de aquecimento climático global, espera-se que o Cerrado sofra secas prolongadas e extremas, aumento da atividade de incêndios e diminuição das chuvas até o final de 2100 (IPCC, 2022). As consequências de um clima mais quente e seco podem incluir perda de cobertura arbórea, redução da riqueza de espécies e maior vulnerabilidade à extinção, que afetam a distribuição espacial dos táxons (FRANCO et al., 2014; VELAZCO et al., 2019), queimadas mais severas e intensas, destruição da infraestrutura socioeconômica e degradação dos serviços ecossistêmicos (BOWMAN et al., 2011). No entanto, as previsões das respostas do Cerrado a essas mudanças são complexas devido às interações de longo prazo entre <u>vegetação heterogênea + fatores naturais + influência humana</u>. A pesquisa paleoecológica pode ser utilizada para reconstruir essas dinâmicas em intervalos de tempo decenal, centenário a milenar, o que permite a reconstituição em escalas locais e regionais (CHEVALIER et al., 2020; LEDRU et al., 2020).

As mudanças climáticas durante a transição Pleistoceno/Holoceno (~11.700 anos AP), e durante o Holoceno (~11.700 anos AP até o presente) são responsáveis por expansões e retrações da cobertura arbórea do Cerrado e mudanças na atividade do fogo (CASSINO et al., 2020; CASSINO; MARTINHO; DA SILVA CAMINHA, 2018). Entre ~10.000 e ~8000 anos AP, a expansão de florestas e veredas no sudeste do Cerrado central indicam um clima úmido (BEHLING, 1995, 2003; CASSINO; MEYER, 2013; HORÁK-TERRA et al., 2015; LEDRU, 1993), enquanto condições secas foram observadas no noroeste, às vezes com queimadas (BARBERI; SALGADO-LABOURIAU; SUGUIO, 2000; CASSINO; MARTINHO; DA SILVA CAMINHA, 2018; FERRAZ-VICENTINI; SALGADO-LABOURIAU, 1996). Por volta de 7.000 anos AP, a expansão da floresta de galeria, cerrado arbóreo e veredas no noroeste mostraram aumento da umidade, enquanto a predominância de uma cobertura esparsa de cerrado no sudeste indicou mudanças entre episódios secos e úmidos, nem sempre síncronos (BEHLING, 1995; CASSINO et al., 2020, 2018; LEDRU, 1993). A partir de ~4.000 anos AP, o Cerrado central tornou-se mais úmido que as fases anteriores, configurando o clima sazonal moderno. Essas mudanças estão correlacionadas com as oscilações da atividade das monções na América do Sul e variação da insolação (CASSINO et al., 2020, 2023; PRADO et al., 2013). Embora os incêndios tenham sido mais frequentes durante as fases secas, a atividade do fogo pode não seguir a mesma frequência durante períodos semelhantes (BEHLING, 2003). As relações entre clima e incêndios nem sempre são claras, e às vezes pode ser difícil determinar se são naturais ou antrópicos (BEHLING, 1995; PESSENDA et al., 2010). Isso exemplifica a complexidade entre as paisagens do Cerrado, clima e atividade humana, e aponta a necessidade de abordagens integrativas de pesquisa para compreender essas dinâmicas em diferentes contextos espaço-temporais e históricos.

1.2. Nordeste do Brasil

1.2.1. Contexto climático

A região possui clima semiárido tropical e quente, com sazonalidade pluviométrica interanual. No norte, o pico da estação chuvosa ocorre durante fevereiro-maio (4-5 meses), induzido pela Zona de Convergência Intertropical (ZCIT) (MARENGO et al., 2017). No oeste/sudoeste da região, a estação chuvosa ocorre de outubro a março (5-6 meses), modulada pelo fluxo de umidade amazônico do Sistema de Monções da América do Sul (SMAS) (Figura I.3) (NASCIMENTO, 2014). A precipitação média anual varia entre 400 e 1800 mm (Figura I.3) (INMET, 2023; SILVA; PEREIRA; ALMEIDA, 2012), mas a maior parte da região leste e central recebe apenas 300-800 mm de precipitação anual entre fevereiro e maio

(MARENGO et al., 2020). Por outro lado, foram registrados mais de 2.000 mm de precipitação anual no noroeste, onde a estação chuvosa dura de janeiro a julho (7 meses) (INMET, 2023). A temperatura média anual varia entre 23º e 28ºC (Figura I.3). A média mínima nunca cai abaixo de 20ºC enquanto a média máxima não ultrapassa 32ºC (INMET, 2023). A variabilidade interanual da precipitação é influenciada por anomalias na temperatura da superfície do mar (TSM) nos oceanos Atlântico e Pacífico (MARENGO et al., 2017). Atualmente, a região está sujeita a episódios recorrentes de seca, que podem ser intensificados pela ocorrência do El Niño no Oceano Pacífico tropical, um Oceano Atlântico Norte tropical mais quente ou uma combinação de ambos (MARENGO et al., 2017, 2020).

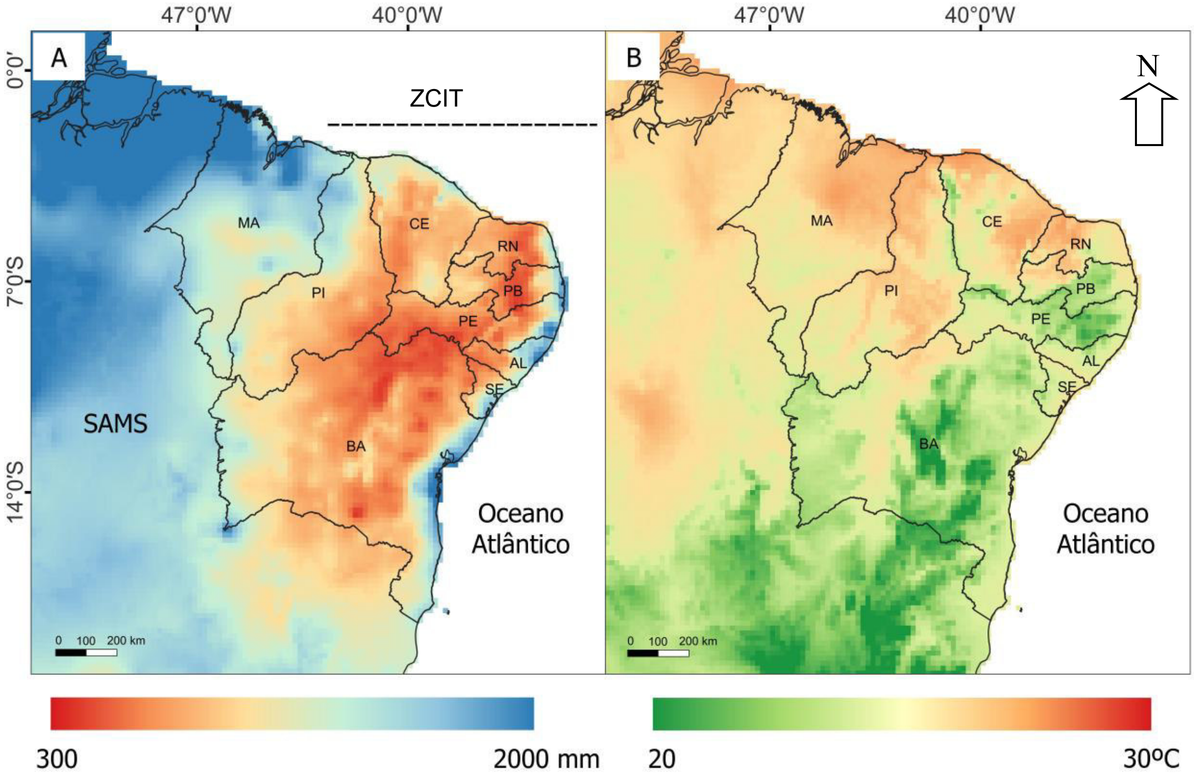

Figura I.3. a) Média anual de precipitação mostrando a zona de influência da ZCIT (Fevereiro-Maio) no norte do Nordeste e SMAS (Outubro-Março) a oeste/sudoeste do Nordeste. b) Média da temperatura anual (fonte: FICK; HIJMANS, 2017).

A posição da ZCIT e a força de convecção do SMAS têm oscilado em escalas de tempo centenárias e milenares como resultado da variabilidade térmica no Oceano Atlântico tropical e da insolação. Durante o Holoceno Inferior (~11.700 anos a ~8.200 anos AP), o Nordeste experimentou condições mais úmidas associadas à baixa insolação no hemisfério sul e ao deslocamento da ZCIT para o sul (CRUZ et al., 2009; UTIDA et al., 2020). Essas condições eram opostas a um clima mais seco nos Andes tropicais, Amazônia Ocidental e sudeste do Brasil (SELTZER; RODBELL; BURNS, 2000; VAN BREUKELEN et al., 2008; WANG et al., 2007). Tendências mais úmidas continuaram no Nordeste até cerca de 5.000 anos AP (UTIDA et al., 2020), enquanto o Oeste e Centro/Sul do Brasil experimentaram instabilidade climática (CHENG et al., 2013; GORENSTEIN et al., 2022). Menor insolação e anomalias na TSM do Atlântico resultaram em uma SMAS enfraquecida, em oscilações da posição da Zona de Convergência do Atlântico Sul (SCAS) que causaram clima seco no Holoceno médio-tardio no leste da América do Sul, exceto no Nordeste (PRADO et al., 2013; UTIDA et al., 2020). Por volta de 4.200 anos AP, a precipitação na região diminuiu abruptamente (CRUZ et al., 2009; UTIDA et al., 2020), enquanto as monções aumentaram no oeste da Amazônia e sudeste do Brasil (VAN BREUKELEN et al., 2008), respondendo a insolação mais forte e TSM do Atlântico mais quente (CHIESSI et al., 2021). Essas mudanças refletiram nas contrações latitudinais da ZCIT (VÁSQUEZ P et al., 2022) e fortaleceram a atividade do SMAS, o que contribuiu para a aridez no Nordeste após 4.000 anos AP, configurando o clima moderno (CHIESSI et al., 2021).

1.2.2. Vegetação e atividade do fogo

O Nordeste possui quatro biomas, a Floresta Amazônica localizada a noroeste; a Mata Atlântica ao longo da costa leste; a Caatinga na região leste e central, e o Cerrado na região oeste/sudoeste (Figura I.4). A distribuição espacial de cada domínio fitogeográfico é fortemente influenciada pela variabilidade da precipitação. Por exemplo, a floresta amazônica nas terras baixas do noroeste, onde a estação chuvosa dura de janeiro a julho (7 meses), a temperatura anual varia entre 25º e 27ºC e a precipitação média anual é superior a 1800 mm (INMET, 2023). Entre janeiro-maio, as chuvas são mantidas pela ZCIT, e de maio a julho pelo fluxo leste amazônico (NASCIMENTO, 2014). A longa estação chuvosa e a umidade constante permitem o estabelecimento da floresta tropical úmida. Devido ao alto teor de umidade, eventos naturais de incêndio são raros (HARDESTY; MYERS; FULKS, 2005).

A Caatinga é uma floresta seca caracterizada por vegetação caducifólia espinhosa esparsa, com pequenas árvores e arbustos adaptados ao clima semiárido quente com estação chuvosa variável de janeiro a maio (3-5 meses) (NIMER, 1989), temperatura média anual de 28ºC e precipitação média anual entre 400 e 800 mm (INMET, 2023). O pico da estação chuvosa entre fevereiro e maio corresponde à posição sul da ZCIT (MARENGO et al., 2017).

A Caatinga tolera a variabilidade interanual da precipitação e eventos recorrentes de seca (VELLOSO; SAMPAIO; PAREYN, 2002). Os 10 gêneros mais comuns são *Croton* (Euphorbiaceae), *Mimosa* (Fabaceae), *Ipomoea* (Convolvulaceae), *Chamaecrista* (Fabaceae), *Erythroxylum* (Erythroxylaceae), *Senna* (Fabaceae), *Cyperus* (Cyperaceae), *Eugenia* (Myrtaceae), *Sida* (Malvaceae) e *Evolvulus* (Convolvulaceae) (MORO et al., 2014). Na Caatinga, os incêndios naturais são raros devido à baixa frequência de descargas elétricas atmosféricas e a vegetação esparsa dificulta uma queima contínua (PIVELLO et al., 2021).

O Cerrado inclui florestas secas e úmidas, savanas lenhosas, pântanos e campos. O clima é tropical sazonal, com estação chuvosa de outubro a março (5-6 meses), temperatura anual variando de 22º a 27ºC e precipitação média anual variando entre 1000 e 1800 mm (SILVA; ASSAD; EVANGELISTA, 2008). Sua localização entre a Caatinga seca e o fluxo de umidade amazônico (CASTRO; MARTINS; FERNANDES, 1998), e sua distribuição latitudinal de 2º a 15ºS acarreta uma variabilidade significativa no início e duração da estação chuvosa e temperaturas médias (CASTRO; MARTINS, 1999). No norte, a estação chuvosa corresponde à posição sul da ZCIT entre fevereiro-maio (4-5 meses), enquanto no sudoeste é modulada pela fase madura do SMAS, de outubro a março (5-6 meses). No entanto, a duração da estação chuvosa pode ser encurtada para até quatro meses durante anos com episódios de seca em algumas áreas de Cerrado no sul do Maranhão e Piauí (SILVA; ASSAD; EVANGELISTA, 2008). Nessas áreas, a temperatura média mínima varia de 21º a 23ºC, enquanto a média máxima varia entre 31º e 33ºC (SILVA; ASSAD; EVANGELISTA, 2008). Incêndios naturais são comuns durante a transição da estação seca para chuvosa, devido à frequência recorrente de descargas elétricas e à disponibilidade contínua de biomassa inflamável (GOMES; MIRANDA; BUSTAMANTE, 2018).

Em termos de composição florística, o Cerrado nordestino difere da região central do Brasil (VIEIRA et al., 2022). No Nordeste, os 10 gêneros mais comuns são *Qualea* (Vochysiaceae), *Byrsonima* (Malpighiaceae), *Anacardium* (Anacardiaceae), *Bowdichia* (Fabaceae), *Annona* (Annonaceae), *Caryocar* (Caryocaraceae), *Dimorphandra* (Fabaceae), *Hymenaea* (Fabaceae), *Stryphnodendron* (Fabaceae) e *Curatella* (Dilleniaceae) (VIEIRA et al., 2019). No Brasil Central, os 10 gêneros mais comuns são *Paepalanthus* (Eriocaulaceae), *Mimosa* (Fabaceae), *Chamaecrista* (Fabaceae), *Myrcia* (Myrtaceae), *Hyptis* (Convolvulaceae), *Vellozia* (Velloziaceae), *Croton* (Euphorbiaceae), *Syngonanthus* (Eriocaulaceae), *Xyris* (Xyridaceae) e *Paspalum* (Poaceae) (MENDONÇA et al., 2008). Assim, o Cerrado nordestino é classificado como uma província periférica com assembleia de espécies únicas, distinta do Brasil Central (FRANÇOSO et al., 2019; RATTER; BRIDGEWATER; RIBEIRO, 2003;

VIEIRA et al., 2019). Esse provincialismo é atribuído à dispersão geográfica, à variabilidade climática da região e à mistura de espécies tanto da Caatinga quanto da Amazônia (CASTRO; MARTINS, 1999; VIEIRA et al., 2019).

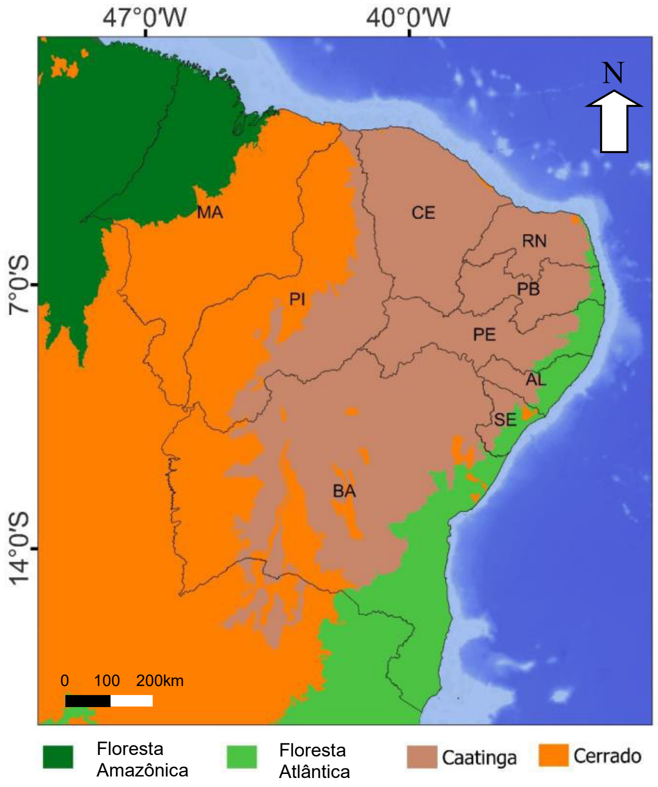

Figura I.4. Mapa dos domínios fitogeográficos do Nordeste (VIEIRA et al., 2022).

Mudanças pretéritas nas condições climáticas do Nordeste levaram a alterações na distribuição dos domínios fitogeográficos durante o Holoceno. A partir de aproximadamente 6.000 anos cal AP no oeste do Nordeste, a reorganização dos táxons do Cerrado e da floresta amazônica foi causada pela alternância de condições secas e úmidas durante o início do Holoceno médio (LEDRU et al., 2006; MORAES et al., 2021, 2022). No leste da região, a predominância de táxons de floresta semidecídua, caducifólia e ombrófila, Cerrado e Caatinga foi influenciada por oscilações de um transecto de umidade leste-oeste do Holoceno médio-final (MONTADE et al., 2014; MORAES; DE OLIVEIRA; BEHLING, 2020; OLIVEIRA et al., 1999). Por volta de 4.200 anos cal AP, os táxons arbóreos da Amazônia aumentaram progressivamente durante um clima úmido no oeste (MORAES et al., 2021, 2022), enquanto a vegetação da Caatinga se expandiu durante um clima seco no leste (MORAES; DE OLIVEIRA; BEHLING, 2020; OLIVEIRA et al., 1999). Florestas caducifólias, semidecíduas e ombrófilas formavam refúgios isolados nos enclaves de montanha no meio da Caatinga

(MONTADE et al., 2014).

A partir de ~6000 anos cal AP, ocorreu baixa frequência de incêndios na maior parte da região (MORAES et al., 2021, 2022; OLIVEIRA et al., 1999; PESSENDA et al., 2010). Durante o Holoceno médio-tardio, a atividade do fogo aumentou progressivamente no leste do Nordeste (PESSENDA et al., 2010), mas não aumentou no oeste (LEDRU et al., 2006; MORAES et al., 2021, 2022). Isso mudou durante o Holoceno tardio, quando ocorreu intensa atividade de fogo na região. Esses incêndios estavam relacionados a diferentes fontes. No leste seco, as queimadas foram atribuídas às mudanças climáticas (OLIVEIRA et al., 1999) e presença humana (MORAES; DE OLIVEIRA; BEHLING, 2020), enquanto no oeste úmido do Nordeste, fogos eram relacionados à atividade antrópica (MORAES et al., 2021, 2022). Além disso, os incêndios do Holoceno tardio também podem ter sido uma combinação de interações clima-homem (PESSENDA et al., 2010).

1.2.3. Ocupação humana

O Nordeste é a região mais populosa do mundo no hemisfério sul e a segunda região mais populosa do Brasil, com 55 milhões de pessoas (IBGE, 2023). Tem sido povoada desde antes da chegada dos europeus por volta de 1500 EC (DANTAS; SAMPAIO; CARVALHO, 1992; MEDEIROS, 2002; PRADO JR, 2011). Registros arqueológicos sobre a presença humana datam do final do Paleolítico (~50.000 anos AP) (MARTIN, 2013), incluindo os patrimônios mundiais da UNESCO Geoparque Seridó, no Rio Grande do Norte, o Geoparque Araripe, no Ceará, e o Parque Nacional da Serra da Capivara, no Piauí. Fogueiras, artefatos líticos e pinturas rupestres podem ser encontrados em todo o Cerrado e Caatinga (BUENO; DIAS, 2015; ETCHEVARNE, 2000; GUIDON et al., 1994; MARTIN, 2013).

Apesar do rico registro arqueológico, os dados dispersos dificultam uma interpretação regional precisa da dinâmica homem-ambiente (ARAUJO et al., 2006, 2005), agravado também pela falta de datações arqueológicas para o Holoceno médio-tardio. No entanto, inferências locais têm sido feitas sobre a distribuição dos grupos humanos, relacionando-os com mudanças paisagísticas, culturais e climáticas. Durante o Holoceno inicial e médio, grupos de caçadores-coletores habitavam abrigos rochosos e áreas abertas quando um clima mais úmido predominava no Nordeste (LAROCHE; SILVA LAROCHE, 1987; MARTIN, 2013; MELO, 2007). Artefatos líticos e pinturas rupestres de tradições semelhantes também são encontrados no Brasil Central, evidenciando uma rede cultural compartilhada em larga escala (BUENO; ISNARDIS, 2018).

Após a aridez da região por volta de 4.200 anos cal AP, o Holoceno tardio mostra a predominância de grupos agricultores-ceramistas próxima a rios e campos úmidos. Estas estão relacionadas às antigas tradições Jê e Tupiguarani, grupos indígenas que habitavam a Caatinga e o Cerrado (MARTIN, 2013; PEROTA, 1987; SOUZA; MATEOS; MADELLA, 2020). O uso da terra por esses grupos nativos consistia em menos incêndios e nenhum desmatamento. No entanto, essas práticas mudaram ao longo do último milênio, principalmente após 1492 EC (KOCH et al., 2019), durante a era colonial do Brasil com a extração de madeira, pecuária e atividades agrícolas (MOURA et al., 2019; SLUYTER; DUVALL, 2016). Atualmente, a região enfrenta avançada degradação ambiental da cobertura vegetal e esgotamento dos recursos naturais devido à combinação de efeitos de secas severas e pressões antrópicas (SILVA et al., 2023).

1.3. Objetivos e justificativa

O Nordeste é um vasto território com densidade populacional irregular, diferentes sistemas climáticos e uma vegetação heterogênea que sofre com intenso uso do solo durante as últimas décadas. A variabilidade das chuvas, o elevado potencial de evapotranspiração, a alta insolação e a degradação do solo tornam a região vulnerável às mudanças climáticas (IPCC, 2022; MARENGO et al., 2017). Os episódios de seca registados desde o século XVI têm aumentado em número e intensidade, tornando-se mais frequentes nos últimos 30 anos (MARENGO et al., 2017). Projeções futuras mostram diminuição das chuvas em mais de 54% da região com aquecimento acima de 4ºC até 2100 (Figura I.5) (MARENGO et al., 2020), resultando em estações secas prolongadas e episódios extremos de aridez, junto a degradação da terra que acelerará o processo atual de desertificação (MARENGO et al., 2016; VIEIRA et al., 2015). Isso afetará tanto os ecossistemas quanto a manutenção do bem-estar da população em um cenário de recursos hídricos esgotados e recursos naturais degradados (MARENGO; TORRES; ALVES, 2016).

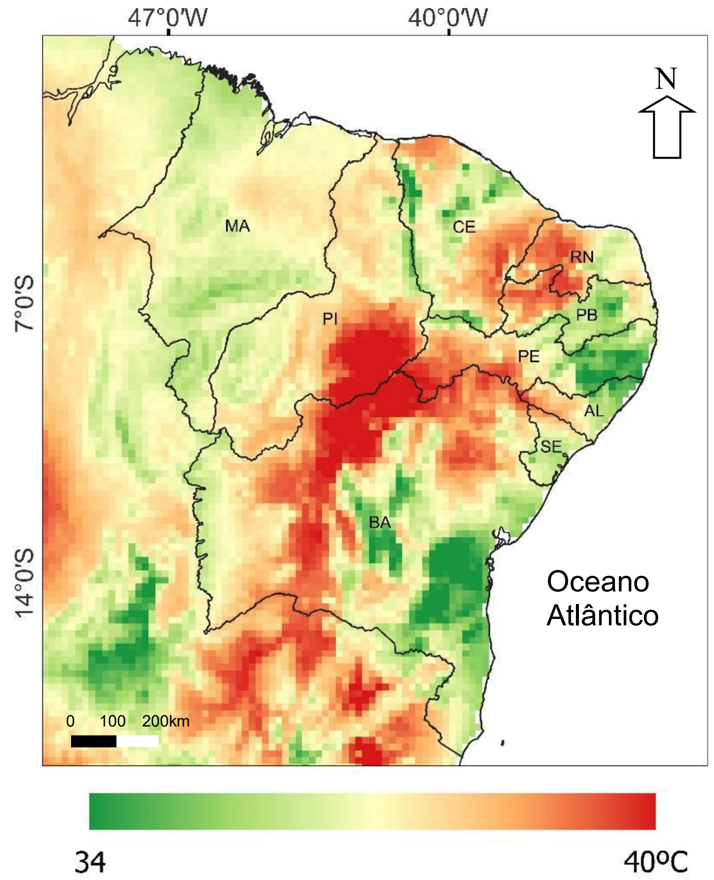

Figura I.5. Projeção futura para média de temperatura máxima mensal (°C) no Nordeste até 2080-2100 (source: CMIP6, 2021).

Neste contexto, o principal objetivo desta tese é reconstituir as respostas da vegetação do Cerrado durante as mudanças climáticas do Holoceno médio-final no Nordeste, para entender as interações clima-vegetação-homem e o impacto futuro das mudanças climáticas em curso e pressões antrópicas nesses ecossistemas. Esta pesquisa é baseada em pólen e macro-carvão depositados em sedimentos pantanosos como *bioproxies* paleoclimáticos e paleoambientais. Os três artigos incluídos nesta tese contribuem de forma complementar para abordar o objetivo principal. Cada artigo com seus próprios objetivos específicos é descrito a seguir:

Artigo 1. Chapter II: Changes in fire activity and biodiversity in a Northeast Brazilian Cerrado over the last 800 years. Objetivos: Descrever como mudanças passadas na ocupação humana e no clima afetaram um ecótono Cerrado-Caatinga no último milênio.

Artigo 2. Chapter III: Millennial-scale variability of vegetation and fire activity in a northern Cerrado driven by an east-west rainfall gradient during the Holocene.

Objetivos: Analisar as respostas da vegetação e da atividade do fogo de um Cerrado localizado a sudoeste no Nordeste à variabilidade da precipitação durante os últimos 6.000 anos AP, com foco na dinâmica da vegetação de uma área de transição climática localizada entre o fluxo de umidade amazônico e o domínio semiárido.

Artigo 3. Chapter IV: 6000 years of monsoon driven east-west antiphasing of Northeastern Brazil vegetation. Objetivos: Avaliar a dinâmica da vegetação, do fogo e os impactos antrópicos das paisagens do Nordeste do Brasil durante o Holoceno. Apresenta uma síntese de todos os estudos paleoecológicos (pólen e carvão) realizados na região e analisa as respostas da vegetação ao longo de dois transectos espaço-temporais, um leste-oeste e outro norte-sul.

Esta tese faz parte do INCT IN-TREE (FAPESB, CNPq, CAPES), projetos CNPQ/ICMBIO/FAPs n 18/2017, Labex CEBA, Paleoecologia humana, Evoluções sociais e culturais entre os primeiros assentamentos na América do Sul (ANR SESAME), e o JAI *“Le semi-aride du Nordeste à l'Anthropocène”* (SANA). Este estudo foi parcialmente financiado pela Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Código Financeiro 001, pelo projeto CAPES/PRINT/UFC 88881.311770/2018-01, Campus France, IRD e ISEM.

1.4. Áreas de estudo

Nossa pesquisa foi realizada em duas unidades de conservação: o Parque Nacional das Sete Cidades, no norte do Piauí (artigo 1), e o Parque Nacional da Chapada das Mesas, no sudoeste do Maranhão (artigo 2) (Figura I.6). Criadas por decretos federais em 1961 e 2005, respectivamente, são áreas protegidas com manejo equivalente à categoria II da União Internacional para a Conservação da Natureza (IUCN) (DUDLEY, 2008). A coleta dos testemunhos sedimentares foi realizada em setembro de 2013 em uma vereda nas proximidades da Chapada das Mesas e em junho de 2018 em uma pequena clareira com uma vereda nas proximidades de Sete Cidades. Uma descrição detalhada de cada área de estudo pode ser encontrada nos artigos 1 e 2.

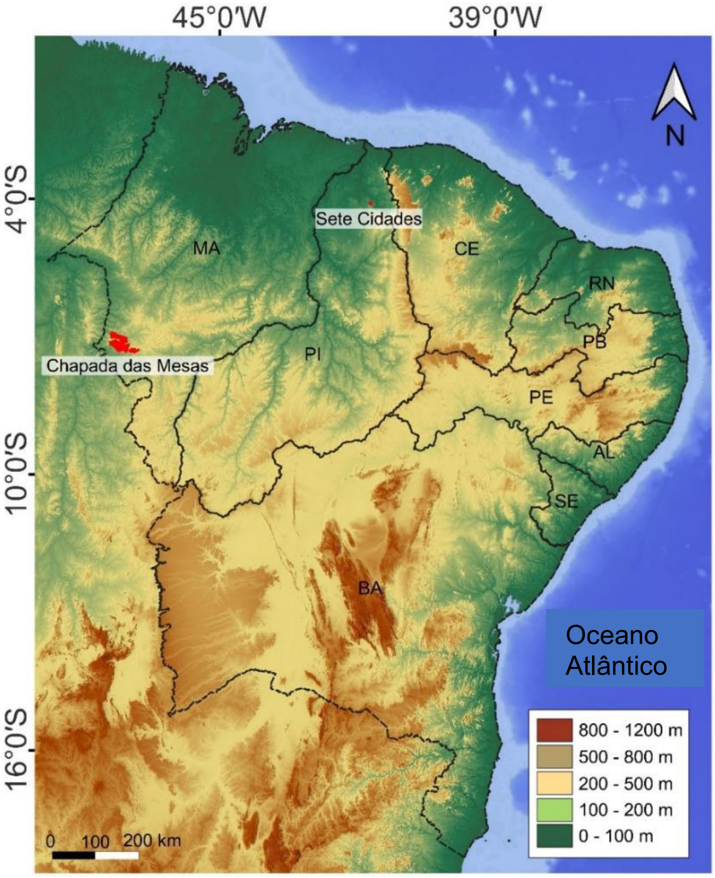

Figura I.6. Mapa hipsométrico do Nordeste mostrando a localização dos parques nacionais "Sete Cidades" e "Chapada das Mesas".

1.5. Métodos

Dois métodos principais foram usados para reconstituir a vegetação passada e a atividade do fogo: análises de pólen e carvão em testemunhos sedimentares coletados em áreas úmidas permanentes. A cada testemunho estudado foi atribuído um modelo idade-profundidade com base em datações calibradas C14. Os modelos de idade foram construídos usando o pacote Rbacon no RStudio (BLAAUW; CHRISTEN, 2011). Adicionalmente, análise granulométrica foi realizada para o artigo 1. A granulometria consiste na determinação da distribuição das partículas primárias no sedimento: argila, silte e areia (WENTWORTH, 1922). Análises estatísticas e modelagem de dados (análise de componentes principais, índice de variação paleoambiental, index de pólen, escalonamento multidimensional não métrico e função ortogonal empíricas) para interpretação dos dados foram realizadas no RStudio. A escolha de cada método é explicada nos artigos 1, 2 e 3.

Subamostras para as análises palinológicas foram coletadas em intervalos de 1 cm para os artigos 1 e 2. As amostras foram preparadas no laboratório de processamento químico do Institut des Sciences de l'Evolution de Montpellier (ISEM), usando uma combinação de técnicas padrão (FAEGRI; IVERSEN, 1989) e um protocolo sem ácido (SANTOS; LEDRU, 2021) para sedimentos quaternários descritos a seguir. Em um tubo Falcon de 50 ml, duas pastilhas do marcador exótico *Lycopodium clavatum* (18.407 esporos por pastilha) foram dissolvidos em 10 ml de água destilada. Em seguida, 0,5 cm^3 de subamostras foram colocadas nos tubos, homogeneizadas com um vortex. O tubo foi centrifugado por quatro minutos a 3000 rpm e o sobrenadante descartado. Uma solução de hidróxido de potássio a 10% foi adicionada para separar o pólen da matéria orgânica, misturada e deixada em água quente a 80ºC por seis minutos, agitada a cada três minutos. Outra centrifugação a 3.000 rpm por quatro minutos e o sobrenadante foi descartado. Essa etapa com hidróxido de potássio seguida da centrifugação foi repetida várias vezes para cada amostra até o clareamento do sobrenadante. O material foi homogeneizado com 10 ml de água destilada utilizando o misturador vórtice, centrifugado a 3.000 rpm por quatro minutos, duas vezes.

Os tubos foram invertidos em uma superfície plana por 60 minutos para remover o excesso de água restante. Uma solução de cloreto de zinco (densidade 1,9 $g.cm^3$) de 10 ml foi adicionada aos tubos, homogeneizada com o vortex, centrifugada a 1000 rpm por quatro minutos para garantir a flotação do resíduo de pólen. O sobrenadante foi transferido para um Becker de 100 ml, adicionado de 10 ml de água destilada para reduzir e homogeneizar o cloreto de zinco. A mistura foi despejada em novos tubos falcon, centrifugada a 3.000 rpm por quatro minutos e o sobrenadante foi descartado. Para garantir a eliminação do cloreto de zinco das amostras, adicionou-se 10 ml de água destilada, repetindo-se esta etapa por duas vezes. A matéria orgânica restante foi removida com 10 ml de solução de hidróxido de potássio e metafosfato de sódio, misturada com o vortex e deixada em banho-maria a 80ºC por 30 minutos, agitada a cada 10 minutos. Em seguida, os tubos foram centrifugados a 3.000 rpm por quatro minutos, o sobrenadante descartado e nova centrifugação com 10 ml de água destilada a 3.000 rpm por quatro minutos, duas vezes, e o sobrenadante descartado. Algumas amostras apresentaram alto teor de silicatos que poderiam interferir nas análises polínicas foram tratadas com 5 ml de ácido fluorídrico por uma hora. Os tubos foram centrifugados a 3.000 rpm por quatro minutos, os sobrenadantes foram descartados e 10 ml de água destilada foram adicionados após centrifugação a 3.000 rpm por quatro minutos. Esta etapa foi repetida três vezes para garantir a remoção de todo o ácido fluorídrico das amostras. O resíduo polínico foi transferido para tubos Eppendorf de 2 ml, o sobrenadante descartado e solução de glicerina 80% foi adicionada aos tubos Eppendorf na proporção de 1:1. O protocolo sem ácido permitiu uma melhor concentração do resíduo polínico, bem como facilitou eventuais tratamentos com ácido fluorídrico em menor quantidade (apenas 5 ml por amostra).

O mínimo de 300 grãos de pólens terrestres foram contados, excluindo táxons aquáticos e relacionados ao nível de água. Os tipos polínicos foram identificados usando a coleção de referência do ISEM, atlas polínicos publicado para Cerrado e outros biomas (CASSINO; MEYER, 2011; COLINVAUX; OLIVEIRA; PATIÑO, 1999; LORENTE et al., 2017; SALGADO-LABOURIAU, 1973) e base de dados *online* (BUSH; WENG, 2007; MARTIN; HARVEY, 2017). A contagem das amostras polínicas foi realizada no Laboratório de Ecologia e Anatomia Funcional (LEAF) da Universidade Federal do Ceará (UFC) e na sala de microscopia do ISEM da Université de Montpellier.

Subamostras para análises de carvão foram retiradas com intervalos de 1 cm para os artigos 1 e 2, preparadas no laboratório Sedimentar do ISEM com protocolo padrão (STEVENSON; HABERLE, 2005) descrita a seguir. As subamostras foram adicionadas a tubos plásticos, tratadas com hipoclorito de sódio e hidróxido de potássio dissolvidos em 10 ml de água destilada para branqueamento do conteúdo orgânico e separação das partículas de carvão. Os tubos foram deixados em mesa vibratória por 24 horas. Em seguida, o conteúdo do tubo foi cuidadosamente despejado em uma peneira de malha de 160 µm e lavado suavemente em água corrente para remover resíduos químicos e sedimentos remanescentes. O processo de lavagem foi realizado com leve jato de água em delicados movimentos circulares e uniformes, para não danificar as partículas de carvão. O resíduo restante foi transferido para uma placa de Petri de aproximadamente 10 cm de diâmetro. Todos os fragmentos de carvão foram quantificados (número de partículas) e qualificados (largura, comprimento e área) por visualização em estereomicroscópio e medidos usando o software WinSeedle (Regent Instruments, Quebec, Canadá). A contagem do carvão foi realizada na sala de carpologia-antracologia do ISEM.

1.6. Resultados principais

Changes in fire activity and biodiversity in a Northeast Brazilian Cerrado over the last 800 years

O estudo *multiproxy* (pólen, carvão, granulometria) de um testemunho sedimentar de alta resolução do Parque Nacional das Sete Cidades revelou mudanças na florística e estrutura do Cerrado durante períodos úmidos e secos, associadas a mudanças na atividade de fogo nos últimos 800 anos. O período seco entre 1200 e 1350 EC foi marcado pelo domínio de táxons resistentes à seca (por exemplo, *Curatella, Cuphea*) que se correlaciona com a Anomalia Climática Medieval entre 950-1250 EC no Hemisfério Norte. Baixa atividade de fogo foi atribuída à ausência humana devido as condições de seca. A partir de 1400 EC, um intervalo mais úmido refletiu a expansão da vereda (*Mauritia flexuosa*) e os táxons relacionados à umidade (por exemplo, *Myrtaceae, Spatiphyllum*), que se correlaciona com a Pequena Idade do Gelo entre 1400-1700 EC no Hemisfério Norte. O aumento da deposição de areia foi relacionado a altas condições erosivas. Um pequeno aumento na queima de biomassa representa a transição do período seco para o úmido, seguido por incêndios constantes até 1650 EC. Isso foi atribuído ao retorno dos grupos indígenas à região após o aumento das condições de umidade, onde suas práticas de uso da terra consistem em menos incêndios e nenhum desmatamento. Uma mudança nas queimadas foi observada após 1650 EC, caracterizada por alta queima de biomassa e picos de carvão indicando incêndios intensos e desmatamento. Correlacionamos essa mudança com a chegada dos europeus ao Norte do Piauí, onde praticavam intensas queimadas e desmatamentos. Os incêndios pararam após a criação do parque das Sete Cidades em 1961 EC, o que resultou na expansão dos táxons arbóreos de Cerrado (por exemplo, *Byrsonima, Caryocar, Mimosa*). Em conclusão, a combinação de análises *multiproxy* com arquivos históricos foi uma abordagem eficaz para reconstituir mudanças climáticas de longo prazo e práticas de uso da terra, detalhando informações ausentes nos documentos históricos. Isso reforça a importância de considerar a história das paisagens para a implementação de planos de conservação.

Millennial-scale variability of vegetation and fire activity in a northern Cerrado driven by an east-west rainfall gradient during the Holocene

O registro de pólen e carvão de alta resolução mostra mudanças alternadas na vegetação durante períodos secos e úmidos no final do Holoceno. Entre 6.000 e 5.200 anos cal AP, uma vegetação aberta composta por herbáceas Asteraceae, *Acalypha, Scoparia* e *Protium* dominou a região da Chapada das Mesas durante condições relativamente secas sem atividade de fogo. Isso foi relacionado a uma convecção de monção enfraquecida registrada no Brasil Central durante este período. A partir de 5200 anos cal AP, um cerrado lenhoso com *Guazuma, Casearia, Alchornea* e vereda (*Mauritia flexuosa*) aumentou durante um período mais úmido e baixa atividade de fogo, sincronizado com o aumento da intensidade da monção no Centro e Nordeste do Brasil. Entre 4.300 e 3.800 anos cal AP, nove amostras estéreis foram atribuídas a um evento seco que causou a oxidação do conteúdo polínico. As condições de seca continuaram até 3.500 anos cal AP, quando os táxons resistentes à seca *Byrsonima, Dimorphandra* foram substituídos por Melastomataceae e Myrtaceae à medida que as taxas de umidade retornaram gradualmente à Chapada das Mesas. A alta queima de biomassa nesse período está ligada às condições sazonais, quando ocorrem queimadas naturais no Cerrado. A partir de 2.600 anos cal AP, a expansão da floresta de galeria, da vereda e do cerrado lenhoso marcou o aumento das taxas de umidade sem queima de biomassa. Uma mudança nos táxons arbóreos e aumento de queimadas foram observados em 270 anos cal AP, relacionados à atividade antrópica na Chapada das Mesas, uma vez que nenhuma mudança climática foi registrada naquele período. A vegetação do Cerrado do nordeste mostrou uma grande sensibilidade às oscilações da convecção das monções desde meados do Holoceno tardio como ocorreu no Brasil Central.

6000 years of monsoon driven east-west antiphasing of Northeastern Brazil vegetation

Uma melhor compreensão das mudanças paleoecológicas regionais depende de uma base de dados de alta qualidade. Integramos os resultados desta tese (artigos 1 e 2) a outros seis registros de pólen e três registros de carvão do Nordeste do Brasil que capturam a variabilidade ambiental durante os últimos 6.000 anos. Discutimos sua evolução para a assinatura espacial das mudanças climáticas e presença antrópica em toda a região. Padrões semelhantes de resposta da vegetação às mudanças climáticas são observados entre 6.000 e 4.200 anos cal AP. Alternância de táxons de Cerrado, Caatinga e Floresta Amazônica durante as oscilações de um transecto pluviométrico leste-oeste em toda a região, com intensidade variável de alguns locais no noroeste da região. Após 4.200 anos cal AP, um evento seco que marcou o início da aridez na região foi registrado em muitos locais. No oeste do Nordeste, a baixa preservação do pólen em nove amostras da Chapada das Mesas foi atribuída à oxidação devido às condições de seca. No leste do Nordeste, a baixa preservação do pólen seguida pela expansão da floresta seca da Caatinga foi observada no registro do Vale do Icatu. Este evento seco também causou a substituição da floresta ombrófila de montanha pela floresta semidecídua durante um período de 750 anos. Por outro lado, os táxons da floresta amazônica e o cerrado lenhoso se expandiram a oeste do Nordeste, seguindo o fluxo de umidade amazônico sob intensificada convecção das monções do Brasil Central. Nenhuma presença humana foi inferida até cerca de 3.000 anos cal AP, quando a atividade antrópica se intensificou em toda a região. Incêndios antrópicos intensos foram registrados durante condições secas no leste e condições úmidas no oeste, variando em intensidade e padrões de acordo com os aspectos históricos de cada local. Durante um clima seco no leste do Nordeste, mudanças nas queimadas relacionadas a práticas indígenas seguidas pela presença europeia durante o período colonial brasileiro. Durante as condições úmidas no noroeste da região, grupos nativos praticavam queimadas nas paisagens costeiras. Apesar do número crescente de pesquisas paleoecológicas na região na última década, mais estudos são necessários para ampliar a distribuição espacial dos conjuntos de dados e melhorar a precisão do quadro regional.

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2. CAPÍTULO II / CHAPITRE II

CHANGES IN FIRE ACTIVITY AND BIODIVERSITY IN A NORTHEAST BRAZILIAN CERRADO OVER THE LAST 800 YEARS

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Changes in fire activity and biodiversity in a Northeast brazilian Cerrado over the last 800 years

Sergio Augusto Santos Xavier[a, b,] , Francisca Soares de Araújo[b], Marie Pierre Ledru[a]

[a]ISEM, Univ Montpellier, CNRS, IRD, University of Montpellier, Place Eugène Bataillon, 34095 Montpellier, France
[b] Graduate Course of Ecology and Natural Resources, Department of Biology, Campus of Pici, Federal University of Ceará, Fortaleza - 60440-900, CE, Brazil

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Abstract

Understanding vegetation dynamics is essential to interpret long-term ecological changes under different precipitation regimes and land use scenarios. Northeastern Brazil has been subjected to both climatic and anthropic disturbances in recent centuries. This paper presents a high-resolution record from the SAC18 sediment core, collected in a Cerrado ecotone in the Sete Cidades National Park. Multiproxy analyses based on pollen, charcoal and grain size showed the Cerrado landscape was restructured during dry and wet intervals over a period of 800 years. The beginning of the record was marked by a dry episode, testified by the presence of a drought resistant taxon *Curatella* (wild cashew tree) and coincided with the Medieval Climate Anomaly (950-1250 CE). Almost no fire activity was observed between 1210 and 1300 CE, linked to reduced human presence during this dry period. A wetter interval began in 1400 CE, with expansion of the palm swamp and the moisture-related tree/herbaceous taxa Myrtaceae and *Spathiphyllum*, which was synchronous with the Little Ice Age (1400-1700 CE). Reduced burning of biomass and the absence of deforestation at the beginning of the wet interval changed to extensive fires and deforestation after 1650 CE, enabling dating of the arrival of European colonists in the north of Piauí State. Fires stopped after the creation of Sete Cidades National Park in 1961 CE, resulting in the expansion of the Cerrado arboreal cover. This study provides new knowledge about past human occupation of the Northeastern Cerrado, defined by three types of land use practices (indigenous, colonist and protection policy), and underlines the importance of including historical aspects of the landscape in

future conservation scenarios.

Keywords: Pollen, Charcoal, Human impact, Climate change, Land use, Conservation unit

1. Introduction

Multiproxy approaches and high-resolution environmental reconstructions are essential to understand the historical background of modern landscapes, as they address both human impacts and climate changes (Flantua et al., 2016). In this context, the paleoenvironmental history of Northeastern Brazil (hereafter NE Brazil) is still poorly known. In the last two decades, only seven paleoecological studies have been carried out in the region (de Medeiros et al., 2018; de Moraes et al., 2020, 2021; Ledru et al., 2006; Montade et al., 2014; Oliveira et al., 1999; Pessenda et al., 2010) (Fig. II.1A), mainly at multi millennial-scale with scarce information on the Late Holocene.

Landscapes in NE Brazil are characterized by different types of vegetation, dominated by the semiarid Caatinga, patches of semi-deciduous forests, cerrados, and transition areas (ecotones) (Fig. II.1A). Past changes in the structure and composition of Cerrado biome were often linked to precipitation seasonality with an increase in fire activity during the glacial to interglacial transition, ~11.000 yrs Before Present (BP) (Ledru et al., 2006; Cassino et al., 2020). Moisture rates in Early Holocene climates in NE Brazil were higher than today and became drier after 4200 yr BP, when montane evergreen forest was replaced by semi-deciduous forest (Cruz et al., 2009; Montade et al., 2014; Tabor et al., 2020). During the last 2000 years, alternating wet/dry episodes occurred due to expansion/retraction of the Inter Tropical Convergence Zone (ITCZ) in response to warming/cooling of the equatorial Atlantic and changes in trade winds (Utida et al., 2019).

The Cerrado is the second largest biome in Brazil, extending geographically from the equatorial zone to latitude 23ºS (Motta et al., 2002), from the Northeastern to the Central Region. In NE Brazil, the Cerrado extends from the western region to the southwest and north of the State of Piauí (Castro et al., 2007) (Fig. II.1), with a high proportion of monospecific taxa and lower species richness resulting in a unique flora compared to the Central Region Cerrado (Ratter et al., 2011; Vieira et al., 2019). Natural fires occur in the Cerrado vegetation during the transition period from the dry to the rainy season (Gomes et al., 2018). Natural fires can be less damaging than anthropogenic fires due to higher moisture content in the environment, soil, and vegetation (Sluyter and Duvall, 2016). Fires that occur during the dry season are mainly caused by people and may cause greater damage to vegetation, spread faster and burn larger areas than wildfires. In the last millennium, changes in land use practices were observed before and after European colonisation (Loughlin et al., 2018), with less fires and no deforestation before AD 1492 followed by intense fires and extensive deforestation after AD 1492 (Iriarte et al., 2012; Koch et al., 2019). Anthropogenic burning practices shifted from the early to late dry season during the Brazilian colonial rangeland era (Sluyter and Duvall, 2016).

Approximately 63% of the NE Brazil region is semi-arid, with no permanent lakes or swamps, thus rendering any paleoecological research challenging. However, studying past expansion or regression of the Northeastern Cerrado is a good alternative way to improve knowledge of past climates and biodiversity in NE Brazil, which is also the richest region in Brazil in terms of archeological remains. NE Brazil includes one world heritage site, the Serra da Capivara National Park, where the most ancient South American human occupation dates back 40000 years (Guidon et al., 1994) and evidence of megafauna is present until the mid-Holocene (Parenti et al., 2021).

Sete Cidades National Park, in the State of Piauí, is located in the semi-arid Cerrado, which contains permanent swamps suitable for paleoecological study. The park hosts a rich collection of rock paintings and evidence for human occupation dates back more than 800 years (Cavalcante, 2018) to the first Amerindians and after ~1600 CE, with European colonization (Alves, 2003), according to historical records (e.g., Prado Jr, 1987; Queiroz, 1984; Oliveira 2002; Alves, 2003; De Negreiros Oliveira, 2004; Cabral, 2020). After its creation in 1961, Sete Cidades National Park environmental management was based on protection policies (investigation, monitoring, and conservation of natural resources), management of use of the park by the general public (recreation, education, tourism, extension activities, and public relations) and operational management (protection and administration of the park) (IBDF, 1979).

This article describes how past changes in human occupation and climate have affected the Cerrado over the last millennium, with the aim of understanding the future impact of ongoing climate change in a currently very densely populated region (Marengo et al., 2017). In this context and in the absence of detailed historical archives, the investigation addresses two research questions: (1) How to distinguish between Amerindian and European impacts on the Northeastern Cerrado landscape during the pre- and post-colonial era? (2) What effect did the creation of Sete Cidades National Park have on the environment after such a long history of land exploitation? To answer these questions, high-resolution pollen, charcoal, and grain size analyses were performed on a sediment core collected in a *Mauritia* swamp (*vereda* in Portuguese), which enabled evaluation of the effects of climate and human activities on plant diversity.

2. Study area

Created by a federal decree on June 8, 1961, Law Nº 50.744, the Sete Cidades National Park (SCNP) (04º05' to 04º15'S, 41º30' to 41º45'W, 100 to 290 m a.s.l.) is located in the northeast of the State of Piauí, in the Parnaíba Sedimentary Basin, and covers a total area of 6,221.48 ha (Fig. II.1B). The Parnaiba Basin is formed by Paleozoic rocks from the Silurian and the Late Devonian. The park is situated in the southern section over a sandy wedge that dates as Famennian age (371.1 ± 1.1 – 359.3 ± 0.3 Ma) (Della Fávera, 2002). It contains a unique collection of natural monuments, ruiniform sandstone outcrops grouped in "seven cities" (Santos, 2001; Della Fávera, 2002). Mean annual temperatures range from 26.7 ºC to 34.2 ºC, and mean annual precipitation from 1,040.6 mm to 1,393.2 mm, with a 4-month rainy season lasting from January to April (Santos et al., 2017) (Fig. II.1C).

The official document approved by the *Instituto Chico Mendes de Conservação da Biodiversidade* – ICMBio (IBDF 1979) describes 15 landowners within the park perimeter at the time of its creation. These lands were legally notarized, purchased and recorded for full protection. Four management zones were defined: (1) intensive use: where the aim is to facilitate environmental education and enable intensive recreation with minimal impact; (2) extensive use: where the aim is to maintain natural landscapes with minimal human impact to be used for educational and recreational purposes with moderate public access; (3) recovery zone: where the aim is to stop the degradation of natural resources and to support landscape recovery; and (4) special use zone: where the aim is to minimise anthropic impacts by removing everything not related to the park (IBDF 1979). Currently, there is no private property within the park limits.

Between 1999 and 2018, a total of 1930 spot fires were recorded in and around the park (INPE 2020) (Supplementary Fig. 1), with the highest fire incidence in 2012, 2015 and 2018. Most fires occurred in October and November during the dry season, as a consequence of pasture renewal and cropping practices (Da Silva Souza and Pereira, 2019). However, fires that occur within the park limits and in the vicinity are monitored under an operational fire control plan that includes an agreement between the park management (PREVFOGO team) and farmers concerning fire control. Three types of surveillance and communication systems are implemented to monitor fires: fixed observatories, mobile teams, and *online* systems (satellite) (IBDF, 1979; Da Silva Souza and Pereira, 2019).

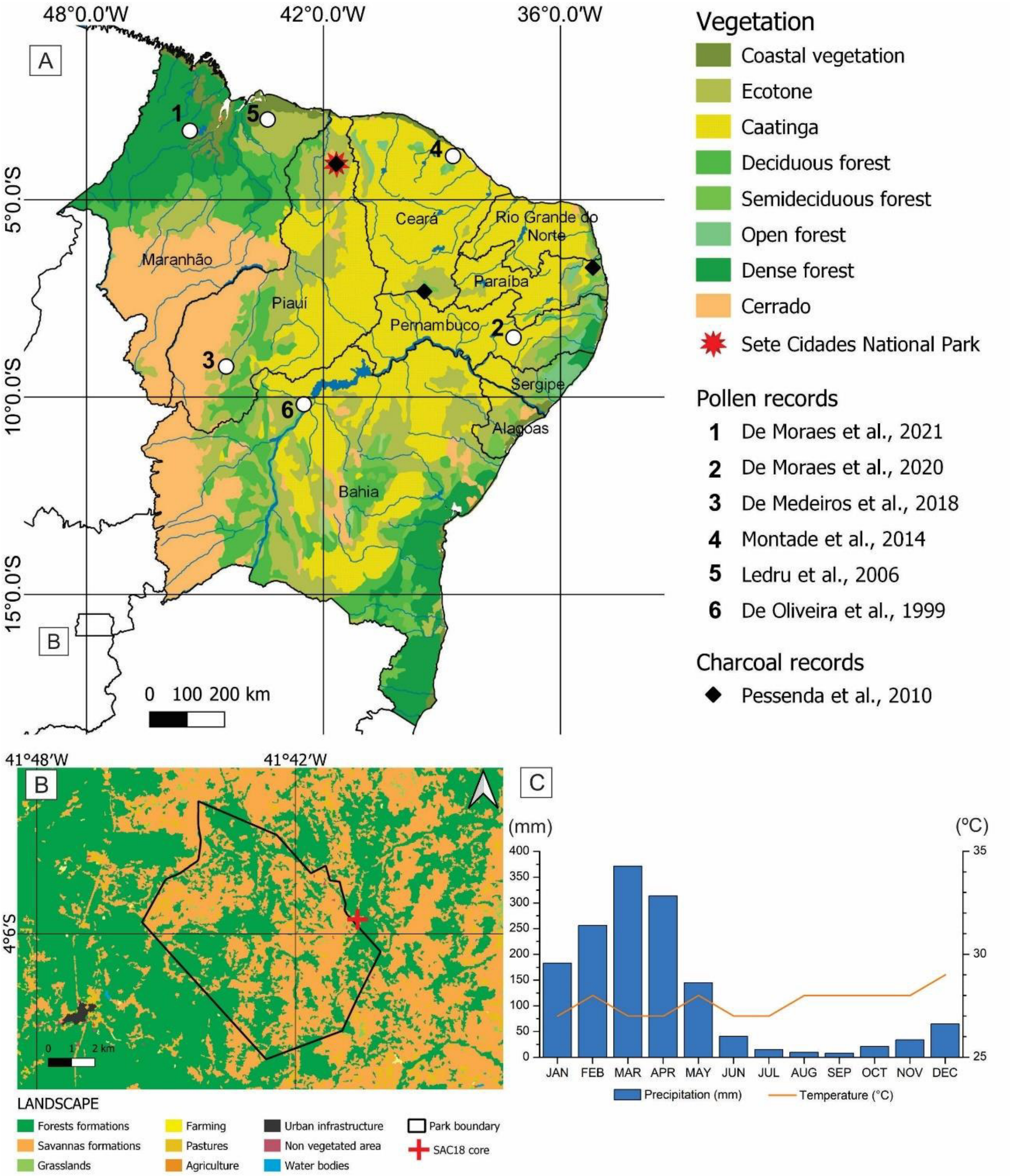

Fig. II.1. (a)Vegetation distribution in north-eastern Brazil with the paleoecological records mentioned in this paper (QGIS software 3.12). (b) Vegetation map of the region containing Sete Cidades National Park showing the limits of the park (black line) and the location of the swamp (red cross) (source: Project MapBiomas 2021). (c) Ombrothermic diagram showing mean monthly temperatures (1994-2018) and mean calculated monthly precipitation (1913-2018) (data source: Superintendency for the Development of the Northeast (SUDENE) and the National Institute of Meteorology (INMET) https://portal.inmet.gov.br/).

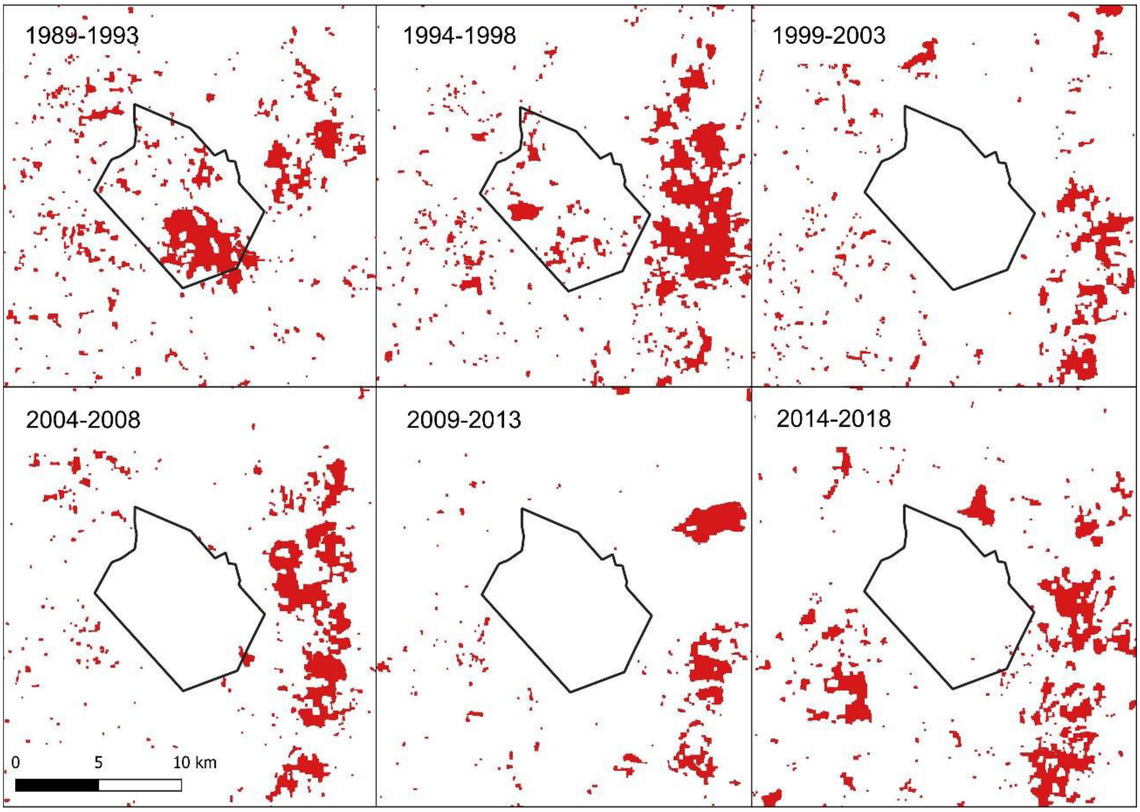

Fig. II.2. Annual burned area for a period of 30 years inside and outside Sete Cidades National Park (area outlined in black) (source Project MapBiomas 2021).

2.1. Climate

Precipitation in the SCNP is regulated by the seasonal shifts of the ITCZ characterised by a layer of clouds currently located near the geographic equator (Santos et al., 2017), where the northeast and southeast surface winds converge in ascending motion between the Hadley cells (Yan, 2005). ITCZ interannual shifts are influenced by the annual cycle of sea surface temperature (SST) of the tropical Atlantic Ocean and by the semi-annual insolation cycle. The thermal variability of the Atlantic Ocean between winter and summer controls rainfall seasonality over NE Brazil (Grodsky and Carton, 2003; Rodrigues et al., 2011).

El Niño South Oscillation (ENSO) is an interannual variation in winds and SST over the eastern Pacific Ocean that occurs every 2 to 7 years (Shimizu and Ambrizzi, 2016). It has two phases, El Niño and La Niña that are modulated by the air flow in the tropics caused by the Walker Circulation (Lau and Yang, 2002; L'Heureux et al., 2013). As an intrinsic component of ENSO, the Southern Oscillation is defined as differences in sea level pressure over the western and eastern Pacific Ocean (Yan et al., 2011). This antiphase behaviour is measured by the Southern Oscillation Index (SOI) which characterizes drier or moister periods based on the strength of El Niño and La Niña episodes (Yan et al., 2011). In NE Brazil, the effects of ENSO enhance or weaken interannual precipitation.

Despite incomplete historical records, SCNP shows a variation in the total annual precipitation since the beginning of the 20th century (Fig. II.3). Here only the years with at least six months of observation including the wet season (December-May) were taken into consideration. The two years with highest rainfall were 1924 with 3,755 mm and 1925 with 3,343 mm, while the mean annual precipitation for the period 1913-2018 was 1,476 mm (Fig. II.3). La Niña events lead to above-average precipitation over NE Brazil, reflecting high interannual rainfall values, like that recorded for the year 1924 (Araújo et al., 2013) preceded by increasingly wet years (1922-23), and a La Niña event recorded in 1922. Precipitation trends in NE Brazil under the influence of La Niña are usually more intense in the south-central State of Maranhão and in the State of Piauí at the beginning and/or in the middle of the summer season (November-January) (Souza et al., 2000; FUNCEME, 2020). Conversely, a strong El Niño event in 1951 was reported as the likely cause of intense drought episodes in NE Brazil (Alvarez et al., 2015; Marengo et al., 2017). Such events can be correlated with the below-average precipitation in SCNP for 1951, 512 mm, the driest year of the interval (Fig. II.3).

According to the ombrothermic diagram (Fig. II.3), precipitation in the SCNP seems to have followed the dry/wet patterns that have affected NE Brazil over the last 10 years. After 2010, below average rainfall was recorded for 2012, 2013, 2015 and 2016, while during the same period, severe drought conditions were established over NE Brazil, aggravated by the northward position of ITCZ (Marengo et al., 2017).

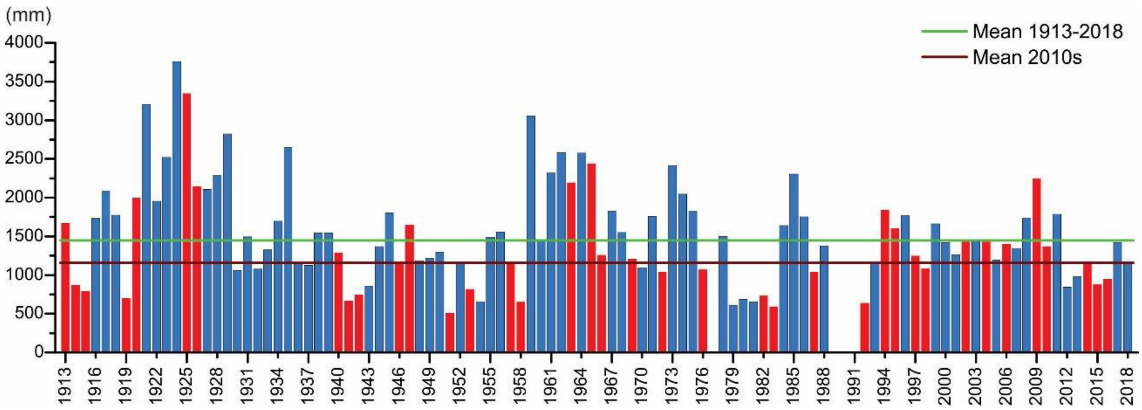

Fig. II.3. Mean annual precipitation for the period (1913-2018) recorded at Piripiri weather station (OMM: 82480, 161 m a.s.l.), located 19 km from Sete Cidades National Park (114 m a.s.l.), showing the decrease in rainfall in the last decade (brown line). The red bars represent El Niño years (NOAA 2021). (Data from the National Institute of Meteorology – INMET, Development Superintendence of the Northeast – SUDENE, and

National Water Agency – ANA).

2.2. Vegetation

About 33.3% of the State of Piauí is covered by Cerrado vegetation, and 14% of transition areas between Cerrado, Caatinga and gallery forests (Fundação CEPRO, 1992; Castro et al., 1998). This differs from the Cerrado of Central Brazil, where the ecotones with Amazon and Atlantic forests characterise different floristic compositions (Castro, 1994; Silva-Moraes et al., 2018; Nepomuceno et al., 2021).

Phytosociological surveys conducted in the Cerrado of SCNP identified six physiognomies: gallery forests, semi-deciduous forests, Cerradão (a type of Cerrado with a denser tree cover), Cerrado *sensu stricto*, rocky grassland (campo rupestre), and open grassland (campo limpo) (Barroso and Guimarães, 1980; Mesquita, 2003; Oliveira, 2004; Matos and Felfili, 2010; Moura, 2010; Mendes et al., 2012, 2014). Cerrado *sensu stricto* (37.6%) is the dominant physiognomy, followed by the Cerradão (24.3%) a humid semi-deciduous forest, and open grasslands (14.3%) (Oliveira, 2004).

In gallery forests, the plant families with the highest species richness are Fabaceae (14 species), Myrtaceae (8 species), Chrysobalanaceae (7 species), and Anacardiaceae (4 species), representing more than 44% of the total richness. *Virola surinamensis* is the species with the highest value index (45%). The genera *Hirtella* (Chrysobalanaceae), *Licania* (Chrysobalanaceae), and *Myrcia* (Myrtaceae) are the most frequent, with three species each, followed by *Aspidosperma* (Apocynaceae), *Brosimum* (Moraceae)*, Casearia* (Salicaceae), *Tabebuia* (syn. *Handroanthus*) (Bignoniaceae), and *Vitex* (Lamiaceae), with two species each (Matos and Felfili, 2010).

In the semi-deciduous forests, the richest families are Fabaceae (29 species) Bignoniaceae (12 species), Myrtaceae (8 species), and Combretaceae (6 species). Moraceae, Nyctaginaceae, Phytolaccaceae, Solanaceae, Malvaceae – Sterculiaceae type and Malvaceae – Tiliaceae type are exclusive to this physiognomy (Oliveira, 2004). In the Cerradão, the main families are Malvaceae – Bombacaceae type and Clusiaceae (Oliveira, 2004).

In the Cerrado *sensu stricto*, the most frequently represented arboreal and herbaceous families are Fabaceae (27 species) and Combretaceae (6 species), whereas the most represented genera are *Combretum* (3 species), *Byrsonima* (3 species), and *Tabebuia* (syn. *Handroanthus*) (3 species) (Mesquita, 2003). When the importance value index (IVI) is taken into consideration, Fabaceae (23.4%) surpass the families Combretaceae (16%), Vochysiaceae

(12.8%), Annonaceae (6.6%), Malpighiaceae (5.3%), and Caryocaraceae (4.3%) (Mesquita, 2003). Caryocaraceae, Dilleniaceae, Hippocrateaceae were the only examples of this physiognomy.

In the rocky grassland, the richest tree families are Fabaceae (14 species), Bignoniaceae (4 species), Vochysiaceae (4 species), Myrtaceae (3 species) and Apocynaceae (3 species) (Moura, 2010). The 10 species with the highest IVI are represented by three species of the Vochysiaceae (89.4%): *Qualea parviflora* (45.8%), *Salvertia convallariodora* (23.3%), and *Callisthene microphylla* (19.8%). Fabaceae (56.4%) is the second richest family with four species, *Plathymenia reticulata* (19%), *Parkia platycephala* (14.3%), *Copaifera coriaceae* (13.8%), and *Vatairea macrocarpa* (9.69%) (Moura 2010). In the open grassland, Cyperaceae is the richest family (12 species) followed by Poaceae (9 species), Fabaceae (8 species), and Melastomataceae (5 species) (Mendes et al., 2014).

A group of environmental factors are related to variations in the vegetation in SCNP, including soil fertility gradients, pH, and salinity that affect plant physiognomy (Lindoso, 2008; Mendes et al., 2012). The humidity gradient also has a significant influence on the differentiation of vegetation structure, even when the same physiognomies were compared in different areas in the park (Mendes et al., 2012). Such differences are commonly observed in the region's community vegetation mosaic in the Northeastern Cerrado (Castro, 1994, 2003). In addition, *Mauritia flexuosa* is the palm swamp taxon indicator of the Cerrado in the Brazilian Central Region (da Silva et al., 2018).

3. Modern pollen assessment

Modern pollen "rain" analyses are useful tools for environmental research because the pollen assemblage represents a mix of local and regional taxa, hence allowing a correlation between vegetation and climate (Chevalier et al., 2020). Studies of modern pollen "rain" performed in the Cerrado were based on surface soil samples (Ledru, 1991; Franco Cassino et al., 2015; Cassino and Ledru, 2021), artificial pollen traps or surface lake samples (Gosling et al., 2009).

Associations of taxa in modern pollen spectra sampled in the Bolivian Cerrado revealed three physiognomies: evergreen tropical forest with Moraceae (>40%), *Cecropia*, *Hyeronima*, and *Celtis*; semi-deciduous dry tropical forest with *Anadenanthera, Apuleia, Ferdinandusa,* Bromeliaceae*, Piper*, and ferns; Cerradão pollen spectra are defined by Poaceae, Myrtaceae, *Borreria*, *Solanum*, Asteraceae, and ferns (Gosling et al., 2009). In the

Cerrado *senso stricto* and in the Cerradão of Central Brazil, dominant pollen types are *Byrsonima*, *Curatella, Davilla*, *Didymopanax*, and *Diospyros* (Ledru, 1991).

In the central/south-eastern region of Brazil, the borders of the palm swamps are characterised by Poaceae, Cyperaceae, and a low abundance of *Mauritia,* while typical palm swamps show high abundance of *Mauritia*, together with surrounding trees, mainly *Erythroxylum* and Melastomataceae/Combretaceae (Franco Cassino et al., 2015). Gallery forests contain high percentages of *Tapirira*, *Alchornea*, *Euplassa*, *Hedyosmum, Ilex, Protium, Trema, Matayba*, and Myrtaceae. Cerrado *sensu stricto* includes *Caryocar*, *Curatella*, *Plenckia,* and *Eriotheca* type (Franco Cassino et al., 2015). Another study in the southern Cerrado assigned *Mauritia* as the key taxon for palm swamps (Cassino and Ledru, 2021). Poaceae are indicators of marshes, Cyperaceae, *Drosera*, and *Eryngium* are also present, but not only in this environment. *Hedyosmum*, *Banisteriopsis*-type, *Symplocos*, *Trichilia*, and *Euplassa* characterize the gallery forests (Cassino and Ledru, 2021).

4. Methods

A 100-cm core (SAC18) was collected in July 2018 in a hollow located in Brejo do Saco palm swamp (4°5’39.8”S 41°40’33.3”W, 146 m a.s.l.) using a Russian corer. Core SAC18 consisted of two sections each 50 cm long, composed of organic peat with variable amounts of root detritus. Sediment cores were transferred into PVC half-tubes and sealed in a plastic sheath for transport to the Biology Department of the Federal University of Ceará, Brazil. The core was then cut into 1-cm slices, placed in labelled plastic bags, and stored at 4 °C at the University of Montpellier, France.

4.1. Chronology

Eight samples were radiocarbon dated by the Accelerator Mass Spectrometry at the French *Laboratoire de Mesure du Carbone 14* (LMC14), UMS 2572 (CEA/DSM, CNRS, IRD, IRSN). The radiocarbon dates were calibrated with the SHCal20 curve (Hogg et al., 2020), calculated by linear interpolation. The ^{14}C ages were calibrated to BC/AD calendar years (Railsback, 2006). According to scientific convention, the chronology used here the before the current era/current era (BCE/CE) format. The age-depth model was built using the Bacon package (Blaauw and Christen, 2011) in RStudio software, an open-source tool for statistical computing and graphics.

4.2. Pollen analyses

Subsamples (0.5 cm^3) for palynological analyses were taken at 1-cm intervals using a combination of standard techniques (Faegri and Iversen, 1989), and an acid free protocol to achieve better concentration of the final residue (Santos and Ledru, 2021). Two tablets of the exotic marker *Lycopodium clavatum* were added to the subsamples prior to chemical treatments to calculate the pollen concentration. At least 300 terrestrial pollen grains were counted, excluding aquatic and water level-related taxa (e.g., *Mauritia* and Cyperaceae). Pollen, spores and other palynomorph frequencies were calculated relative to the terrestrial pollen sum. The pollen types were identified using the ISEM reference collection, a published pollen atlas for the Cerrado and other biomes (Salgado-Labouriau, 1973; Colinvaux, 1999; Cassino and Meyer, 2011; Cassino, 2014), and online databases (Bush and Weng, 2006; Martin and Harvey, 2017). Graphics were built using Psimpoll, a pollen-diagram plotting software (Bennett, 2009). The results are presented along a depth-scale in Fig. II.5, and along a timescale in Fig. II.6. Representative taxa were selected based on their percentage (≥5%) relative to the terrestrial pollen sum, assigned to arboreal pollen (AP), non-arboreal pollen (NAP), and pollen linked to water levels (e.g., moist, damp and waterlogged soils). Constrained cluster analysis based on incremental sum of squares (Grimm, 1987) was performed of all the samples and resulted in four pollen zones, named SAC-1 to SAC-4. Representative pollen taxa were assigned to one of five different ecological groups: semideciduous forest, Cerrado trees, Cerrado shrubs and herbaceous plants, grasslands, and palm swamps (Table II.1). Identified taxa were assigned to ecological groups defined by floristic surveys based on their habit and ecology. The paleoclimatic background is given by published data based on estimated precipitation values (hydrogen isotope δDwax) from NE Brazil (Utida et al., 2019), and Southern Oscillation Index from South America (Yan et al., 2011).

Additionally, principal component analysis (PCA) was performed of the 28 most representative taxa in all the samples using the RStudio software. Taxa were selected based on their percentage (≥1%) relative to the terrestrial pollen sum, then assigned to the taxon or family that defined the modern Cerrado vegetation in the study site (Table II.1). PCA is a multivariate method for reducing the dimensionality of large, interrelated datasets (reducing the eigenvalues) while preserving most of the information (Jollife and Cadima, 2016). In this study, PCA was used to differentiate the taxa distribution through the temporal scale.

Taxon/Family	**Plant habit**	**Ecology**	**Reference**
***Alternanthera* (Amaranthaceae)**	Herb	Herbaceous strata of Cerrado ruderal plant	Oliveira, 2004
***Astronium* (Anacardiaceae)**	Tree	Cerrado, pioneer species in open areas of forests	Medeiros, 2003; Oliveira, 2004; Moura, 2010; Matos and Felfili, 2010
***Andira* (Fabaceae)**	Tree	Fire-resistant taxon in Cerrado, may occur in grasslands as subshrubs	Medeiros, 2003; Oliveira, 2004
Arecaceae	Tree	Forested habitats, may occur in Cerrado	Barroso and Guimarães, 1980; Medeiros, 2003; Oliveira, 2004
***Byrsonima* (Malpighiaceae)**	Tree	Cerrado *sensu stricto* and Cerradão	Barroso and Guimarães, 1980; Medeiros, 2003; Oliveira, 2004; Moura, 2010; Matos and Felfili, 2010
***Borreria* (Rubiaceae)**	Shrub	Humid soils under prolonged flooding	Mendes et al., 2014
Fabaceae	Tree	Cerrado *sensu stricto*, also occurs in semi-deciduous forest	Barroso and Guimarães, 1980; Medeiros, 2003; Oliveira, 2004; Moura, 2010; Matos and Felfili, 2010
***Caryocar* (Caryocaraceae)**	Tree	Typical of Cerrado *sensu stricto*	Barroso and Guimarães, 1980; Medeiros, 2003; Oliveira, 2004
***Crotalaria* (Fabaceae)**	Herb	Open and disturbed habitats, forest margins, transition between Caatinga and Cerrado	Oliveira, 2004
***Cuphea* (Lythraceae)**	Herb	Open mesophytic habitats, some species occupy humid areas and seasonally burnt	Oliveira, 2004; Mendes et al., 2014

		fields	
Cyperaceae	Herb	Marsh, bog, swamp	Oliveira, 2004; Mendes et al., 2014
***Curatella* (Dilleniaceae)**	Tree	Drought adapted taxa indicator of Cerrado *sensu stricto*	Medeiros, 2003; Oliveira, 2004; Moura, 2010; Matos and Felfili, 2010
***Erytrhoxylum* (Erythroxylaceae)**	Tree or shrub	Humid areas and seasonally dry environments	Medeiros 2003; Oliveira 2004; Matos and Felfili 2010
***Gomphrena* (Amaranthaceae)**	Herb	Caatinga, herbaceous strata of Cerrado and grassland	Oliveira, 2004
***Guazuma* (Malvaceae)**	Tree	Fast-growing elements of secondary forests	Carvalho, 2006; *species*Link 2021
***Hyptis* (Lamiaceae)**	Herb	Open fields	Oliveira, 2004; Mendes et al., 2014
***Mauritia flexuosa* (Arecaceae)**	Tree	Indicator of palm swamps with waterlogged soils	Barroso and Guimarães, 1980
Melastomataceae/ Combretaceae	Tree	Pioneer taxon in forested physiognomies	Barroso and Guimarães, 1980; Medeiros, 2003; Oliveira, 2004; Moura, 2010; Matos and Felfili, 2010
***Mimosa* (Fabaceae)**	Tree or shrub	Seasonal forests, also frequent in Cerrado, sometimes in open fields	Oliveira, 2004
Myrtaceae	Tree	Cerrado, also frequent in semi-deciduous forest and Cerradão	Medeiros, 2003; Oliveira, 2004
Poaceae	Herb	Open fields and	Oliveira, 2004; Mendes et al., 2014

		marginal habitats. Also found in the understory	
Portulaca **(Portulacaceae)**	Herb	Open fields, drought-resistant, also grows in disturbed habitats	Oliveira, 2004
Sauvagesia **(Ochnaceae)**	Herb	Ruderal plant, grows in damp fields and humid soils	Oliveira, 2004; Mendes et al., 2014
Sloanea **(Elaeocarpaceae)**	Tree	Secondary succession and climax forest taxa	Carvalho, 2006
Solanum **(Solanaceae)**	Tree or shrub	Secondary forests and forest margins	Oliveira, 2004
Spathiphyllum **(Araceae)**	Herb	Humid forest and damp soil under partial shade	Oliveira, 2004
Tapirira **(Anacardiaceae)**	Tree	Mostly found in forested habitats, sometimes in Cerrado, tolerates drier soil conditions	Barroso and Guimarães, 1980; Oliveira, 2004; Matos and Felfili, 2010
Xyris **(Xyridaceae)**	Herb	Marsh, bog, damp areas, sometimes in sandy soils along streams	Oliveira, 2004; Mendes et al., 2014

Table II.1

Alphabetical list of the 28 most representative taxa observed in core SAC18 with their ecology and physiognomy.

4.3. Charcoal

Subsamples (0.5 cm^3) were taken at 1-cm intervals and prepared for the macro-charcoal analysis using bases NaOCl and KOH for bleaching, and a 160-µm mesh for sieving (Stevenson and Haberle, 2005). Before the macro-charcoal analysis, the subsamples were analysed under a stereoscope using WinSeedle software (Regent Instruments, Quebec, Canada) to count the number of particles and measure their size. Results are expressed as influx (number of particles/cm²), surface area of the charcoal (total area/cm²/year), and average width/length (W/L ratio) (Aleman et al., 2013). The W/L ratio measures burnt vegetation, where W/L < 0.5 indicates burnt grasses and W/L > 0.5 indicates burnt woody material (Umbanhowar and McGrath, 1998).

4.4. Granulometry

Granulometry was performed at intervals of about 5 cm (from 93 to 0 cm) giving a total of 20 subsamples. The samples were sieved through a 200 µm mesh to remove plant fibres and analysed with a Universal Liquid Module – ULM, Laser Beckman Coulter LS at the *Laboratoire Environnements Dynamiques Territoires Montagnes* - EDYTEM (UMR 5204 CNRS/Université Savoie Mont-Blanc, France). Grain size classification followed the Wentworth scale for clastic sediments (Wentworth, 1922).

5. Results

5.1. Age model

From the eight dates obtained, two showed inversions at 86 cm, 1799-1950 CE and 77 cm, 1483-1640 C, and were discarded (Table II.2). The age model gave 1210 CE as the age of the base of the core (Fig. II.4). Sedimentation rates were intermediate in the basal part of the core, ranging between 0.05 and 0.1 mm/year, low between 69 and 45 cm in depth (maximum of 0.03 mm/year) and higher in the upper part of the core (around 0.1 mm/year).

Lab Code	**Depth (cm)**	**$\delta^{13}C$**	**^{14}C yrs BP**	**Age range (cal yrs BP) 2σ**	**Calibrated yrs CE**
SacA57449	29	-27,2	-24 ± 17	-42 — -10	1975
SacA60357	44	-29,7	99 ± 30	-14 — 197	1856
SacA57450	55	-26,4	228 ± 30	98 — 283	1725
SacA61869	67	-29,5	511 ± 30	471 — 538	1439
SacA64070	69	-24,5	535 ± 30	509 — 560	1415
SacA60358	77	-24,1	365 ± 30	310 — 467	1483 — 1640
SacA57451	86	-25,6	165 ± 30	151 — 0	1799 — 1950
SacA57451	92	-29,1	719 ± 30	660 — 880	1234

Table II.2

Radiocarbon dates of the core SAC18 with 14C calibrated BP ages (two standard deviations (2σ ranges) and calibrated CE ages obtained using the Bacon package (Blaauw and Christen, 2011) in RStudio software.

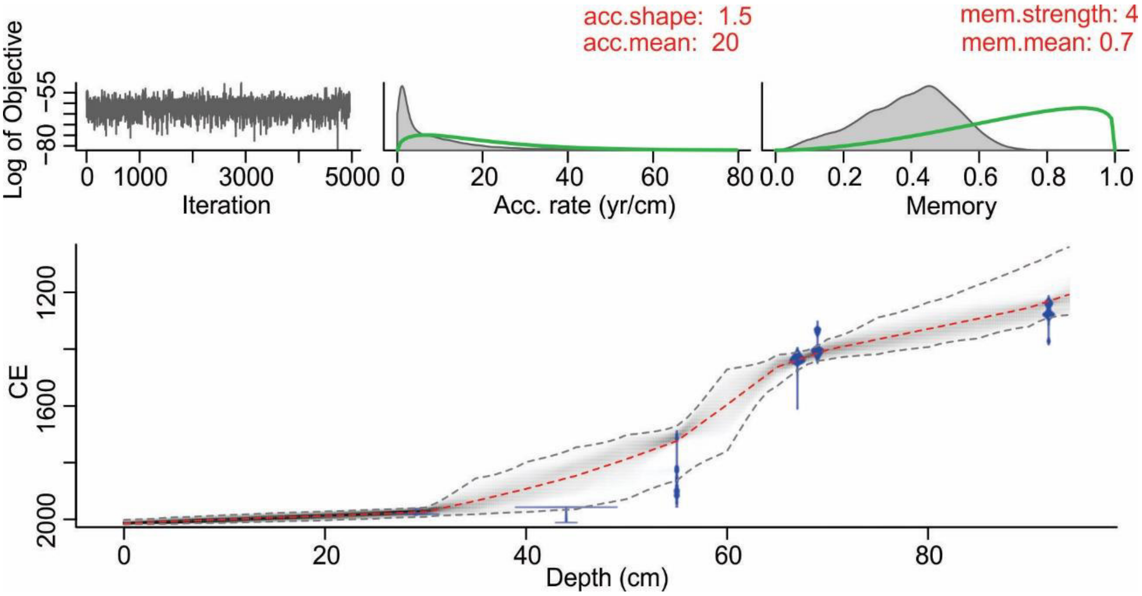

Fig. II.4. Age-depth model for the core SAC18 based on linear interpolation between calibrated ages (Blaauw and Christen, 2011). The iterations are the number of repetitions that generates a robust estimation of the age-model distribution. The iterations estimate the accumulation rate (yr/cm), a gamma distribution of the sedimentation time for each section in the core (Blaauw, 2010). The memory consists of the coherence in accumulation rates along the core, to what extent the accumulation rates of a sample in the core depend on the depth above it (Blaauw and Christen, 2011).

5.2. Erosion and accumulation

Changes in sand accumulation rates revealed three sedimentation phases (Supplementary Fig. 2). The first phase began at 93 cm, 1221 CE (38.7%) with a sand peak at 85 cm, 1293 CE (79.9%), and decreased to 75 cm, 1366 CE (42.7%). Silt exhibited the opposite percentages to sand, while clay showed high accumulation at 75 cm, 1366 CE (15.5%) whereas sand deposition was reduced (42.5%). The second phase began at 75 cm, 1366 CE, with fluctuations in sand deposition, peaking at 60 cm, 1594 CE (63.4%), and 45 cm, 1849 CE (53.6%). Clay tended to fluctuate in the opposite way to sand, with high values at 50 cm, 1785 CE (13.8%), and 35 cm, 1933 CE (14.4%). The third phase began at 30 cm, 1973 CE, the lowest sand accumulation in the whole core (38.2%). Sand accumulation increased towards the top, peaking at 10 cm, 2001 CE (61%), in contrast to clay deposition which gradually decreased, but peaked again at 0 cm (8.2%). High sand accumulation is an indicator of erosion, whereas high clay accumulation indicates slow deposition in low energy environments.

5.3. *Fire activity*

Resolution of charcoal analysis gave an average of 8.6 years per sample. The charcoal influx varied between 0 and 1,640 particles/cm²/year (Supplementary Fig. 3). Low influx values were observed at the base of the record between 1223 CE (93 cm) and 1345 CE (78 cm), ranging from 42 to 158 particles/cm²/year. The interval with the highest influx was between 1352 CE (77 cm) and 1403 CE (70 cm), ranging from 498 to 1,266 particles/cm²/year, including three peaks exceeding 500 particles/cm²/year, at 1352 CE (75 cm), 1381 CE (73 cm) and 1395 CE (71 cm). Charcoal influx fluctuated between 408 and 36 particles/cm²/year, between 1415 CE (69 cm) and 1965 CE (31 cm). After a peak with ~200 particles /cm²/year at 1973 CE (30 cm), the influx reached its lowest values between 1975 CE and 2018 CE with less than 50 particles/cm²/year.

The ratio of the width to the length of the charcoal particles (W/L) was homogeneous for the bottom half of the core, ranging between 0.4 and 0.5 (Supplementary Fig. 3). This pattern changed between 1975 CE (29 cm) and 2001 CE (10 cm), when ratio ranged between 0.5 and 0.6. From 2002 to 2018 CE, the W/L ratio ranged between 0.4 and 0.6.

5.4. *Pollen analyses*

The 77 samples distributed along the 100 cm depth core were taken at 1-cm intervals between 94 and 24 cm, at 2-cm intervals between 24 and 14 cm, and the top core sample. Resolution of analysis gave an average of 8.6 years per sample. A total of 133 pollen and spore taxa were identified comprising 96 arboreal pollen taxa, 32 non-arboreal pollen taxa, 3 water level-related taxa (e.g., sampled in damp, moist or waterlogged soils) and two types of spore ferns (Supplementary Table 1).

5.4.1. *Zone SAC-1 (94-81 cm, 1210 to 1323 CE, 14 samples)*

Zone SAC-1 was characterised by high percentages of arboreal pollen (82%) including *Guazuma* (11%), *Curatella* (7%), Melastomataceae/Combretaceae (6%), and *Byrsonima* (5%) (Fig. II.6). Myrtaceae (2%) appeared at the end of this zone. Other taxa accounted for less than 5%, including *Mimosa* (3%) *Erythroxylum* (1%), and *Tapirira* (<1%). Soil moisture related taxa were mainly represented by Cyperaceae (12%), low frequency of *Borreria* (2%), *Spathiphyllum* (<1%), and *Sauvagesia* (<1%). *Mauritia* fluctuated between 1%-11%. High percentages of herbaceous taxa (18%) included *Cuphea* (13%), Poaceae (7%), *Portulaca* (6%), and *Crotalaria* (3%) (Fig. II.6). Charcoal influx was low in the bottom part of this zone (>200 particles/cm²/year). Sand deposition was high between 1257 and 1320 CE, but decreased towards the end of the zone (Fig. II.6).

5.4.2. Zone SAC-2 (81-73 cm, 1323 to 1381 CE, 8 samples)

Zone SAC-2 was characterised by an increase in arboreal pollen (91%). *Guazuma* (6%), *Curatella* (0-7%), *Byrsonima* (1-4%) decreased, while Myrtaceae (8%) increased at the beginning of the zone. Soil moisture related taxa were present including *Mauritia* (19%), Cyperaceae (12%), and low percentages of *Borreria* (2%), *Sauvagesia* (<1%), and *Spathiphyllum* (<1%) (Fig. II.6). Herbaceous taxa were also represented: Poaceae (4%), *Crotalaria* (3%), and a decreasing number of *Portulaca* (<1%), and *Cuphea* (<1%). A peak in charcoal influx was observed at 1366 CE (1,266 particles/cm²/year). Sand accumulation was low in this zone (Fig. II.6).

5.4.3. Zone SAC-3 (73-33 cm, 1381 to 1941 CE, 39 samples)

Zone SAC-3 was characterised by high percentages of *Guazuma* (20%), and fluctuating percentages of Melastomataceae/Combretaceae (4-48%), *Byrsonima* (0-17%), Myrtaceae (0-5%), and Arecaceae (0-3%) (Fig. II.6). Other arboreal taxa included *Sloanea* (0-5%), *Mimosa* (3%) *Curatella* (1%), and *Erythroxylum* (1%). Soil moisture related taxa varied and included *Mauritia* (4-20%), Cyperaceae (5-22%), *Sauvagesia* (0-4%), and *Borreria* (0-3%). *Spathiphyllum* (35%) increased in this zone (Fig. II.6). Poaceae (1-7%) fluctuated and other herbaceous taxa were present at lower frequencies: *Crotalaria* (0-2%), and *Portulaca* (<1%). One notable feature was the presence of two *Podocarpus* pollen grains and three *Zea mays* pollen grains. Charcoal influx was high at around 1789 CE (1,640 particles/cm²/year), which is the highest peak in the core SAC18. Charcoal influx fluctuated between 100 and 400 particles/cm²/year until 1916 CE, then decreased to <100 particles/cm²/year in the upper part of the zone. Sand accumulation peaked at 1847 CE before decreasing towards the end of the zone (Fig. II.6).

5.4.4. Zone SAC-4 (33 cm to top, 1941 to 2018 CE, 16 samples)

Zone SAC-4 was characterised by a total of 92% arboreal pollen with changes in the frequencies of the arboreal taxa, mainly a decrease in *Guazuma* (12%), Melastomataceae/Combretaceae (8%), *Curatella* (1%), and an increase in *Byrsonima* (3-9%), and *Mimosa* (4%) (Fig. II.6). Arecaceae (0-2%), *Erythroxylum* (0-1%), and *Tapirira* (0-1%) were present at but at low percentages. *Mauritia* (3-18%), Cyperaceae (2-12%), *Borreria* (0-2%), and *Spathiphyllum* (0-2%) decreased in comparison to the previous zone, while

Sauvagesia (0-4%) remained stable. Herbaceous taxa comprised low percentages of *Crotalaria* (<1%), and *Portulacca* (<1%). This zone had one peak of charcoal influx in 1973 CE, decreasing to <50 particles/cm²/year until the top of the zone (Fig. II.6). Sand accumulation increased towards the top of the zone, peaking in 2001 CE.

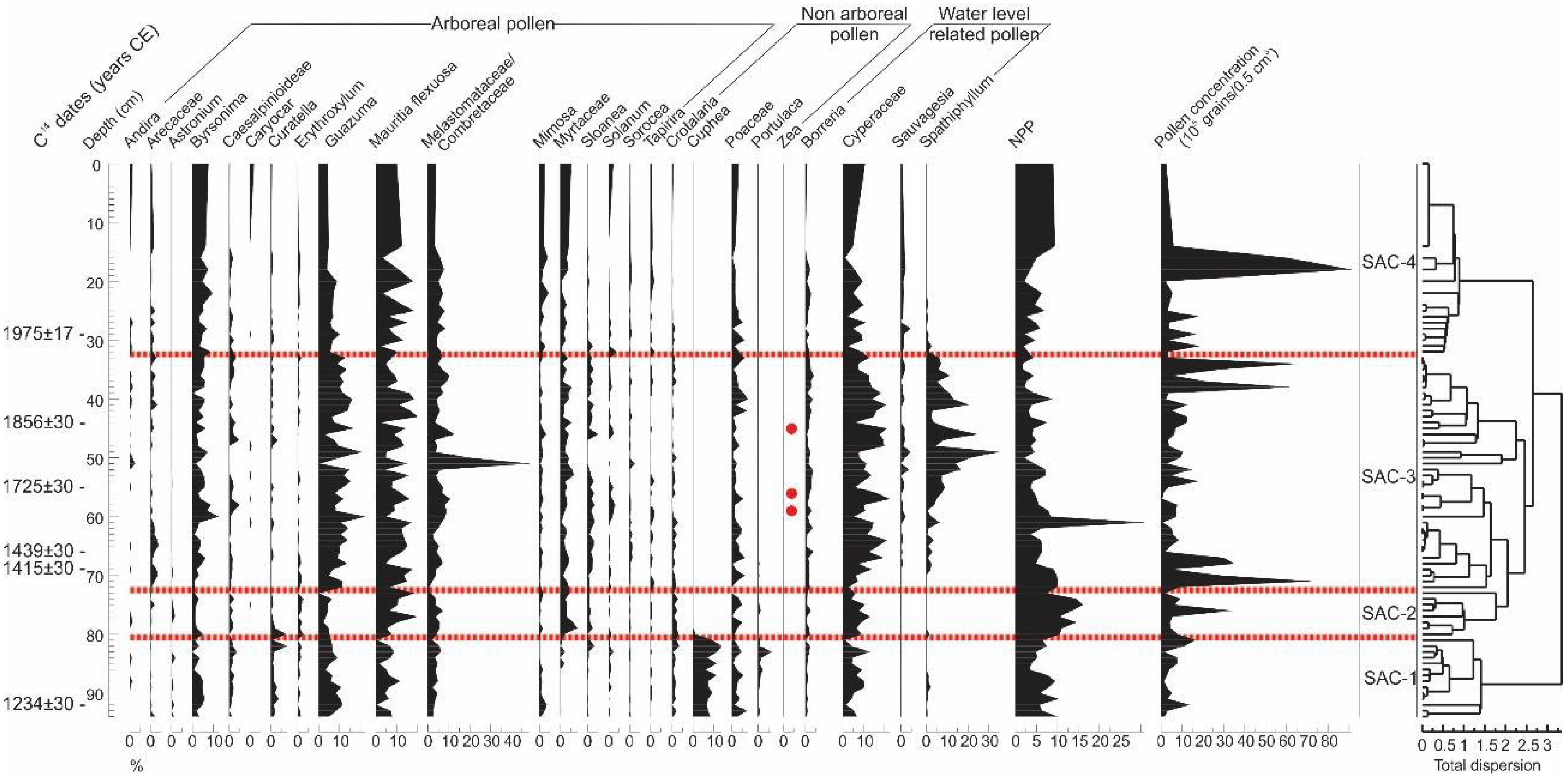

Fig. II.5. Percentage pollen diagram of core SAC18 presenting 26 selected taxa of arboreal, non-arboreal, water level related pollen, non-pollen palynomorphs (NPP) and pollen concentrations plotted along a depth scale (y-axis). The red dots represent <1% of *Zea mays* relative to the terrestrial pollen sum. The pollen zones and the cluster dendrogram were obtained using CONISS (Grimm, 1987).

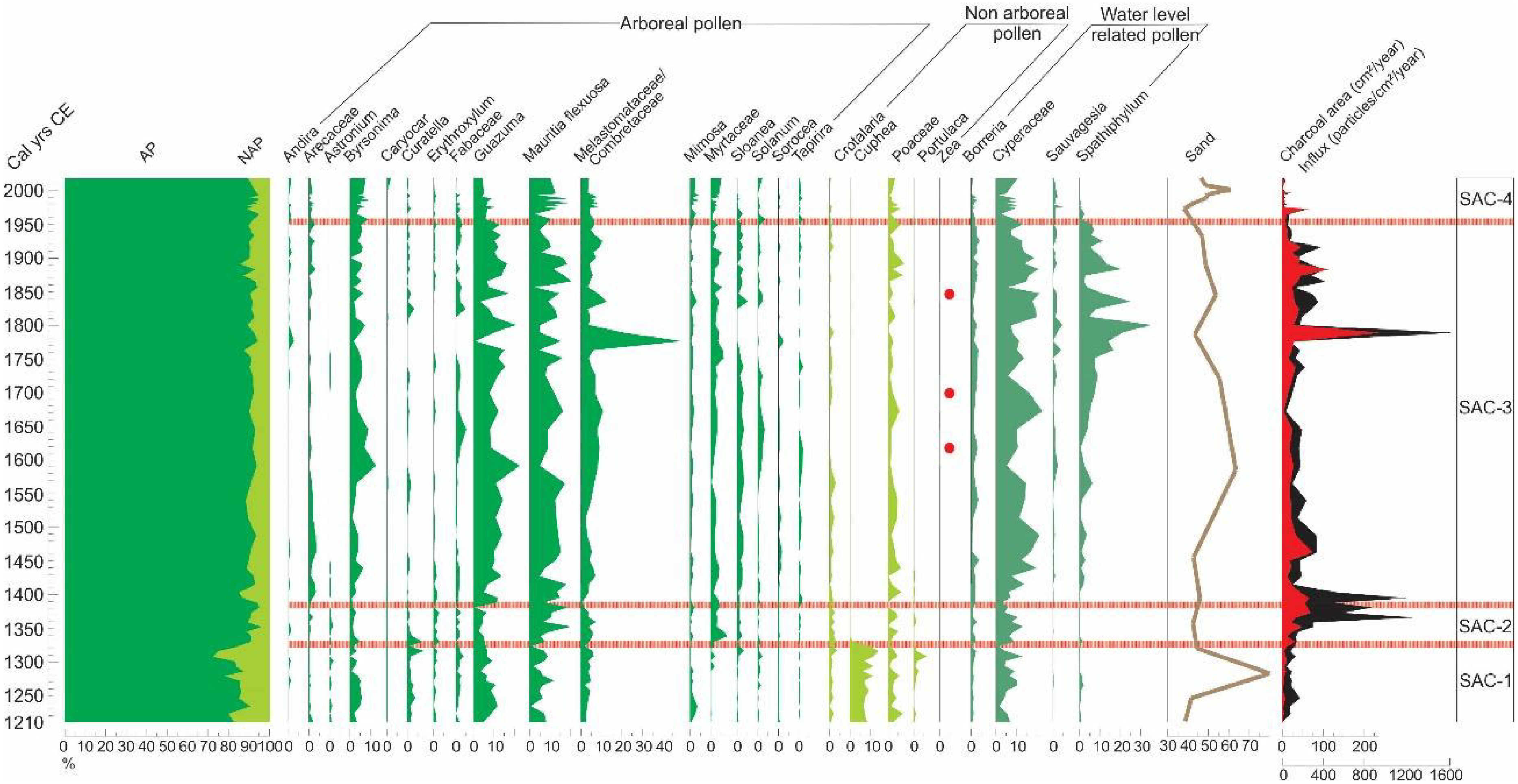

Fig. II.6. Percentage pollen diagram of core SAC18 with 26 selected taxa of arboreal/non-arboreal pollen frequency, sand content, charcoal influx and charcoal area plotted along a time scale (y-axis). The red dots represent <1% of *Zea mays* relative to the terrestrial pollen sum.

5.5. *Principal Component Analysis (PCA)*

A PCA was performed on 28 of the most representative taxa (Table II.1) (Fig. II.7). The two main components of the PCA analysis (hereafter PCA1 and PCA2), explained 16.8% and 13.3% of the total variance, respectively. Changes in vegetation dynamics occurred from SAC-1 to SAC-4. The PCA1 axis (positive values), mostly composed of samples from zone SAC-1 (light green dots) characterises dry/mesophytic vegetation represented by the tree taxa *Curatella and Erythroxylum*, and herbaceous taxa such as *Crotalaria*, *Cuphea*, and *Portulaca*. Most samples from SAC-2 (orange dots) and SAC-3 (brown dots) are positioned on the PCA2 axis (positive values). SAC-2 represents a period of transition to SAC-3 with the expansion of Cerrado arboreal vegetation and the establishment of a herbaceous stratum. The two types of vegetation were mainly represented by *Andira*, *Astronium*, *Caryocar*, *Tapirira*, *Alternanthera, Hyptis* and *Gomphrena*. Cyperaceae and *Mauritia* were attributed to the local palm swamp environment. The PCA1 and PCA2 (negative values), composed of some samples from SAC-3 and SAC-4, was represented by arboreal taxa such as Melastomataceae/Combretaceae, *Byrsonima*, *Mimosa*, *Guazuma* and *Sloanea*. The PCA1 and PCA2 (positive values) were mainly composed of samples from zone SAC-4 (dark green dots), represented by arboreal taxa Myrtaceae, *Solanum*, and shrubs and herbaceous species such as *Sauvagesia*, *Spathiphyllum*, and *Xyris*.

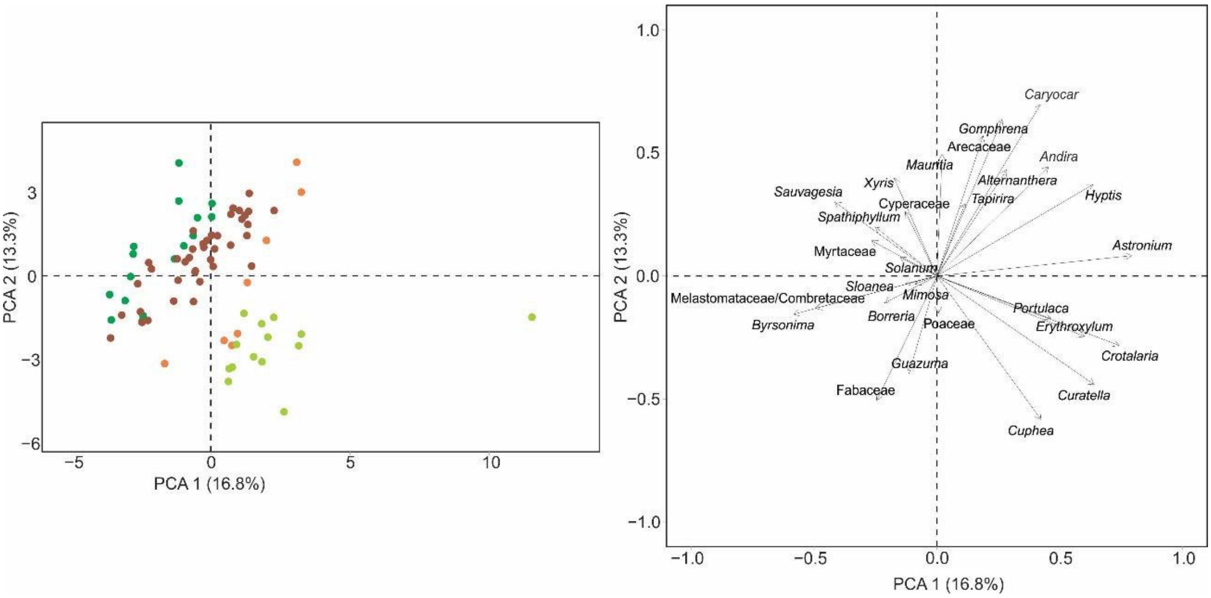

Fig. II.7. Principal component analysis (PCA) of the 77 samples collected from the core SAC18. Zone SAC-1 is represented by light green dots, Zone SAC-2 by orange dots, Zone SAC-3 by brown dots, and zone SAC-4 by dark green dots.

6. Discussion

Currently, six different physiognomies – gallery forest, semi-deciduous forest, Cerradão, Cerrado *sensu stricto*, rocky grassland, and open grassland – are present in the Sete Cidades National Park (SCNP) (Barroso and Guimarães, 1980; Mesquita, 2003; Oliveira, 2004; Matos and Felfili, 2010; Moura, 2010; Mendes et al., 2014). A discernible difference in pollen spectra became apparent when the modern pollen assemblage of Brazilian core Cerrado ecosystems was compared with this study. For example, the semi-deciduous forests of Central Brazil are characterised by *Copaifera*, *Chorisia*, *Chrysophyllum*, and *Metrodorea* (Ledru, 2002), whereas core SAC18 showed Arecaceae, *Mimosa*, *Tapirira*, and *Sloanea* to be dominant. Conversely, *Mimosa* appeared to be dominant in the xerophytic caatinga (Behling et al., 2000).

The composition of arboreal strata surrounding typical palm swamp also differed, with *Erythroxylum* and Melastomataceae/Combretaceae characterising the Central Brazilian Cerrado (Franco Cassino et al., 2015). In Brejo do Saco, other taxa appeared alongside *Erythroxylum* and Melastomataceae/Combretaceae, including *Guazuma*, Myrtaceae and *Solanum*. The Cerrado *sensu stricto* and the Cerradão of the Central/Southern Region are represented by *Byrsonima, Caryocar*, and *Curatella* (Ledru, 2002; Franco Cassino et al., 2015), three taxa that were also found in core SAC18. Cerrado *sensu stricto* is the dominant physiognomy in SCNP, followed by Cerradão (Oliveira, 2004),

Floristic surveys already pointed to differences between central/southern and north-eastern Cerrados (Ratter et al., 2011; Vieira et al., 2019). These surveys indicated distinct regional biodiversity in NE Brazil, especially in the Cerrado transitional landscapes in Piauí State (Ratter et al., 2011; Françoso et al., 2019). Such differences were also observed in core SAC18 record, with the representative taxa comprising semi-deciduous forest and Cerrado surrounding a palm swamp.

6.1. Climate variability

Between 1210 and 1325 CE, an environment dominated by Poaceae, *Cuphea*, and *Curatella* (Fig. II.6) suggests drier soil conditions than those that prevail today in SCNP. Indeed, the distribution of Cerrado grassland species is closely linked to soil moisture content (e.g., drainage, groundwater level, flooding), soil heterogeneity (Leite et al., 2018) usually with acidic, low fertile soils with high aluminium saturation (Mendes et al., 2012). The tree *Curatella americana* is a Cerrado *sensu stricto* indicator that can survive dry seasons thanks to physiological plasticity (Brodribb et al., 2002; Dalmolin et al., 2014). The PCA showed that samples from this period are positioned on the PCA1 axis (positive values), indicating a tendency toward drier conditions. According to a study based on the hydrogen isotope composition of leaf waxes (δDwax values), the NE Brazil region was subjected to a long dry period between 500 and 1300 CE, when the ITCZ shifted to a northern position, a shift caused by south-easterly trade winds and cooling of tropical South Atlantic sea surface temperatures (Utida et al., 2019) (Fig. II.8). This interval includes the Medieval Climate Anomaly (MCA) between 950 and 1250 CE, when the tropical North Atlantic Ocean was warmer than the South Atlantic Ocean (Mann et al., 2009; Vuille et al., 2012).

Between 1325 and 1500 CE, evidence for an increasingly humid trend at Brejo do Saco was the expansion of *Mauritia* and Cyperaceae (Fig. II.6). *Mauritia* is a palm tree whose fruitification peak and seedling survival are directly linked to waterlogged soils and flooding (Galeano et al., 2015; Virapongse et al., 2017). The ecological difference in this period was also apparent in the PCA analysis, which showed a transition from a dry/mesophytic, open vegetation to an arboreal Cerrado. Variations between Cerrado physiognomies, in this case, dry and moist, are linked to a group of environmental features including soil fertility and soil moisture content (Lindoso, 2008; Mendes et al., 2012). The increasingly humid trend observed at Brejo do Saco is in agreement with the record of Boqueirão Lake located further east (Utida et al., 2019) (Fig. II.8). Between 1325 and 1500 CE, the climate over NE Brazil transitioned to wetter conditions influenced by ITCZ interannual shifts (Asmerom et al., 2020). Speleothem records show strong multi-decadal to centennial-scale rainfall variability in the core region of the South Atlantic Convergence Zone (Novello et al., 2018), associated with a shift toward moister climate from 1500 CE on (Utida et al., 2019) compared to the two preceding centuries.

From 1500 CE on, the vegetation at Brejo do Saco was characterised by the expansion of Cerrado (*Byrsonima*, *Guazuma*, and Myrtaceae), palm swamp (*Mauritia*), and semi-deciduous forest (Arecaceae, *Sloanea*, and *Tapirira*). The composition of the vegetation closely resembled that observed in the botanical surveys conducted in the park today, where Myrtaceae is well represented with 8 species, *Byrsonima* with 5 species, Arecaceae with 4 species, and the tree *Tapirira guianensis* is present in all the forested physiognomies (Barroso and Guimarães, 1980; Mesquita, 2003; Oliveira, 2004; Matos and Felfili, 2010; Moura, 2010). The groups identified by PCA showed two types of vegetation for this period, represented by an arboreal Cerrado with a herbaceous stratum surrounding a palm swamp. *Spathiphyllum* is a terrestrial herbaceous plant that grows in the understorey of humid forests (Oliveira, 2004; De Andrade et al., 2013). Humid conditions intensified in NE Brazil between 1580 and 1900 CE (Utida et al., 2019) (Fig. II.8), due to the southward displacement of the ITCZ resulting from warming of the South Atlantic sea surface during the interval corresponding to the Northern Hemisphere Little Ice Age (LIA), between 1400 and 1700 CE (Mann et al., 2009; Vuille et al., 2012). Post-1400 CE is defined as "the ITCZ period", when seasonal rainfall cycles were established over tropical Central America (Asmerom et al., 2020).

After 1950 CE, the vegetation assemblage observed at Brejo do Saco includes indicator tree taxa of the Cerrado (e.g., *Byrsonima*, *Caryocar*), semi-deciduous forest taxa (e.g., *Mimosa, Tapirira*), and herbaceous taxa associated with high soil moisture content (e.g., *Sauvagesia*, *Xyris*). This was observed in the PCA analysis, where most samples from this period are positioned on the PCA1 and PCA2 axes (positive values).

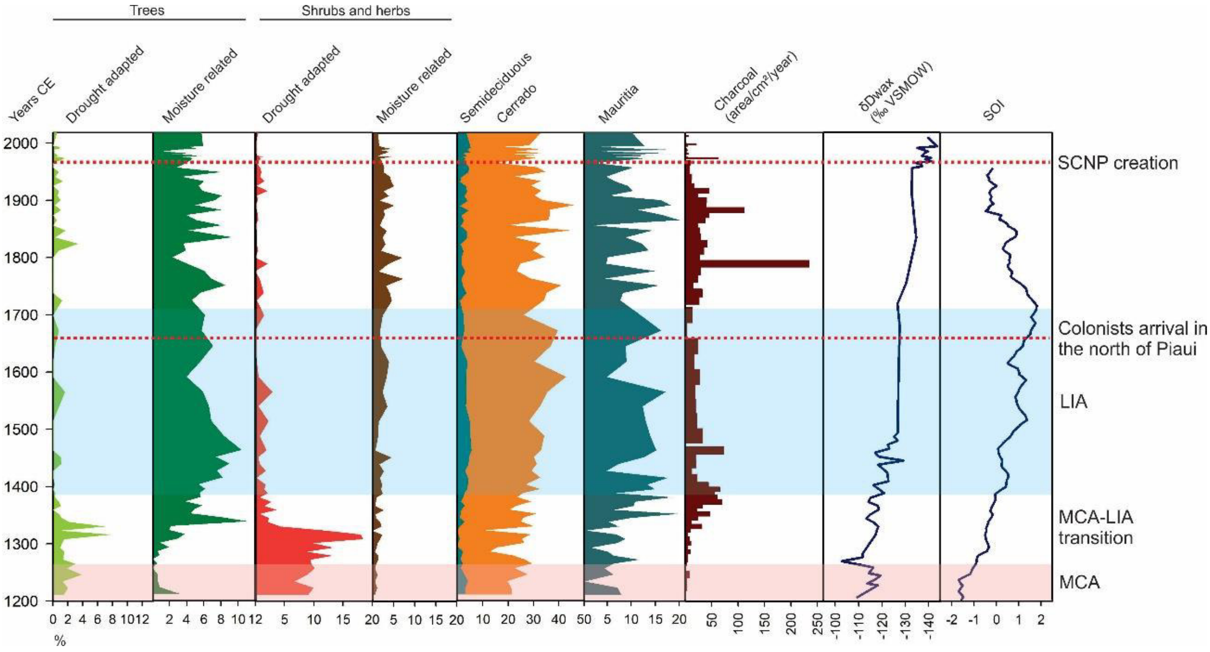

Fig. II.8. Comparison of the changes in vegetation composition and fire activity in the core SAC18 that testify to changes in precipitation in South America over the last 800 years. From left to right: 1) Drought-adapted tree taxa (pale green) and moisture-adapted tree taxa (dark green); 2) Drought-adapted shrubs and herbaceous plants (red) and moisture-adapted shrubs and herbaceous plants (brown); 3) Semi-deciduous forest trees (blue) and Cerrado trees (orange); 4) *Mauritia* indicator of palm swamps; 5) Charcoal surface area; 6) Changes in δDwax, a precipitation proxy from Utida et al. (2019); 7) Changes in the Southern Oscillation Index (SOI) from Yan et al. (2011). The end of the Medieval Climate Anomaly (MCA) is represented by the pink shaded area, and the Little Ice Age (LIA) by the blue shaded area.

6.2. Fire activity and anthropogenic impacts

Archaeological studies found evidence for human presence in the Sete Cidades region since at least 932 CE (Cavalcante, 2018) with 24 archaeological sites out of 80 located within the boundaries of SCNP (Magalhães, 2011). Archaeological material consists of polished lithics, traces of bonfires, ceramics, and rock paintings (Cavalcante, 2015), 2018; Cavalcante et al., 2016). A recent study revealed that the coastal region of NE Brazil experienced low population growth and hosted small populations between 1000 and 1400 CE (Riris and de Souza, 2021), suggesting lower anthropogenic pressure at Brejo do Saco during this interval. Considering the increase in fire activity between 1350 and 1400 CE during the MCA-LIA transition (Fig. II.8), and the fact that wildfires in the Cerrado generally occur during dry to wet transitions (Gomes et al., 2018), fires in Brejo do Saco region were more related to climate change than to human activity during this interval.

After 1400 CE, the demographic growth in Piauí was marked by several native groups: the Gê in the southeast (De Negreiros Oliveira 2004, 2007) next to the headstreams; the Tabajara in the north (Medeiros, 2002; Sousa, 2020); the Tremembé and Tapuia in the north and coastal area of Parnaiba Delta (IBDF, 1979; Medeiros, 2002; dos Santos et al., 2012). Historical records suggest the Tapuia were expulsed from the coast by rival groups, forcing them to move inland where they practiced rudimentary forms of agriculture, growing maize and vegetables (Oliveira, 2002). The decrease in charcoal at 1500 CE suggests less fire activity while the slight increase in sand content indicates erosive conditions at Brejo do Saco that lasted until 1650 CE, suggesting wetter climatic conditions. In addition, the presence of pollen grains of *Zea mays* at 1618 and 1699 CE indicates human presence but low fire activity.

Historical archives mention the colonial occupation in the North of Piauí began in 1700 CE, (Alves, 2003) when itinerant cattle herders started to migrate from the south-eastern region of NE Brazil to the almost unknown north-western territories (Prado Jr, 1987). Indeed, during the second half of the seventeenth century, cattle herders moved along smaller rivers (Piauí, Gurgéia, Canindé and Paraim), and reached the Parnaíba river in the western part of the region (Abreu, 1998; Alves, 2003). In NE Brazil, the interval between 1700 and 1900 CE is characterised by intensification of moist climatic conditions compared to the two previous centuries (Utida et al., 2019).

At Brejo do Saco, from 1750 to 1925 CE, the increase in charcoal area revealed an abrupt change in fire activity but no change in vegetation composition. In densely populated regions, peaks in charcoal influx are associated with increased burning after local deforestation (Ledru et al., 2020). Consequently, to explain the increase in fire activity, stronger anthropogenic pressure from the colonists rather than climate variability is inferred 50 years earlier than mentioned in the historical archives, in 1650 CE (Fig. II.8). Also, in 1789 CE, the observation of a sudden but brief increase in Melastomataceae, a pioneer tree taxon, followed by a high influx of charcoal is likely due to deforestation by cattle herders. Straight after deforestation, the dominance of other arboreal taxa, *Byrsonima* and *Guazuma*, a fast-growing tree of the Cerrado, was observed.

The presence of *Zea mays* in 1874 CE suggests agricultural activity in parallel with burning activity. Historical archives mention that after 1700 CE, colonists fought with Amerindian groups for land and slave labor (IBDF, 1979; Medeiros, 2009). Then, in the 1800s, established ranchers in the region burned vegetation in the early dry season, a practice inherited from the Amerindians and enslaved West African descendants (Sluyter and Duvall, 2016). Considering the almost complete extermination of Piauí native groups in the second half of 1700s (IBDF, 1979; Medeiros, 2009), ranchers were most likely the cause of deforestation characterized by high biomass burning at Brejo do Saco (Fig. II.8). Ranchers also possessed smaller agriculture settlements located near bogs and moist grasslands between 1800 and 1900 CE (Queiroz, 1984; Cabral, 2020).

Livestock raising practices declined in the State of Piauí in the early 1900s, while subsistence farming increased (Queiroz, 1984; Cabral, 2020). A reconstruction of the Southern Oscillation Index (SOI) for the past 2000 years (Yan et al., 2011), revealed a negative tendency after 1900 CE (Fig. II.8), pointing to more El Niño dominated conditions. In the last 105 years (1913-2018), 38 El Niño events have been reported (Fig. II.3). An abrupt decrease in the charcoal influx was observed from 1925 CE on, with one peak in 1973 CE, whereas sand content first decreased and then increased (Fig. II.6). In the ensuing decades, the influx was dominated by particles originating from the burning of woody rather than herbaceous vegetation (Supplementary Fig. 3). A larger charcoal area (>50 cm^2/year) (Fig. 8) was recorded only in 1975 CE, so no direct correlation could be established between ENSO anomalies and fire activity. Consequently, the reduction in burning observed since 1925 CE in the record of Brejo do Saco and in the surroundings is likely a result of the change in anthropogenic pressures on the landscape rather than of climate change. No macrocharcoal particles were found after the area was came under Full Protection in 1961, evidence that the SAC18 sediment core collected in a hollow perfectly trapped the local signal, in agreement with other European forest hollow studies (e.g., Finsinger et al., 2022).

In 1975 CE, the influx of charcoal was lower in Brejo do Saco (<50 particles/cm^2).

Before this interval, a moisture-related forest and burnings were simultaneous, the later due to anthropogenic activities. After 1975 CE, the expansion of the forest and the end of burning in Brejo do Saco are the result of the conservation policies that mitigated exploitative human practices (rangeland burning and deforestation) after the creation of SCNP in 1961 CE.

6.3. Conservation policies

Sete Cidades park is a Full Protected Area with management equivalent to the International Union for Conservation of Nature (IUCN) category II (Dudley, 2008). A complete conservation plan (IBDF, 1979) was implemented in 1979, 18 years after the creation of the park and three years after burnings came to a halt in Brejo do Saco (Fig. II.5). The complete suppression of anthropic fires observed in core SAC18 resulted in the expansion of the Cerrado arboreal cover over the following 43-year period.

However, fire is still used by neighbouring local communities for pasture renewal and to prepare land for subsistence crops, these being two main reasons for burning outside the park limits (Da Silva Souza and Pereira, 2019) (Fig. II.2). In 1991 and 1996, around 79% of recorded burnings occurred outside the park (IBAMA, 2005), but extreme burnings nevertheless occurred within the protected area. The PREVFOGO team has been preventing intense burning within the park limits since 1998 (Fig. II.2).

Phytosociological studies of the effect of SCNP priority policy on biodiversity conservation highlighted increased diversity. For instance, 21 out of 75 species in gallery forests showed restricted distribution in the region (Matos and Felfili, 2010). Cerrado *senso stricto* showed high species diversity compared to the results of other north-eastern botanical surveys (Mesquita, 2003), while in a rocky grassland area, the presence of 8 out of 47 species was restricted in north-eastern cerrados (Moura, 2010). The stability of grassland fragments over a four-year study period was attributed to moisture variability and the absence of human disturbance (Mendes et al., 2014). Further, the occurrence of species from different Cerrado physiognomies and from the Caatinga and Amazon Forest biomes (Oliveira, 2004) suggests that SCNP is a frontier for species distribution within an ecotonal community mosaic. Something that needs to be considered when defining conservation policies for the 21st century is distinguishing between biodiversity conservation and human protection in ecotonal regions.

7. Conclusions

This high-resolution study provides unique evidence from the Northeastern Cerrado landscapes during the pre- and post-colonial era, covering a centennial-decennial time interval not previously accessed in this region, and answers the research questions as follows: (1) Amerindians and Europeans left different land use marks on the landscape with two distinct patterns of fire activity. Less biomass burning and no deforestation were recorded before 1650 CE when Amerindians inhabited the region. Then, during the European colonial occupation after 1650 CE, these practices changed to extensive burning with frequent deforestation that continued for 400 years. (2) The creation of Sete Cidades National Park mitigated four centuries of intense deforestation and fire activity, and resulted in the expansion of the current Cerrado forest cover.

These conclusions highlight the fact the dynamics of the Cerrado landscapes are intrinsically interlinked with human disturbances and historical events in Northeastern Brazil, a densely populated region since before the arrival of Europeans. Three main land use shifts were detected during the last 800 years, from indigenous to colonial practices and modern environmental policies. This helps understand how closely linked the responses of the Northeastern Cerrado are to human activities at least during the last millennium, and underlines the contrast between the recent full protection policy and the history of the region during the Late Holocene. Knowledge of past changes in the biome in both local and regional contexts should not be underrated when constructing future scenarios for full protection policies.

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Supplementary material

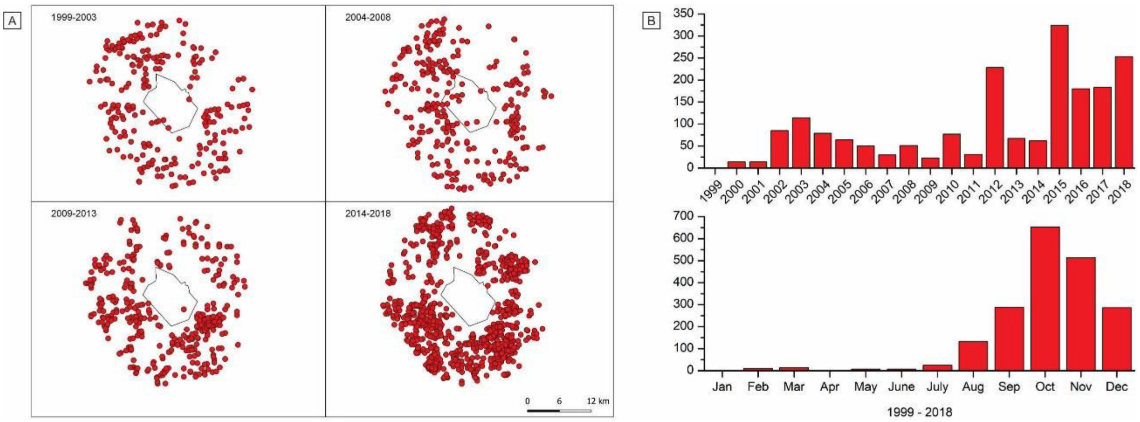

Fig. 1. (a) Fires observed within a 15-km radius around Sete Cidades National Park (SCNP) limits (black line) over a period of 20 years (1999-2018). (b) Number of fire events per year in the region of SCNP since 1999 and monthly distribution of the fire events over the same period (Data source: the National Institute for Space Research – INPE, 2020 https://queimadas.dgi.inpe.br/queimadas/portal).

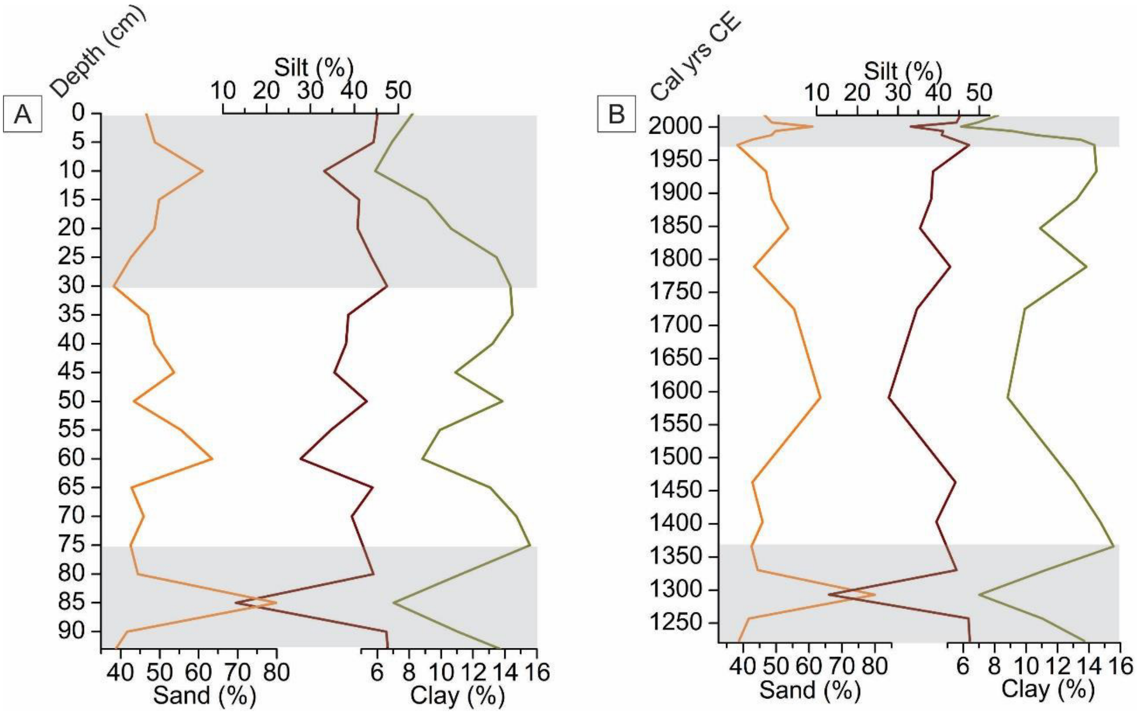

Fig. 2. Results of granulometric analyses of core SAC18 with sand (orange), silt (brown) and clay (green) accumulation curves represented along (a) a depth axis and (b) an age axis. Grey and white shaded areas represent sedimentation phases based on sand deposition.

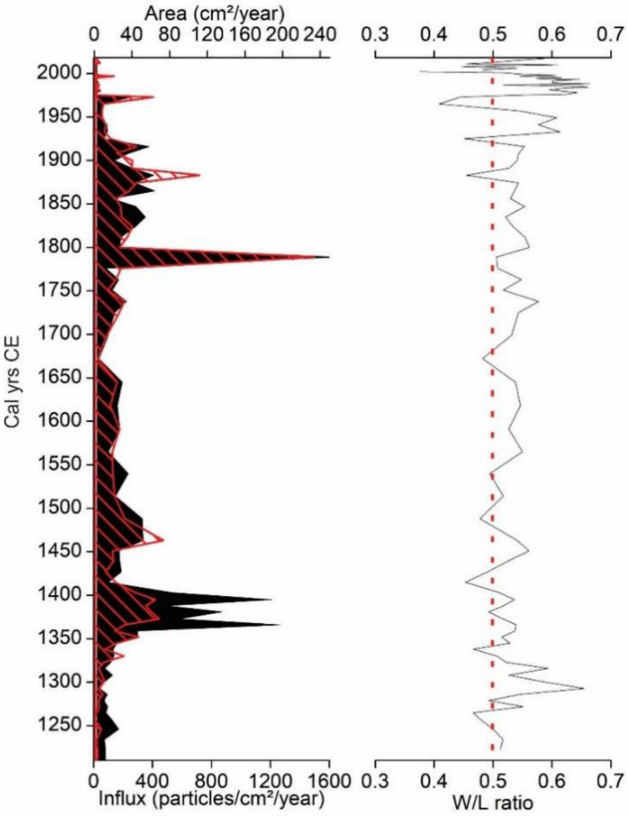

Fig. 3. Influx (black area), area (hatched black/red) and W/L ratio for charcoal particles in the core SAC18 represented along an age scale (y-axis).

Table 1

List of pollen taxa identified in the Brejo do Saco core. Habitat refers to Cerrado physiognomies to which the respective species found in Sete Cidades National Park were attributed. [1]Species absent in SCNP surveys. [2]Checklists and online databases of Brazilian flora were used to assign absent species to habitats.

Pollen taxa	Family	Habitat (Cerrado physiognomy)	Life-form type	References
Alibertia	Rubiaceae	Gallery forest, semi-deciduous forest, Cerrado *sensu stricto*	Tree	Medeiros 2003; Oliveira 2004; Matos and Felfili 2010
Alternanthera	Amaranthaceae	Semi-deciduous forest, Cerrado sensu stricto, Campo limpo	Herb	Oliveira 2004
Amaryllidaceae-type[1]	Amaryllidaceae	Cerrado	Herb	*species*Link 2021[2]
Andira	Fabaceae (Papilionoideae)	Gallery forest, semi-deciduous forest, Cerradão, Cerrado *sensu stricto*, Campo rupestre, Campo limpo	Tree, shrub	Medeiros 2003; Oliveira 2004; Moura 2010; Matos and Felfili 2010
Apiaceae[1]	Apiaceae	Amazon rainforest, Caatinga, Cerrado, Atlantic rainforest, Pampa, Pantanal	Subshrub, herb	Flora do Brasil 2020[2]
Apocynaceae	Apocynaceae	Gallery forest, semi-deciduous forest, Cerradão, Cerrado *sensu stricto*, Campo limpo, Campo rupestre	Tree	Barroso and Guimarães 1980; Medeiros 2003; Oliveira 2004; Moura 2010; Matos and Felfili 2010
Apuleia-type[1]	Fabaceae (Caesalpinioideae)	Semi-deciduous forest	Tree	Carvalho 2003[2]
Arecaceae	Arecaceae	Gallery forest, Cerradão, Cerrado *sensu stricto*, Campo limpo	Tree	Barroso and Guimarães 1980; Medeiros 2003; Oliveira 2004
Asteraceae (Liguliflorae)	Asteraceae	Semi-deciduous forest, Cerrado *sensu stricto*, Campo limpo	Tree, shrub	Barroso and Guimarães 1980; Medeiros 2003; Oliveira 2004; Mendes et al 2014
Asteraceae (Tubuliflorae)	Asteraceae	Semi-deciduous forest, Cerrado *sensu stricto*, Campo limpo	Tree, shrub	Barroso and Guimarães 1980; Medeiros 2003; Oliveira 2004; Mendes et al 2014
Astronium	Anacardiaceae	Gallery forest, semi-deciduous forest, Cerrado *sensu*	Tree	Medeiros 2003; Oliveira 2004; Moura 2010;

		stricto, Campo rupestre		Matos and Felfili 2010
Bauhinia	Fabaceae (Caesalpinioideae)	Gallery forest, semi-deciduous forest, Cerrado *sensu stricto*	Tree	Barroso and Guimarães 1980; Medeiros 2003; Oliveira 2004; Matos and Felfili 2010
Begonia[1]	Begoniaceae	Amazon rainforest, Caatinga, Cerrado, Atlantic rainforest, Pampa	Sunshrub, herb, bindweed	Flora do Brasil 2020[2]
Boraginaceae	Boraginaceae	Cerrado *sensu stricto*	Tree; shrub	Medeiros 2003; Oliveira 2004
Borreria	Rubiaceae	Cerrado *sensu stricto*, Campo limpo	Shrub	Oliveira 2004; Mendes et al. 2014
Bromeliaceae	Bromeliaceae	Semi-deciduous forest, Cerradão, Cerrado *sensu stricto*, Campo rupestre, Campo limpo	Herb	Oliveira 2004
Burseraceae[1]	Burseraceae	Cerrado	Tree	*species*Link 2021[2]
Byrsonima	Malpighiaceae	Gallery forest, semi-deciduous forest, Cerradão, Cerrado *sensu stricto*, Campo limpo, Campo rupestre	Tree, shrub	Barroso and Guimarães 1980; Medeiros 2003; Oliveira 2004; Moura 2010; Matos and Felfili 2010
Caesalpinia-type	Fabaceae (Caesalpinioideae)	Cerrado *sensu stricto*	Tree	Oliveira 2004
Caesalpinioideae	Fabaceae (Caesalpinioideae)	Gallery forest, semi-deciduous forest, Cerrado *sensu stricto*	Tree	Barroso and Guimarães 1980; Medeiros 2003; Oliveira 2004; Moura 2010; Matos and Felfili 2010
Caryocar	Caryocaraceae	Cerrado *sensu stricto*	Tree	Barroso and Guimarães 1980; Medeiros 2003; Oliveira 2004
Cecropia	Urticaceae	Gallery forest, semi-deciduous forest	Tree	Oliveira 2004; Matos and Felfili 2010
Celtis-Type[1]	Cannabaceae	Amazon rainforest, Caatinga, Cerrado, Atlantic rainforest, Pampa, Pantanal	Tree, shrub, subshrub	Flora do Brasil 2020[2]
Cestrum type[1]	Solanaceae	Cerrado	Shrub	*species*Link 2021[2]

Chamaecrista	Fabaceae (Caesalpinioideae)	Cerrado *sensu stricto*, Campo limpo	Shrub, subshrub, herb	Medeiros 2003; Oliveira 2004; Mendes et al 2014
Chrysobalanaceae	Chrysobalanaceae	Gallery forest, Cerrado *sensu stricto*	Tree	Medeiros 2003; Oliveira 2004; Moura 2010; Matos and Felfili 2010
Clusiaceae	Clusiaceae	Gallery forest, semi-deciduous forest, Cerrado *sensu stricto*	Tree	Medeiros 2003; Oliveira 2004; Matos and Felfili 2010
Convolvulaceae	Convolvulaceae	Cerrado *sensu stricto*, Campo limpo	Subshrub, herb, bindweed	Oliveira 2004; Mendes et al 2014
Copaifera	Fabaceae (Caesalpinioideae)	Gallery forest, semi-deciduous forest, Cerradão, Cerrado *sensu stricto*, Campo rupestre	Tree	Medeiros 2003; Oliveira 2004; Moura 2010; Matos and Felfili 2010
Crotalaria	Fabaceae (Papilionoideae)	Semi-deciduous forest, Cerrado *sensu stricto*	Subshrub	Oliveira 2004
Cuphea	Lythraceae	Campo rupestre, Campo limpo	Herb	Oliveira 2004, Mendes et al. 2014
Curatella	Dilleniaceae	Gallery forest, Cerrado *sensu stricto*, Campo rupestre	Tree	Medeiros 2003; Oliveira 2004; Moura 2010; Matos and Felfili 2010
Cybianthus-type[1]	Myrsinaceae	Amazon rainforest, Cerrado, Atlantic rainforest	Tree, shrub	Flora do Brasil 2020[2]
Cyperaceae	Cyperaceae	Gallery forest, Cerrado *sensu stricto*, Campo limpo	Herb	Oliveira 2004; Mendes et al 2014
Dalbergia	Fabaceae (Papilionoideae)	Gallery forest, Semi-deciduous forest, Cerrado *sensu stricto*	Tree	Medeiros 2003; Oliveira 2004
Diospyros	Ebenaceae	Gallery forest, Semi-deciduous forest	Tree	Oliveira 2004; Matos and Felfili 2010
Dodonaea-type[1]	Sapindaceae	Ombrophilous forest, Caatinga	Tree, shrub	Carvalho 2008[2]
Doliocarpus	Dilleniaceae	Semi-deciduous forest, Cerrado *sensu stricto*	Tree	Oliveira 2004
Dulacia-type[1]	Olacaceae	Amazon rainforest, Caatinga, Cerrado, Atlantic rainforest, Pantanal	Tree, shrub, bindweed	Flora do Brasil 2020[2]

Erythroxylum	Erythroxylaceae	Gallery forest, semi-deciduous forest, Cerrado *sensu stricto*	Tree, shrub	Medeiros 2003; Oliveira 2004; Matos and Felfili 2010
Euphorbiaceae	Euphorbiaceae	Semi-deciduous forest, Cerradão, Cerrado *sensu stricto*	Tree, shrub	Barroso and Guimarães 1980; Medeiros 2003; Oliveira 2004
Evolvulus	Convolvulaceae	Cerrado *sensu stricto*, Campo rupestre, Campo limpo	Herb	Oliveira 2004; Mendes et al 2014
Fabaceae	Fabaceae	Gallery forest, semi-deciduous forest, Cerradão, Cerrado *sensu stricto*, Campo rupestre, Campo limpo	Tree, shrub	Barroso and Guimarães 1980; Medeiros 2003; Oliveira 2004; Moura 2010; Matos and Felfili 2010
Gomphrena	Amaranthaceae	Cerrado *sensu stricto*, Campo limpo	Herb	Oliveira 2004
Guarea-type[1]	Meliaceae	Amazon rainforest, Caatinga, Cerrado, Atlantic rainforest, Pampa	Tree	Flora do Brasil 2020[2]
Guazuma[1]	Malvaceae	Amazon rainforest, Caatinga, Cerrado, Atlantic rainforest, Pantanal	Tree	Carvalho 2006[2], *species*Link 2021[2]
Helicteres	Malvaceae	Gallery forest, semi-deciduous forest, Cerradão, Cerrado sensu stricto	Tree	Oliveira 2004
Heliotropium-type[1]	Boraginaceae	Amazon rainforest, Caatinga, Cerrado, Atlantic rainforest, Pampa, Pantanal	Shrub, herb	Flora do Brasil 2020[2]
Humiriaceae	Humiriaceae	Gallery forest, semi-deciduous forest	Tree	Oliveira 2004; Matos and Felfili 2010
Hyptis	Lamiaceae	Campo rupestre, campo limpo	Herb	Oliveira 2004; Mendes et al 2014
Ilex[1]	Aquifoliaceae	Cerrado	Tree	speciesLink 2021[2]
Inga-type	Fabaceae (Mimosoideae)	Gallery forest, semi-deciduous forest, Cerrado *sensu stricto*	Tree	Oliveira 2004; Matos and Felfili 2010
Lamiaceae	Lamiaceae	Gallery forest, semi-deciduous forest, Cerradão, Cerrado *sensu stricto*	Tree, shrub	Medeiros 2003; Oliveira 2004; Moura 2010; Matos and Felfili 2010

Malpighiaceae	Malpighiaceae	Semi-deciduous forest, Cerrado *sensu stricto*	Tree, shrub, bindweed	Medeiros 2003; Oliveira 2004
Malvaceae	Malvaceae	Cerrado *sensu stricto*	Tree	Oliveira 2004
Mandevilla[1]	Apocynaceae	Cerrado	Herb	*species*Link 2021[2]
Maprounea	Euphorbiaceae	Gallery forest, Cerrado *sensu stricto*	Tree, shrub	Oliveira 2004; Matos and Felfili 2010
Mauritia flexuosa	Arecaceae	Brazilian palm swamp (vereda)	Tree	Barroso and Guimarães 1980
Melastomataceae/ Combretaceae	Melastomataceae/ Combretaceae	Gallery forest, semi-deciduous forest, Cerradão, Cerrado *sensu stricto*, Campo rupestre, Campo limpo	Tree	Barroso and Guimarães 1980; Medeiros 2003; Oliveira 2004; Moura 2010; Matos and Felfili 2010; Mendes et al. 2014
Meliaceae [1]	Meliaceae	Amazon rainforest, Caatinga, Cerrado, Atlantic rainforest, Pampa, Pantanal	Tree, shrub	Flora do Brasil 2020[2]
Melicoccus-type[1]	Sapindaceae	Amazon rainforest, Cerrado, Atlantic rainforest, Pantanal	Tree	Flora do Brasil 2020[2]
Mimosa-type	Fabaceae (Mimosoideae)	Semi-deciduous forest, Cerradão, Cerrado *sensu stricto*, Campo rupestre, campo limpo	Tree; shrub	Barroso and Guimarães 1980; Medeiros 2003; Oliveira 2004; Moura 2010
Molluginaceae[1]	Molluginaceae	Amazon rainforest, Caatinga, Central Brazilian savanna, Atlantic rainforest, Pampa, Pantanal	Subshrub, herb	Flora do Brasil 2020[2]
Myracrodruon-Type	Anacardiaceae	Semideciduous forest	Tree	Oliveira 2004
Myrtaceae	Myrtaceae	Gallery forest, semi-deciduous forest, Cerradão, Cerrado *sensu stricto*, Campo rupestre, campo limpo	Tree	Medeiros 2003; Oliveira 2004; Matos and Felfili 2010
Neea-type[1]	Nyctaginaceae	Amazon rainforest, Cerrado, Atlantic rainforest, Pantanal	Tree, shrub, bindweed	Flora do Brasil[2]
Nyctaginaceae[1]	Nyctaginaceae	Amazon rainforest, Caatinga, Cerrado, Atlantic rainforest, Pampa, Pantanal	Tree, shrub, bindweed	Flora do Brasil 2020, *species*Link 2021[2]
Ouratea	Ochnaceae	Semi-deciduous forest, Cerradão, Cerrado *sensu stricto*,	Shrub, subshrub	Medeiros 2003; Oliveira 2004; Moura 2010

		Campo rupestre		
Peixotoa-type	Malpighiaceae	Semideciduous forest, Cerrado *sensu stricto*	Shrub, subshrub, bindweed	Oliveira 2004
Phyllanthus	Phyllanthaceae	Campo limpo	Herb	Mendes et al. 2014
Piper[1]	Piperaceae	Amazon rainforest, Caatinga, Cerrado, Atlantic rainforest, Pampa, Pantanal	Tree, shrub	*species*Link 2021, Flora do Brasil 2020[2]
Piptadenia	Fabaceae (Mimosoideae)	Semi-deciduous forest, Cerradão, Cerrado *sensu stricto*	Tree	Medeiros 2003; Oliveira 2004
Poaceae	Poaceae	Gallery forest, semi-deciduous forest, Cerradão, Cerrado *sensu stricto*, Campo rupestre, campo limpo	Herb	Oliveira 2004; Mendes et al 2014
Podocarpus[1]	Podocarpaceae	Deciduous forest, Ombrophilous forest	Tree	Carvalho 2003[2]
Polygalaceae	Polygalaceae	Semi-deciduous forest, Cerrado *sensu stricto*, Campo rupestre, campo limpo	Shrub, herb	Medeiros 2003; Oliveira 2004; Mendes et al 2014
Portulaca	Portulacaceae	Campo rupestre	Herb	Oliveira 2004
Protium	Burseraceae	Gallery forest, Cerrado sensu stricto, Campo rupestre	Tree	Oliveira 2004; Matos and Felfili 2010
Psidium-type	Myrtaceae	Gallery forest, Cerrado *sensu stricto*	Tree, shrub	Medeiros 2003; Oliveira 2004; Moura 2010; Matos and Felfili 2010
Qualea	Vochysiaceae	Cerrado *sensu stricto*, Campo rupestre, campo limpo	Tree, shrub	Barroso and Guimarães 1980; Medeiros 2003; Oliveira 2004; Moura 2010
Ramisia-type[1]	Nyctaginaceae	Atlantic rainforest	Tree	Flora do Brasil 2020[2]
Rhamnaceae[1]	Rhamnaceae	Amazon rainforest, Caatinga, Cerrado, Atlantic rainforest, Pampa, Pantanal	Tree, shrub, bindweed	Flora do Brasil 2020, *species*Link 2021[2]
Ricinus-type[1]	Euphorbiaceae	Amazon rainforest, Caatinga, Cerrado, Atlantic rainforest, Pampa, Pantanal	Tree, shrub	Flora do Brasil 2020[2]

Sapindaceae	Sapindaceae	Semi-deciduous forest, Cerradão, Cerrado *sensu stricto*	Tree, shrub, bindweed	Barroso and Guimarães 1980; Medeiros 2003; Oliveira 2004
Sapotaceae	Sapotaceae	Gallery forest, semi-deciduous forest, Cerradão, Cerrado *sensu stricto*, Campo rupestre	Tree, shrub	Barroso and Guimarães 1980; Medeiros 2003; Oliveira 2004; Moura 2010; Matos and Felfili 2010
Sauvagesia	Ochnaceae	Campo limpo	Herb	Oliveira 2004; Mendes et al 2014
Schinus [1]	Anacardiaceae	Semi-deciduous forest, Ombrophilous forest	Tree, shrub	Carvalho 2003[2]
Sebastiania[1]	Euphorbiaceae	Ombrophilous forest	Tree, shrub	Carvalho 2003[2]
Senna-type	Fabaceae (Caesalpinioideae)	Semi-deciduous forest, Cerradão, Cerrado *sensu stricto*	Tree	Medeiros 2003; Oliveira 2004
Sida	Malvaceae	Cerrado *sensu stricto*, Campo limpo	Herb	Oliveira 2004; Mendes et al 2014
Sloanea-type[1]	Elaeocarpaceae	Deciduous forest, semideciduous forest, Ombrophilous forest	Tree	Carvalho 2006[2]
Solanum	Solanaceae	Semi-deciduous forest, Cerradão, Cerrado *sensu stricto*	Tree, shrub	Oliveira 2004
Sorocea [1]	Moraceae	Deciduous forest, semi-deciduous forest, Ombrophilous forest	Tree	Carvalho 2008[2]
Spathiphyllum	Araceae	Gallery forest	Herb	Oliveira 2004
Stryphnodendron	Fabaceae (Mimosoideae)	Gallery forest, Cerrado *sensu stricto*, Campo rupestre	Tree	Medeiros 2003; Oliveira 2004; Moura 2010; Matos and Felfili 2010
Tabebuia-type	Bignoniaceae	Gallery forest, semi-deciduous forest, Cerrado *sensu stricto,* Campo limpo	Tree	Medeiros 2003; Oliveira 2004; Matos and Felfili 2010
Tapirira	Anacardiaceae	Gallery forest, semi-deciduous forest, Cerradão, Cerrado *sensu stricto*, Campo limpo	Tree	Barroso and Guimarães 1980; Oliveira 2004; Matos and Felfili 2010
Thinouia[1]	Sapindaceae	Amazon rainforest, Caatinga, Atlantic rainforest, Pampa,	Shrub, bindweed	Flora do Brasil 2020[2]

		Pantanal		
Toulicia sp. 01[1]	Sapindaceae	Amazon rainforest, Caatinga, Cerrado, Atlantic rainforest	Tree, shrub	Flora do Brasil 2020[2]
Trema-Type[1]	Cannabaceae	Ombrophilous forest, deciduous forest, semi-deciduous forest	Tree	Carvalho 2003[2]
Trichilia-Type[1]	Meliaceae	Amazon rainforest, Caatinga, Cerrado, Atlantic rainforest, Pantanal	Tree, shrub	Flora do Brasil 2020[2]
Vochysiaceae	Vochysiaceae	Semi-deciduous forest, Cerradão, Cerrado *sensu stricto*, Campo rupestre	Tree, shrub	Medeiros 2003; Oliveira 2004; Moura 2010
Xyris sp.	Xyridaceae	Campo rupestre, campo limpo	Herb	Oliveira 2004; Mendes et al 2014
Zea mays[1]	Poaceae	Anthropic area	Herb	Flora do Brasil 2020[2]
Zollernia-Type[1]	Fabaceae (Papilionoideae)	Amazon rainforest, Caatinga, Cerrado, Atlantic rainforest	Tree, shrub	Flora do Brasil 2020[2]
Zornia-Type	Fabaceae (Papilionoideae)	Cerrado *sensu stricto*, Campo rupestre, campo limpo	Subshrub, herb	Oliveira 2004

3. CAPÍTULO III / CHAPITRE III

MILLENNIAL-SCALE VARIABILITY OF VEGETATION AND FIRE ACTIVITY IN A NORTHERN CERRADO DRIVEN BY AN EAST-WEST RAINFALL GRADIENT DURING THE HOLOCENE

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Millennial-scale variability of vegetation and fire activity in a northern Cerrado driven by an east-west rainfall gradient during the Holocene

Sergio Augusto Santos Xavier[a, b, *], Marie Pierre Ledru[a], Laurent Bremond[a], Charly Favier[a], Francisca Soares Araújo[b]

[a]ISEM, University of Montpellier, CNRS, EPHE, IRD, Place Eugène Bataillon, 34095 Montpellier, France
[b] Graduate Course of Ecology and Natural Resources, Department of Biology, Campus of Pici, Federal University of Ceará, Fortaleza - 60440-900, CE, Brazil

*Corresponding author
E-mail: sergio-augusto.santos-xavier@etu.umontpellier.fr

Abstract

This palaeoecological study investigates vegetation variability and fire regimes in Northeastern Brazil (NEB)'s Cerrado. We present high-resolution pollen and charcoal records from a palm swamp located in a Cerrado in Chapada das Mesas National Park, in the southwest of Maranhão State. The Vereda do Dodó sedimentary core is 187 cm deep and covers the past 6000 years. Our results show first the presence of an open cerrado between 6000 and 5200 cal yr BP with no fire activity and a gradual expansion of the palm *Mauritia* and woody cerrado after 5000 cal yr BP. This is synchronous with other studies of northeastern and central Brazil. At ~4300 cal yr BP, sterile samples suggest a strong dry event, also recorded in other eastern NEB records. Frequent burnings lasted until 2600 cal yr BP, when fires stopped and *Mauritia*, arboreal cerrado, and rainforest taxa expanded under increased moisture rates. The increase of southern hemisphere summer insolation and warmer tropical Atlantic Ocean enhanced the monsoon system over the eastern Amazon and western

NEB as observed today, what accords with isotopic records. This study reveals that northern Cerrado biodiversity has been very sensitive to monsoon strength and boundaries and by strong drought events over the past 6000 years.

Keywords: pollen, charcoal, South American Monsoon System, North-eastern Brazil, 4.2 ka event, Neotropics.

Introduction

The north-eastern Brazil (NEB) is one of the least addressed regions in terms of paleoecological research regarding the establishment of modern vegetation. Different approaches have been used to reconstruct the dynamics of past environments and to explain the distribution of species richness that we find today. For example, niche model-based studies indicated the region harbored biotic routes between the Amazon and Atlantic rainforests' species during several periods of the Quaternary (Ledo and Colli, 2017; Santos et al., 2007; Sobral-Souza et al., 2015). A pollen-databased reconstruction concluded the Cerrado biome represented pathways that have linked both rainforests, from high altitudes to the lowlands across the NEB, since the early Pleistocene (Ledru and Araújo, 2023). Moister forests were interpreted between the mid and late Holocene in the area presently occupied by dry Caatinga (a xeric shrubland vegetation) in the central East (Moraes et al., 2020; Oliveira et al., 1999) and as a microrefugia in the northern mountains (Montade et al., 2014), while rainforest (Moraes et al., 2021, 2022) and a woody Cerrado (Ledru et al., 2006) predominated in the northwestern coastal lowlands. In north-eastern Brazil, the Cerrado is distributed across Piauí and Maranhão States, and covers 14% of the region (Castro et al., 2007; Ratter et al., 2003), with ecotones with the Caatinga and Amazon forest (Figure III.1A) (Sano et al., 2009). These ecotones are characterized by a mix of species from the adjacent biomes, and are floristically different from the central Cerrado (Ratter et al., 2011; Vieira et al., 2019, 2022).

Of 1071 plant species recorded in the Cerrado of north-east Brazil, 670 (62.5%) are also found in the Caatinga, 601 (56.1%) in the Atlantic forest, and 548 (51.2%) in the Amazon forest (Vieira et al., 2019). The current species richness and vegetation found in the region are considered an outcome of evolutionary processes (Vieira et al., 2019) and climate changes during the Holocene (Ledru et al., 2006).

Isotopic records show an east-west moisture gradient across the north-eastern Brazil during the mid-late Holocene (Cruz et al., 2009; Utida et al., 2020) and a dipole between northern and southern Brazil was established (Bernal et al., 2016; Wang et al., 2017). Between 6000 and 5000 yr BP, the region was predominantly wet, with lower insolation, the Intertropical Convergence Zone (ITCZ) sitting in a southward position (Utida et al., 2020) and dry conditions over the tropical Andes and western Amazon (Seltzer et al., 2000; van Breukelen et al., 2008). In central Brazil, oscillating rainfall events were associated with weakened monsoon activity from the mid Holocene onwards (Prado et al., 2013; Stríkis et al., 2011). Then, at 4200 yr BP, an abrupt decrease in moisture rates over the northeast was driven by higher insolation and intensification of ITCZ interhemispheric shifts (Chiessi et al., 2021; Utida et al., 2020; Vásquez et al., 2022), while increased humidity in the western Amazon and southern Brazil resulted from enhanced monsoon activity (van Breukelen et al., 2008). The '4.2 ky event' is considered to be one of the most prominent climate changes during the Holocene (Renssen, 2022), and it marked the onset of aridification in north-eastern Brazil (Utida et al., 2020). Currently, regional precipitation is modulated by the ITCZ in the northern section (Yan, 2005) and influenced by the South Atlantic Convergence Zone (SACZ), a feature of the monsoon system in the southwestern portion (Carvalho et al., 2011; Vera et al., 2006).

Changes in the intensity and position of Intertropical Convergence Zone during the mid-late Holocene have been linked to the expansion and retraction of moist forests, Caatinga and Cerrado in the region. So far, most paleoecological studies in NEB have been in the north-western at sea level (Moraes et al., 2021; 2022; Ledru et al., 2006), one in the northernmost mountains at 900 m a.s.l. (Montade et al., 2014) and two sites in the central semi-arid area (Moraes et al., 2020; Oliveira et al., 1999). The limitations of the reconstructions made so far are that: 1) they only provide data for the northern and eastern portion of the region under the Intertropical Convergence Zone influence; 2) most of the studies that cover the last 6000 years have a resolution of 30-46 samples (Moraes et al., 2021, 2022; Oliveira et al., 1999), what could mask the occurrence of smaller scale variations; 3) Half of them were carried out in environments with marine influence. A study from the Lake Caçó in the north of Maranhão state (Ledru et al., 2006) is the only one with a high resolution for the mid-late Holocene, were a progressive expansion of Cerrado species towards a denser forested landscape was interpreted. However, no major changes were recorded. As yet, there has not been a detailed reconstruction of Cerrado vegetation in the southwestern portion of north-eastern region under the monsoon convection. Due to its westward position within the region, the Maranhão state is located in a climatic transition zone between the moisture flux associated with the Amazon and more semiarid climatic features. Rainfall is modulated by the ITCZ in the north-northwest region, and the monsoon and SACZ in the southernmost region (Nascimento, 2014). Thus, the extension and effects of the mid-late Holocene east-west rainfall gradient and monsoon oscillations in the Cerrado vegetation of north-eastern Brazil have yet to be documented.

Because humans were present in the region throughout the Holocene (Goldberg et al., 2016; Martin, 2013), their presence is interpreted by fires and anthropogenic pollen indicators, independently or interlinked with. The occurrence of human fires has been related under the wet conditions in the northwest (Moraes et al., 2021) and dry conditions in the east (Moraes et al., 2020) of the region. However, other burnings in the wider region have been attributed to climate (Ledru et al., 2006) or climate-human interactions (Pessenda et al., 2010). Pollen grains of *Phaseolus* (bean) and *Orbignya* syn. *Attalea* (the palm tree *babaçu* in Portuguese) combined with abundant charcoal suggest strong anthropogenic activities under dry conditions in the east of the region (Moraes et al., 2020). The presence of *Mauritia flexuosa* (buriti) and increased fires under wet conditions in the northwest of Maranhão state were related to human presence (Moraes et al., 2021). *Mauritia* distribution ranges from approximately 12°N to 20°S, occurring within the Amazon forest and the Cerrado since the late Pleistocene (Hermanowski et al., 2012; Rull and Montoya, 2014). It forms communities with a high herb-shrub rich flora on flooded areas that are floristically different within the Cerrado biome (Silva et al., 2018). Studies suggest that the distribution of *Mauritia* communities of South America were influenced by variability in local moisture (Rull, 1998) and human activities during the Holocene (Rull and Montoya, 2014). Although the state of Maranhão is rich in archaeological sites, the excavations have largely concentrated on the northern coastal sites where evidence for human occupation dates back over 5000 cal yr BP and shows a demographic increase during the late Holocene (Martin, 2013; Navarro, 2018a, 2018b; Navarro and Roosevelt, 2021).

The present study aims to investigate the responses of Cerrado in northeastern Brazil to mid-late Holocene climate change and potential human influence in the vegetation. Our research questions are: 1) How the east-west rainfall gradient across the region and the monsoon oscillations affected the Cerrado during the mid-late Holocene? 2) Was the fire activity climate or human induced? The discussion is based on high-resolution pollen and charcoal records collected in a palm swamp (*vereda* in Portuguese) near the Chapada das Mesas National Park (CNMP) (Figure III.1A, C). This study contributes to our understanding of the evolution of Cerrado landscapes in the north-east Brazil during the Holocene, evaluating the vegetation dynamics of a transitional climate zone experiencing variable tropical rainfall.

Study site, climate, and vegetation

Created by federal decree on 12 December 2005, Law Nº 9.985, Chapada das Mesas National Park (7°10'30.98''S to 47°07'56.28''W, 120 to 604 m a.s.l) is located in the southwest of Maranhão State (Figure III.1B), in the mid-section of the Tocantins basin, and covers an area of 160,046 ha. The parks is characterised by ruiniform tabular sandstones with flat top hills (Figure III.1D) (ICMBio, 2019). Annual temperature ranges from 36ºC to 25ºC, and annual precipitation ranges from 1.500 to 1.250 mm, with a six-month rainy season lasting from November to April (ICMBio, 2019) (Figure III.1C). Subsistence farming is practiced by smallholders who occupy 30% of the park (ICMBio, 2019). Since 2014, to protect biodiversity, prescribed burnings have been carried out as part of an integrated fire management approach (Pivello et al., 2021).

The park is a Full Protected Area managed in alignment with International Union for Conservation of Nature (IUCN)'s category II for protected areas (Dudley, 2008). It hosts a collection of archeological sites including rock paintings, which are currently threatened by anthropic fires and vandalism, and degraded due to a lack of subsidy for conservation activity. A management plan developed by the *Instituto Chico Mendes de Conservação da Biodiversidade* (ICMBio, 2019) has noted the need for partnerships with universities who can carry out detailed research on the archeological sites (dating of rock paintings, their origin and significance), and for better control of visitors and public access. A recent study (Carvalho et al., 2023) has suggested that the politics of conservation in the park are influenced by both its geographical position and the expansion of agriculture.

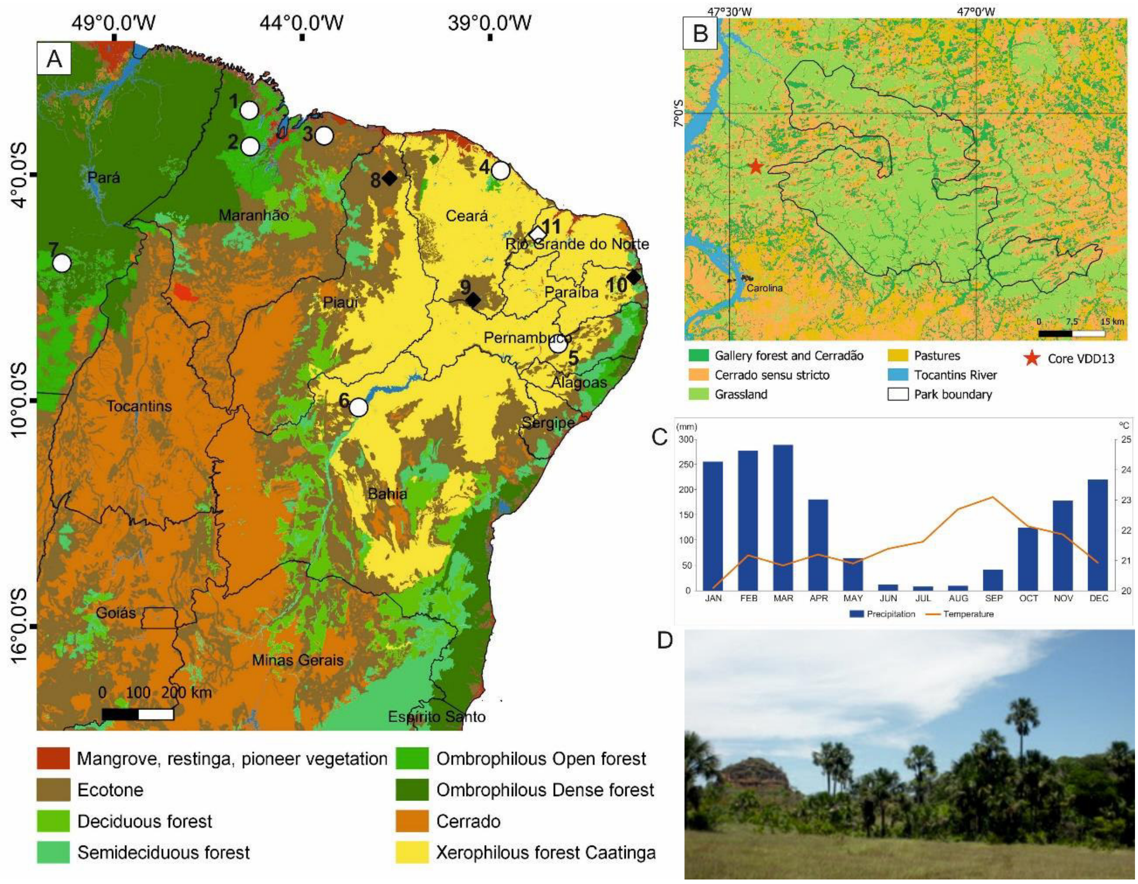

Figure III.1. (a) Map of vegetation types in Northeastern Brazil, showing the location of Chapada das Mesas National Park (red) and state boundaries (black line). White circles represents the pollen records discussed in the text: 1. Cabeludo site (Moraes et al., 2022), 2. Lake Formoso (Moraes et al., 2021), 3. Lake Caço (Ledru et al., 2006), 4. Serra do Maranguape (Montade et al., 2014), 5. Catimbau (Moraes et al., 2020), 6. Icatu Valley (Oliveira et al., 1999), 7. Carajás (Hermanowski et al., 2012). Black diamond represents the charcoal records discussed in the text: 8. Sete Cidades National Park, 9. Araripe Forest, 10. Guaribas Reserve (Pessenda et al., 2010). White diamond represents the isotopic records: 11. Chapada do Apodi (Cruz et al., 2009; Utida et al., 2020). (b) Vegetation physiognomies of the biome Cerrado in the region of Chapada das Mesas National Park (black line) (from MapBiomas 2022). (c) Ombrothermic diagram of the region of Chapada das Mesas showing mean monthly temperature (1969-2018) and mean precipitation (1914-2013) (INMET, 2021; SUDENE, 1990). (d) The vereda do Dodó (VDD) coring site showing moist grassland and palm (*Mauritia flexuosa*) swamp and a table-top mountain in the background (©MP Ledru).

While Chapada das Mesas is within the domain of the Cerrado, it shares a considerable number of species with Amazon Forest (76.03%). However, the park also has a high level of floristic similarity with the Caatinga, in both woody (60%) and herbaceous strata (65%) (Saraiva et al., 2020). Five Cerrado physiognomies can be observed: gallery forest, woody cerrado or *cerradão*, cerrado *sensu stricto*, palm swamp, and rocky grassland (Gouvêa, 2021; Moraes and Lima, 2007; Saraiva et al., 2020). Cerrado *sensu stricto* and rocky grassland dominate on the nutrient-poor shallow sandy soils (Moraes and Lima, 2007; Marques, 2012).

In the gallery forest, Rubiaceae is the most prevalent family (18 species), followed by Cyperaceae (10 species), Fabaceae (8 species), Asteraceae (7 species), Malvaceae (8 species), Melastomataceae and Myrtaceae (together, 5 species) (Saraiva et al., 2020; Gouvêa, 2021). In the woody cerrado, Fabaceae is the family with the highest number of species. In the cerrado *sensu stricto*, the most numerous families are Fabaceae (37 species), Bignoniaceae (5 species), Vochysiaceae (5 species), Poaceae (5 species), and Myrtaceae (3 species) (Saraiva et al., 2020).

The species *Byrsonima crassa* (Malpighiaceae), *Curatella americana* (Dilleniaceae), *Callisthene fasciculata* (Vochysiaceae), *Qualea parviflora* (Vochysiaceae), *Q. grandiflora* (Vochysiaceae), *Salvertia convallariaeodora* (Vochysiaceae), *Hirtella ciliata* (Chrysobalanaceae), *Vochysia rufa* (Vochysiaceae), *Combretum duarteanum* (Combretaceae) and *Plathymenia reticulata* (Fabaceae) comprise 58.2% of the total importance value (IVI) of the park's ecology (Medeiros et al. 2008). Of these, Vochysiaceae is the predominant family, with four genera and five species (Medeiros et al. 2008; Saraiva et al. 2020).

In rocky grassland, families with the greatest number of species are Fabaceae (11 species) and Poaceae (7 species) (Saraiva et al., 2020). In terms of habitat distribution, woody cerrado characterizes 64.6% of the arboreal strata, followed by gallery forest with 46.5%, and cerrado *sensu stricto* with 35.4%. Rocky grassland showed the highest proportion of herbaceous components of all the physiognomies, with 39% (Saraiva et al., 2020).

The palm swamp is characterized by waterlogged soils with an herb-subshrub strata and the presence of *Mauritia flexuosa* (Arecaceae) (Ribeiro and Walter, 2008; Silva et al., 2018). The palm swamp investigated in this paper, named Vereda do Dodó (7º06'30,21"S, 47º26'48,35"W, 307 m a.s.l.) (Figure III.1D) is associated to a nearby gallery forest surrounded by cerrado *sensu stricto* and rocky grassland.

Material and methods

Coring and sampling

A 187-cm core (VDD-13) was collected in September 2013 in the Vereda do Dodó palm swamp using a Russian corer. Core VDD-13 is composed of sand, silt, and organic matter with variable amounts of root remains. Sediment cores were transferred into PVC half-tubes and sealed in a plastic sheath for transport. Thereafter, the core was cut into 1-cm slices which were placed in labelled plastic bags and stored at 4 °C at the University of Montpellier, France.

Chronology

Nine samples were radiocarbon dated by the Accelerator Mass Spectrometry at the French Laboratoire de Mesure du Carbone 14 (LMC14), UMS 2572 (CEA/DSM, CNRS, IRD, IRSN). The radiocarbon dates were calibrated with the SHCal20 curve (Hogg et al., 2020), calculated by linear interpolation. The ^{14}C ages were calibrated to BP years (Railsback, 2006). The age-depth model was built using the Bacon package (Blaauw and Christen, 2011) in RStudio. The sedimentation rate (SR) was calculated by diving the sediment accumulated (s2-s1) per unit time (ts2-ts1) of each subsample, $SR = \frac{(s2-s1)}{(ts2-ts1)}$.

Pollen

Samples of 0.5 cm³ were analysed at 1-cm intervals for the bottom part of the core (101 to 187 cm), and at 2-cm intervals for the upper (31 to 97 cm) and top (11-16 cm) parts of the core. A total of 113 samples was analysed using standard techniques (Faegri and Iversen, 1989) and an acid free protocol (Santos and Ledru, 2021) for better concentration of the pollen residue. Two tablets of *Lycopodium clavatum* were added prior to the chemical treatments to calculate the pollen concentration. At least 300 terrestrial pollen grains were counted, excluding aquatic and water level-related taxa. Following analysis, 16 of the 113 samples showed very low terrestrial pollen concentrations (< 10,000 grains/cm^3) and were considered sterile (< 300 pollen grains). The ISEM pollen reference collection, pollen atlases for the Cerrado and other biomes (Cassino, 2014; Cassino et al., 2016; Cassino and Meyer, 2011; Colinvaux et al., 1999; Lorente et al., 2017; Salgado-Labouriau, 1973), and online database (Bush and Weng, 2007; Martin and Harvey, 2017) were used to identify the pollen types. Pollen diagrams were built using Psimpoll (Bennett, 2009). A constrained cluster analysis based on sum of squares (Grimm, 1987) was performed in Psimpoll.

Representative pollen taxa were assigned to one of four vegetation types: rainforest, arboreal cerrado, open cerrado and palm swamp (Supplementary Table 1). Habitat and ecology were defined according to floristic surveys carried out in the Chapada das Mesas region and the central Brazilian Cerrado (Supplementary Table 1). Rate of change analysis was performed in the RStudio using the package RRatepol (Mottl et al., 2021), to quantify the dissimilarity between all samples, and estimates the magnitude of compositional change through time, using an age-weighed smoothing of the data and Chord dissimilarity coefficient (binning with the mowing window approach of 400 years). A pollen index was created based on the ratio of the most characteristic moisture pollen taxa (*Alchornea*, *Borreria*, *Casearia*, *Cecropia*, *Ilex*, *Mauritia flexuosa*, Myrtaceae, *Sloanea*, *Tapirira*) to the most characteristic drought tolerant taxa (*Acalypha*, Asteraceae – tubuliflorae, *Byrsonima*, *Erythroxylum*, *Mimosa*, *Protium*) in Chapada das Mesas vegetation (Supplementary Table 1). Additionally, a non-metric multidimensional scaling analysis (NMDS) with the standardised raw data values and the Bray-Curtis dissimilarity was performed for all samples using the *vegan* package and *metaMDS* function in RStudio. NMDS is an unconstrained ordination method that condense information from multidimensional data and avoids the assumption of a linear or unimodal response between the taxa and samples (Manly and Alberto, 2017).

Sedimentary charcoals

Samples of 1 cm^3 were taken at 1-cm intervals and prepared for macro-charcoal analysis using NaOCl, KOH and NaPO3 for bleaching, and a 160-µm mesh for sieving (Stevenson and Haberle, 2005). The charcoal content was analysed under a stereoscope using WinSeedle software (Regent Instruments, Quebec, Canada) to count the number of particles and measure their size. Charcoal data are expressed as a number of particles and charcoal particle area for each sample. Then, the total sum of the charcoal-particle areas is calculated for each sample. Results are presented as the charcoal-accumulation rate by number of particles (CHARc/cm^2/year), charcoal-accumulation rate by surface area (CHARa mm^2/cm^2/year), and average width/length (W/L ratio) (Aleman et al., 2013). The W/L ratio is used to characterize burnt vegetation where $W/L < 0.5$ represents grass charred particles and $W/L > 0.5$ represents woody charred particles (Umbanhowar and McGrath, 1998). The average W/L ratio is calculated for each sample (1cm).

To determine fire episodes over time, we analysed the CHAR data using CharAnalysis v1.1 (Higuera et al., 2009). The charcoal record was decomposed to a background trend using a moving median (with a 1000-year smoothing window) to identify local charcoal peaks defined by threshold values, based on a percentile modeled with a Gaussian mixture model. Peak samples were evaluated using the 99th percentile of the modeled noise distribution (Higuera et al., 2009), interpreted as fire events.

Results

Chronology

Based on the nine radiocarbon dates (Table III.1), the base of the core was dated at 5850 cal yr BP and the top of the core is modern (post-bomb) (Figure III.2). Sedimentation rates were intermediate at the basal part of the core between 187 and 116 cm (around 0.03 mm/year), high between 115 and 97 cm (around 0.1 mm/year), intermediate between 96 and 60 cm (around 0.03 mm/year), low from 59 to 40 cm (ranging between 0.008 and 0.01 mm/year) and high from 39 cm to the upper part of the core (around 0.1 mm/year).

Table III.1

Radiocarbon dates of the core VDD-13 with calibrated BP ages (two standard deviations, 2σ ranges) and median probability (95.4%, 2σ ranges) obtained using the Bacon package (Blaauw and Christen, 2011).

Lab Code	**Depth (cm)**	**Material**	**$\delta^{13}C$**	**^{14}C age (yr BP)**	**Calibrated age range (yr BP)**	**Median probability**
SacA36114	11	Bulk	-16.4	-799 ± 21	1 — 246	58
SacA36116	38	Bulk	-27	105 ± 30	211 — 720	280
SacA36116	51	Bulk	-30.6	1360 ± 30	1062 — 1295	1211
SacA36117	60	Bulk	-32	2410 ± 30	2146 — 2478	2341
SacA36118	93	Bulk	-32.6	3025 ± 30	2998 — 3241	3145
SacA38978	97	Bulk	-26.1	3130 ± 35	3077 — 3325	3217
SacA38979	115	Bulk	-28.2	3140 ± 35	3283 — 3727	3386
SacA38980	149	Bulk	-26.5	4205 ± 35	4519 — 4828	4688
SacA38981	179	Bulk	-25.6	5030 ± 35	5351 — 5867	5679

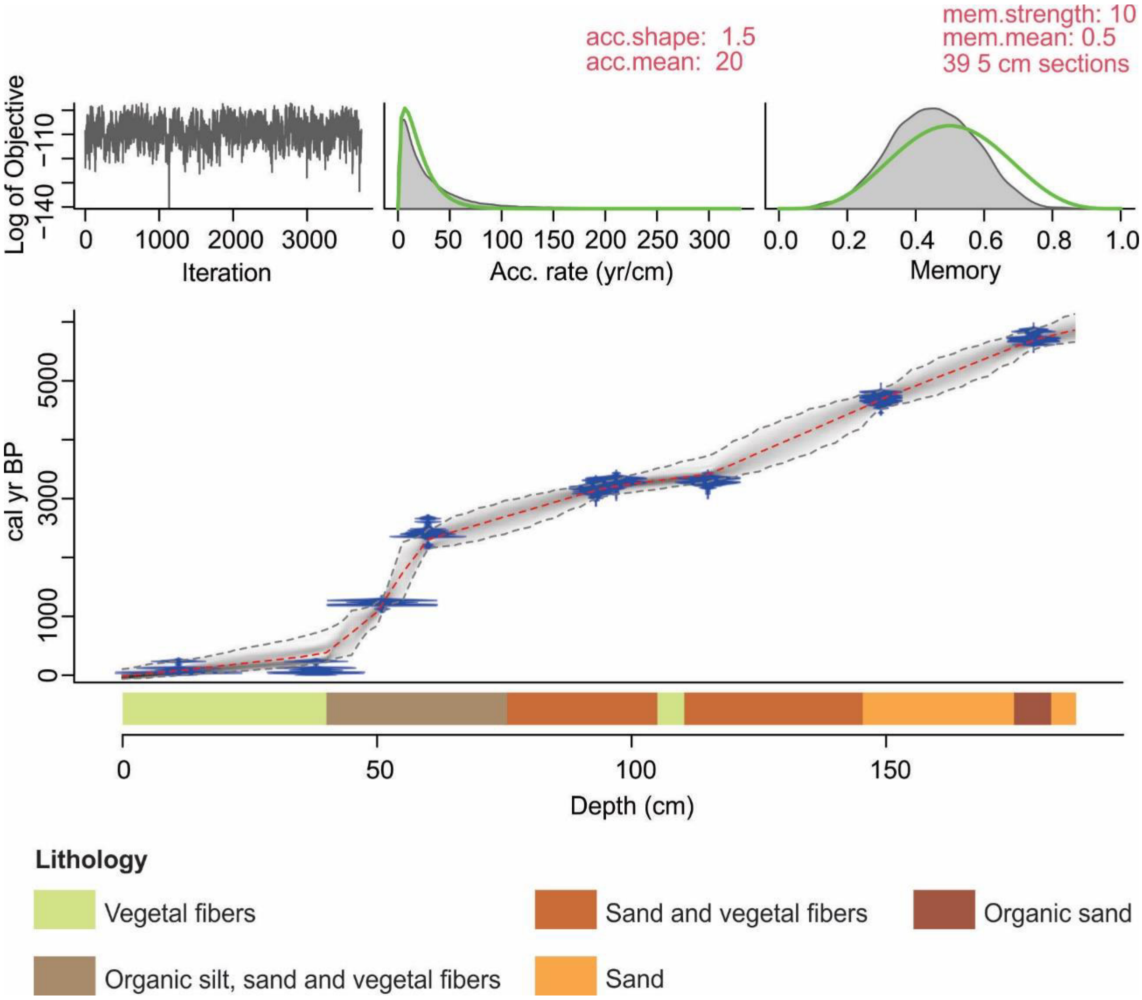

Figure III.2. Age-depth model and lithology of core VDD-13. Error intervals for ^{14}C dates were based on linear interpolation between calibrated ages (Blaauw and Christen, 2011).

Sedimentary charcoals

The resolution of charcoal analyses is an average of 26 years per sample. CHARc ranged between 0 and 5 particles/cm²/year, with low influx between 5845 and 2340 cal yr BP (185 and 60 cm, <0.5 particles/cm²/year), two peaks at 3325 and 2950 cal yr BP (0.7 and 1.5 particles/cm²/year, respectively), and no particles were recovered between 2335 and 270 cal yr BP (59 to 37 cm). The highest CHARc ranges from 255 cal yr BP to the present (35 cm to top, >1.0 particles/cm²/year). CHARa ranged between 0.0 and 0.12 mm²/cm²/yr, with low values between 5845 and 3385 cal yr BP (185 and 115 cm, <0.01 mm²/cm²/yr), and oscillating values between 3380 and 2695 cal yr BP (114 and 75 cm, > 0.0 and < 1.2 mm²/cm²/yr). No area was recorded between 2670 and 280 cal yr BP (74 and 38 cm, <0.0 $mm^2/cm^2/yr$). A small increase was recorded from 270 cal yr BP to the present (37 cm to top, > 0.01 $mm^2/cm^2/yr$). The ratio of the width to the length of the charcoal particles (W/L) between 5845 and 4545 cal yr BP (186 and 145 cm) was >0.5 (Supplementary Figure 1). Between 3800 and 2070 cal yr BP (126 and 58 cm), charred particles ranged 0.1> W/L <1.0. This pattern changed in the period from 855 cal yr to present (47 cm to top), when charred particles were <0.5. The CharAnalysis detected fire events at 4825, 3810, 3525, 3450, 2979, and 250 cal yr BP (153, 126, 118, 116, 86 and 34 cm).

Pollen

The resolution of pollen analyses is an average of 49 years per sample. A total of 121 pollen and spore taxa were identified: 79 arboreal pollen taxa, 31 non-arboreal pollen taxa, 2 water level-related taxa (e.g., damp, moist and waterlogged soils), and 9 types of spore ferns (Supplementary Table 2). Results are presented along a depth-scale (Figure III.3) and a timescale (Figure III.4).

Zone V-1 (187-165 cm, 5845 to 5220 cal yr BP, 23 samples)

52% of the pollen in Zone V-1 is arboreal, primarily comprising, with *Lithraea* (3-21%), *Protium* (3-10%), *Ilex* (1-7%), *Erythroxylum* (1-7%) and *Casearia* (0-3%). Other arboreal taxa contributed less than 5%, including *Tapirira* (0-4%), *Guazuma* (0-3%), *Alchornea* (0-1%), *Vochysia* (0-1%), Melastomataceae (0-1%), and Myrtaceae (0-1%). Soil moisture related taxa were represented by *Mauritia* (5-14%), Cyperaceae (0-20%) and *Borreria* (0-6%). High percentages of herbaceous pollen (48%) included Poaceae (7-33%), *Scoparia* (2-20%), and *Lindernia* (5-19%). Other herbaceous taxa represented less than 5%, including *Acalypha* (0-3%), *Mimosa* (0-2%) and Asteraceae Tubuliflorae (0-1%). CHARc and CHARa were low at

<50 particles/cm²/year and <0.01 mm²/cm²/year respectively, and no fire event was detected (Figure III.4). The rate of change and the pollen index showed an increase at the end of this zone (Figure III.5), with the pollen index oscillating between 0.0 and 0.5.

Zone V-2 (165-140 cm, 5220 to 4355 cal yr BP, 25 samples)

Zone V-2 is characterized by an increase in arboreal pollen (65%), dominated by *Casearia* (2-19%), *Alchornea* (1-10%), *Protium* (3-12%), and *Guazuma* (0-7%), and a decrease in *Lithraea* (2-9%), *Erythroxylum* (0-6%), and *Ilex* (0-1%). Other arboreal taxa were less frequent, including Myrtaceae (0-5%), *Tapirira* (1-3%), *Vochysia* (0-1%) and Melastomataceae (0-1%). Soil moisture related taxa *Mauritia* (4-32%) and *Borreria* (1-8%) increased, while Cyperaceae (1-7%) decreased. Herbaceous pollen decreased (35%) as did the relative percentages of Poaceae (4-24%), *Scoparia* (3-13%), and *Lindernia* (1-19%). Other herbaceous taxa contributed less than 5%, including *Acalypha* (1-3%), Asteraceae Tubuliflorae (0-2%) and *Mimosa* (0-1%). 12 of the 16 sterile samples were found in this zone (Figure III.4). CHARc and CHARa were low at <50 particles/cm²/year, and <0.02 mm²/cm²/year, respectively, with one fire event. The rate of change and pollen index both increased compared to the previous zone (Figure III.5). The pollen index varied from 0.1 to 1.0.

Zone V-3 (140-71 cm, 4355 to 2590 cal yr BP, 44 samples)

Zone V-3 is characterized by an increase in arboreal pollen (68%) and higher percentages of *Lithraea* (2-37%), Myrtaceae (0-14%), and *Erythroxylum* (0-11%). Other arboreal taxa show low frequency, including *Casearia* (0-8%), *Protium* (0-7%), *Tapirira* (0-4%), *Guazuma* (0-4%), *Vochysia* (0-3%) and *Ilex* (0-2%). Levels of the soil moisture-related taxa *Mauritia* (6-19%) and Cyperaceae (0-14%) were lower in comparison to the previous zone, while *Borreria* was higher (1-6%). Levels of herbaceous taxa, including Poaceae (7-27%), *Lindernia* (3-11%) and *Scoparia* (1-10%), were also lower (32%). Other taxa represented less than 5%, including *Mimosa* (0-4%), Asteraceae Tubuliflorae (0-1%) and *Acalypha* (<1%). CHARc was higher (>100 particles/cm²/year) than in the previous zone (Figure III.4) with four fire events, and CHARa also increased compared to the previous zone (between 0.01 and 0.12 mm²/cm²/year). The rate of change showed constant reorganisation of pollen taxa, and the pollen index showed frequent oscillations from 0.0 to 1.1, the highest variation between the zones (Figure III.5).

Zone V-4 (71-37 cm, 2590 to 270 cal yr BP, 17 samples)

Zone V-4 is characterized by 68% arboreal pollen, dominated by *Erythroxylum* (0-10%), *Ilex* (1-8%), *Lithraea* (0-8%), *Tapirira* (0-8%) and *Protium* (1-5%). Other arboreal taxa were less frequent, including *Guazuma* (0-1%), *Vochysia* (0-2%), *Byrsonima* (0-4%), *Casearia* (0-1%), Melastomataceae (0-1%) and Myrtaceae (0-1%). *Mauritia* (11-32%) increased while Cyperaceae (0-7%) and *Borreria* (2-5%) decreased. Herbaceous taxa were represented by Poaceae (5-12%), *Lindernia* (2-16%) and *Scoparia* (1-12%). *Acalypha* (0-1%), Asteraceae Tubuliflorae (0-1%) and *Mimosa* (<1%) showed low percentages. CHARc was low in this zone (<10 particles/cm²/year) (Figure III.4), CHARa decreased to <0.00 mm²/cm²/year, and no fire event was identified. The rate of change decreased significantly and stabilised at 0.2, the lowest value between the zones. The pollen index showed an increase, ranging between 0.3 and 0.9 (Figure III.5).

Zone V-5 (37-11 cm, 270 cal yr BP to AD 2013, 4 samples)

Zone V-5 is characterized by high arboreal pollen frequency (70%) with an increase in *Piper* (0-10%), Melastomataceae (2-9%), and Myrtaceae (0-8%). Other arboreal taxa were represented at low frequencies, including *Tapirira* (0-5%), *Ilex* (0-5%), *Erythroxylum* (0-2%), *Guazuma* (0-2%), *Lithraea* (0-2%), and *Vochysia* (0-1%). *Mauritia* (13-32%) and Cyperaceae (11-41%) increased while *Borreria* (0-5%) decreased. Herbaceous taxa included lower levels of *Lindernia* (0-2%) and *Scoparia* (<1%), while Poaceae (13-20%) and *Mimosa* (0-2%) increased. In this zone, CHARc was high (>300 particles/cm^2/year), CHARa increased to >0.01 mm^2/cm^2/year (Figure III.4), and a single fire event was recorded. The rate of change showed an abrupt increase and the pollen index varied from 0.5 to 1.0 (Figure III.5).

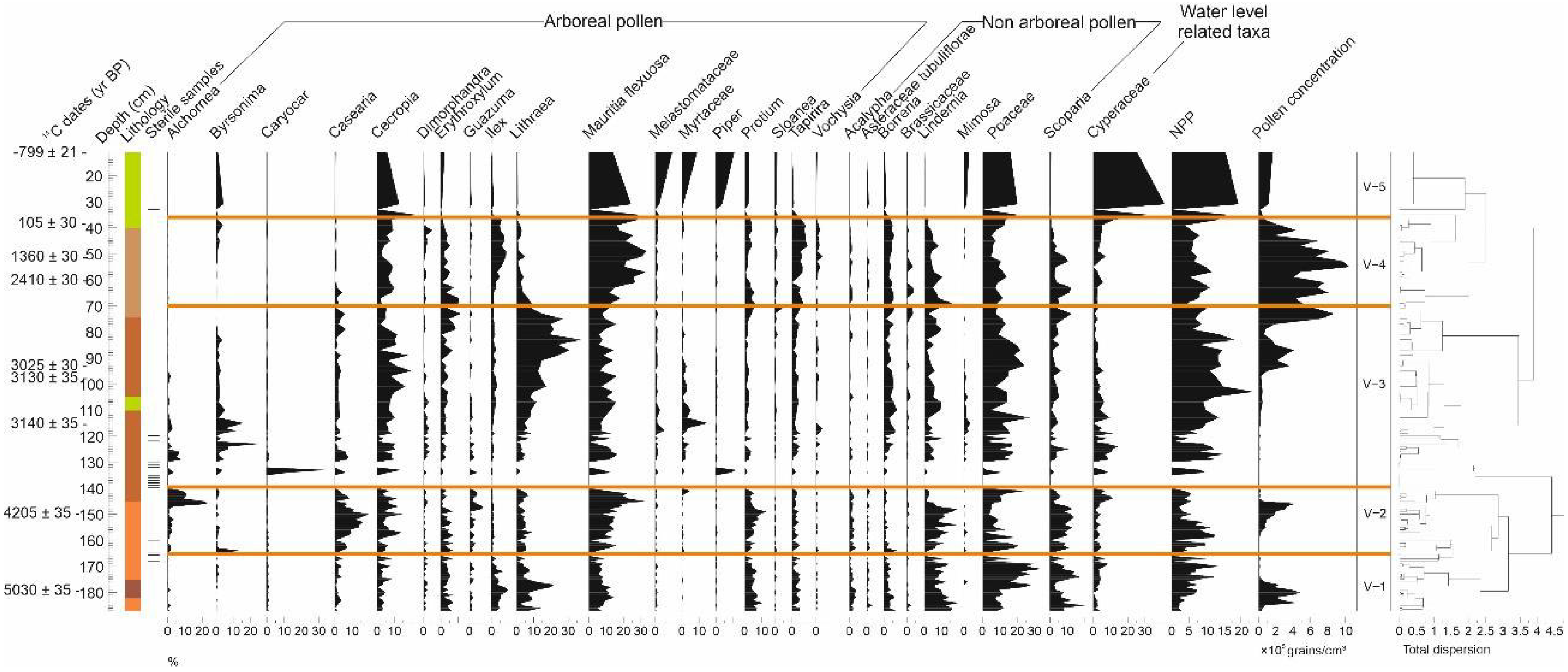

Figure III.3. Percentage pollen diagram of core VDD-13 presenting radiocarbon dates, lithology, sterile sample locations, 27 selected taxa of arboreal, non-arboreal, water level related pollen taxa, non-pollen palynomorphs (NPP), and pollen concentration plotted along a depth scale (y-axis). The pollen zones and the cluster dendrogram were obtained using CONISS (Grimm, 1987).

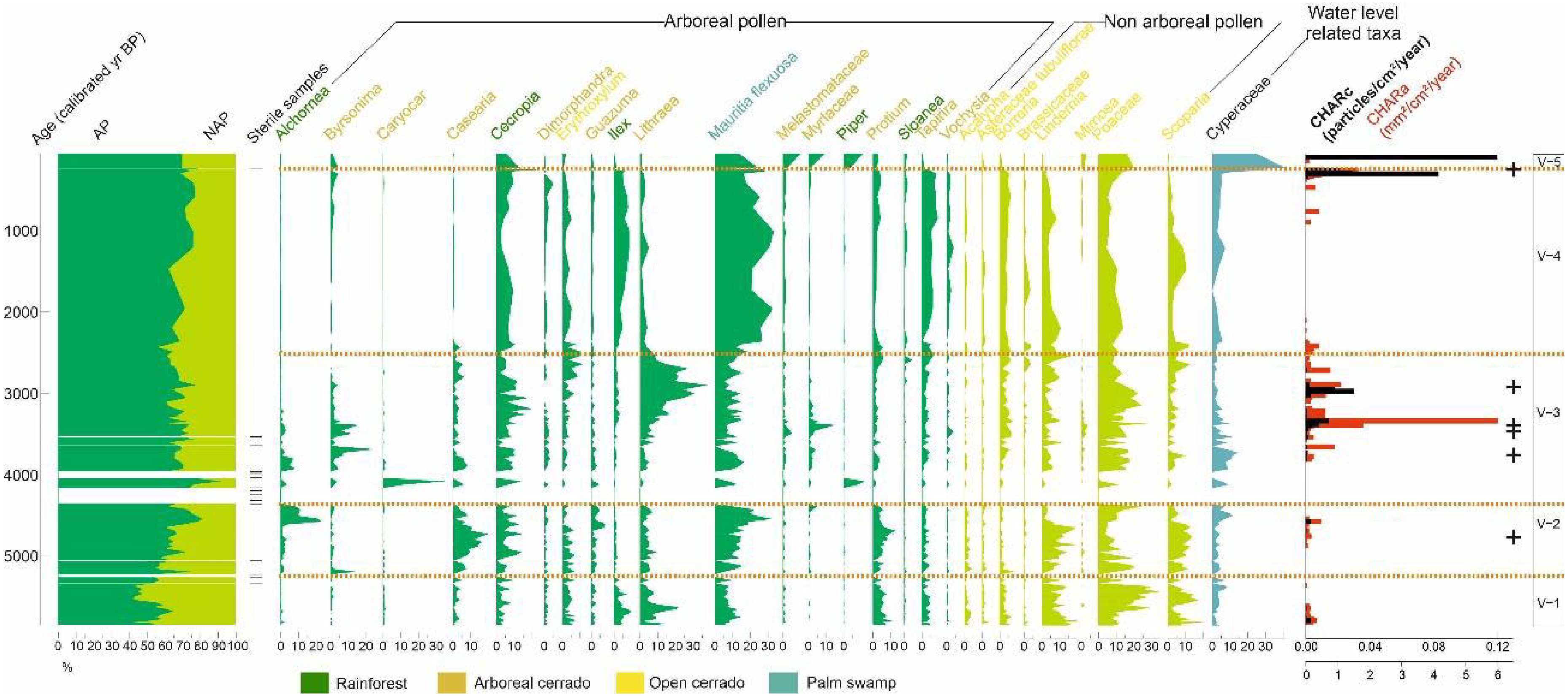

Figure III.4. Percentage pollen diagram of core VDD-13 showing 27 selected taxa of arboreal, non-arboreal and water level related pollen taxa, CHARc (black bars) and CHARa (red bars) and the pollen zones plotted along a time scale (y-axis). The white horizonal bands show the sterile samples and fire events are represented by a cross.

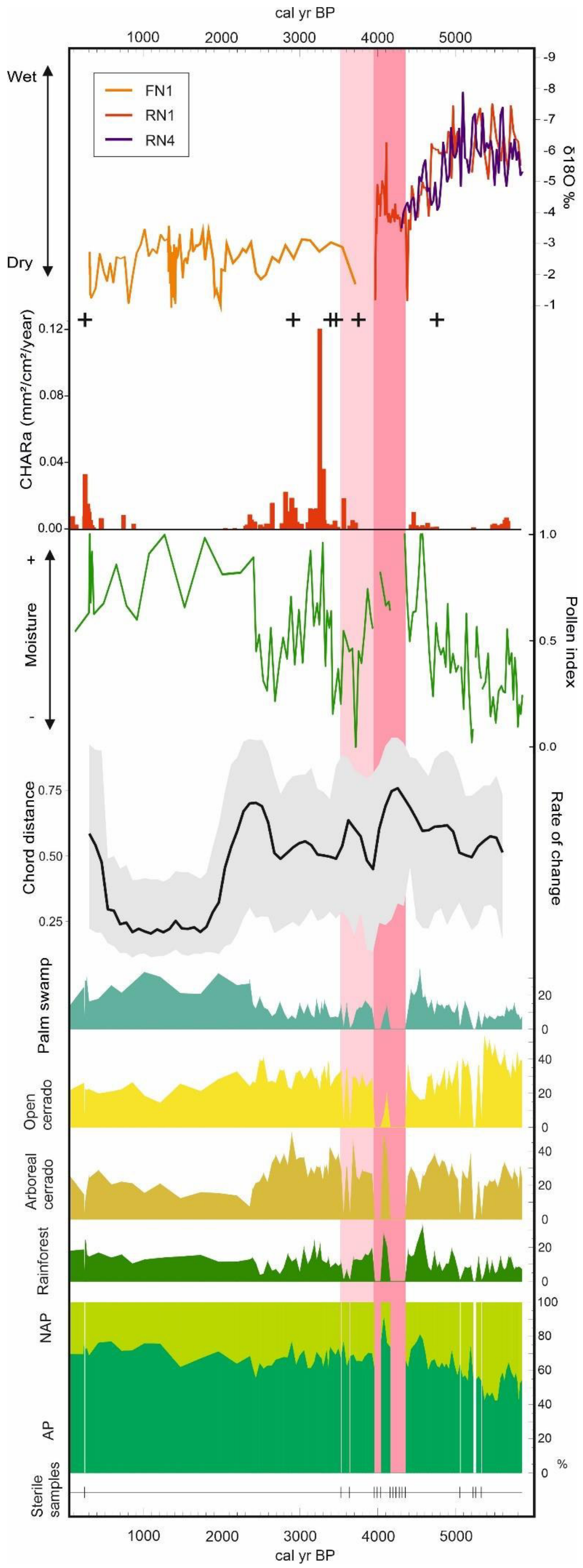

Figure III.5. Changes in vegetation, fire and climate in western NEB over the past 6000 years from left to right: 1) total sum of arboreal (AP) and non-arboreal pollen (NAP); 2) 4 ecological groups; 3) Rate of change score of pollen spectra; 4) Pollen index expressed as changes in moisture taxa; 5) CHARa (red bars) (mm²/cm²/yr); 6)

Changes in $\delta^{18}O$ from north-east speleothem records (Cruz et al., 2009; Utida et al., 2020). Pink shaded area represents the "4.2 dry event" in the region with dark pink showing the immediate response of the vegetation record and light pink the delayed response of the speleothem record to the 4.2 kyr event. Major fire events are represented by a cross.

Non-metric multidimensional scaling (NMDS)

The NMDS analysis show relative amounts of environmental change over the last 6000 years in Chapada das Mesas (Figure III.6). Samples between 6000 and 5200 cal yr BP are clustered with open cerrado taxa, mostly herbs and shrubs from dry environment (*Acalypha,* Asteraceae – tubuliflorae, *Erythroxylum*). Most samples between 5200 and 4200 cal yr BP are related to open cerrado taxa but associated with arboreal cerrado (*Casearia, Guazuma, Protium, Vochysia, Tapirira*) and rainforest elements (*Alchornea, Sloanea*). Samples between 4200 and 2600 cal yr BP are related to an assemblage of dry/moisture taxa from open cerrado (*Borreria, Mimosa*, Poaceae), arboreal cerrado (*Byrsonima, Caryocar, Dimorphandra*, Melastomataceae, Myrtaceae), and rainforest (*Cecropia*). From 2600 cal yr BP to present, samples are associated mostly with arboreal cerrado (*Tapirira, Vochysia*), palm swamp indicator (*Mauritia flexuosa*) and rainforest elements (*Ilex*, *Piper, Sloanea*).

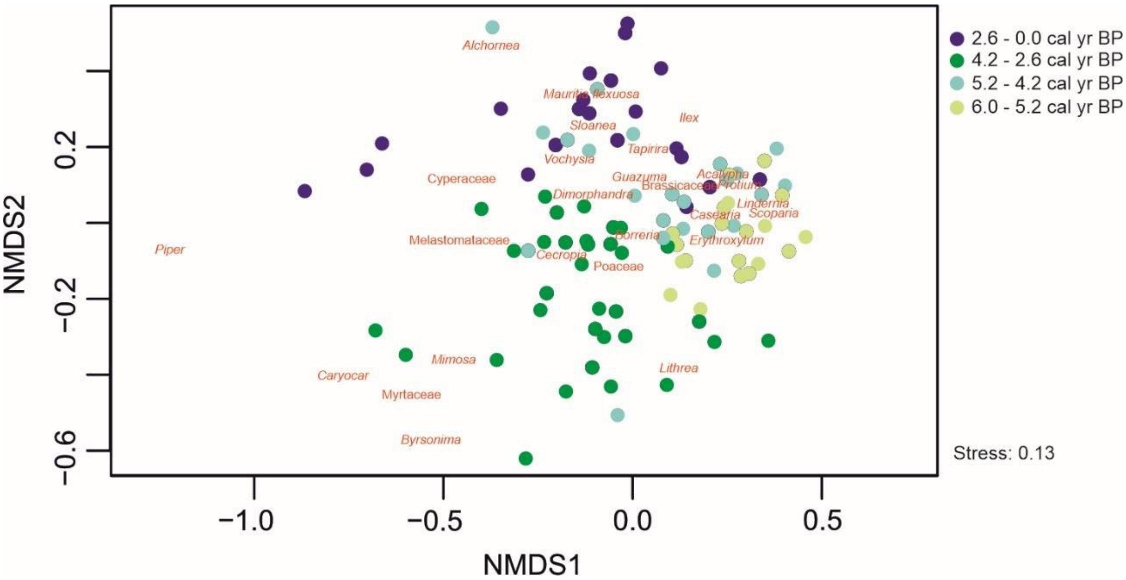

Figure III.6. Non-metric multidimensional scaling (NMDS) scatter plot of 27 most representative taxa and 97 samples from core VDD13. Position of each pollen taxa are indicated in red. The colored dots indicate the position of samples for each period.

Interpretation and discussion

To analyse how the climate, fire and potential human presence influenced the landscape of Chapada das Mesas, we interpreted the vegetation and compared with other pollen records for the mid-late Holocene in the north-east region. From ~6000 to 5200 cal yr BP, the landscape was drier than today, open with the herbaceous layer characterized by the dominance of *Lindernia*, *Acalypha*, Asteraceae – tubuliflorae, the shrub *Erythroxylum* and the tree taxa *Protium* (Figure III.6). In the Cerrado, the distribution of herbaceous species is directly related to edaphic conditions and seasonality (Leite et al., 2018). *Lindernia* is associated with moist open grassland (Souza, 2023). *Acalypha* and *Erythroxylum* can withstand seasonally dry conditions (Alonso and Machado, 2007). The Cerrado tree taxa *Protium* is heliophilous, and is commonly found on forest edges and open fields (Carvalho, 2006). Similarly, pollen records for the coastal Lake Formoso and Cabeludo showed open vegetation with Poaceae, Cyperaceae, Asteraceae and mangroves receding (Moraes et al., 2021; 2022), while those for Lake Caço, located ~100 km inland, showed an open cerrado dominated by Poaceae and *Byrsonima* (Ledru et al., 2006). However, the vegetation cover recorded at Icatu in eastern NEB suggests a moister climate than that of today (Oliveira et al 1999), with expansion of *Mauritia* palm swamp and decrease of *Cuphea* and *Mimosa*, typical Cerrado and Caatinga taxa.

From ~5200 to 4300 cal yr BP, increases in *Casearia, Guazuma*, *Alchornea*, and *Mauritia* (Figure III.4) suggest that a denser cerrado tree cover expanded across the herbaceous strata that composed the previously open vegetation (Figure III.6). In the Cerrado the distribution of arboreal cover is related to soil moisture, with vegetation gradients from grassland to forest physiognomies (Assis et al., 2011; Terra et al., 2018). The tree *Casearia* colonizes open fields and tolerates moisture oscillations (Carvalho, 2010). *Guazuma* is a fast growing tree on open cerrado (Carvalho, 2006), and *Alchornea* is a semideciduous tree or shrub which can be found today in the rocky grassland of CMNP (Saraiva et al., 2020). The genus *Alchornea* has great phenotypic plasticity, occurring in woody cerrado, gallery forest, and Amazon rainforest (see Carvalho, 2003; Secco, 2004). The abundance and dispersal of *Mauritia* relates to water saturated soil (Virapongse et al., 2017). Low fire activity dominated by wood burnings (Supplementary Figure 1), expansion of rainforest taxa, arboreal cerrado, the palm swamp, and the absence of strong biomass burning (Figure III.5) all suggest that climatic conditions were wetter in this interval than in the previous one.

The expansion of rainforest and arboreal cerrado in Chapada das Mesas was also suggested in the northern coastal of Maranhão, where *Sebastiana, Alchornea,* Anacardiaceae, *Byrsonima*, Euphorbiaceae, Fabaceae and Moraceae characterized the arboreal vegetation (Moraes et al., 2021; 2022). No such changes were recorded at Lake Caço (Ledru et al., 2006). In eastern NEB, a wet forest composed of Moraceae, Arecaceae, and Myrtaceae was recorded at Maranguape (Montade et al., 2014). However, a retraction of the palm swamp and increase of Cerrado and Caatinga taxa was interpreted at Icatu Valley (Oliveira et al., 1999). During this interval it therefore appears that climatic conditions in the west of the region were moister than in the east.

The period between ~4300 and 3900 cal yr BP is characterized by nine sterile samples (Figure III.4), suggesting drier conditions on the grassland and an absence of pollen preservation (see Cassino et al., 2020). From ~3900 to 2600 cal yr BP, tree cover fluctuated between typical cerrado taxa, *Byrsonima, Caryocar*, *Lithraea* and arboreal/shrub Myrtaceae, Melastomataceae (Figure III.6), taxa associated with gallery forest, woody cerrado, cerrado *sensu stricto,* and rocky grassland (Figure III.4). *Byrsonima*, *Caryocar* and *Lithraea* are drought tolerant tree taxa. The former two characterize the cerrado *sensu stricto* of north-eastern and central Brazil (see Ledru, 2002; Vieira et al., 2019), while the latter is found in woody cerrado (see Carvalho, 2006). A marked increase in CHARa (between 0.01 and 0.12 $mm^2/cm^2/yr$) shows higher fire activity than between 5200 and 4300 cal yr BP, with particles originating from both woody and herbaceous vegetation (Supplementary Figure 1). From ~3900 cal yr BP, an expansion of *Byrsonima, Dimorphandra,* and *Guazuma* was recorded until ~3300 cal yr BP, when these taxa were replaced by the gradual increase of Myrtaceae, *Lithraea,* and *Ilex* (Figure III.4). This two-step pattern of vegetation change was not recorded in the low-resolution pollen records of northern Maranhão or the records for most of the north-eastern region. Lake Caço showed a slight increase in *Mauritia* (Ledru et al., 2006), and those for Lake Formoso and Cabeludo showed an increase in Amazon rainforest taxa (Moraes et al., 2021; 2022). The drier interval between 4300 and 3900 cal yr BP was also recorded at Maranguape, where the ombrophilous forest was initially replaced by an *Alchornea*-dominated semideciduous forest, until ~3500 cal yr BP when the ombrophilous forest returned (Montade et al., 2014). Further east, the Catimbau and Icatu pollen records showed an expansion of dry vegetation represented by *Cuphea*, *Mimosa* and *Byrsonima* (Moraes et al., 2020; Oliveira et al., 1999), thus differing from Chapada das Mesas record.

The interval ~2600 cal yr BP to the present is characterized by a change in the pollen assemblage with increasing proportions of *Ilex*, *Sloanea, Tapirira*, *Dimorphandra*, *Vochysia*, *Borreria,* and *Mauritia* (Figure III.4, III.6). *Ilex* and *Sloanea* are gallery forest taxa in north-eastern and central Brazil. In central Brazil, *Ilex* is often associated with palm swamp (see Carvalho, 2008). *Protium, Dimorphandra,* and *Vochysia* are cerrado tree taxa. The arboreal taxa *Tapirira* is found in all forested physiognomies in the Amazon and Cerrado, and as a shrub in the Caatinga (Carvalho, 2006; Gouvêa, 2021; Saraiva et al., 2020). There was no fire activity during this interval. At ~270 cal yr BP decreases in *Ilex, Tapirira, Vochysia,* *Dimorphandra,* and *Borreria,* and increases in Melastomataceae, Myrtaceae, *Piper, Mimosa*, Poaceae, and Cyperaceae were noted. *Piper* is an arboreal/shrub element of gallery forest and Amazon forest (Guimarães et al., 2023). *Mimosa* is a shrub both of the Cerrado and of the xerophilous Caatinga (Mendonça et al., 2008; REFLORA, 2023). An increase in fire activity (CHARa between 0.01 and 0.04 mm²/cm²/yr) was recorded around 270 cal yr BP (Figure III.4), and associated with the burning of the herbaceous vegetation layer (Supplementary Figure 1). Fluctuations in soil moisture and biomass burning suggest successive reorganization of the vegetation in the vicinity of the palm swamp. The influx of high levels of charcoal recorded may be related to anthropogenic activity (see Ledru et al., 2020).

The expansion of the arboreal cerrado, rainforest, and palm swamp show the establishment of moist climatic conditions in the region of the Chapada das Mesas (Figure III.5) and on the coast of Maranhão state (Moraes et al., 2021; 2022). Further east, the Maranguape and Catimbau pollen records also showed an increase in local moist arboreal cover (Montade et al., 2014; Moraes et al., 2020), opposing the dominant dry Caatinga at Icatu (Oliveira et al., 1999). After 450 cal yr BP, *Byrsonima, Mimosa*, Poaceae and Asteraceae expanded at Catimbau (Moraes et al 2020), suggesting a dry open vegetation, while there was no sediment recovery in the other records.

How the east-west rainfall gradient across the region and the monsoon oscillations affected the Cerrado during the mid-late Holocene?

Between 6000 and 5000 cal yr BP, when the Chapada das Mesas record and the low values of the moisture pollen index suggests conditions were drier than today, the speleothem showed predominantly wet conditions in the east of north-east (Figure III.5, III.7A). Indeed, lower than present levels of summer insolation in the southern hemisphere led to the Intertropical Convergence Zone being more active across north-eastern Brazil (Utida et al., 2020) and weaker monsoons in central Brazil (Prado et al., 2013). The east-west humidity gradient that established over north-east (Cruz et al., 2009) was antiphased with the rest of tropical South America (Escobar-Torrez et al., in review; van Breukelen et al., 2008; Wang et al., 2007). Thus, our record located on the westernmost boundary of north-eastern Brazil shows an in-phase response with eastern Amazon and central Brazil, rather than with the eastern portion of north-east region (Figure III.7A).

After 5000 cal yr BP, the high moisture rate in Chapada das Mesas was also suggested in most pollen records for western and eastern NEB (with the exception of Icatu record in Oliveira et al., (1999)) (Figure III.7B) and for central Brazil (Escobar-Torrez et al., in review), in phase with the increase in summer insolation in the southern hemisphere, and the ITCZ being at its most southerly position. The pollen index increased gradually, and rate of change increased twice, around 5000 cal yr BP and 4600 cal yr BP (Figure III.5), indicating environmental changes linked to higher precipitation. Speleothem record show increased precipitation around ~5200 cal yr BP in central-eastern Brazil (Stríkis et al., 2011). On the coast, sea level reached its highest level between 5000 and 4000 cal yr BP as a result of the thermal expansion of increasingly warm seawater (Caldas et al., 2006; Suguio et al., 2013). These moister and warmer conditions enabled regional expansion of palm swamps (*Mauritia flexuosa)* and tree cover in the western part of north-east, and favored the expansion of Amazon rainforest tree taxa and mangrove in the western coastal region (Moraes et al., 2022). Climate models suggest that increased summer insolation and warmer sea surface temperature accentuated the latitudinal contractions of the ITCZ, and drove changes in monsoon activity (Campos et al., 2022; Chiessi et al., 2021).

The absence of pollen content in our record between 4300 and 3900 cal yr BP was attributed to oxidation of the biogenic content due to dry environmental conditions (see Cassino et al., 2020; Oliveira et al., 1999). In north-eastern Brazil, the date of 4200 cal yr BP heralded an abrupt decrease in precipitation which is considered to signal the onset of aridification in the region (Figure III.5, III.7C) (Cruz et al., 2009; Utida et al., 2020). In the eastern part of the region this dry event caused changes in the forest refugia of Maranguape (Montade et al., 2014) and the expansion of Caatinga dry forest at Icatu and Catimbau (Moraes et al., 2020; Oliveira et al., 1999). Our record shows that western NEB was not synchronous with eastern NEB, as the driest interval was between 4300 and 4000 cal yr BP in Chapada das Mesas and 4200 and 3700 cal yr BP in the speleothem records (Cruz et al., 2009). However, in the Maranguape (Montade et al., 2014), the change in vegetation composition occurred between 4300 and 4000 cal yr BP, with a slow recovery up to 3600 cal yr BP. Simultaneously, the RN4 speleothem stopped growing at 4200 cal yr BP, while the RN1 stopped growing at 3900 cal yr BP. Only the FN1 stalagmite cover the last 3700 cal yr BP (Figure III.5). This suggests that vegetation responded earlier than the speleothems to an abrupt change in precipitation. During periods of increased rainfall, the water percolates faster with a shorter residence time in the karst system (Utida et al., 2020). When precipitation decreases, the reduction of water infiltration led to slower speleothems deposition. The time lag between speleothem and pollen records may be explained by this slow rate of water percolation, which in NEB occurred around 100 years. Models of the '4.2 ky event' (Renssen, 2022) considered to be an important climatic event during the late Holocene, suggest that unusual changes in tropical sea surface temperature induced both aridification in Africa, from west to east, and increased precipitation in South America. However, in this study, we show that north-eastern Brazil deviates from this general pattern, with an antiphase relationship with the western Amazon (van Breukelen et al., 2008), central Brazil (Escobar-Torrez et al., 2023) and northern South America (Haug et al., 2001).

The dry conditions at Chapada das Mesas between 3900 and 3600 cal yr BP were followed by a gradual increase in precipitation at ~3300 cal yr BP, which was most likely related to a longer rainy season. Decreasing values of the pollen index after 4000 cal yr BP, followed by a moderate increase after 3300 cal yr BP indicate a progressive transition to wetter climate (Figure III.5). In addition, variations in the rate of change between 3900 and 2500 cal yr BP indicated recurrent vegetation responses linked to changes in precipitation (Figure III.5). Isotopic records also show a return to intermediate moisture conditions at ~3500 cal yr BP in eastern NEB (Cruz et al., 2009), close to the equator in Amazon lowlands (Wang et al., 2017), in southwestern Amazon (Bush et al., 2004) and the Andes (Seltzer et al., 2000). In eastern Amazon, a sedimentological record (Sifeddine et al., 2001) from Carajás region detected increased moisture conditions after ~3400 cal yr BP that enabled the establishment of the modern rainforest, what accords with a palynological study (Hermanowski et al., 2012). From 2600 cal yr BP onwards, a sharp decrease in rate of change following by a low stabilised score and increased pollen index indicate an environmental change to predominant humid climate at Chapada das Mesas. This suggests stronger monsoon activity in the western part of the region, probably influenced by increased Amazonian circulation and the position of the South American Convergence Zone as observed today (Figure III.7D) (Nascimento, 2014) rather than a shift in the Intertropical Convergence Zone as suggested by the advent of drier conditions in eastern NEB (Utida et al., 2019).

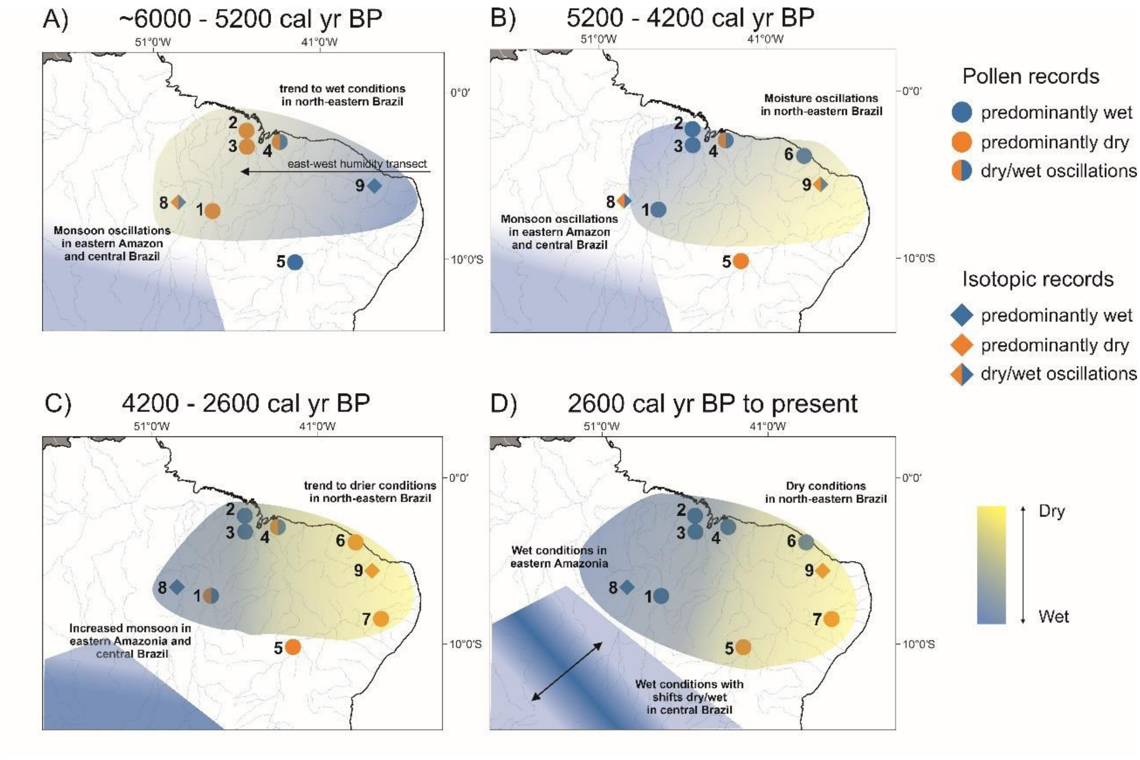

Figure III.7. Schematic representation of east-west rainfall transect and monsoon activity during the mid-late Holocene in north-eastern Brazil. a) ~6000 to 5200 cal yr BP; b) 5200 to 4200 cal yr BP; c) 4200 to 2600 cal yr BP; d) 2600 cal yr BP to present. Pollen sites: 1. Chapada das Mesas (this study); 2. Cabeludo (Moraes et al., 2022); 3. Lake Formoso (Moraes et al., 2021); 4. Lake Caçó (Ledru et al., 2006); 5. Icatu River (Oliveira et al., 1999); 6. Serra do Maranguape (Montade et al., 2014); 7. Catimbau (Moraes et al., 2020). Isotopic records: 8. Carajás (Sifeddine et al., 2001); 9. Apodi (Cruz et al., 2009; Utida et al., 2020).

Was the fire activity climate or human induced?

The low levels of biomass burning at Chapada das Mesas between 6000 and 5200 cal yr BP (CHARa <0.01 mm²/cm²/yr) were associated with drier-than-present climatic conditions with a short rainy season and limited availability of fuel. Vegetation density has been linked with fire propagation since the late Paleozoic, as it provides a connective fuel source (Glasspool et al., 2015). In the Cerrado today, natural fires are more frequent under a bimodal climate, during the transition from dry to wet season (Gomes et al., 2018). However, fire behavior is not homogenous across the Cerrado, and varies independently of the spatial scale (local to regional), temporal scale (short to long-term) and source drivers (natural, anthropic) (Escobar-

Torrez et al., in review; Gomes et al., 2018).

The first evidence of a human presence in Maranhão State dates back to ~6700 cal yr BP (Martin, 2013). Although there are numerous archaeological sites in the state, this early human presence has not yet been studied except at some northern coastal sites which relate to the late Holocene (Navarro, 2018a,b). Until 4300 cal yr BP little biomass burning was recorded (CHARa >0.01 $mm^2/cm^2/yr$), and one fire event was noted (Figure III.5). Studies carried out in the Cerrado by Gomes et al. (2018), and Ramos-Neto and Pivello (2000) showed that during the rainy season ignition is less frequent and less intense than during the dry season, as it is controlled by edaphic moisture and vegetation.

From 4300 to 2600 cal yr BP the increase of CHARa at Chapada das Mesas revealed a change in fire activity and reorganization of the vegetation (Figure III.5). Fire fuel included both grasses and woody material (Supplementary Figure 1). The fluctuations in Cerrado fire resistant taxa (e.g. *Byrsonima, Mimosa*), moisture related taxa, fast growing tree taxa (e.g. Myrtaceae, Melastomataceae, *Guazuma*) and higher fire activity (CHARa between 0.01 and 0.12 $mm^2/cm^2/yr$), suggest that a predominantly seasonal climate had become established in the region of Chapada das Mesas (Figure III.5, III.7C). However, the hypothesis of anthropogenic fires, and even the combination of fire-climate-human interactions is not dismissed. Considering ancient migration routes for Amazonian populations in South America (Goldberg et al., 2016), the lack of radiocarbon dates between 4000 and 2600 cal yr BP for Chapada das Mesas may reflect lack of archeological sampling rather than human absence. Based on Martin (2013) and Souza et al. (2020), the late Holocene was a period of increased anthropic activity in north-eastern Brazil, with lithic artifacts, pottery, agriculture, and rock paintings found in coastal regions and inland close to the headstreams. In eastern NEB, intense fire activity was recorded under dry climatic conditions and thus attributed to land use practices in the Cerrado (Pessenda et al., 2010). In the north of Maranhão state, no fires were recorded due to the predominantly wet climate on the coast before establishment of humans (Moraes et al., 2021, 2022). Therefore, more data are needed to constrain the human presence in Chapada das Mesas during the late Holocene to fully verify the hypothesis of anthropic fires.

At 2600 cal yr BP, the abrupt decrease of charcoal (CHARa <0.01 $mm^2/cm^2/yr$) suggests a shift in fire activity which was simultaneous with the expansion of rainforest, woody cerrado, and palm swamp (Figure III.5). The absence of fire events can probably be related to moist and warm conditions which induced less frequent biomass burning in the palm swamp. Interestingly, Moraes et al., (2021) detected an increase in *Mauritia* and fire activity during a wet climate in the north of Maranhão state, while Moraes et al. (2020) detected the bean *Phaseolus,* the palm tree *Orbignya* and high fire activity in eastern NEB during a dry climate: these observations were attributed to anthropogenic practices. Conversely, Ledru et al., (2006) interpreted an increase of *Mauritia* driven solely by climatic conditions in the north of Maranhão. The palm is also recorded in the east of the region in low frequencies and absence of human presence (Moraes et al., 2020; Oliveira et al., 1999). *Mauritia* has been widespread recorded across northern South America in microrefugia since the late Pleistocene, from where the palm expanded as the climate became moister and warm during the mid-late Holocene (Rull, 1998; Rull and Montoya, 2014). During the late Holocene, *Mauritia* communities underwent an expansion often related to anthropogenic character (Rull and Montoya, 2014). The occurrence of *Mauritia* is detected in the whole VDD record in varying frequencies with a remarkable increase and stabilisation from 2600 cal yr BP onwards, when fires stopped. Considering the heterogeneity of factors that influence *Mauritia* distribution in the north-east region, the expansion recorded in Chapada das Mesas could be of anthropogenic character or a combination of climate-human activity, but we did not find strong evidence to support one of these interpretations.

Between ~ 270 cal yr BP and the present at Chapada das Mesas, the highest charcoal influx (between 125 and 350 particles/cm²/yr) and one fire event at 250 cal yr BP were recorded to stem from grass burning (W/L < 0.5). Since no change in climate or vegetation were recorded during this interval, we inferred an increase in anthropogenic activity, from the beginning of 18th century, itinerant cattle herders occupied the natural grassland in the South of Maranhão State (Cunha, 2015; Rocha, 2015), where they practiced patch-burn grazing (Pivello et al., 2021).

Conclusion

Our results show that the Cerrado of Chapada das Mesas was affected by millennial-scale climatic events during the mid-late Holocene. We found the vegetation responded rather to monsoon oscillations in eastern Amazon and central Brazil than to the east-west rainfall gradient across the north-eastern Brazil. The Chapada das Mesas record shows a drier-than-present open landscape with low fire activity from 6000 to 5200 cal yr BP, which was gradually replaced by a woody cerrado and rainforest elements until 4300 cal yr BP when summer insolation started to increase, and the monsoon became stronger. A drought characterized by the oxidation of pollen content was suggested at ~4300 cal yr BP, lasting for 400 years, followed by a change in the vegetation and fire activity. This highlights a faster response by vegetation to a regional climatic event compared to the deposition of the speleothems. Between 3900 and 2600 cal yr BP high levels of fire activity were interpreted under a seasonal climate. Despite records of human presence in the region during the Holocene and even though the hypothesis of anthropogenic fires is not entirely dismissed, we could not draw conclusions from the lack of archeological dates. The advent of moister climatic conditions from 2600 cal yr BP onwards led to the expansion of the rainforest, woody cerrado, and palm swamp, and a low fire signal.

Comparison with other palaeoecological studies of the region showed that Chapada das Mesas and the eastern portion of north-eastern Brazil were anti-phased during most of mid-late Holocene, except during the 4.2 ky arid event which affected the east-west precipitation band across the region, registered in both pollen and speleothem records. The 4.2 ky event was not recorded in central Brazil but solely in two sites in the east, interpreted as cause of dryness and vegetation changes in Chapada das Mesas and the eastern of north-east region. Thus, our study highlights the heterogeneity of the climate and vegetation responses of the northeastern Cerrado during the mid-late Holocene, with western portion of north-eastern Brazil strongly influenced by the strength and the position of the monsoon core region.

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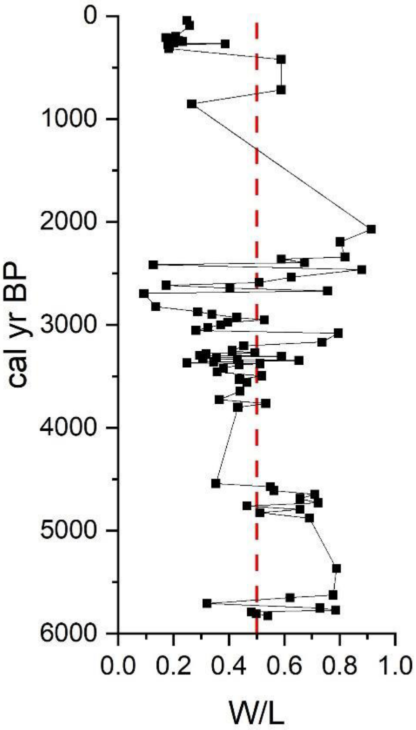
Supplementary material



Supplementary Figure 1. Graphic representation of the variation of the W/L ratio in function of time.

Supplementary Table 1. Alphabetical list of the 25 most representative taxa observed in core VDD13 with their habit and ecology.

Taxa/Family	**Plant habit**	**Ecology**	**Vegetation type**	**Reference**
Acalypha (Euphorbiaceae)	Shrub	Open fields under full sun or partial shade, drought tolerant	Open cerrado	SpeciesLink, 2023
Alchornea (Euphorbiaceae)	Shrub	Secondary formations, forest borders	Rainforest	Saraiva et al. 2020
Asteraceae – tubuliflorae (Asteraceae)	Herb	Drought tolerant	Open cerrado	Saraiva et al. 2020; Gouvêa 2021
Borreria (Rubiaceae)	Herb	Humid soils under prolonged flooding	Open cerrado	Saraiva et al. 2020
Brassicaceae	Herb	Open fields	Open cerrado	REFLORA, 2023
Byrsonima (Malpighiaceae)	Tree	Pioneer taxon, drought resistant	Arboreal cerrado	Saraiva et al. 2020
Caryocar (Caryocaraceae)	Tree	Pioneer tree, drought resistant	Arboreal cerrado	Saraiva et al. 2020
Casearia (Salicaceae)	Tree, shrub	Pioneer taxon to secondary formations, humid rain forests	Arboreal cerrado	Saraiva et al. 2020; SpeciesLink, 2023
Cecropia (Urticaceae)	Tree	Pioneer taxon of disturbed environments, humid forests	Rainforest	Medeiros et al. 2008
Dimorphandra (Caesalpinioideae)	Tree	Heliophilous taxon, well-drained soils	Arboreal cerrado	Medeiros et al. 2008; Saraiva et al. 2020
Erythroxylum (Erythroxylaceae)	Shrub	Pioneer taxon, drought tolerant	Open cerrado	SpeciesLink, 2023
Guazuma (Malvaceae)	Tree	Fast-growing taxon of secondary forests	Arboreal cerrado	SpeciesLink, 2023
Ilex (Aquifoliaceae)	Tree	Humid forests and dense primary formations	Rainforest	Saraiva et al. 2020
Lindernia (Linderniaceae)	Herb	Moist open fields	Open cerrado	Souza, 2023; SpeciesLink, 2023
Lithraea (Anacardiaceae)	Tree	Secondary formations, forest borders and open fields	Arboreal cerrado	Carvalho 2006

Mauritia flexuosa Arecaceae)	Tree	Indicator of palm swamps with waterlogged soils	Palm swamp	SpeciesLink, 2023
Melastomataceae	Tree	Pioneer elements of forested vegetation	Arboreal cerrado	Medeiros et al. 2008; Saraiva et al. 2020
Mimosa (Mimosoideae)	Herb	Seasonal dry forests and open fields, drought tolerant	Open cerrado	Saraiva et al. 2020
Myrtaceae	Tree	Moist forested formations	Arboreal cerrado	Medeiros et al. 2008; Saraiva et al. 2020; Gouvêa 2021
Piper (Piperaceae)	Tree	Moist forested formations	Rainforest	Gouvêa 2021
Poaceae	Herb	Open fields, herbaceous stratum and marginal habitats	Open cerrado	Saraiva et al. 2020; Gouvêa 2021
Protium (Burseraceae)	Tree	Secondary formations and forest borders, very frequent in open fields, drought tolerant	Arboreal cerrado	Saraiva et al. 2020; Gouvêa 2021
Sloanea (Elaeocarpaceae)	Tree	Secondary to climax taxon of humid forests	Rainforest	SpeciesLink, 2023
Tapirira (Anacardiaceae)	Tree, shrub	Dense moist forested formations, but can tolerate dry conditions	Arboreal cerrado	Saraiva et al. 2020
Vochysia (Vochysiaceae)	Tree	Forested formations	Arboreal cerrado	Saraiva et al. 2020; Gouvêa 2021

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Supplementary Table 2. List of pollen taxa identified in the Vereda do Dodo core. Habitat refers to Cerrado physiognomies to which respective species found in Chapada das Mesas National Park were attributed. [1]Species absent in CMNP surveys. [2]Checklists and online databases of Brazilian flora were used to assign absent species to habitats.

Pollen type	Family	Habitat (Cerrado physiognomy)	Life-form type	References
Acalypha[1]	Euphorbiaceae	Grasslands	Herb	(SpeciesLink, 2023)[2]
Actinostemon[1]	Euphorbiaceae	Amazon Rainforest, Caatinga, Central Brazilian Savanna, Atlantic Rainforest, Pampa	Tree, shrub	(REFLORA, 2023)[2]
Alchornea	Euphorbiaceae	Campo rupestre	Shrub	(Saraiva et al., 2020)
Alternanthera	Amaranthaceae	Cerrado	Herb	(SpeciesLink, 2023)[2]
Anacardium	Anacardiaceae	Cerradão, cerrado *sensu stricto*	Tree	(Medeiros et al., 2008; Saraiva et al., 2020)
Andira	Fabaceae (Papilionoideae)	Gallery forest, Cerradão, cerrado *sensu stricto*, Campo rupestre	Tree	(Medeiros et al., 2008; Saraiva et al., 2020)
Anonnaceae	Anonnaceae	Gallery forest, Cerradão, cerrado *sensu stricto*	Tree	(Gouvêa, 2021; Saraiva et al., 2020)
Apocynaceae	Apocynaceae	Gallery forest, Cerradão, cerrado *sensu stricto*, Campo rupestre	Tree, shrub	(Gouvêa, 2021; Saraiva et al., 2020)
Apuleia[1]	Fabaceae (Caesalpinoideae)	Cerrado	Tree	(SpeciesLink, 2023)[2]
Arecaceae	Arecaceae	Gallery forest, Cerradão, cerrado *sensu stricto*	Tree	(Saraiva et al., 2020)
Aristolochia[1]	Aristolochiaceae	Cerrado	Shrub or vine	(SpeciesLink, 2023)[2]
Asteraceae - liguliflorae	Asteraceae	Gallery forest, Cerradão, Cerrado *sensu stricto*	Subshrub, herb	(Gouvêa, 2021; Saraiva et al., 2020)
Asteraceae - tubuliflorae	Asteraceae	Gallery forest, Cerradão, Cerrado *sensu stricto*	Subshrub, herb	(Gouvêa, 2021; Saraiva et al., 2020)
Astronium	Anacardiaceae	Cerradão, cerrado *sensu stricto*	Tree	(Medeiros et al., 2008; Saraiva et al., 2020)
Ayenia	Malvaceae	Cerrado *sensu stricto*	Subshrub	(Saraiva et al., 2020)
Banisteriopsis[1]	Malpighiaceae	Cerrado	Vine	(SpeciesLink, 2023)[2]
Begonia[1]	Begoniaceae	Amazon Rainforest, Caatinga, Central Brazilian Savanna, Atlantic Rainforest, Pampa	Herb, subshrub, vine	(REFLORA, 2023)[2]
Bignoniaceae	Bignoniaceae	Cerrado *sensu stricto*	Tree	(Saraiva et al., 2020)
Borreria	Rubiaceae	Cerradão	Herb	(Saraiva et al., 2020)
Brassicaceae[1]	Brassicaceae	Amazon Rainforest, Caatinga, Central Brazilian Savanna, Atlantic Rainforest, Pampa, Pantanal	Herb, subshrub	(REFLORA, 2023)[2]
Burseraceae	Burseraceae	Gallery forest, cerrado *sensu stricto*	Tree	(Gouvêa, 2021; Saraiva et al., 2020)
Byrsonima	Malpighiaceae	Gallery forest, Cerradão, cerrado *sensu stricto*	Tree, shrub	(Gouvêa, 2021; Medeiros et al., 2008; Saraiva et al., 2020)
Callisthene	Vochysiaceae	Cerrado *sensu stricto*	Tree	(Medeiros et al., 2008)
Caryocar	Caryocaraceae	Cerradão, cerrado *sensu stricto*	Tree	(Medeiros et al., 2008; Saraiva et al., 2020)

Casearia	Salicaceae	Gallery forest, Cerrado *sensu stricto,* Campo rupestre	Tree, shrub	(Gouvêa, 2021; Saraiva et al., 2020)
Cavanillesia[1]	Bombacaceae	Amazon Rainforest, Caatinga, Central Brazilian Savanna, Atlantic Rainforest	Tree	(REFLORA, 2023)[2]
Cecropia	Urticaceae	Cerrado *sensu stricto*	Tree	(Medeiros et al., 2008)
Cedrela	Meliaceae	Cerradão	Tree	(Saraiva et al., 2020)
Celtis[1]	Cannabaceae	Amazon Rainforest, Caatinga, Central Brazilian Savanna, Atlantic Rainforest, Pampa, Pantanal	Tree	(REFLORA, 2023)[2]
Chamaecrista	Fabaceae (Caesalpinioideae)	Cerrado *sensu stricto,* campo rupestre	Herb, subshrub	(Saraiva et al., 2020)
Chelonanthus[1]	Gentianaceae	Cerrado	Herb	(SpeciesLink, 2023)[2]
Clarisia[1]	Moraceae	Amazon rainforest, Atlantic rainforest	Herb	(REFLORA, 2023)[2]
Copaifera	Fabaceae (Caesalpinioideae)	Gallery forest	Tree	(Gouvêa, 2021; Saraiva et al., 2020)
Croton	Euphorbiaceae	Cerrado *sensu stricto*	Herb, subshrub	(Saraiva et al., 2020)
Cuphea	Lythraceae	Campo rupestre	Herb	(Saraiva et al., 2020)
Curatella	Dilleniaceae	Gallery forest, Cerradão, Cerrado *sensu stricto*	Tree	(Gouvêa, 2021; Medeiros et al., 2008; Saraiva et al., 2020)
Cyperaceae	Cyperaceae	Gallery forest, Cerradão, Cerrado *sensu stricto*, campo rupestre	Herb	(Saraiva et al., 2020)
Dalbergia[1]	Fabaceae (Faboideae)	Cerrado	Tree	(SpeciesLink, 2023)[2]
Davilla	Dilleniaceae	Gallery forest, Cerradão, Cerrado *sensu stricto*	Vine	(Saraiva et al., 2020)
Diospyros[1]	Ebenaceae	Cerrado	Tree	(SpeciesLink, 2023)[2]
Doliocarpus[1]	Dilleniaceae	Cerrado	Tree	(SpeciesLink, 2023)[2]
Dulacia	Olacaceae	Campo rupestre	Shrub	(Saraiva et al., 2020)
Dimorphandra	Fabaceae (Caesalpinoideae)	Cerrado *sensu stricto*, campo rupestre	Tree	(Medeiros et al., 2008; Saraiva et al., 2020)
Eriotheca	Malvaceae	Gallery forest	Tree	(Saraiva et al., 2020)
Erythroxylum[1]	Erythroxylaceae	Cerrado	Shrub	(SpeciesLink, 2023)[2]
Euphorbiaceae	Euphorbiaceae	Gallery forest, Cerradão, Cerrado sensu stricto	Tree, subshrub, herb	(Gouvêa, 2021; Saraiva et al., 2020)
Evolvulus	Convolvulaceae	Cerrado *sensu stricto*	Herb	(Saraiva et al., 2020)
Fabaceae[1]	Fabaceae	Amazon rainforest, Caatinga, Cerrado, Atlantic rainforest, Pampa, Pantanal	Tree, subshrub	(REFLORA, 2023)[2]
Flacourtia[1]	Salicaceae	Amazon Rainforest	Tree	(REFLORA, 2023)[2]

Fridericia[1]	Bignoniaceae	Cerrado	Vine	(REFLORA, 2023)[2]
Geonoma[1]	Arecaceae	Cerrado	Tree	(SpeciesLink, 2023)[2]
Gomphrena	Amaranthaceae	Cerradão, Cerrado *sensu stricto*	Herb, subshrub	(Saraiva et al., 2020)
Guazuma[1]	Malvaceae	Cerrado	Tree	(SpeciesLink, 2023)[2]
Helicteres	Malvaceae	Gallery forest, Cerradão, campo rupestre	Tree	(Gouvêa, 2021; Saraiva et al., 2020)
Heliotropium[1]	Boraginaceae	Amazon Rainforest, Caatinga, Central Brazilian Savanna, Atlantic Rainforest, Pampa, Pantanal	Herb, vine, liana	(REFLORA, 2023)[2]
Humiria	Humiriaceae	Gallery forest	Tree	(Saraiva et al., 2020)
Hyptis	Lamiaceae	Cerrado *sensu stricto*	Subshrub	(Saraiva et al., 2020)
Ilex	Aquifoliaceae	Gallery forest, Cerrado *sensu stricto*	Tree	(Saraiva et al., 2020)
Iochroma[1]	Solanaceae	Atlantic Rainforest	Tree	(REFLORA, 2023)[2]
Lindernia[1]	Linderniaceae	Cerrado	Herb	(SpeciesLink, 2023)[2]
Lithraea[1]	Anacardiaceae	Cerrado, Atlantic Rainforest, Pampa, Pantanal	Tree	(REFLORA, 2023)[2]
Lueheopsis[1]	Malvaceae	Amazon Rainforest, Central Brazilian Savanna	Tree	(REFLORA, 2023)[2]
Mabea	Euphorbiaceae	Cerradão	Shrub	(Saraiva et al., 2020)
Malvaceae	Malvaceae	Gallery forest, Cerradão, cerrado *sensu stricto*	Tree, shrub, herb	(Gouvêa, 2021; Saraiva et al., 2020)
Manilkara[1]	Sapotaceae	Cerrado	Tree	(REFLORA, 2023)[2]
Maprounea	Euphorbiaceae	Gallery forest	Shrub	(Saraiva et al., 2020)
Mauritia flexuosa	Arecaceae	Palm swamp	Tree	(Saraiva et al., 2020)
Mauritiella[1]	Arecaceae	Cerrado	Tree	(SpeciesLink, 2023)[2]
Melastomataceae	Melastomataceae	Gallery forest, Cerradão, cerrado *sensu stricto,* campo rupestre	Tree, shrub	(Gouvêa, 2021; Medeiros et al., 2008; Saraiva et al., 2020)
Melicoccus[1]	Sapindaceae	Amazon Rainforest, Cerrado, Atlantic Rainforest, Pantanal	Tree	(REFLORA, 2023)[2]
Microstachys[1]	Euphorbiaceae	Cerrado	Herb	(SpeciesLink, 2023)[2]
Mimosa	Fabaceae (Mimosoideae)	Cerradão, Cerrado *sensu stricto*	Herb	(Saraiva et al., 2020)
Myroxylon[1]	Fabaceae (Papilionoideae)	Cerrado, Atlantic Rainforest	Tree	(REFLORA, 2023)[2]
Myrtaceae	Myrtaceae	Gallery forest, Cerradão, cerrado *sensu stricto*	Tree, shrub	(Gouvêa, 2021; Medeiros et al., 2008; Saraiva et al., 2020)
Ouratea	Ochnaceae	Gallery forest, cerrado *sensu stricto*	Tree, shrub	(Medeiros et al., 2008; Saraiva et al., 2020)
Perebea[1]	Moraceae	Amazon Rainforest, Cerrado	Tree	(REFLORA, 2023)[2]
Piper[1]	Piperaceae	Cerrado	Tree	(SpeciesLink, 2023)[2]

Piptadenia[1]	Fabaceae (Mimosoideae)	Cerradão	Tree	(SpeciesLink, 2023)[2]
Platymiscium	Fabaceae (Papilionoideae)	Cerrado, Amazon Rainforest, Caatinga, Atlantic Rainforest	Tree	(REFLORA, 2023)[2]
Poaceae	Poaceae	Gallery forest, Cerradão, cerrado *sensu stricto*, Campo rupestre	Herb	(Saraiva et al., 2020)
Podocarpus[1]	Podocarpaceae	Amazon rainforest, Caatinga, Cerrado, Atlantic rainforest, Pampa, Pantanal	Tree	(REFLORA, 2023)[2]
Poeppigia[1]	Fabaceae (Caesalpiniaceae)	Amazon Rainforest, Caatinga, Atlantic Rainforest	Tree, shrub	(REFLORA, 2023)[2]
Polemoniaceae[1]	Polemoniaceae	Atlantic Rainforest	Vine	(REFLORA, 2023)[2]
Polygala	Polygalaceae	Cerradão, Cerrado *sensu stricto*, Campo rupestre	Herb	(Saraiva et al., 2020)
Protium	Burseraceae	Gallery forest, cerrado *sensu stricto*	Tree	(Gouvêa, 2021; Saraiva et al., 2020)
Psidium	Myrtaceae	Cerrado *sensu stricto*	Shrub	(Saraiva et al., 2020)
Psittacanthus[1]	Loranthaceae	Cerrado	Herb	(REFLORA, 2023)[2]
Pterogyne[1]	Fabaceae (Caesalpinioideae)	Caatinga, Cerrado, Atlantic Rainforest	Tree	(REFLORA, 2023)[2]
Qualea	Vochysiaceae	Gallery forest, Cerradão, Cerrado *sensu stricto*	Tree	(Gouvêa, 2021; Saraiva et al., 2020)
Sauvagesia[1]	Ochnaceae	Campo rupestre	Herb	(SpeciesLink, 2023)[2]
Schefflera	Araliaceae	Cerrado *sensu stricto*	Shrub	(Saraiva et al., 2020)
Schinus[1]	Anacardiaceae	Caatinga, Cerrado, Atlantic Rainforest, Pampa	Tree	(REFLORA, 2023)[2]
Scoparia[1]	Plantaginaceae	Campo rupestre	Herb, subshrub	(REFLORA, 2023)[2]
Sebastiania[1]	Euphorbiaceae	Campo rupestre	Herb	(SpeciesLink, 2023)[2]
Senna	Fabaceae (Caesalpinioideae)	Gallery forest, Cerrado *sensu stricto*	Tree	(Saraiva et al., 2020)
Serjania	Sapindaceae	Cerrado *sensu stricto*	Vine	(Saraiva et al., 2020)
Sloanea[1]	Elaeocarpaceae	Amazon Rainforest, Cerrado, Atlantic Rainforest, Pantanal	Tree	(REFLORA, 2023)[2]
Solanum	Solanaceae	Cerrado *sensu stricto*	Shrub	(Saraiva et al., 2020)
Sommera[1]	Rubiaceae	Amazon Rainforest	Shrub	(REFLORA, 2023)[2]
Sorocea[1]	Moraceae	Amazon Rainforest, Cerrado, Atlantic Rainforest, Pampa, Pantanal	Tree, shrub	(REFLORA, 2023)[2]
Spathiphyllum[1]	Araceae	Gallery forest	Herb	(SpeciesLink, 2023)[2]
Symphonia[1]	Clusiaceae	Amazon Rainforest, Cerrado, Atlantic Rainforest	Tree	(REFLORA, 2023)[2]
Tapirira	Anacardiaceae	Gallery forest, Campo rupestre	Tree	(Saraiva et al., 2020)

Toulicia[1]	Sapindaceae	Amazon Rainforest, Caatinga, Cerrado, Atlantic Rainforest	Tree, shrub	(REFLORA, 2023)[2]
Vatairea	Fabaceae (Papilionoideae)	Gallery forest, Cerrado *sensu stricto*	Tree	(Saraiva et al., 2020)
Virola	Myristicaceae	Gallery forest	Tree	(Saraiva et al., 2020)
Vochysia	Vochysiaceae	Gallery forest, Cerradão, Cerrado *sensu stricto*	Tree	(Gouvêa, 2021; Saraiva et al., 2020)
Waltheria	Malvaceae	Gallery forest	Shrub	(Saraiva et al., 2020)
Xyris	Xyridaceae	Gallery forest	Herb	(Gouvêa, 2021)
Zeyheria	Bignoniaceae	Cerrado *sensu stricto*	Tree	(Saraiva et al., 2020)
Zollernia[1]	Fabaceae (Papilionoideae)	Amazon Rainforest, Caatinga, Cerrado, Atlantic Rainforest	Tree, shrub	(REFLORA, 2023)[2]
Zornia[1]	Fabaceae (Faboideae)	Campo rupestre	Herb	(SpeciesLink, 2023)[2]

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4. CAPÍTULO IV / CHAPITRE IV

6000 YEARS OF MONSOON DRIVEN EAST-WEST ANTIPHASING OF NORTHEASTERN BRAZIL VEGETATION

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6000 years of monsoon driven east-west antiphasing of northeastern Brazil vegetation

Sergio Augusto Santos Xavier[a,b*], Francisca Soares de Araújo[b], Ilana Wainer[c], Marie Pierre Ledru[a]

[a]ISEM, University of Montpellier, CNRS, EPHE, IRD, Place Eugène Bataillon, 34095 Montpellier, France
[b]Graduate Course of Ecology and Natural Resources, Department of Biology, Campus of Pici, Federal University of Ceará, Fortaleza - 60440-900, CE, Brazil
[c]Oceanographic Institute, University of São Paulo, São Paulo, Brazil

*Corresponding author
E-mail: sergio.s.xavier@hotmail.com

Abstract

The Northeastern Brazil (NEB) is a vast region with irregular rainfall distribution and various vegetation types, as the xerophilous Caatinga on the east, Cerrado and Amazon rainforests on the west. Thus, palaeoecological archives from NEB can provide unique information about the landscapes changes (vegetation, fires, human presence), reconstruct the effects of past precipitation variability. We present a climate reconstruction for the last 6000 years in NEB, based on eight pollen records and three charcoal records from all major vegetation types in the region. Through this multiproxy approach, our climate reconstruction on regional scale showed four paleoenvironmental phases for the last 6000 years. Oscillations in the east-west humidity transect across western and eastern NEB caused alternated changes in the Cerrado and Amazon forest during dry and wet periods, reflecting the weakening/strengthening of the South America monsoon between 6.0-4.2 ka BP. After 4.2 ka BP, an inversion of this east-west dipole caused the expansion of Caatinga dry forest on the eastern NEB, Cerrado and Amazon rainforests on the western/southwestern NEB, reflecting the strengthened monsoon convection over Amazon and Central Brazil. Natural fires occurred mostly on the eastern

NEB during the mid-late Holocene. Anthropogenic activities caused fire increase on the region under dry and wet conditions after ~3.0 ka BP. Despite the increasing number of studies in the region, more high-resolution Holocene records are necessary to improve this regional framework, especially on southwest and eastern NEB. This will strength our knowledge on the extension and amplitude of South America monsoon over NEB.

Keywords: late Holocene, proxy data, pollen, charcoal, northeast Brazil vegetation, 4.2 ka event, compilation

Introduction

The reconstruction of past large-scale environment systems is a major challenge because such studies require long dataset of records to achieve reliable models. Although palaeoecological studies across Northeastern Brazil (NEB) are scarce in comparison to Central and Southeastern Brazil, they provide an opportunity to investigate vegetation changes and climatic patterns in the region. Today, the precipitation is seasonal, mainly modulated by the Intertropical Convergence Zone (ITCZ) (Marengo et al., 2017), an equatorial band of convection whose interannual shifts are controlled by changes in trade winds, annual insolation cycle and by the thermal variability of the Atlantic Ocean surface (Yan, 2005). Between February-May, with warmer (colder) South Atlantic Ocean and colder (warmer) North Atlantic Ocean, the ITCZ migrates southward (northward), leading above (below) average precipitation over NEB (Marengo et al., 2017). The ITCZ moisture influx contributes to the development of the South American Monsoon System (SAMS) and its mature phase between December-February in the region (Vera et al., 2006). The SAMS boundary belt may oscillate between 10º-15º S reaching the southwestern NEB depending the influence of Atlantic Ocean thermal gradients (Nascimento, 2014). In March-May, the SAMS precipitation weakens as migrates Northwest equator, marking the start of the dry season in southwestern NEB (VERA et al., 2006).

During the Last Glacial Maximum (~21-16 kyr BP) speleothem records (Cruz et al., 2009) and sedimentary records (Sifeddine et al., 2003) show predominantly dry conditions with short humid phases in NEB. During the Heinrich event 1 (~17-15 kry BP), an abrupt change to wet conditions were caused by reduced overturning circulation and cooler SST in North Atlantic Ocean, resulting on the southward shift of the ITCZ (Jaeschke et al., 2007; Wang et al., 2007a). A dry event recorded between ~15 and 13 kyr BP related to warmer SST in the Northern Hemisphere (Jaeschke et al., 2007) was observed in eastern and southwestern NEB (Wang et al., 2007b). After ~13 kyr BP, the precipitation variability over eastern NEB was in phase with southern summer insolation. Between 10.0 and 5.0 ka BP, a predominantly wet period coincides with minimum insolation in the region (Cruz et al., 2009; Utida et al., 2020), while oscillations in the monsoon boundary belt caused wet and dry events in the west/southwest (Sifeddine et al., 2001). An abrupt decrease in precipitation around 4.2 ka BP indicate dry conditions over eastern NEB due to increased summer insolation and higher variability of the ITCZ (Utida et al., 2020), opposing to the wet climate observed in the western NEB-Amazon boundary (Sifeddine et al., 2001).

Past changes in vegetation have been related to variations in rainfall regimens thorough the Holocene. However, there are no syntheses of palaeoecological studies specifically in the entire NEB regarding the vegetation patterns and responses to long-term climate changes, so the regional dynamics have yet to be completely understood. Given this general context, we hypothesize that a southward ITCZ position between 6.0 and 4.2 ka BP caused longer rainy season, resulted in the expansion and dominance of Cerrado and Amazon arboreal cover during the mid-late Holocene across the region. During the late Holocene, an inversion of the east-west humidity transect led to an abrupt decrease in moisture around 4.2

ka BP. The second hypothesis is this dryness was responsible for the decrease of arboreal cover from east to west. Considering the duration of rainy season and annual precipitation in western NEB is higher than the east because of the monsoon convection, we infer the 4.2 ka BP dry event only affected the vegetation in the east, not reaching the west. This investigation is of great concern, given the region's vulnerability to climate changes and drought events, these have been increasing in frequency and intensity over the last 30 years (Marengo et al., 2017). Furthermore, climatic models project an increase in temperatures of 4ºC will impact around 54% of the region by the end of the century, with great adverse effects on the natural ecosystems, water supply and human population (Marengo et al., 2020).

Here, we will present the available pollen and charcoal for NEB, discussing the palaeoecological records within the climatic and anthropic context for the last 6000 years. Since there is no orbital influence for such a short term, the centennial to millennial-scales events allows us to discuss the ITCZ influence and monsoon strength over NEB. We built a framework based on the past climate changes across the region, to identify the effects of rainfall variability on the vegetation and human influence. Records were discussed according to their geographical settings, an evaluation was undertaken for certain areas prone to particular climate signals, for example, Serra do Maranguape (Montade et al., 2014), so local environmental conditions were carefully considered.

Study area

Climate and precipitation

The Northeast region (12°58'S 38°31'W) has a tropical and hot semiarid climate. Both precipitation and temperature exhibit significant variability on interannual scale across the region. In northern NEB, peak of the rainy season occurs during February-May (4-5 months), induced by the ITCZ (Marengo et al., 2017). In western/southwestern NEB, rainy season occurs during October-March (5-6 months), modulated by the amazonian moisture flux from the SAMS (Fig. IV.1) (Nascimento, 2014). The mean annual precipitation ranges between 400 and 1800 mm (Fig. 1A) (INMET, 2023; Silva and Kousky, 2012). However, between February-May, most of the eastern and central region receive only 300-800 mm of annual precipitation (Marengo et al., 2020). Conversely, annual precipitation exceeding 2000 mm has been recorded in the northwest, during the rainy season from January to July (7 months) (INMET, 2023). The mean annual temperature varies between 23º and 28ºC (Fig. IV.1B), with a mean minimum that never falls below 20ºC and mean maximum do not exceeds 32ºC (INMET, 2023). The seasonal displacement of the ITCZ combined with the monsoon convection produces an east-west climatic gradient of mean temperature and of the length of the rainy season (Fig. IV.1C). The variability in annual precipitation is influenced by sea surface temperature anomalies (SST) in the Atlantic and Pacific Oceans (Marengo et al., 2017; Rodrigues et al., 2011). The region is subject to recurrent drought episodes, that can be intensified by the occurrence of El Niño in the tropical Pacific Ocean, warmer tropical North Atlantic Ocean or a combination of both anomalies (Marengo et al., 2020, 2017).

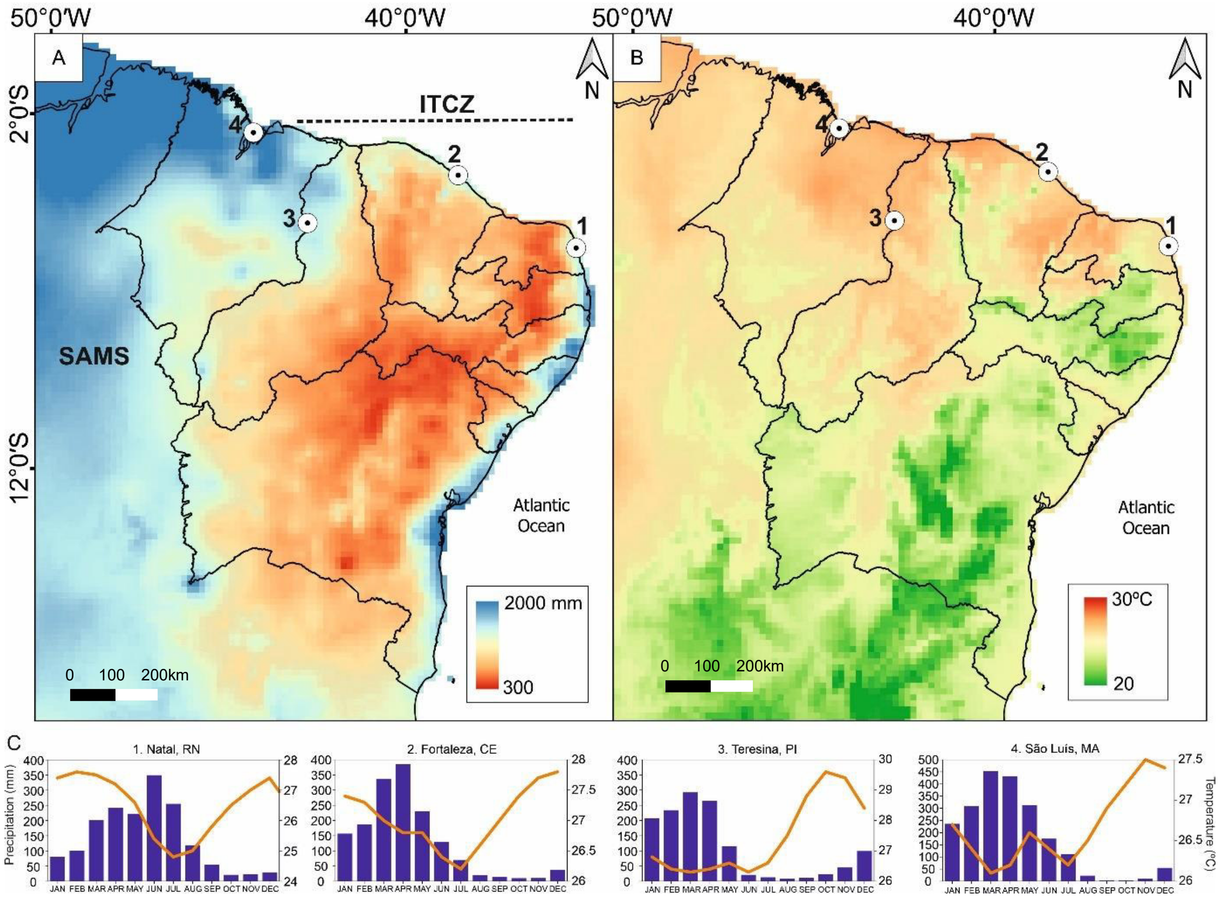


Fig IV.1. map of Northeastern Brazil showing a) mean annual precipitation and b) annual mean temperature (source: Fick and Hijmans, 2017). The ITCZ and SAMS convection during the austral summer, from December to February). c) from left to right, ombrothermic diagrams of 1. Natal (Rio Grande do Norte), 2. Fortaleza (Ceará), 3. Teresina (Piauí) and 4. São Luís (Maranhão), showing the mean monthly temperature (orange line) and mean precipitation (blue bars, 1991-2020) (source: INMET, 2023).

Vegetation

The Northeast has four biomes: the Amazon Forest located on the northwest, the Atlantic Forest along the east coast, the Caatinga in the eastern and central region, and the Cerrado in the western/southwestern (Fig. IV.2). The precipitation variability in the region has a strong influence on the spatial distribution of each phytogeographic domain. For instance, the Amazon rainforest in the northwestern lowlands, rainy season lasts from January to July (7 months), annual temperature ranges from 25° and 27ºC and mean annual precipitation is higher than 1800 mm (INMET, 2023). The rainfall is modulated by the ITCZ between

January-May, and by the eastern amazonian flux from May to July (Nascimento, 2014). The 7-months long rainy season with constant humidity enables the establishment of the evergreen forest. Due to the high moisture content, natural fire events are rare. Thus, the Amazon rainforest is classified as fire-sensitive biome (Hardesty et al., 2005).

The Caatinga is a dry forest characterized by sparse deciduous thorny vegetation, with small trees and shrubs. Adapted to a hot semiarid climate with a variable rainy season from January to May (3-5 months) (Nimer, 1989), mean annual temperature is 28ºC and mean annual precipitation varies from 400 to 800 mm (INMET, 2023). Peak of the rainy season corresponds to the ITCZ southern position between February-May (Marengo et al., 2017). The Caatinga tolerates interannual precipitation variability and recurrent drought events (Velloso et al., 2002). The 10 most common genera are *Croton* (Euphorbiaceae), *Mimosa* (Fabaceae), *Ipomoea* (Convolvulaceae), *Chamaecrista* (Fabaceae), *Erythroxylum* (Erythroxylaceae), *Senna* (Fabaceae), *Cyperus* (Cyperaceae), *Eugenia* (Myrtaceae), *Sida* (Malvaceae) and *Evolvulus* (Convolvulaceae) (Moro et al., 2014). Natural fires are rare because the low frequency of lightning and the sparse vegetation hindering a continuous burn (Pivello et al., 2021), what classifies the Caatinga as fire-independent biome (Hardesty et al., 2005).

The Cerrado includes dry and moist forests, woody savannas, palm swamps and grasslands. Climate is tropical seasonal, with rainy season from October to March (5-6 months), annual temperature ranges from 22º to 27ºC and mean annual precipitation varies between 1000 and 1800 mm (Silva et al., 2008). Its location between the dry Caatinga and the Amazon moisture flux (Castro et al., 1998), and the latitudinal range 2º to 15ºS entails significant variability on the onset and duration of rainy season and mean temperatures (Castro and Martins, 1999). In the north (5-2ºS), rainy season corresponds to the ITCZ southern position between February-May (4-5 months), while in the southwest (15-5ºS) its modulated by the mature phase of SAMS, from October to March (5-6 months). However, the duration of the rainy season can be shortened up to four months during years with drought episodes in some Cerrado areas of southern Maranhão and Piauí (Silva et al., 2008). In these areas, the mean minimum temperature ranges from 21° to 23ºC, while mean maximum varies between 31° and 33ºC (Silva et al., 2008). Natural fires are common during the transition from dry to rainy season, because of the recurrent frequency of lightning and the availability of continuous flammable fuel (Gomes et al., 2018). The Cerrado is a fire-dependent biome (Durigan, 2020; Hardesty et al., 2005), with a large number of species whose life cycles depends on seasonal fire regimens (Simon and Pennington, 2012).

In terms of floristic composition, the NEB Cerrado differs from the core region in Central Brazil (Vieira et al., 2022). In NEB, the 10 most common genera are *Qualea* (Vochysiaceae), *Byrsonima* (Malpighiaceae), *Anacardium* (Anacardiaceae), *Bowdichia* (Fabaceae), *Annona* (Annonaceae), *Caryocar* (Caryocaraceae), *Dimorphandra* (Fabaceae), *Hymenaea* (Fabaceae), *Stryphnodendron* (Fabaceae) and *Curatella* (Dilleniaceae) (Vieira et al., 2019). In Central Brazil, the 10 most common genera are *Paepalanthus* (Eriocaulaceae), *Mimosa* (Fabaceae), *Chamaecrista* (Fabaceae), *Myrcia* (Myrtaceae), *Hyptis* (Convolvulaceae), *Vellozia* (Velloziaceae), *Croton* (Euphorbiaceae), *Syngonanthus* (Eriocaulaceae), *Xyris* (Xyridaceae) and *Paspalum* (Poaceae) (Mendonça et al., 2008). Thus, the NEB Cerrado is classified as a peripheral province with unique species assemblage apart from those of Central Brazil (Françoso et al., 2019; Ratter et al., 2003; Vieira et al., 2019). This provincialism is attributed to the geographic dispersal, NEB climate variability and intermixing of species from both Caatinga and Amazon vegetation (Castro and Martins, 1999; Vieira et al., 2019).

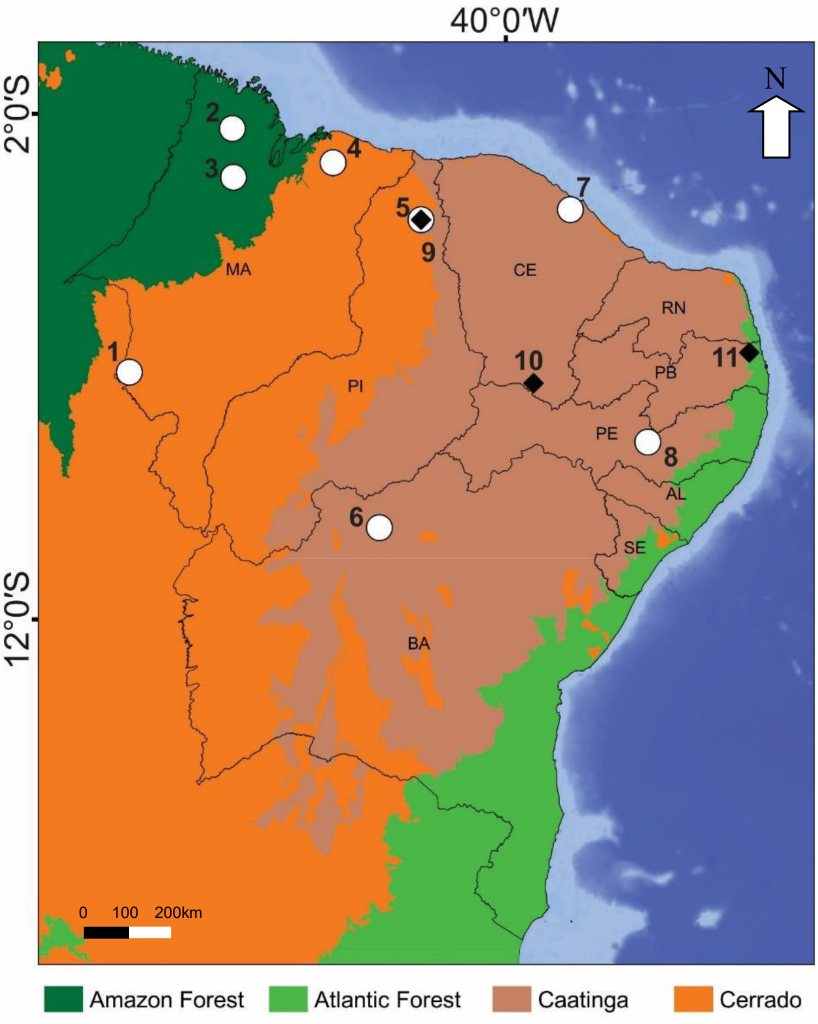


Fig IV.2. map of biomes in NEB, showing the pollen and charcoal records mentioned in the discussion. White circles represent pollen records: 1. Chapada das Mesas (Xavier et al., in review), 2. Cabeludo (Moraes et al., 2022), 3. Lake Formoso (Moraes et al., 2021), 4. Lake Caço (Ledru et al., 2006), 5. Sete Cidades (Xavier et al., 2022), 6. Icatu Valley (Oliveira et al., 1999), 7. Serra do Maranguape (Montade et al., 2014), 8. Catimbau (Moraes et al., 2020). Black diamond represents charcoal records: 9. Sete Cidades, 10. Araripe Forest, 11. Guaribas Reserve (Pessenda et al., 2010).

Methods

Eight pollen records (Table IV.1) and three charcoal records (Table IV.2) have been selected according to their age (covering the last 6000 years), sample resolution and location in the considered area. Records were assigned into two groups: western NEB and eastern NEB. On western NEB, Chapada das Mesas (Xavier et al., in review), in the South of

Maranhão State; Cabeludo (Moraes et al., 2022), Lake Formoso (Moraes et al., 2021) and Lake Caço (Ledru et al., 2006) on the northern coast of Maranhão State. On the eastern NEB, Sete Cidades (Xavier et al., 2022) in the North of Piauí State; Serra do Maranguape (Montade et al., 2014) in the North of Ceará State; the Icatu Valley (Oliveira et al., 1999) in the North of Bahia State and Catimbau (Moraes et al., 2020) in the east of Pernambuco State. Although Sete Cidades and Catimbau records do not cover the entirety of 6000 years, they were included to improve the regional framework for the late Holocene. All pollen records also include charcoal analyses, except for Serra do Maranguape. Charcoal records from Sete Cidades, Araripe Forest and Guaribas Reserve (Pessenda et al., 2010) were also included in the framework.

Four time periods for interpretation of pollen assemblages were assigned: 6.0-5.2 ka BP, 5.2-4.2 ka BP, 4.2-2.6 ka BP and 2.6-0.0 ka BP. The environmental interpretation was based on the description of pollen assemblages in each site during the four time periods defined, considering the response of the different vegetation types to climate changes that occurred during each period. Then, a vegetation gradient was built: rainforest, arboreal cerrado, open cerrado and Caatinga. For the reconstruction of fire activity, an intensity level of more fires (plus sign), constant fires (plus-minus sign) and less fires (minus sign) was based on the description and interpretation in each site for the four time periods defined. The comparison of the vegetation changes and fire activity between sites allows to draw a general pattern of climate changes on western and eastern NEB. The vegetation gradient was represented by gradient-colored bar, from rainforest to Caatinga, and colored dots on a dot distribution map. To represent and compare the intensity of climate conditions between sites with two isotopic records: Carajás (Sifeddine et al., 2001), on western NEB boundary with Amazon Forest, and Apodi (Utida et al., 2020) on the eastern NEB. A gradient-colored bar represents wet and dry climate. Drier conditions are represented by orange increase, while moister conditions are represented by blue increase. Seasonal conditions (periodicity of dry and wet events) are represented by an orange/blue dot. Human presence was compared based on pollen indicators of anthropogenic activity and interpretation of fire activity in each site, considering the archaeological data available, local history and regional context.

Additionally, to detect spatiotemporal precipitation variability over South America and Northeastern region at 6.0 ka BP, the empirical orthogonal function technique (EOF) was performed. The EOF analysis was used to find patterns or structures that explain maximum variance in a dataset. Patterns of precipitation variability (modes) were detected in a matrix time series and temporal changes were analyzed (amplitude time series) for the last 6000 years (Hannachi et al., 2007).

Site	**Core (cm)**	**Depth (cm)**	**14C dates (yr BP)**	**Environment**	**Vegetation**	**Reference**
1. Chapada das Mesas (7ºS/47ºW; 307m)	186	11	-799 ± 21	Palm swamp (western NEB)	Cerrado-Amazon ecotone	(Xavier et al., in review)
		38	105 ± 30			
		51	1360 ± 30			
		60	2410 ± 30			
		93	3025 ± 30			
		97	3130 ± 35			
		115	3140 ± 35			
		149	4205 ± 35			
		179	5030 ± 35			
2. Cabeludo (2ºS/45ºW; 4m)	450	20	955 ± 30	Lake (northwestern NEB)	Amazon rainforest with marine influence	(Moraes et al., 2022)
		57	1430 ± 30			
		125	5180 ± 40			
		158	6870 ± 40			
		200	6930 ± 40			
		450	7130 ± 40			
3. Lake Formoso (3ºS/45ºW; 3-10m)	300	28	1160 ± 30	Lake (northwestern NEB)	Amazon rainforest with marine influence	(Moraes et al., 2021)
		46	1555 ± 30			
		73	2410 ± 30			
		120	4415 ± 35			
		178	5270 ± 40			
		270	6280 ± 40			
4. Lake Caço (2ºS 43ºW)	277	18-23	3060 ± 50	Lake (northwestern NEB)	Cerrado	(Ledru et al., 2006)
		31-32	3830 ± 60			

		40-45	5090 ± 60			
		48-49	5580 ± 80			
		68-70	6010 ± 50			
		95-100	7660 ± 50			
		118-120	9040 ± 90			
		135-140	9720 ± 50			
		150-151	10,220 ± 40			
		158-160	10,170 ± 40			
		172-174	10,880 ± 50			
		178-180	11,600 ± 120			
		200-202	12,640 ± 135			
		215-218	12,930 ± 90			
		241-242	13,560 ± 185			
		259-260	15,400 ± 180			
		275-277	15,870 ± 60			
5. Sete Cidades (4ºS 41ºW; 100-290m)	100	29	-24 ± 17	Palm swamp (eastern NEB	Cerrado-Caatinga ecotone	(Xavier et al., 2022)
		44	99 ± 30			
		55	228 ± 30			
		67	511 ± 30			
		69	535 ± 30			
		77	365 ± 30			
		86	165 ± 30			
		92	719 ± 30			
6. Icatu Valley (10-11ºS	340	143.5–148.5	4240 ± 70	Peat bog	Caatinga	(Oliveira et al., 1999)

42-43ºW; 800m)		214.5–215.5	6790 ± 80	(southeastern NEB)		
		264.5–269.5	8910 ± 80			
		279.5–284.5	8920 ± 120			
		316.5–321.5	10540 ± 80			
		324.5–329.0	11040 ± 80			
7. Serra do Maranguape	150	6–7	1105 ± 30	Forest hollow	Ombrophilous montane	(Montade et al., 2014)
(3ºS 38ºW; 900m)		25–27	1600 ± 40	(northeastern NEB)	forest	
		44–46	2580 ± 35			
		64–66	2710 ± 40			
		90–92	3960 ± 40			
		97-98	3695 ± 45			
		110-112	3975 ± 35			
		128-130	4020 ± 35			
		147-149	4455 ± 35			
8. Catimbau (8ºS 37ºW;	420	160	820 ± 30	Swamp (eastern	Caatinga	(Moraes et al., 2020)
200-727m)		280	2.280 ± 30	NEB)		
		410	2.670 ± 30			

Table IV.1. Eight pollen records selected according to their age, sample resolution and location in the considered area.

Site	**Core (cm)**	**Depth (cm)**	**14C dates (yr BP)**	**Environment**	**Vegetation**	**Reference**
Sete Cidades (4ºS 41ºW; 100-290m)	400	90-100	3440 ± 60	Forest trenches	Cerrado-Caatinga ecotone	
		140-150	10,350 ± 90	(eastern NEB)		
Araripe Forest 7°11′42″-7°28′38″S and 39°13′	400	60-70	2900 ± 60	Forest trenches	Cerrado-Caatinga ecotone	
28″-39°36′33″W, 700-900m)		170-180	5780 ± 80	(eastern NEB)		(Pessenda et al.,
		270-280	11,280 ± 90			2010)
		330-340	8950 ± 90			
Guaribas Reserve (6°40′–6°45′S, 35°07′–	400	110-11	4660 ± 60	Forest trenches	Semideciduous forest	
35°12′W, 130-200m)				(eastern NEB)		

Table IV.2. Three charcoal records selected according to their age, sample resolution and location in the considered area.

Results

6.0 - 5.2 ka BP

In western NEB, pollen sites 1 and 2 showed predominance of herbaceous taxa represented by Poaceae, Asteraceae, and *Cuphea* in spite of arboreal taxa, interpreted as a dry period with short rainfall events. In site 3, dominant herbaceous taxa indicated drier conditions while pollen site 4 showed a mix of herbs and trees, plotted with a seasonal climate. Isotopic site 9 showed a seasonal climate. In eastern NEB, only pollen site 6 was recorded for this period, with predominance of herbs over trees interpreted as dry conditions with short moisture content. Isotopic site 10 showed a moist phase. No human presence was recorded during this period (Fig. IV.3).

5.2 - 4.2 ka BP

In western NEB, pollen sites 1 and 2 showed an increase in arboreal taxa represented by rainforest elements *Alchornea,* Moraceae and Arecaceae, and the cerrado tree *Byrsonima,* interpreted as a moister period with short dry events. Pollen site 3 also showed arboreal and ferns increase represented by *Acrostichum*, indicating predominant wet conditions. Pollen site 4 showed no changes in comparison to the previous period. Isotopic site 9 showed seasonal climate. In eastern NEB, pollen site 6 showed alternance of trees and herbs *Byrsonima* and *Cuphea*, with increase of *Mauritia*, indicating warm temperature and moister conditions. Pollen site 7 showed dominance of moist forest, represented by *Alchornea,* Moraceae and Arecaceae, interpreted as wet conditions. Isotopic site 10 showed a slight decrease in moisture in comparison to the previous period. No human presence was recorded during this period (Fig. IV.3).

4.2 – 2.6 ka BP

In western NEB, pollen sites 1 and 4 showed a mix of herbaceous and arboreal taxa, represented by Asteraceae, *Borreria*, *Mimosa*, Poaceae, and *Alchornea, Byrsonima*, Myrtaceae, interpreted as seasonal conditions. In pollen sites 2 and 3, an increase in rainforest taxa indicated moister conditions. Isotopic site 9 showed a wet climate. In eastern NEB, pollen sites 6 and 8 showed increase of xerophilous dry forest taxa represented by *Cuphea, Mimosa* and *Byrsonima*, while in pollen site 7 a more open forest dominated, represented by *Alchornea*, *Dalbergia, Myrsine* and *Protium,* interpreted as dry condition with increasing tempratures in three sites. Isotopic site 10 recorded a dry period. Human presence during this period was attested by increased fires (Fig. IV.3).

2.6 – 0 ka BP

In western NEB, pollen sites 1, 2, and 3 showed dominance of rainforest taxa represented by *Alchornea, Cecropia, Ilex,* Moraceae, while site 4 exhibited a full developed Cerrado represented by *Byrsonima, Cecropia* and Melastomataceae, what indicates increased moisture rates and warm temperatures. Isotopic site 9 recorded the same wet signal observed in the previous period. In eastern NEB, pollen site 5 showed herbaceous vegetation composed of *Cuphea* and Poaceae was replaced by arboreal cover composed of *Guazuma*, Myrtaceae, Melastomataceae, interpreted as a short dry period followed by increased moisture. *Mauritia* increased in sites 1, 4 and 5. Pollen site 6 showed expansion of xerophilous dry forest taxa *Cuphea* and *Byrsonima*, continued under dry conditions and warmer temperatures. In pollen site 7, an increase in trees of Moraceae and *Piper* indicated return to moist conditions. Pollen site 8 showed a mix of moisture related and xerophilous taxa represented by *Cecropia, Euphorbiaceae*, Moraceae, and Asteraceae, Poaceae, interpreted as drier conditions with short wet events. Isotopic site 10 recorded a predominant dry climate. Anthropic presence intensified in comparison to the previous period, recorded by fire activity and human pollen indicators *Zea mays*, *Phaseolus* and *Orbignya* (Fig. IV.3).

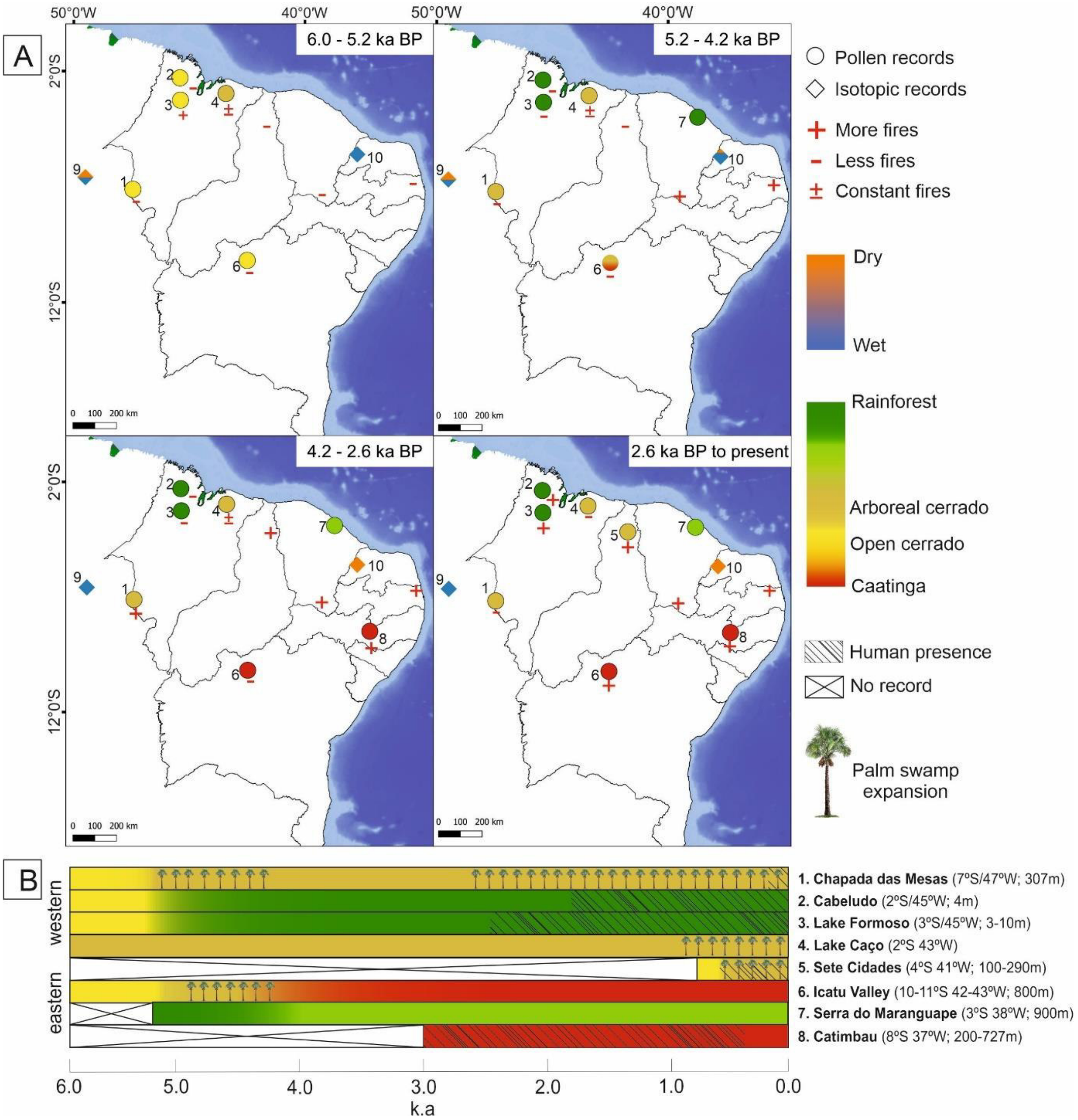


Fig IV.3. a) Northeastern Brazil vegetation reconstruction for the last 6000 years. Circles for pollen records, diamonds for isotopic records. Dark green indicates rainforest, beige indicates arboreal cerrado, yellow indicates open cerrado and red indicates Caatinga. Orange indicates drier conditions, blue indicates moister conditions and orange/blue indicate seasonal conditions. Plus sign for intense fire activity, minus sign for less fire activity and plus/minus for constant fire activity. b) summary vegetation changes based on the interpretation of the pollen records discussed. Human presence indicated by hachures and *Mauritia* expansion indicated by the palm tree.

Discussion

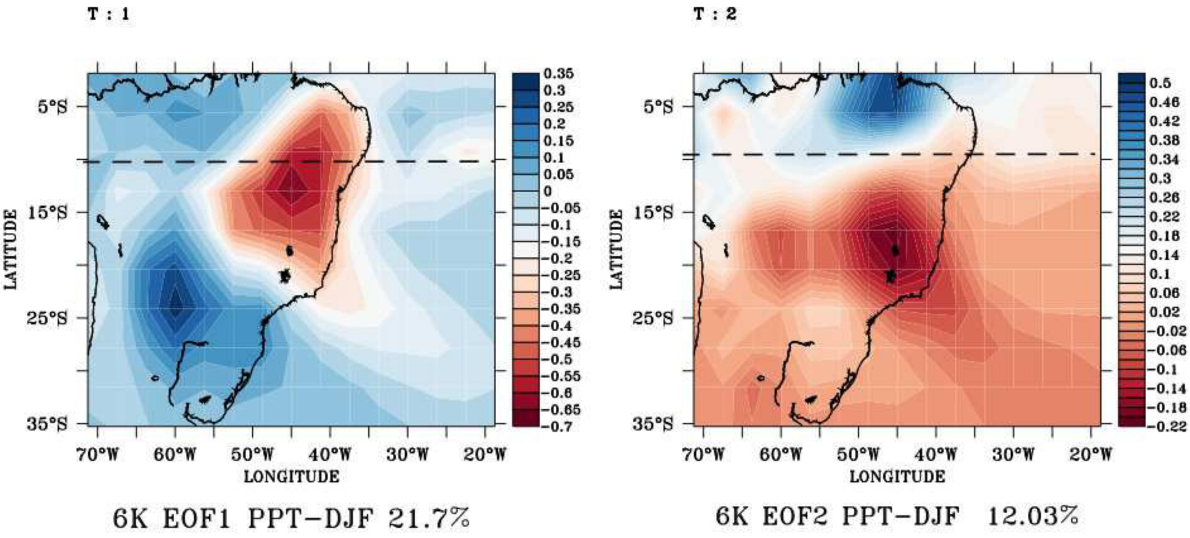
The vegetation and fire dynamics can be interpreted according to the climate factor during the mid-late Holocene. Between 6.0 and 5.2 ka BP, an open vegetation with less tree cover were dominant on the western and eastern NEB sites (Fig. IV.3A). An exception is site 4 where a woody cerrado is recorded. During this period, eastern NEB recorded higher moisture rates than today, while precipitation oscillated on western NEB. The east-west humidity transect established across the region was antiphased with the rest of South America and Central Brazil (Cruz et al., 2009; Sifeddine et al., 2001), where a weakened monsoon convection caused precipitation variability (Prado et al., 2013). Thus, the pollen records located on NEB westernmost limits shows an in-phase climate response with Central Brazil rather than with the moister conditions on eastern NEB. This east-west dipole behavior is consistent with empirical orthogonal function (EOF) for precipitation modes at 6.0 ka BP in South America and NEB (Fig. IV.4).

From 5.2 to 4.2 ka BP, the expansion of woody cerrado and arboreal rainforest taxa on the western NEB, palm swamp taxa *Mauritia flexuosa* and arboreal cover on eastern NEB characterized increase in temperatures and precipitation (Fig. IV.3A). This moister interval was a result of warmer sea surface Atlantic temperatures that caused sea level maximum (Caldas et al., 2006; Suguio et al., 2013), increased southern hemisphere summer insolation (Berger and Loutre, 1991), and southernmost position of ITCZ (Utida et al., 2020). This influenced the monsoon moisture flux over Amazon and Central Brazil, what led to strong precipitation events around 5.2 ka BP (Stríkis et al., 2011) and a strengthened SACZ convection on the southwest NEB. Higher moisture conditions led to expansion of palm swamps on the inland sites, domination of ombrophilous forest in the montane, increase of

Amazon rainforest taxa and mangroves on the western coastal region.

At ~4.2 ka BP, an abrupt decrease in precipitation on NEB was observed on pollen records (Fig. IV.3A). In the eastern NEB, this marked regional expansion of Caatinga xerophilous forest (Moraes et al., 2020; Oliveira et al., 1999), and a change in the structure of montane forests, from a dense ombrophilous forest to a semideciduous, more open forest (Montade et al., 2014). Most of the western NEB sites showed no evidence of this dry event. An exception is Chapada das Mesas in the southwest, where poor-pollen sediments were recorded from ~4.3 to 3.5 ka BP, interpreted as a result of oxidation under extreme dry conditions (Xavier et al., in review). Woody cerrado and Amazon rainforest trees expanded in the western, while arboreal cerrado gradually expanded in the southwest after an increase in moisture conditions around 3.5 ka BP. These vegetation changes are synchronous with dry conditions recorded on eastern NEB speleothems (Utida et al., 2020) and wet conditions on the western (Sifeddine et al., 2001). A strengthened monsoon activity marked the late Holocene on Central Brazil (Stríkis et al., 2011) and eastern Amazon (Sifeddine et al., 2001), what influenced the vegetation on western NEB boundary but not reached the eastern. The “4.2 ka event” is one of the most remarkable climate events of the Holocene, where models suggest that a warm Pacific SST and cold Atlantic SST produced decrease in precipitation in west and east Africa and increased precipitation on South America (Renssen, 2022). However, this was not observed in NEB. In fact, 4.2 ka BP marks the onset of aridification in the region (Utida et al., 2020), similar to west/east Africa and opposed to the wet climate for the rest of tropical South America (Cruz et al., 2009; Sifeddine et al., 2001; van Breukelen et al., 2008).

After 2.6 ka BP, pollen records showed a biomodal climate with a dry eastern and wet western NEB (Fig. IV.3A). Woody cerrado, gallery forest and palm swamp expanded on the southwest, while rainforest vegetation and palm trees dominated the northwest coast. The Caatinga dry forest dominated most of the eastern landscapes, except for the recovery of ombrophilous montane forest (Montade et al., 2014). While the monsoon convection modulate the precipitation on the southwestern NEB, (Nascimento, 2014), the ITCZ is responsible for the rainfall on the northern NEB (Marengo et al., 2017). On eastern Amazon, wet conditions has not changed after 4.2 ka BP, except for short periods of instability between 2.7 and 1.3 ka BP (Sifeddine et al., 2001). Variability of SAMS strength over the past two millennia (Novello et al., 2018; Wang et al., 2017) has caused oscillations in the moisture flux boundary belt, influenced by Atlantic thermal gradients and higher variability of the ITCZ (Novello et al., 2018).



6K EOF1 PPT-DJF 21.7%

6K EOF2 PPT-DJF 12.03%

Fig. IV.4. Empirical orthogonal function (EOF) analysis of precipitation during the austral summer (DJF) over South America and Northeastern region at 6.0 ka BP. The amplitude of EOF corresponds to one standard deviation of the corresponding principal component. The fractional variance explained by the two EOFs are labeled in percentages.

Human presence in the Northeast

The Northeast has vast archaeological records, but no interpretations have been made yet regarding the relationship between humans, climate variability and vegetation on a regional scale. Here, the demographic dynamics of the region were evaluated and compared with the paleoclimatic data. While the absence of data for the mid-late Holocene difficult interpretations, chronologies for the late Holocene allows some inferences about the human occupation. Over the mid-late Holocene, intense fires observed in Lake Formoso (Moraes et al., 2021), Icatu Valley (Oliveira et al., 1999) and Chapada das Mesas were attributed to climate changes. Despite one of the earliest archaeological evidences of human presence in western NEB dates back to ~6000 cal yr BP, in the Maranhão lowlands (Navarro, 2018), no direct correlation was made between mid-late Holocene fires and human activity in Lake Formoso (Moraes et al., 2021). Archaeological data from central Bahia points to human presence between ~6.0 and 2.0 ka BP, but no evidence of anthropic activities has been recorded on pollen records (Fig. IV.3B).

The late Holocene showed intense human activities in both western and eastern NEB (Fig. IV.3B). Around 3.0 ka BP on the eastern NEB, the occurrence of intense fires and a few pollen grains of *Phaseolus* (bean) and *Orbignya* (palm tree babaçu) in Catimbau during a dry period were related to land use practices by Amerindians (Moraes et al., 2020). Radiocarbon dating point out human presence in the area around Catimbau since at least ~4.0 ka BP. Archaeological artifacts comprises bonfires, pottery and rock paintings (Martin, 2013). After 0.45 ka BP, human occupation declined as consequence of arid conditions and conflict with Europeans. In Sete Cidades region, human presence has been recorded since the last millennium (Cavalcante, 2018) by native groups (IBDF, 1979; Medeiros, 2002). However, the region faced low demographics due to dry conditions until 0.6 ka BP (Fig. IV.3B), when the onset of a wetter climate allowed the return of native groups. Their presence was attested by the presence of a few pollen grains of *Zea mays*. Land use practices intensified after 0.45 ka BP with the arrival of Europeans in the north of Piauí state. Anthropogenic pressures continued for 400 years until the creation of Sete Cidades National Park in 1961.

In the western NEB, the first record of human activity observed in the pollen records dates back to ~2.5 ka BP in Lake Formoso (Fig. IV.3B). Presence of palm trees indicated the beginning of human settlements and intense anthropic fires after 1.3 ka BP (Moraes et al., 2021). Stilt-house settlements and pottery has been recorded over the last millennium during a wet period in Maranhão lowlands (Navarro, 2018). In Cabeludo site, anthropic fires and pottery fragments pointed out human influence after 1.8 ka BP wet period (Moraes et al., 2022). In Chapada das Mesas, intense fires were attributed to land use practices over the last 300 years during the Brazilian colonial period.

Conclusion

Pollen studies from Northeastern Brazil has captured changes in vegetation over the last 6000 years that track back the east-west precipitation transect during the mid-late Holocene. Previous studies have documented shifts in monsoon and ITCZ in the past in response to thermal changes in the tropical Atlantic Ocean at millennial timescales. The first hypothesis set out in the beginning of this study is confirmed, as during the mid-late Holocene the distribution of Amazon Forest and Cerrado in NEB was wider than today, spreading towards the east. However, the vegetation showed phases of retraction and expansion from east to west due to the variability in the SAMS convection over Amazon and Central Brazil and oscillations in the ITCZ over eastern NEB. After 4.2 ka BP, an inversion of the east-west precipitation transect caused dryness over eastern NEB and increased moisture flux over western NEB, reflecting the strengthened monsoon convection on Amazon and Central Brazil. This confirmed the second hypothesis, as the climate dipole caused expansion of the Caatinga on the east, while Cerrado and Amazon rainforest taxa retracted to the west/northwest. However, the amplitude of the 4.2 dry event was wider than previously thought, since it affected the vegetation in the southwestern NEB limits under the monsoon influence and longer rainy season. Natural fires occurred during the mid-late Holocene but were absent over most of the region until 3.0 ka BP, when intensified anthropic activities were attributed to increased burnings during both wet and dry conditions on the west and east, respectively. The currently available database do provide a solid framework for both short and long-term spatiotemporal scales. However, focusing on further studies regarding transitional climatic areas would reinforce and refine the database, increasing our knowledge on the amplitude of the monsoon oscillations and ITCZ precipitation over NEB during the Holocene.

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5. DISCUSSION ET CONCLUSION

Ce travail a permis de progresser dans la compréhension des dynamiques de végétation à long terme du NEB au cours des 6000 dernières années. Il combine des analyses multi proxy à haute résolution (pollen, charbon) à partir de carottes sédimentaires afin de retracer les changements de la végétation du Cerrado et le régime des incendies dans des conditions de climat et de pression anthropique différentes de celles d'aujourd'hui.

5.1. Relation climat-végétation dans le Nordeste brésilien

La distribution actuelle de la végétation du NEB est le résultat des changements des précipitations à long terme à travers la région depuis l'Holocène moyen. Les réponses de la végétation reflètent des variations centennales à millénaires dans l'intensité et la position de la ZCIT en suivant un gradient est – ouest. Les études de dynamique de végétation montrent que la distribution de la forêt amazonienne et du Cerrado était plus étendue qu'aujourd'hui en s'étirant de l'ouest vers l'est et le nord-est (LEDRU et al., 2006; MONTADE et al., 2014; MORAES et al., 2021, 2022; OLIVEIRA et al., 1999) lorsque les conditions climatiques étaient plus humides. (Utida et al., 2020). Pendant l'Holocène récent, un changement environnemental vers des conditions climatique plus sèches a entrainé l'expansion de la Caatinga (Moraes et al., 2020; Oliveira et al., 1999) alors que la forêt amazonienne et le Cerrado se sont rétractés vers le nord-ouest où les conditions climatiques étaient plus humides. Les résultats de cette thèse ont montré que la distribution du Cerrado du NEB et la végétation du NEB étaient fortement influencée pas seulement par la ZCIT mais aussi par l'intensité et l'amplitude de la mousson à des échelles de temps millénaires à centenaires-décennales. La région est divisée en deux zones avec des régimes climatiques différents : l'est du NEB avec des précipitations modulées par le déplacement saisonnier interannuel de la ZCIT recouvert de Caatinga et l'ouest du NEB influencé par le régime de la mousson recouvert de Cerrado. Pendant l'Holocène récent, la pluie liée à la ZCIT était réduite et l'augmentation de l'insolation ont conduit à un des conditions climatiques sèches avec une saison des pluies plus courte à l'est du NEB (Cruz et al., 2009; Utida et al., 2020). Les événements secs et la diminution des précipitations sont largement attribués aux perturbations environnementales observées dans les forêts d'altitude et la Caatinga à l'est du NEB (Montade et al., 2014; Oliveira et al., 1999). Nos résultats montrent que ces événements secs ont aussi affecté le Cerrado au sud-ouest du NEB avec. Toutefois un effet plus modéré du fait de la saison des pluies plus longue et des précipitations liées à la mousson. Nous concluons que la végétation du NEB, y compris les régions du Cerrado, sont des écosystèmes très sensibles, vulnérables à la diminution des précipitations, aux sécheresses et à l'augmentation des températures.

5.2. Impacts anthropiques dans le NEB

L'occupation humaine du NEB au cours de l'Holocène moyen et récent est très peu documentée et le faible nombre de datations radiocarbone masque les interprétations locales et régionales. Toutefois, la dynamique démographique du NEB peut être caractérisée par deux groupes : les chasseur-cueilleurs qui fabriquaient des outils lithiques au début de l'Holocène ancient (Bueno and Isnardis, 2018; Martin, 2013; Melo, 2007) et les cultivateurs-céramistes à la fin de l'Holocène (Martin, 2013; Souza et al., 2020). Les enregistrements les plus anciens de cultivateur-céramistes remontent à 3000 ans AP, le long des rivières au sud du NEB. C'est après 2000 ans AP que de telles pratiques se sont répandues dans la région. Des groupes attribués aux traditions Jê et Tupiguarani ont adapté leurs techniques aux différents environnements, la Caatinga à l'est et le Cerrado à l'ouest (Cavalcante, 2015; Martin, 2013; Negreiros Oliveira, 2004). Les dynamiques démographiques et les pratiques ont changé drastiquement avec l'arrivée des Européens vers 1500 CE. Les résultats de cette thèse ont montré que les activités anthropiques étaient plus intenses pendant l'holocène récent, avec une augmentation des feux d'origine anthropique après 3000 ans AP. Toutefois, l'intensité et la fréquence n'étaient pas synchrones en fonction de différentes périodes d'occupation des terres et des adaptations des pratiques culturelles aux différents types de paysage. Pendant le dernier millénaire, des groupes indigènes ont utilisé le feu comme outil agricole pour des petits défrichements avant l'arrivée des Européens. Après 1500 CE, les feux ont augmenté en fréquence et en intensité à la fois à l'ouest et à l'est du NEB, démontrant ainsi les changements de pratiques d'utilisation des terres, la déforestation pour l'élevage et les conflits avec les groupes indigènes.

5.3. Histoire des incendies dans le Cerrado du nord-est

Le comportement au feu n'est pas homogène à travers l'ensemble du Cerrado. Il montre des variations spatiales (du niveau local au biome), temporelles (du court- au long-terme) et sur les types de forçage (naturel, anthropique) à l'échelle prédictive d'un à plusieurs facteurs (Gomes et al., 2018). Au cours de l'Holocène moyen et récent, le régime régional des incendies était un résultat de la dynamique naturelle entre la végétation locale et les conditions climatiques. Les incendies se produisaient des zones avec du cerrado boisé sous un climat de type saisonnier lorsque la végétation plus dense constituait une source de combustion pour la propagation du feu (Ledru et al., 2006; Moraes et al., 2021; Pessenda et al., 2010). En conséquent, la fréquence du feu était basse et asynchrone entre l'est et l'ouest pendant les périodes d'oscillation de la ZCIT et de la mousson. Après l'Holocène récent, la fréquence des incendies a progressivement augmenté à travers la région, synchrone avec une plus forte activité humaine. Ceci est observé à l'est du NEB lorsque le climat était sec (Pessenda et al., 2010). Inversement, les incendies ont diminué dans le Cerrado à l'ouest du NEB où le climat était plus humide et où la présence humaine n'est pas enregistrée (Ledru et al., 2006). Ainsi, nous concluons que pendant l'Holocène récent, les régimes régionaux des feux étaient fortement influencés par la présence humaine qui a contribué à façonner le paysage actuel.

6. PERSPECTIVES

L'étude des changements de précipitations dans le NEB a une importance socio-environnementale significative, si l'on considère l'impact du réchauffement climatique en cours sur les ressources en eau, sur la population et sur la végétation. L'étude paléoécologique (pollen et charbon déposés dans les sédiments) dans le Cerrado du NEB s'est avérée efficace dans la reconstruction des oscillations climatiques et des impacts anthropiques à des échelles millénaire, centennale et décennale, en montrant que ces effets sont plus prononcés dans les zones de transition.

Au cours des deux dernières décennies, la région a souffert des événements climatiques extrêmes caractérisés par l'augmentation de la fréquence des sécheresses, la forte variabilité des précipitations et des températures (Marengo et al., 2017). Les prédictions indiquent une diminution des précipitations sur 54% du territoire et une augmentation des températures de 4°C à la fin du siècle (Marengo et al., 2020). Si l'on considère que les précipitations et les températures sont les principaux facteurs de changement de la végétation dans le NEB (Marengo et al., 2020) le stress hydrique et le réchauffement du climat plus chaud pourront favoriser des épisodes secs extrêmes plus nombreux et la diminution de la durée de la saison sèche. De tels changements peuvent conduire à une réduction drastique de la couverture végétale. Compte tenu de la sensibilité du Cerrado du NEB aux changements de précipitation et de température, une saison des pluies plus courte impliquera une couverture arborée moins importante et une perte de la biodiversité, aggravé par les activités de déforestation. Les extrêmes de variabilité climatique du NEB soulèvent aussi des discussions sur le sujet socio-économico-environnemental. La sécheresse de 2012-2017 (Marengo et al., 2017) a conduit les gouvernements, fédéral et d'état, à mettre en œuvre des politiques publiques afin de minimiser la vulnérabilité de la population subsistant de petite agriculture et d'élevage, la plus affectée par les changements climatiques de la région (Marengo et al., 2020). Le contrôle des sécheresse and les prévisions climatiques saisonnières créés par le centre Nationale de Gestion et d'Alerte des Risques Naturels (CEMADEN) (Alvalá et al., 2019) apporte un moyen d'identifier les impacts et les risques da la variabilité climatique, en favorisant des plans de gestions raisonnés pour la conservation des ressources naturelles et la santé.

A ce sujet, la création d'aires entièrement protégées a pour but de sauvegarder la biodiversité du Cerrado du NEB. Les parcs nationaux « Sete Cidades » et « Chapada das Mesas » sont des aires protégées qui combinent généralement la protection de l'écosystème avec la visite du public, et où des lieux situés à l'intérieur des parcs font l'objet de délimitation à des fins culturelles, éducatives et récréatives (IBDF, 1979; ICMBio, 2019). Les deux parcs sont inclus dans le programme PREVFOGO (MMA, 2007), une opération anti feux qui comprend un accord entre les gestionnaires de parc cet les fermiers voisins sur la question du contrôle des incendies. A « Sete Cidades », le feu est toujours utilisé par les communautés locales pour renouveler les pâturages et préparer les terres pour l'agriculture de subsistance. La plupart des incendies proviennent d'incendies criminels et d'un manque de gestion par les communautés locales, et constituent une menace majeure pour les écosystèmes du Cerrado (Souza and Pereira, 2019). Dans ce cas, davantage d'investissements publiques dans l'infrastructure des ressources humaines et l'éducation environnementale pourrait contribuer à atténuer les impacts des feux d'origine anthropique sur le Cerrado. Des conflits entre les populations locales et la gestion des parcs du fait de l'existence de propriétés privées à l'intérieur des parcs ont soulevé des questions sur la protection et les objectifs récréatifs (Marques and Fernandes, 2016). De tels conflits ont eu une influence négative sur l'efficacité des mesures de conservation (Carvalho et al., 2023). De plus, un plan de gestion de *Instituto Chico Mendes de Conservação da Biodiversidade* (ICMBio, 2019) a montré des actions prioritaires pour la conservation de la biodiversité, les ressources naturelles et culturelles et l'héritage historique. De nouvelles formes de gestion sont cruciales pour définir des stratégies tenant compte des spécificités environnementales et socio-économiques du NEB, pour sauvegarder la biodiversité et soutenir les populations vulnérables du Cerrado du NEB.

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5. DISCUSSÃO E CONCLUSÃO

Esta tese avança o conhecimento sobre a dinâmica da vegetação ao longo prazo nos últimos 6.000 anos no Nordeste do Brasil. Ele combina análises *multiproxy* de alta resolução (pólen e carvão) de testemunhos sedimentares para identificar mudanças na vegetação do Cerrado e regimes de fogo durante diferentes condições climáticas e pressões humanas diferentes das observadas hoje.

5.1. Relação clima-vegetação no Nordeste do Brasil

A distribuição atual da vegetação no Nordeste é resultado de mudanças de longo prazo nas taxas de precipitação em toda a região durante o Holoceno médio-final. As respostas da vegetação refletiram variações milenares a centenárias na intensidade e posição da convecção da ZCIT de leste a oeste. Estudos de dinâmica da vegetação relatam que a distribuição da floresta amazônica e do Cerrado era muito mais ampla do que a observada hoje, estendendo-se do oeste para o leste e nordeste (LEDRU et al., 2006; MONTADE et al., 2014; MORAES et al., 2021, 2022; OLIVEIRA et al., 1999) sob um clima predominantemente úmido (UTIDA et al., 2020). Durante o Holoceno tardio, uma mudança ambiental para condições climáticas mais secas levou à expansão da Caatinga (MORAES; DE OLIVEIRA; BEHLING, 2020; OLIVEIRA et al., 1999) enquanto a floresta amazônica e o Cerrado retraíram para o noroeste do Nordeste, onde as condições climáticas eram mais úmidas. Os resultados desta tese mostraram que a distribuição dos Cerrados do Nordeste e da vegetação da região foi fortemente influenciada não apenas pela ZCIT, mas também pela força e amplitude da monção em escalas de tempo milenares a centenárias-decenais. A região é dividida em duas zonas sob diferentes regimes climáticos: a leste do Nordeste com precipitação modulada pelas mudanças interanuais da ZCIT e coberta por Caatinga e a oeste do Nordeste sob a convecção das monções coberta por Cerrado. Durante o Holoceno tardio, as chuvas limitadas relacionadas à ZCIT e o aumento da insolação levaram a um clima seco predominante com estação chuvosa mais curta no leste da região (CRUZ et al., 2009; UTIDA et al., 2020). Eventos de seca e precipitação reduzida são amplamente atribuídos a distúrbios ambientais observados em florestas úmidas de montanha e Caatinga no leste do Nordeste (MONTADE et al., 2014; OLIVEIRA et al., 1999). Nossos resultados sugerem que tais eventos de seca também afetaram o Cerrado do sudoeste do Nordeste, porém em menor amplitude e intensidade devido à estação chuvosa mais longa e à precipitação relacionada às monções. Inferimos que a vegetação do Nordeste, incluindo as áreas de Cerrado, são ecossistemas muito sensíveis, vulneráveis ao declínio abrupto da precipitação, episódios de seca e aumento das temperaturas.

5.2. Impactos antrópicos no Nordeste do Brasil

A ocupação humana do Nordeste durante o Holoceno médio-tardio é pouco documentada e o baixo número de datações por radiocarbono dificulta as interpretações locais e regionais. No entanto, a dinâmica demográfica da região pode ser definida por dois grupos distintos: caçadores-coletores generalistas que produziam ferramentas líticas durante o início do Holoceno (BUENO; ISNARDIS, 2018; MARTIN, 2013; MELO, 2007) e agricultores-ceramistas durante o Holoceno tardio (MARTIN, 2013; SOUZA; MATEOS; MADELLA, 2020). Os primeiros registros de cerâmica e agricultura datam de cerca de 3.000 anos cal AP, ao longo dos principais rios no sul do Nordeste. Foi a partir de 2.000 anos cal AP que tais práticas se difundiram na região. Os primeiros grupos atribuídos às tradições Jê e Tupiguarani adaptaram suas técnicas a diferentes ambientes, na Caatinga a leste e no Cerrado a oeste (CAVALCANTE, 2015; MARTIN, 2013; NEGREIROS OLIVEIRA, 2004). A dinâmica e as práticas demográficas mudaram drasticamente após a chegada dos europeus por volta de 1500 EC. Os resultados desta tese mostraram que a atividade antrópica foi mais forte durante o Holoceno tardio, com o aumento de incêndios induzidos pelo homem após 3000 anos cal AP. No entanto, a intensidade e a frequência não foram sincronizadas devido aos diferentes períodos de ocupação do solo na região e às adaptações das práticas culturais aos diferentes tipos de paisagem. Durante o último milênio, os grupos indígenas usavam o fogo como ferramenta agrícola para abertura de pequenas clareiras antes da chegada dos europeus. Depois de 1500 EC, os incêndios aumentaram em frequência e intensidade no leste e no oeste do Nordeste, refletindo as mudanças nas práticas de uso da terra, o desmatamento para a criação de gado e os conflitos com grupos nativos.

5.3. História dos fogos no Cerrado nordestino

O comportamento do fogo não é homogêneo no Cerrado. Ele varia em relação à escala espacial (de nível local ao bioma), à escala temporal (de curto ao longo prazo) e à origem (naturais, antropogênicos) em escala preditiva que pode ser de um a vários fatores de origem (GOMES; MIRANDA; BUSTAMANTE, 2018). Durante o Holoceno médio-tardio no Nordeste, o regime de fogo regional foi resultado da dinâmica natural entre a vegetação local e as condições climáticas. Os incêndios ocorreram em áreas de cerrado arbóreo sob clima sazonal, quando a vegetação mais densa formava uma fonte conectiva de combustível para a propagação do fogo (LEDRU et al., 2006; MORAES et al., 2021; PESSENDA et al., 2010). Consequentemente, a frequência do fogo foi baixa e assíncrona de leste a oeste durante o período de oscilações da ZCIT e convecção da monção. Após o Holoceno tardio, a frequência de incêndios aumentou progressivamente em toda a região, em sincronia com o aumento da atividade humana. Isso foi observado no leste do Nordeste sob clima seco (PESSENDA et al., 2010). Por outro lado, os incêndios diminuíram no Cerrado a oeste sob um clima mais úmido, onde a presença humana não foi registrada (LEDRU et al., 2006). Assim, concluímos que durante o Holoceno tardio, o regime de fogo regional foi fortemente influenciado pela presença humana que moldou a paisagem local.

6. PERSPECTIVAS

Investigar as mudanças de precipitação no Nordeste do Brasil tem grande importância socioambiental, considerando o impacto do aquecimento global em curso no abastecimento de água, na população e na vegetação da região. O estudo paleoecológico (pólen e carvão sedimentar) dos Cerrados nordestinos provou ser eficaz na reconstrução das mudanças climáticas e impactos antrópicos em escalas de tempo milenares a centenárias-decenárias, sugerindo que esses efeitos são bem pronunciados nas áreas de transição. Durante as últimas duas décadas, a região tem sido fortemente caracterizada por eventos climáticos extremos como o aumento do número de episódios de seca, alta variabilidade de chuvas e temperaturas (MARENGO et al., 2017).

Projeções futuras apontam diminuição das chuvas em mais de 54% da região e aumento das temperaturas acima de 4ºC até o final do século (MARENGO et al., 2020). Considerando que a precipitação e a temperatura são os principais causadores de mudanças na vegetação da região (MARENGO et al., 2020), espera-se que o estresse hídrico e o clima mais quente causem episódios de seca mais extremos e uma estação chuvosa mais curta. Tais mudanças podem levar a uma redução drástica da cobertura vegetal regional. Considerando a sensibilidade dos Cerrados nordestinos às mudanças de precipitação e temperatura, uma estação chuvosa mais curta implicaria em menor cobertura arbórea e perda de biodiversidade, agravada pela intensificação da remoção da vegetação natural pelo homem. Extremos de variabilidade climática no Nordeste também levantam uma série de discussões em um contexto socioeconômico-ambiental. As recentes secas de 2012-2017 (MARENGO et al., 2017) levaram os governos federal e estadual a implementar políticas públicas para minimizar a vulnerabilidade das populações que vivem da agricultura familiar e da pecuária, as mais afetadas pelas mudanças climáticas na região (MARENGO et al., 2020). Os programas de monitoramento de secas e previsão climática sazonal criados pelo Centro Nacional de Monitoramento e Alertas de Desastres Naturais (CEMADEN) (ALVALÁ et al., 2019) fornecem uma maneira de identificar impactos e riscos da variabilidade climática, levando a planos de manejo mais eficazes para a conservação dos recursos naturais e do bem-estar humano.

Nesse sentido, a criação de Áreas de Proteção Integral atua para preservar a biodiversidade das paisagens do Cerrado nordestino. Os parques nacionais de Sete Cidades e Chapada das Mesas são áreas protegidas que combinam preservação dos ecossistemas com visitação do público em geral, onde áreas dentro dos limites dos parques são zoneadas para fins culturais, científicos, educacionais e recreativos (IBDF, 1979; ICMBIO, 2019). Ambos os parques fazem parte do programa PREVFOGO (MMA, 2007), uma equipe de operação de combate a incêndios que inclui um convênio entre a direção dos parques (equipe PREVFOGO) e habitantes locais quanto ao controle de incêndios. Em Sete Cidades, o fogo ainda é utilizado pelas comunidades ao redor para a renovação das pastagens e para a preparação da terra para agricultura de subsistência. A maioria das queimadas tem origem em incêndios criminosos e falta de manejo por parte das comunidades locais, representando grandes ameaças aos ecossistemas do Cerrado (SOUZA; PEREIRA, 2019). Nesse caso, mais investimentos públicos em infraestrutura de recursos humanos e educação ambiental poderiam ajudar a mitigar as pressões antrópicas. Na Chapada das Mesas, o cenário atual é mais complicado. Embora o parque tenha sido criado para reduzir os impactos do fogo antrópico sobre a vegetação do Cerrado, os conflitos entre a população local e a gestão do parque devido a áreas privadas dentro dos limites do parque têm levantado questões sobre sua proteção e fins recreativos (MARQUES; FERNANDES, 2016). Tais conflitos têm influenciado negativamente a eficácia das medidas de conservação (CARVALHO et al., 2023). Além disso, um plano de manejo do Instituto Chico Mendes de Conservação da Biodiversidade (ICMBIO, 2019) apontou ações prioritárias para a conservação da biodiversidade, dos recursos naturais, do patrimônio cultural e histórico. Novas formas de gestão são cruciais para definir estratégias que contemplem as especificidades ambientais e socioeconômicas do Nordeste, para salvaguardar a biodiversidade e apoiar as populações mais vulneráveis do Cerrado nordestino.

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SÉRGIO AUGUSTO SANTOS XAVIER

RESPOSTAS DA VEGETAÇÃO DE CERRADO ÀS MUDANÇAS CLIMÁTICAS E ATIVIDADES ANTRÓPICAS NO NORDESTE DO BRASIL DURANTE O HOLOCENO TARDIO

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Volume 2

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Orientadora: Profª. Drª. Francisca Soares de Araújo (Universidade Federal do Ceará).
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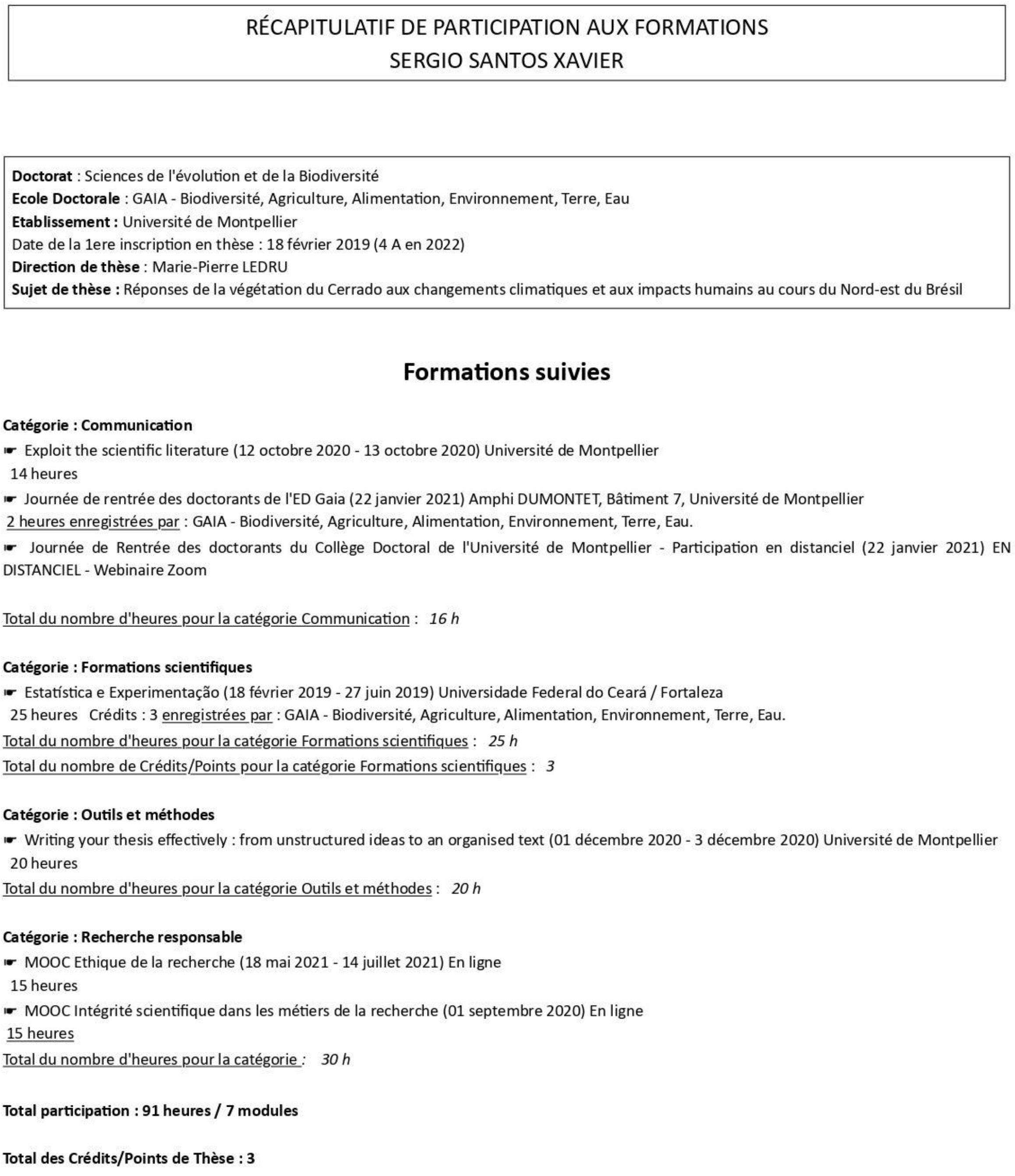
1.1. Université de Montpellier



RÉCAPITULATIF DE PARTICIPATION AUX FORMATIONS
SERGIO SANTOS XAVIER

Doctorat : Sciences de l'évolution et de la Biodiversité
Ecole Doctorale : GAIA - Biodiversité, Agriculture, Alimentation, Environnement, Terre, Eau
Etablissement : Université de Montpellier
Date de la 1ere inscription en thèse : 18 février 2019 (4 A en 2022)
Direction de thèse : Marie-Pierre LEDRU
Sujet de thèse : Réponses de la végétation du Cerrado aux changements climatiques et aux impacts humains au cours du Nord-est du Brésil

Formations suivies

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☛ Exploit the scientific literature (12 octobre 2020 - 13 octobre 2020) Université de Montpellier
14 heures

☛ Journée de rentrée des doctorants de l'ED Gaia (22 janvier 2021) Amphi DUMONTET, Bâtiment 7, Université de Montpellier
2 heures enregistrées par : GAIA - Biodiversité, Agriculture, Alimentation, Environnement, Terre, Eau.

☛ Journée de Rentrée des doctorants du Collège Doctoral de l'Université de Montpellier - Participation en distanciel (22 janvier 2021) EN DISTANCIEL - Webinaire Zoom

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☛ Estatística e Experimentação (18 février 2019 - 27 juin 2019) Universidade Federal do Ceará / Fortaleza
25 heures Crédits : 3 enregistrées par : GAIA - Biodiversité, Agriculture, Alimentation, Environnement, Terre, Eau.

Total du nombre d'heures pour la catégorie Formations scientifiques : *25 h*

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Catégorie : Outils et méthodes

☛ Writing your thesis effectively : from unstructured ideas to an organised text (01 décembre 2020 - 3 décembre 2020) Université de Montpellier
20 heures

Total du nombre d'heures pour la catégorie Outils et méthodes : *20 h*

Catégorie : Recherche responsable

☛ MOOC Ethique de la recherche (18 mai 2021 - 14 juillet 2021) En ligne
15 heures

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Total participation : 91 heures / 7 modules

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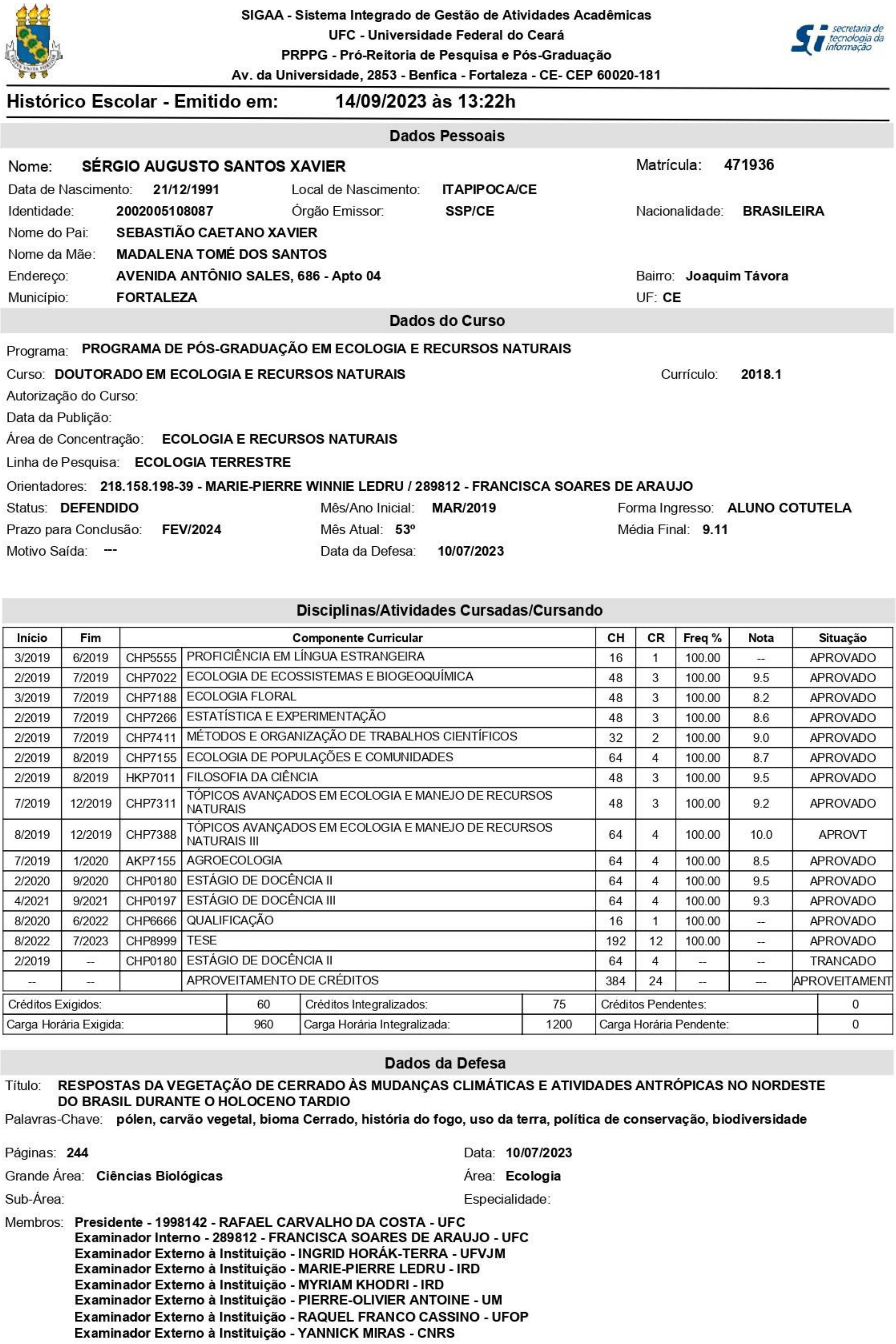

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Nome: **SÉRGIO AUGUSTO SANTOS XAVIER** Matrícula: **471936**
Data de Nascimento: **21/12/1991** Local de Nascimento: **ITAPIPOCA/CE**
Identidade: **2002005108087** Órgão Emissor: **SSP/CE** Nacionalidade: **BRASILEIRA**
Nome do Pai: **SEBASTIÃO CAETANO XAVIER**
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Programa: **PROGRAMA DE PÓS-GRADUAÇÃO EM ECOLOGIA E RECURSOS NATURAIS**
Curso: **DOUTORADO EM ECOLOGIA E RECURSOS NATURAIS** Currículo: **2018.1**
Autorização do Curso:
Data da Publição:
Área de Concentração: **ECOLOGIA E RECURSOS NATURAIS**
Linha de Pesquisa: **ECOLOGIA TERRESTRE**
Orientadores: **218.158.198-39 - MARIE-PIERRE WINNIE LEDRU / 289812 - FRANCISCA SOARES DE ARAUJO**
Status: **DEFENDIDO** Mês/Ano Inicial: **MAR/2019** Forma Ingresso: **ALUNO COTUTELA**
Prazo para Conclusão: **FEV/2024** Mês Atual: **53º** Média Final: **9.11**
Motivo Saída: **---** Data da Defesa: **10/07/2023**

Disciplinas/Atividades Cursadas/Cursando

Início	Fim	Componente Curricular		CH	CR	Freq %	Nota	Situação
3/2019	6/2019	CHP5555	PROFICIÊNCIA EM LÍNGUA ESTRANGEIRA	16	1	100.00	--	APROVADO
2/2019	7/2019	CHP7022	ECOLOGIA DE ECOSSISTEMAS E BIOGEOQUÍMICA	48	3	100.00	9.5	APROVADO
3/2019	7/2019	CHP7188	ECOLOGIA FLORAL	48	3	100.00	8.2	APROVADO
2/2019	7/2019	CHP7266	ESTATÍSTICA E EXPERIMENTAÇÃO	48	3	100.00	8.6	APROVADO
2/2019	7/2019	CHP7411	MÉTODOS E ORGANIZAÇÃO DE TRABALHOS CIENTÍFICOS	32	2	100.00	9.0	APROVADO
2/2019	8/2019	CHP7155	ECOLOGIA DE POPULAÇÕES E COMUNIDADES	64	4	100.00	8.7	APROVADO
2/2019	8/2019	HKP7011	FILOSOFIA DA CIÊNCIA	48	3	100.00	9.5	APROVADO
7/2019	12/2019	CHP7311	TÓPICOS AVANÇADOS EM ECOLOGIA E MANEJO DE RECURSOS NATURAIS	48	3	100.00	9.2	APROVADO
8/2019	12/2019	CHP7388	TÓPICOS AVANÇADOS EM ECOLOGIA E MANEJO DE RECURSOS NATURAIS III	64	4	100.00	10.0	APROVT
7/2019	1/2020	AKP7155	AGROECOLOGIA	64	4	100.00	8.5	APROVADO
2/2020	9/2020	CHP0180	ESTÁGIO DE DOCÊNCIA II	64	4	100.00	9.5	APROVADO
4/2021	9/2021	CHP0197	ESTÁGIO DE DOCÊNCIA III	64	4	100.00	9.3	APROVADO
8/2020	6/2022	CHP6666	QUALIFICAÇÃO	16	1	100.00	--	APROVADO
8/2022	7/2023	CHP8999	TESE	192	12	100.00	--	APROVADO
2/2019	--	CHP0180	ESTÁGIO DE DOCÊNCIA II	64	4	--	--	TRANCADO
--	--		APROVEITAMENTO DE CRÉDITOS	384	24	--	---	APROVEITAMENT

Créditos Exigidos:	60	Créditos Integralizados:	75	Créditos Pendentes:	0
Carga Horária Exigida:	960	Carga Horária Integralizada:	1200	Carga Horária Pendente:	0

Dados da Defesa

Título: **RESPOSTAS DA VEGETAÇÃO DE CERRADO ÀS MUDANÇAS CLIMÁTICAS E ATIVIDADES ANTRÓPICAS NO NORDESTE DO BRASIL DURANTE O HOLOCENO TARDIO**
Palavras-Chave: **pólen, carvão vegetal, bioma Cerrado, história do fogo, uso da terra, política de conservação, biodiversidade**

Páginas: **244** Data: **10/07/2023**
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2. CERTIFICADOS

2.1. Encontros Universitários UFC 2020

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CERTIFICADO

Certificamos que o trabalho 'OS VISITANTES FLORAIS DE MENTHA ARVERNSIS L. OBSERVADOS NO CAMPUS DO PICI - UFC' do(s) autor(es) MARIA VIRGINIA OLIVEIRA DA SILVA, SERGIO AUGUSTO SANTOS XAVIER, ITALO ANTONIO COTTA COUTINHO e LÍGIA QUEIROZ MATIAS foi apresentado na modalidade 'Pôster' no XII Encontro de Pesquisa e Pós-Graduação realizado no período de 20 a 22 de Maio de 2020.

Fortaleza, 29 de Novembro de 2021

Jorge Herbert Soares de Lira
Pró-Reitor de Pesquisa e Pós-Graduação

Geovana M Cartaxo de Arruda
Geovana Maria Cartaxo de Arruda Freire
Coordenadora Geral dos EU2019

Geanne Matos de Andrade
Coordenadora de Pesquisa

Emitido em http://sysprppg.ufc.br/eu/2019 (Certificados)

3. PARTICIPAÇÃO EM EVENTOS CIENTÍFICOS

3.1. 5th MEDPALYNOS SYMPOSIUM 2022, PAESTUM, ITALY

CERTIFICATE OF ATTENDANCE

This is to certify that

SERGIO AUGUSTO XAVIER

has attended as Speaker at

5TH MEDPALYNOS SYMPOSIUM
13th-15th September 2022
Paestum (Salerno) - Italy

ONE HEALTH
PAESTUM

3.2. XXI INQUA ROMA 2023

XXI CONGRESS OF THE INTERNATIONAL UNION FOR QUATERNARY RESEARCH

CERTIFICATE OF ATTENDANCE

THIS IS TO CERTIFY THAT

SERGIO SANTOS XAVIER

ATTENDED THE XXI INQUA CONGRESS IN ROME, ITALY 14-20 JULY 2023

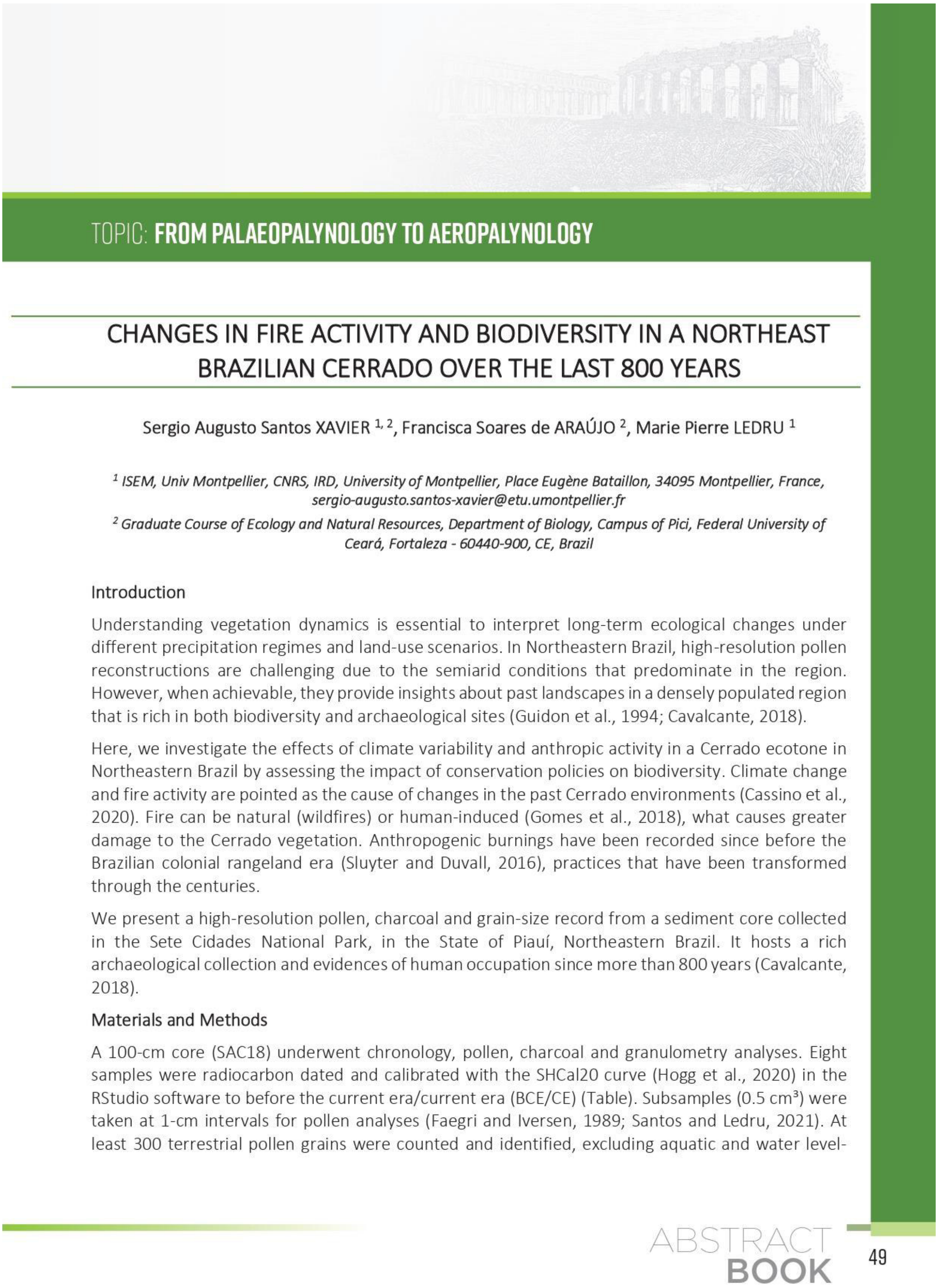
PRESIDENT OF XXI INQUA CONGRESS

FRANCESCO LATINO CHIOCCI

Francesco Latino Chiocci

4. RESUMOS PUBLICADOS EM EVENTOS CIENTÍFICOS

4.1. 5th MEDPALYNOS SYMPOSIUM 2022, PAESTUM, ITALY



TOPIC: **FROM PALAEOPALYNOLOGY TO AEROPALYNOLOGY**

CHANGES IN FIRE ACTIVITY AND BIODIVERSITY IN A NORTHEAST BRAZILIAN CERRADO OVER THE LAST 800 YEARS

Sergio Augusto Santos XAVIER [1, 2], Francisca Soares de ARAÚJO [2], Marie Pierre LEDRU [1]

[1] *ISEM, Univ Montpellier, CNRS, IRD, University of Montpellier, Place Eugène Bataillon, 34095 Montpellier, France, sergio-augusto.santos-xavier@etu.umontpellier.fr*

[2] *Graduate Course of Ecology and Natural Resources, Department of Biology, Campus of Pici, Federal University of Ceará, Fortaleza - 60440-900, CE, Brazil*

Introduction

Understanding vegetation dynamics is essential to interpret long-term ecological changes under different precipitation regimes and land-use scenarios. In Northeastern Brazil, high-resolution pollen reconstructions are challenging due to the semiarid conditions that predominate in the region. However, when achievable, they provide insights about past landscapes in a densely populated region that is rich in both biodiversity and archaeological sites (Guidon et al., 1994; Cavalcante, 2018).

Here, we investigate the effects of climate variability and anthropic activity in a Cerrado ecotone in Northeastern Brazil by assessing the impact of conservation policies on biodiversity. Climate change and fire activity are pointed as the cause of changes in the past Cerrado environments (Cassino et al., 2020). Fire can be natural (wildfires) or human-induced (Gomes et al., 2018), what causes greater damage to the Cerrado vegetation. Anthropogenic burnings have been recorded since before the Brazilian colonial rangeland era (Sluyter and Duvall, 2016), practices that have been transformed through the centuries.

We present a high-resolution pollen, charcoal and grain-size record from a sediment core collected in the Sete Cidades National Park, in the State of Piauí, Northeastern Brazil. It hosts a rich archaeological collection and evidences of human occupation since more than 800 years (Cavalcante, 2018).

Materials and Methods

A 100-cm core (SAC18) underwent chronology, pollen, charcoal and granulometry analyses. Eight samples were radiocarbon dated and calibrated with the SHCal20 curve (Hogg et al., 2020) in the RStudio software to before the current era/current era (BCE/CE) (Table). Subsamples (0.5 cm³) were taken at 1-cm intervals for pollen analyses (Faegri and Iversen, 1989; Santos and Ledru, 2021). At least 300 terrestrial pollen grains were counted and identified, excluding aquatic and water level-related taxa. Subsamples (0.5 cm³) taken at 1-cm intervals were prepared for the macro charcoal analysis (Stevenson and Haberle, 2005). Particles were counted and measured under a stereoscope using WinSeedle software (Regent Instruments, Quebec, Canada). Granulometry was carried out about every 5 cm and followed the Wentworth scale for clastic sediments (Wentworth, 1922) (Figure 1).

Results and Discussion

Our record shows that Cerrado vegetation remained dominant over the last 800 years with some reorganization of species assemblages, for instance, the dry-climate related taxa *Curatella* observed at the beginning of the record and the moisture-related tree/herbaceous taxa Myrtaceae and *Spathiphyllum*. Almost no fire activity was observed in the dry period between 1211 and 1300 CE, synchronous with the Medieval Climate Anomaly (Mann et al., 2009) (Figure). A marked increase in biomass burning between 1350 and 1500 CE was linked to anthropogenic activities, first those of Amerindians (Oliveira, 2002), then of European colonists dating back to the arrival of the cattle herders in 1650 CE (Alves, 2003), when fires suddenly stopped for one century (Figure). The second decrease in fire activity was observed shortly after the creation of Sete Cidades National Park in 1961 CE (Figure), resulting in the expansion of a moist forest cover.

Conclusions

Here we show that vegetation in Northeastern Brazil responded to both global climate changes and anthropogenic activities, and how a national park can change the evolution and dynamics of the landscape after more than 700 years of anthropogenic pressure. Something worth considering when defining conservation policies for the 21st century.

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Tables

Table. Radiocarbon dates of the SAC18 core with 14C calibrated BP ages (two standard deviations (2σ ranges) and calibrated CE ages obtained using the RStudio software.

Lab Code	Depth (cm)	$\delta^{13}C$	^{14}C yrs BP	Age range (cal yrs BP) 2σ	Calibrated yrs CE
SacA57449	29	-27,2	-24 ± 17	-42 — -10	1975
SacA60357	44	-29,7	99 ± 30	-14 — 197	1856
SacA57450	55	-26,4	228 ± 30	98 — 283	1725
SacA61869	67	-29,5	511 ± 30	471 — 538	1439
SacA64070	69	-24,5	535 ± 30	509 — 560	1415
SacA60358	77	-24,1	365 ± 30	310 — 467	1483 — 1640
SacA57451	86	-25,6	165 ± 30	151 — 0	1799 — 1950
SacA57451	92	-29,1	719 ± 30	660 — 880	1234

Figures

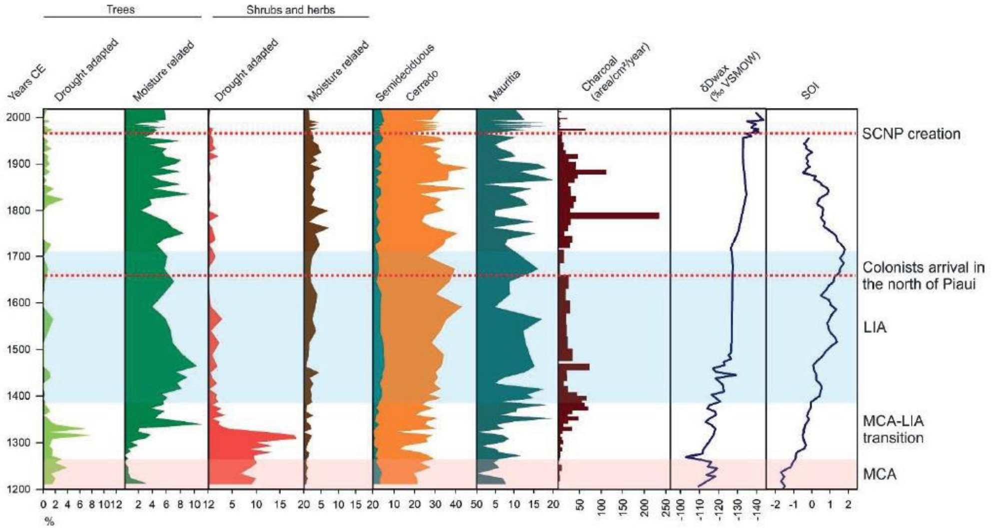

Figure. Comparison of the changes in vegetation composition and fire activity in the SAC18 record that testify to changes in precipitation in South America over the last 800 years. From left to right: 1) Drought adapted tree taxa (pale green) and moisture adapted tree taxa (dark green); 2) Drought adapted shrubs and herbaceous plants (red) and moisture adapted shrubs and herbaceous plants (brown); 3) Semi-deciduous forest trees (blue) and Cerrado trees (orange); 4) Mauritia indicator of palm swamps; 5) Charcoal surface area; 6) Changes in δDwax, a precipitation proxy from Utida et al. (2019); 7) Changes in the Southern Oscillation Index (SOI) from Yan et al. (2011). The end of the Medieval Climate Anomaly (MCA) is represented by the pink shaded area, and the Little Ice Age (LIA) by the blue shaded area. (from Xavier, in review, Anthropocene)

5. OUTROS ARTIGOS CIENTÍFICOS PUBLICADOS

5.1. DIVERSITY OF CLIMBERS OF THE UBAJARA NATIONAL PARK, CEARÁ, BRAZIL

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Diversidade de Lianas e Trepadeiras do Parque Nacional de Ubajara, Ceará, Brasil

Lucas Farias Pinheiro[1], James Castro Alves[2], Sérgio Augusto Santos Xavier[3], Alyne Vasconcelos Cavalcante[3], Maria Iracema Bezerra Loiola[4]

[1]Mestrando, Mestrado Acadêmico em Ciências Naturais, Universidade Estadual do Ceará, Campus Itaperi, CEP 60714-903, Fortaleza-CE. E-mail: luccas.fpinheiro@gmail.com – autor correspondente.
[2]Mestrando, Mestrado Acadêmico em Ecologia e Recursos Naturais, Universidade Federal do Ceará, Campus do Pici, CEP 60440-900, Fortaleza-CE. E-mail: jamescastroalves@gmail.com;
[3]Doutorando, Doutorado Acadêmico em Ecologia e Recursos Naturais, Universidade Federal do Ceará, Campus do Pici, CEP 60440-900, Fortaleza-CE. E-mail: alyneifce@gmail.com; sergio.s.xavier@hotmail.com.
[4]Doutora, Professora Titular do Curso de Ciências Biológicas e do Programa de Pós-Graduação em Ecologia e Recursos Naturais, Universidade Federal do Ceará, Campus do Pici, CEP 60440-900, Fortaleza-CE. E-mail: iloiola@ufc.br.

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RESUMO

As lianas e trepadeiras são importantes componentes das unidades florestais, principalmente em regiões tropicais, as quais se diferenciam, especialmente, pelo grau de lenhosidade no seu caule. Esses grupos contribuem notavelmente para a riqueza de espécies de diferentes ecossistemas, trazendo benefícios para a flora e fauna. No entanto, constituem o componente menos estudado, gerando uma lacuna no conhecimento sobre aspectos florístico-estruturais, regenerativos e fatores que influenciam esses grupos nas diversas formações vegetacionais. Esse estudo objetivou realizar o levantamento das espécies de lianas e trepadeiras registradas no Parque Nacional de Ubajara (PARNA Ubajara), no estado do Ceará. As informações sobre as espécies foram obtidas através de consulta aos bancos de dados digitais Flora do Brasil 2020 e Centro de Referência em Informação Ambiental – CRIA. Com base nessas informações, foi elaborada uma lista de espécies e uma chave de identificação das famílias botânicas registradas. No PARNA Ubajara foram listadas 60 espécies, distribuídas em 42 gêneros e 20 famílias de lianas e trepadeiras, com destaque para Fabaceae (25%), Bignoniaceae (8,3%) e Convolvulaceae (8,3 %), correspondendo a 41,6 % do total de táxons. Tais famílias foram representadas em outros remanescentes de Mata Atlântica, mostrando uma similaridade florística entre essas áreas. O estudo mostrou a importância dos inventários florísticos com esses grupos de plantas, os quais podem servir como subsídio para a criação de programas de conservação de espécies, principalmente para aquelas que estão na categoria de pouco preocupante, segundo o livro vermelho da flora do Brasil, e que foram registradas na área de estudo.

Palavras chaves: Florística, Mata Atlântica, Nordeste do Brasil, Unidade de Conservação.

Diversity of Climbers of the Ubajara National Park, Ceará, Brazil

ABSTRACT

Lianas and vines are important components of forestry units, especially in tropical regions, which are differentiated mainly by the degree of woodiness in their stem. These groups contribute notably to the richness of species from different ecosystems, bringing benefits to flora and fauna. However, they constitute the least studied component, generating a gap in knowledge about floristic-structural, regenerative aspects, and factors that influence these groups in the different vegetation formations. This study aimed to survey the species of lianas and vines recorded in the National Park of Ubajara (PARNA Ubajara), in the state of Ceará. The information about the species was obtained through consultation with the digital databases Flora do Brasil 2020 and Reference Center for Environmental Information - CRIA. Based on this information, a list of species and an identification key for the registered botanical families were prepared. In PARNA Ubajara, 60 species were listed, distributed in 42 genera and 20 families of lianas and vines, with emphasis on Fabaceae (25%), Bignoniaceae (8.3%) and Convolvulaceae (8.3%), corresponding to 41.6 % of total taxa. Such families were represented in other remnants of the Atlantic Forest, showing a floristic similarity between these areas. Floristic inventories are important to these groups of plants, which can serve as a subsidy for the creation of species conservation programs, especially for those that are in the category of little concern, according to the red book on flora in Brazil, and that were recorded in the study area.

Key words: Floristic, Atlantic forest, Northeast of Brazil, Conservation unit.

Introdução

A Mata Atlântica é uma formação florestal com grande diversidade de seres vivos e muitos endemismos (Lagos e Muller, 2007; Oliveira et al., 2011), estando entre os 35 *hot spots* do mundo (Ribeiro et al., 2011). Considerada o terceiro maior bioma brasileiro, perdendo apenas para a Amazônia e o Cerrado, abrange um conjunto de diferentes fitofisionomias, cujas espécies se desenvolvem em condições ecológicas bem particulares (Cunha e Silva Júnior, 2014). No Nordeste brasileiro, a Mata Atlântica apresenta três tipos principais de fisionomias: Floresta Ombrófila, Floresta Estacional Decídua e Semidecídua, e as Formações Pioneiras (Tabarelli et al., 2006).

Um dos componentes encontrados nas diferentes fitofisionomias da Mata Atlântica são as lianas e as plantas trepadeiras. Além de representarem 25% da diversidade de espécies em florestas tropicais, exercem importantes funções dentro da dinâmica ecossistêmica, influenciando a regeneração de árvores, as competições interespecíficas e servindo como recurso alimentar para os animais, além de contribuir para a transpiração e o sequestro de carbono (Emmons e Gentry, 1983; Schnitzer e Bongers, 2002; Arroyo-Rodríguez et al., 2015; Wright et al., 2015). Vale lembrar que existem as espécies invasoras, que prejudicam a harmonia da comunidade vegetal, trazendo prejuízos para as espécies nativas, por competição de nutrientes, como a *Cryptostegia madagascariensis* Bojer ex Decne (Sousa et al., 2017)

Esses grupos de plantas (lianas e trepadeiras) são ainda utilizados como objeto de testes em teorias ecológicas, como facilitação, estrutura de nicho e riqueza de espécies (Schnitzer, 2018) e suas características funcionais ajudam a explicar a estrutura da comunidade em múltiplas escalas espaciais (Clark et al., 2018). Existe uma diferença entre trepadeiras e lianas, apesar das palavras serem usadas frequentemente como sinônimos.

As lianas (conhecidas também como cipós) são plantas com lenhosidade desenvolvida, com gemas situadas acima do solo, protegidas por catáfilos e geralmente encontradas no interior das florestas. As trepadeiras são plantas volúveis, com baixa lenhosidade e caule de pequena espessura, que podem ou não apresentar gavinhas, para facilitar o seu suporte nos outros vegetais, ocorrendo, frequentemente, em áreas mais alteradas, como as bordas das florestas (Gentry 1991; IBGE 2012).

Os ramos dessas plantas podem atingir poucas a várias dezenas de centímetros, em diâmetro, e, devido a forma de crescimento peculiar, necessitam de outras plantas como suporte mecânico para seu crescimento em direção à copa das árvores em busca de luz (Rowe, 2018). Isso influencia, significativamente, o crescimento arbóreo, gerando competições diretas por recursos como água e nutrientes (Gentry, 1991; Rowe, 2018).

No território brasileiro, as lianas e as trepadeiras constituem um grupo característico, especialmente de ambientes mais úmidos, e os estudos sobre essas plantas foram realizados, principalmente, nas regiões Sul (Carneiro e Vieira, 2012; Durigon e Waechter, 2011; Oliveira, 2016; Guerra et al., 2015) e Sudeste (Vargas et al., 2013; Vargas; e Araújo, 2014; Villagra e Romaniuc Neto, 2010; Gomes et al., 2018) do país.

Para o Nordeste brasileiro destacam-se os levantamentos realizados para os estados de Pernambuco (Araújo e Alves, 2010; Delgado Junior e Alves, 2017) e Rio Grande do Norte (Oliveira et al., 2012). No Ceará, os representantes de lianas e trepadeiras são citados em levantamentos mais abrangentes, como os desenvolvidos por Araújo et al. (2011), Ribeiro-Silva et al. (2012) e Loiola et al. (2015). O único estudo, especificamente sobre as lianas, no território cearense foi realizado por Santos e Figueiredo (2018), na Serra de Uruburetama.

Quando levamos em consideração o papel das lianas dentro da comunidade, é nítida a importância deste grupo de plantas, especialmente quando aliado a listagens de outros componentes vegetais que formam a estrutura das florestas estacionais semidecíduas e em florestas ombrófilas. O conhecimento desses táxons fornece um panorama da diversidade de espécies e funciona como um banco de dados, que pode ser utilizado para a elaboração de planos de manejo e preservação de fragmentos e áreas em risco.

Dessa forma, o presente estudo teve como objetivo realizar o levantamento das espécies de lianas e trepadeiras registradas no Parque Nacional de Ubajara, no estado do Ceará. Além disso, com base nas características das famílias botânicas, foi elaborada uma chave de identificação visando facilitar o reconhecimento das mesmas.

Material e métodos

Caracterização da área de estudo

O Parque Nacional de Ubajara (PARNA Ubajara) foi criado pelo Decreto n° 45.954 de 30 de abril de 1959 (Lima e Gualdani, 2008; ICMBIO 2019). É caracterizado como uma Unidade de Conservação de Proteção Integral (UC), que está relacionado ao uso indireto dos seus recursos naturais. O Parque localiza-se no estado do Ceará, abrangendo os municípios de Ubajara, Tianguá e Frecheirinha, distando 320 km da capital Fortaleza.

Localizado entre as coordenadas 3°40'30" S-40°57' 0" W e 3° 49'30"-40°52'30", a área de extensão do PARNA sofreu algumas alterações, estando, atualmente, limitado a uma área de 6.269,51 hectares, com altitudes variando entre 800 a 1.100 m (ICMBIO, 2019), como mostrado na Figura 1.

O clima da área é do tipo Tropical Quente Sub-úmido, com precipitação média anual de 1.483,5 mm, com período chuvoso nos meses de janeiro a abril e temperatura média de 24° a 26°C (Cunha e Araújo, 2014; IPECE 2017; ICMBIO 2019).

Quanto à cobertura vegetal, o local de maior altitude do Parque, que corresponde a uma pequena área do topo do planalto da Ibiapaba, abrange uma estreita faixa de Floresta Estacional Sempre-Verde, denominada de mata úmida serrana (IBGE 2012; Silveira et al., 2020). Na encosta, área de maior abrangência do Parque, predomina a Floresta Estacional Decídua, denominada, popularmente, de mata seca (IBGE 2012; Silveira et al., 2020).

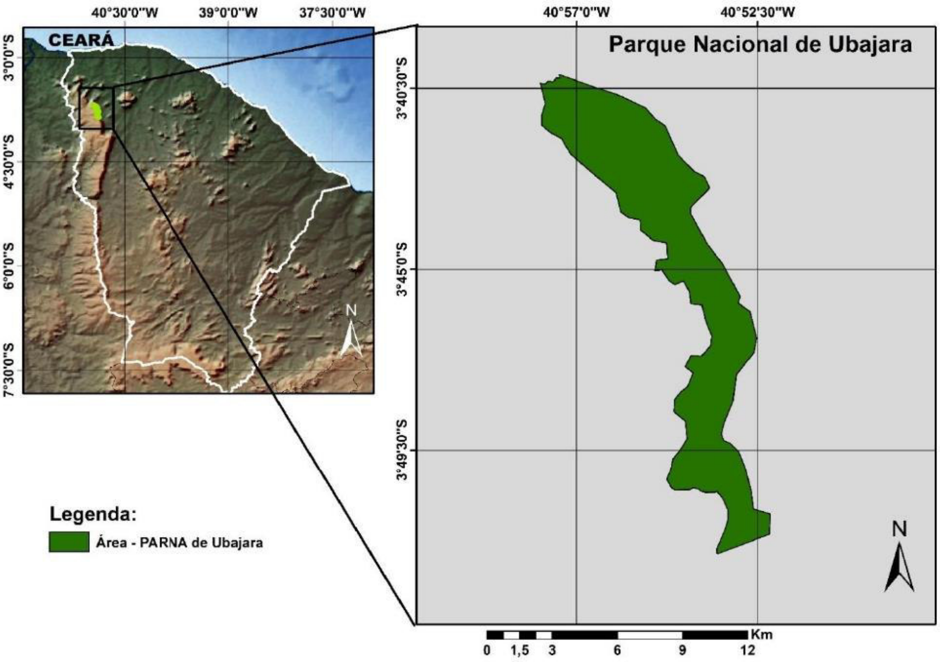

Figura 1. Localização geográfica do Parque Nacional de Ubajara no estado Ceará, nordeste do Brasil.

Coleta de dados

Os dados referentes às espécies vegetais foram obtidos nos bancos de dados digitais dos sítios Flora do Brasil 2020 e Centro de Referência em Informação Ambiental - CRIA, através de consultas à localidade de Ubajara/CE, utilizando como palavras chave "liana", "trepadeira" e "volúvel". As ocorrências foram agrupadas em uma tabela utilizando o *software* Excel 2013, excluindo aquelas que não estavam identificadas em nível de espécie.

Os nomes científicos das espécies estão de acordo com o sítio Flora do Brasil 2020 (http://floradobrasil.jbrj.gov.br/reflora/). Para a elaboração da chave de identificação, em nível de família, foram usadas informações do referido sítio e de literatura especializada (Souza e Lorenzi, 2012).

Os critérios da União Internacional para a Conservação da Natureza (IUCN 2017) e o CNCFlora (2018) foram usados para avaliar o status de conservação das espécies.

Resultados e discussão

Para o PARNA Ubajara foram listadas 60 espécies de lianas ou trepadeiras, distribuídas em 42 gêneros e 20 famílias (Tabela 1). Do total, nove espécies constituem nova ocorrência, de acordo com o sítio da Flora do Brasil 2020. *Bia capivarensis* D. Medeiros, Senna-Valle & Alves (Euphorbiaceae) é a segunda ocorrência para o Brasil, sendo necessários estudos com os representantes desse gênero, para um melhor entendimento da distribuição dessa e das demais espécies do referido grupo taxonômico.

Quanto ao *status* de conservação, nove espécies (15%) foram classificadas na categoria LC (Pouco Preocupante), e as demais não foram avaliadas (NE), até o momento (Tabela 1). Esses dados evidenciam a importância de levantamentos florísticos em diferentes componentes dos ecossistemas florestais, pois nos permite classificar espécies ainda não avaliadas e identificar táxons vulneráveis.

Tabela 1.- Lista de famílias e espécies registradas no Parque Nacional de Ubajara - Ceará, com indicação da forma de crescimento e status de conservação, respectivamente. Legenda: LC= Pouco preocupante; NE= Não avaliado. * = nova ocorrência para o Ceará.

Família/Espécies	Forma de crescimento	Status de conservação
1. Alstroemeriaceae		
Bomarea edulis (Tussac) Herb.	liana	NE
2. Apocynaceae		
Mandevilla hirsuta (Rich.) K.Schum.	liana	LC
Petalostelma martianum (Decne.) E.Fourn.	trepadeira	NE
**Prestonia lindleyana* Woodson	trepadeira	NE
Schubertia grandiflora Mart.	liana	NE
3. Asteraceae		
Mikania glomerata Spreng.	liana	LC
4. Bignoniaceae		
Adenocalymma divaricatum Miers	liana	NE
Anemopaegma parkeri Sprague	liana	NE
Dolichandra unguis-cati (L.) L.G.Lohmann	liana	NE
Fridericia triplinervia (Mart. ex DC.) L. Lohmann	liana	NE
Pyrostegia venusta (Ker Gawl.) Miers	liana	NE
5. Combretaceae		
Combretum fruticosum Stuntz	liana	NE
Combretum laxum Jacq.	liana	NE
6. Commelinaceae		

Dichorisandra hexandra (Aubl.) C.B.Clarke	trepadeira	NE
7. Convolvulaceae		
Calycobolus lanulosus D.F.Austin	trepadeira	NE
Distimake macrocalyx (Ruiz & Pav.) A.R. Simões & Staples	trepadeira	NE
**Ipomoea longibracteolata* Sim.-Bianch. & J.R.I.Wood	trepadeira	NE
Ipomoea magna Simão-Bianchini, R. & Wood, J.R.I.	trepadeira	NE
Jacquemontia nodiflora (Desr.) G.Don	trepadeira	NE
8. Cucurbitaceae		
Cayaponia tayuya (Vell.) Cogn.	trepadeira	NE
Psiguria ternata (M.Roem.) C. Jeffrey	trepadeira	NE
9. Dioscoreaceae		
Dioscorea multiflora Mart. ex Griseb.	trepadeira	NE
Dioscorea orthogoneura Uline ex Hochr.	trepadeira	LC
Dioscorea piperifolia Humb. & Bonpl. ex Willd.	trepadeira	NE
10. Euphorbiaceae		
**Bia capivarensis* D. Medeiros, Senna-Valle & Alves	trepadeira	NE
**Bia lessertiana* Baill.	trepadeira	NE
Dalechampia pernambucensis Baill.	trepadeira	NE
Dalechampia tiliifolia Lam.	liana	NE
11. Fabaceae		
**Ancistrotropis peduncularis* (Kunth) A. Delgado	trepadeira	NE
Calopogonium caeruleum (Benth.) C.Wright	trepadeira	NE
Calopogonium mucunoides Desv.	trepadeira	NE
Calopogonium velutinum (Benth.) Amshoff	liana	NE
**Canavalia grandiflora* Benth.	liana	NE
Centrosema brasilianum (L.) Benth.	trepadeira	NE
Centrosema sagittatum (Humb. & Bonpl. ex Willd.) Brandegee	trepadeira	LC
Dioclea sclerocarpa Ducke	liana	NE
Dioclea virgata (Rich.) Amshoff	liana	NE
Galactia striata (Jacq.) Urb.	trepadeira	LC

Mucuna sloanei Fawc &. Rendle.	liana	NE
Periandra coccinea (Schrad.) Benth.	trepadeira	NE
Rhynchosia phaseoloides (Sw.) DC.	liana	NE
Schnella glabra (Jacq.) Dugand	liana	NE
Schnella outimouta (Aubl.) Wunderlin	liana	NE
12. Malpighiaceae		
Diplopterys pubipetala (A.Juss.) W.R.Anderson & C.C.Davis	liana	NE
13. Malvaceae		
**Byttneria catalpifolia* Jacq.	liana	LC
14. Passifloraceae		
**Passiflora rubra* L.	trepadeira	LC
Passiflora suberosa L.	trepadeira	NE
Passiflora tricuspis Mast.	liana	LC
15. Ranunculaceae		
**Clematis affinis* A.St.-Hil.	liana	NE
16. Rhamnaceae		
Gouania colurnifolia Reissek	liana	NE
Gouania virgata Reissek	liana	NE
17. Rubiaceae		
Manettia cordifolia Mart.	liana	NE
Sabicea grisea Cham. & Schltdl.	liana	LC
18. Sapindaceae		
Serjania glabrata Kunth	liana	NE
Serjania hebecarpa Benth.	liana	NE
Serjania lethalis A.St.-Hil.	liana	NE
Urvillea laevis Radlk.	liana	NE
19. Smilacaceae		
Smilax irrorata Mart. ex Griseb.	liana	NE
20. Vitaceae		
Cissus albida Cambess.	liana	NE

Cissus gongylodes (Baker) Planch.	liana	NE

Fabaceae (15 spp., 25%), Bignoniaceae (5 spp., 8,3%) e Convolvulaceae (5 spp., 8,3%) foram as famílias com maior riqueza de espécies, correspondendo a 43,08% do total de registros. Apocynaceae, Euphorbiaceae e Sapindaceae foram representadas por quatro espécies cada, correspondendo cada família a 6,6 % da representatividade total. As demais famílias estão representadas por um a três espécies, representando 38,46% do total de espécies amostradas (Figura 2).

No único levantamento com ênfase na diversidade de trepadeiras realizado no noroeste do estado do Ceará, Santos e Figueiredo (2018) listaram 53 espécies, pertencentes a 34 gêneros e 21 famílias no Maciço de Uruburetama, sendo Convolvulaceae (10 spp.), Fabaceae (5 spp.) e Passifloraceae (5 spp.) as mais representativas. Como pode-se observar, as famílias botânicas registradas no presente estudo são praticamente as mesmas, mas com inversão na ordem de diversidade. Tal semelhança deve-se provavelmente, à similaridade nos aspectos climáticos e componentes ambientais dessas duas áreas de estudo como altitude, precipitação e temperatura média.

Diferentemente, no levantamento de plantas trepadeiras no município de Parnamirim/Rio Grande do Norte em uma Floresta Estacional Semidecídua realizado por Oliveira et al. (2012), foram catalogadas 20 espécies, pertencentes a 19 gêneros e 11 famílias, sendo que que as famílias com maior diversidade de espécies foram Fabaceae (5 spp.) e Dilleniaceae (3 spp.).

Nos levantamentos florísticos realizados na região Sudeste, as famílias botânicas mais representativas foram: Bignoniaceae, Fabaceae, Malpighiaceae, Sapindaceae, Convolvulaceae (Vargas e Araújo, 2014; Vargas et al., 2013; Villagra e Romaniuc Neto, 2010).

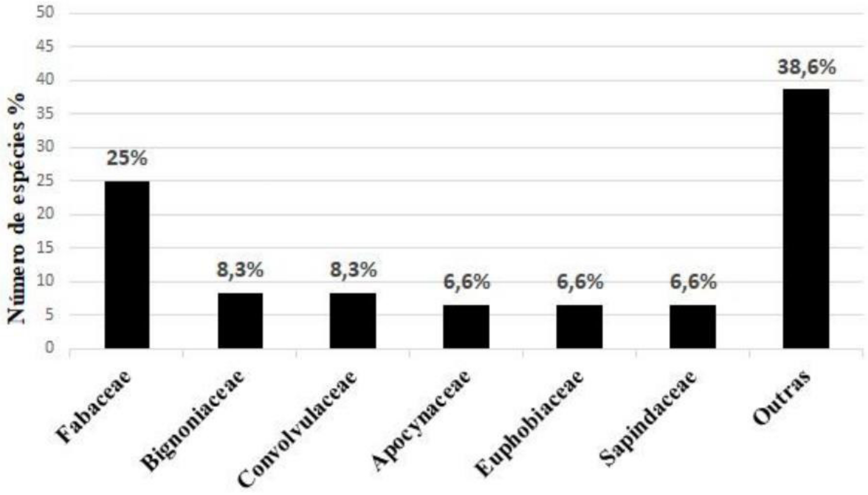

Figura 2. Famílias de lianas e trepadeiras com maior número de representantes no Parque Nacional de Ubajara – CE, nordeste do Brasil.

Destaca-se que os representantes de Bignoniaceae são citados em muitos estudos envolvendo plantas trepadeiras, principalmente na região Neotropical, além de serem muito representativas em florestas estacionais semideciduais (Gentry, 1991).

Para a mesma região (Neotrópicos), vale ressaltar a família Asteraceae, como uma das que apresenta alta diversidade (Villagra e Romaniuc Neto, 2010; Scudeler et al., 2019). Uma possível explicação para esse fato é que geralmente os representantes dessa família são cosmopolitas e ruderais, e crescem, frequentemente, em locais onde a vegetação nativa foi descaracterizada por ações humanas, como, por exemplo, o desmatamento (Pereira et al., 2013).

Nos estudos da região Sul do Brasil destacaram-se Malpighiaceae, Fabaceae, Convolvulaceae, Passifloraceae e Asteraceae como as famílias com maior número de espécies (Durigon e Waechter, 2011; Carneiro e Vieira, 2012; Guerra et al., 2015; Gomes et al., 2018). Isso indica que, apesar de estarem na mesma estrutura vegetacional, a representatividade e a dominância de uma família ou táxon pode depender de outros fatores determinantes, como a paisagem, o relevo, o clima, a latitude e as interações com outras fitofisionomias.

Em comparação com o bioma Caatinga, visto que é o principal ecossistema da região Nordeste, Delgado Júnior e Alves (2017) realizaram um levantamento no Parque Nacional do Catimbau/Pernambuco, com catalogação de 101 espécies de trepadeiras, distribuídas em 54 gêneros e 18 famílias, sendo Convolvulaceae, Fabaceae e Apocynaceae as mais representativas. Isso mostra que Convolvulaceae e Fabaceae possuem uma ampla variedade ecológica, permitindo, consequentemente, uma ampla distribuição regional, mesmo sob diferentes condições ambientais e climáticas, além de ser uma vegetação mais aberta, o que favorece esse tipo de forma de crescimento das lianas e trepadeiras. Os números de espécies e gêneros encontrados pelos autores é superior ao registrado no presente estudo, no entanto, sabe-se que, de acordo com Van Der Heijden e Phillips (2009), as trepadeiras têm maior sucesso em áreas mais abertas e com período de seca mais extenso.

Levantamentos florísticos generalistas indicam que a representatividade das trepadeiras na Caatinga pode variar entre 5% (Araújo et al., 1999) e 23% (Pinheiro et al., 2010) em relação aos demais hábitos. Costa et al. (2007) diferenciaram áreas de Caatinga quanto à presença do hábito trepador. Para esses autores, as áreas mais secas (caatinga *sensu stricto*) têm menor riqueza de espécies que aquelas mais úmidas, bem como tipos vegetacionais que recobrem chapadas, bacias sedimentares e serras/maciços do semiárido. De acordo com a revisão de literatura, observou-se que, apesar dos estudos apontar a importância das lianas e trepadeiras na caracterização das fitofisionomias da Caatinga, poucos estudos florísticos têm consolidado o conhecimento específico da representatividade destas formas de crescimento no respectivo bioma e em quais fisionomias essas formas de crescimento podem ser consideradas um fator determinante.

Em um estudo realizado em remanescente de Mata Atlântica, no município de Moreno – Pernambuco, Oliveira et al. (2015), além de registrarem Convolvulaceae e Fabaceae como as famílias com maior número de representantes, destacaram Apocynaceae e Dioscoreaceae. Segundo os autores, as diferenças, quanto ao número de espécies e famílias de plantas trepadeiras nos estudos florísticos, podem estar interrelacionadas, pois muitas famílias botânicas são subestimadas e outras são identificadas apenas até o nível de gênero.

Segundo Hegarty e Caballé (1991), a diversidade de espécies depende do local onde os indivíduos foram coletados, pois, em ambientes com clareiras e em áreas de bordas, a diversidade aumenta, visto que em áreas com pouca ou ausência de perturbação ambiental, essas plantas contribuem com pouco mais de 5% da biomassa.

Os principais fatores que podem estar relacionados com a taxa de crescimento de lianas e trepadeiras em um determinado ambiente são: o aumento da taxa de pluviosidade (DeWalt et al., 2010; Van Der Heijden e Phillips, 2009); a luminosidade, principalmente em áreas de clareiras (Chettri et al., 2010), e os fatores físico-químico dos solos (Addo- Fordjour et al., 2016), que, de acordo com os últimos autores, alteram a fertilidade e disponibilidade de nutrientes.

Mais recentemente, Laurence et al. (2014) mencionaram três hipóteses para explicar o aumento da abundância de lianas nas florestas maduras. A primeira refere-se às estações secas que podem ter períodos mais longos nas regiões tropicais, possibilitando uma mudança regional e global do clima; a segunda, trata-se do aumento da taxa de gás carbônico atmosférico, que pode beneficiar as lianas, aumentando seu crescimento e fecundidade; e a terceira está relacionada à taxa de mortalidade das árvores e a dinâmica da florestas, o que aumenta as clareiras e beneficia o crescimento e estabelecimento de lianas e trepadeiras.

Dentre os gêneros mais representativos no PARNA Ubajara se destacaram *Calopogonium* / Fabaceae, *Dioscorea* / Dioscoreaceae, *Passiflora*/ Passifloraceae e *Serjania* / Sapindaceae, todos representados por três espécies cada. No estudo desenvolvido por Santos e Figueiredo (2018), na Serra de Uruburetama - Ceará, os gêneros *Centrosema*, *Dioclea* e *Ipomoea* foram citados como os de maior riqueza. Delgado Júnior e Alves (2018), em levantamento realizado no PARNA Catimbau - Pernambuco, os gêneros mais representativos, quanto ao número de espécies, foram *Ipomoea* (12) e *Jacquemontia* (6), seguidos de *Dioscorea* e *Serjania*, com quatro espécies cada gênero.

Quanto à forma de crescimento, 58,3% das espécies registradas no PARNA Ubajara são lianas e 41,7% são trepadeiras volúveis (Tabela 1). Essa grande quantidade de trepadeiras lenhosas (lianas) pode estar relacionada ao estado de conservação do PARNA Ubajara, uma vez que a vegetação está protegida no interior de uma Unidade de Conservação.

Chave de identificação das famílias com representantes de lianas e trepadeiras no Parque Nacional de Ubajara, Ceará, nordeste do Brasil.

1. Folhas compostas 2
2. Folhas opostas, sem estípulas 3
3. Corola gamopétala; estames didínamos; fruto cápsula .... Bignoniaceae
3'. Corola dialipétala; estames numerosos; fruto aquênio .... Ranunculaceae
2'. Folhas alternas, sem estípulas 4
4. Prefloração valvar; flores isostêmones .... Vitaceae
4'. Prefloração imbricada; flores diplostêmones 5
5. Estames diadelfos .... Fabaceae
5'. Estames livres .... Sapindaceae
1'. Folhas simples 6
6. Ovário ínfero 7
7. Planta com estípula interpeciolar .... Rubiaceae
7'. Planta sem estípula 8
8. Corola pentâmera 9
9. Plantas sem gavinhas; inflorescência em capítulo; ovário bicarpelar .... Asteraceae
9'. Plantas com gavinhas; flores solitárias ou paniculiformes, ovário tricarpelar 10
10. Flores sempre unissexuais .... Cucurbitaceae
10'. Flores bissexuais e estaminadas na mesma inflorescência .... Rhamnaceae
8'. Corola trímera 11
11. Folhas paralelinérveas; flores bissexuais .... Alstroemeriaceae
11'. Flores curvinérveas; flores unissexuais .... Dioscoreaceae
6'. Ovário Súpero 12
12. Plantas com gavinhas 13
13. Presença de androginóforo; inflorescência uniflora ou biflora .... Passifloraceae
13'. Ausência de androginóforo; inflorescência umbeliforme .... Smilacaceae
12'. Plantas sem gavinhas 14
14. Venação paralelinérveas; bainha fechada; flores trímeras .... Commelinaceae
14'. Venação reticulada; bainha ausente; flores pentâmeras 15
15. Corola gamopétala 16
16. Folhas alternas; estames com tamanho desiguais .... Convolvulaceae
16'. Folhas opostas; estames do mesmo tamanho .... Apocynaceae
15'. Corola dialipétala 17
17. Folhas opostas 18
18. Folhas pubescentes; cálice com nectários extraflorais .... Malpighiaceae
18'. Folhas com tricomas lepidotos; cálice sem nectários extraflorais ....
.... Combretaceae
17'. Folhas alternas 19
19. Flor com andróforo (tubo formado pela união dos filetes); ovário pluricarpelar
.... Malvaceae
19'. Flor sem andróforo; ovário tricarpelar .... Euphorbiaceae

Segundo Gentry (1991), as lianas se desenvolvem mais facilmente no interior das florestas, isto é, em áreas menos antropizadas, enquanto as trepadeiras volúveis estão em bordas ou regiões que suportaram antropização. Isso mostra que a vegetação do PARNA está bem preservada.

Araújo (2016) e Zhuo e Cao (2010) afirmaram que o aumento do número de trepadeiras em determinada área pode estar associado a expansão urbana, uma vez que ao ser retirada a vegetação nativa, dá espaço para outras plantas se desenvolverem, como as trepadeiras volúveis, causando uma fragmentação dos remanescentes em zonas urbanas. No estudo realizado em um fragmento de mata de Restinga no litoral da Bahia, Queiroz et al. (2012) constataram baixa riqueza de espécies, em comparação às outras áreas com vegetação similar. Os autores constataram que a fragmentação do ambiente e as alterações antrópicas impactaram, diretamente, a diversidade de trepadeiras dessa área.

Os resultados obtidos no PARNA Ubajara são semelhantes aos encontrados por Santos e Figueiredo (2018), que verificaram mais de 50% das espécies na Serra de Uruburetama - Ceará como lianas, assim como aos obtidos por Villagra e Romaniuc (2010), no estudo realizado no Parque Estadual das Fontes do Ipiranga, em São Paulo.

Diferentemente do observado no presente estudo, no levantamento realizado em um fragmento de floresta semidecídua em Minas Gerais, Vargas et al. (2013) encontraram que as trepadeiras lenhosas (lianas) foram as mais representativas, correspondendo a mais de 60% das espécies inventariadas. No estudo desenvolvido no Parque Estadual Porto Ferreira em Minas Gerais, em uma área de Cerrado, Vargas et al. (2018) registraram que 70% das espécies são trepadeiras lenhosas.

Estudos florísticos, envolvendo tal composição, podem fornecer subsídios para o melhor entendimento sobre aquecimento global, pois as lianas e as trepadeiras aumentam a densidade das florestas, reforçando a importância de estudos qualitativos e quantitavos (DeWalt et al., 2010; Schnitzer et al., 2012). Também podem funcionar como espécies indicadoras para as mudanças climáticas (Gerolamo et al., 2018). Segundo Cai et al. (2009), as lianas e trepadeiras em períodos secos, absorvem mais carbono e sofrem menos com esse estresse. Posteriormente, Marvin et al. (2015) constataram que essas formas de crescimento, mesmo em ambientes com baixa luminosidade e pobre em nutrientes conseguem sobreviver, devido a sua elevada capacidade de competição. Asner e Martin (2015) verificaram que, mediante o aumento de nitrogênio nas florestas tropicais, as lianas e trepadeiras, são as primeiras a responderem a tal mudança, devido ao aumento desse nutriente.

O conhecimento da flora de uma determinada área, através de levantamentos florísticos, são indispensáveis para o monitoramento das espécies e o entendimento da diversidade, auxiliando na compreensão de como os organismos se comportam dentro de um ecossistema (Burkmar, 2014). Segundo Meyer e Schwirkowski (2019), a lista de espécies estaduais é um processo contínuo, que está sempre em constante mudança. Espera-se que este seja um dos passos iniciais para dar continuidade aos estudos com foco nas trepadeiras lenhosas e volúveis do território cearense.

Portanto, os dados obtidos no presente estudo evidenciam a importância dos levantamentos florísticos sobre as comunidades de trepadeiras, elucidando o estado da arte sobre sua diversidade para o Ceará e apontam a importância da manutenção das Unidades de Conservação.

Considerações Finais

Apesar da diversidade de trepadeiras encontradas no PARNA de Ubajara ser baixa, em comparação a outros estudos realizados no Nordeste brasileiro, foram registradas 10 novas ocorrências para o Estado do Ceará.

O presente estudo evidenciou o bom estado de conservação em que o PARNA Ubajara se encontra e que a manutenção e a preservação dos ecossistemas em Parques Nacionais refletem positivamente em sua biodiversidade.

Considerando que das 60 espécies registradas no PARNA Ubajara, 51 (85%) não estão avaliadas quanto ao estado de conservação, segundo os critérios do IUCN, ressalta-se a importância dos levantamentos florísticos desses componentes pouco estudados, como as lianas e trepadeiras, especialmente para o Estado do Ceará.

Dessa forma, é possível reunir esforços para a preservação e a criação de políticas ambientais direcionadas à conservação dos ecossistemas florestais.

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6. PRÊMIOS

6.1. BEST SPEECH – 5th MEDPALYNOS SYMPOSIUM 2022

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This is to certificate that

SERGIO AUGUSTO XAVIER

was awarded with the best speech prize of the S5A
'Palaeopalynology'with the paper entitled:
“Changes in fire activity and biodiversity in a Northeast
Brazilian Cerrado over the last 800 years

”

Milano, 10th October 2022