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BRUNA MENDEL NAISSINGER

CONTROLES ABIÓTICOS DE UMA SAVANA AMAZÔNICA:
UMA ABORDAGEM DE SENSORIAMENTO REMOTO MULTISENSOR

BOA VISTA, RR
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Dissertação apresentada ao Programa de Pós-graduação em Recursos Naturais da Universidade Federal de Roraima, requisito parcial para a obtenção do grau de Mestra em Ciências Ambientais, na área de concentração: Manejo e Conservação de Bacias Hidrográficas.

Orientador: Prof. Dr. Stélio Soares Tavares Júnior.

Coorientador: Prof. Dr. Pedro Aurélio Costa Lima Pequeno.

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Prof. Dr. Stélio Soares Tavares Júnior

Orientador - Universidade Federal de Roraima UFRR

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Reinaldo Imbrozio Barbosa
Pesquisador Titular
INPA/Roraima

Prof. Dr. Reinaldo Imbrozio Barbosa

Membro – Instituto Nacional de Pesquisas da Amazônia INPA

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Membra – Universidade Federal de Roraima UFRR

Às meninas, futuras cientistas, dedico.

Questionem. Ocupem.

Resistam!

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que entre raiz e flor há um breve traço:
o silêncio do lenho,
entre a raiz e a flor, o tempo e o espaço.

(Jorge de Lima)

RESUMO

Savanas sustentam grande biodiversidade e altos níveis de endemismo de espécies, ocorrendo em todo o mundo, inclusive em meio à densa floresta Amazônica. Funcionam como áreas de recarga da bacia hidrográfica Amazônica, que, dada a dimensão continental, exerce um papel central no ciclo hidrológico. A despeito dessa importância, a saúde ecológica desses ecossistemas está ameaçada pela expansão do agronegócio e pelo avanço do aquecimento global. Os parâmetros que controlam a distribuição das savanas na Amazônia, em larga escala, ainda são poucos conhecidos. Este trabalho apresenta a verificação e a quantificação dos controles diretos e indiretos de variáveis abióticas na atividade fotossintética da vegetação, representada pelo Índice de Vegetação por Diferença Normalizada (NDVI) em uma série temporal de 5 anos, em um recorte que engloba a Bacia Sedimentar do Tacutu no Brasil, cuja origem e deposição está associada à evolução das Savanas da Guiana. As variáveis abióticas utilizadas foram litologias (rochas), formas de relevo, altitude, declividade, clima (precipitação e temperatura), frequência de inundação e parâmetros dos solos: Capacidade de Troca Catiônica (CTC), Estoque de Carbono Orgânico (ECO), Densidade Aparente e Percentual de Areia. Uma análise confirmatória de Modelagem de Equações Estruturais (SEM) foi aplicada para investigar as relações causais hipotéticas em um diagrama de caminhos. Nove imagens multiespectrais Sentinel-2 de 2017 a 2021, imagens de radar ALOS PALSAR e o modelo digital de elevação NASADEM foram utilizados para construir a frequência de inundação e a forma do relevo das planícies fluviais por meio do Modelo Linear de Mistura Espectral (MLME) e da fusão de imagens ópticas e de imagens de Radar de Abertura Sintética (SAR) em softwares livres. Os resultados mostraram que o NDVI variou 60% entre os períodos secos e úmidos. A configuração atual da paisagem, expressa predominantemente pela Formação Sedimentar Boa Vista e os produtos de seu retrabalhamento, dispostos em longas superfícies de aplainamento, resultantes de ciclos sucessivos de erosão e deposição, pontuado por relevos residuais (inselbergs) afetam indiretamente o NDVI, isto é, rochas e formas de relevo afetam os solos, que afetam o NDVI. As variáveis com efeito direto explicaram 48% da variação no NDVI, sendo que a densidade aparente teve o maior efeito devido à presença de horizontes coesos que dificultam o estabelecimento de raízes e a drenagem da água nos solos. Os indicadores de fertilidade (CTC e ECO) tiveram efeito negativo porque os solos são ácidos e com alto teor de alumínio permutável. O efeito da precipitação é positivo, e o efeito da frequência de inundação é negativo, sendo essas restrições hidroedáficas evidenciadas também pelo efeito positivo da concentração de areia nos solos. Essa abordagem demonstrou a relevância da evolução da paisagem, dos solos e do clima na distribuição espacial e temporal da cobertura vegetal.

Palavras-chave: Bacia Sedimentar do Tacutu. Radar de Abertura Sintética. MLME. SEM.

SUMÁRIO

1 INTRODUÇÃO

Savanas ocorrem pela complexa interação de processos bióticos, abióticos e antrópicos. No âmbito global, os principais controles são: água, fogo, solos, clima, herbivoria, coexistência, competição e facilitação de espécies e a história evolutiva das paisagens (LEHMANN et al., 2011). São compostas por um mosaico de distintas formações vegetais, reconhecidas pela alta razão entre espécies herbáceas e espécies arbóreas, alta riqueza de espécies herbáceas em pequena escala, alto endemismo, banco de sementes transiente, brotos persistentes, alta biomassa subterrânea, pouca acumulação de liteira e dosséis descontínuos e abertos (VELDMAN et al., 2015). O clima em que se desenvolvem é caracteristicamente seco durante praticamente metade do ano e bastante úmido durante a outra metade. O alto grau de endemismo e biodiversidade das savanas está associado aos padrões de herbivoria e de alterações do solo provocados pela fauna local, ao pastoreio de baixa intensidade, à existência de solos rasos, oligotróficos e com altas e por vezes tóxicas concentração de metais, bem como ao déficit hídrico sazonal e à ocorrência de incêndios naturais (VELDMAN et al., 2015). Estes dois últimos fatores acabaram por selecionar uma flora xerofítica, ou seja, adaptada às secas e incêndios através de xeromorfias como cascas, cutículas ou células epiteliais espessas, presença de sílica e/ou tricomas na epiderme, folhas hipoestomáticas, estômatos com cristas, mesófilos dorsiventrais, colênquima e feixes vasculares (MISTRY; BERADI, 2000; SIMIONI et al., 2017).

Embora raro, o fogo pode ocorrer de forma natural em paisagens savânicas durante a estação seca, principalmente porque as gramíneas proporcionam imensas quantidades de matéria orgânica altamente combustível quando desidratadas (BARBOSA; FEARNSIDE, 2005a,b; BARNI et al., 2015). Por esta razão, costuma-se dizer que as savanas são um tipo de vegetação à prova de fogo, porém, este é um mal entendido. Apesar das savanas terem experimentado incêndios naturais desde milhões de anos antes da chegada dos seres humanos, a escala e frequência dos incêndios antropogênicos nos últimos anos estão além da capacidade de resiliência das savanas. Esses incêndios têm resultado em sua desestruturação e perda de equilíbrio fitossociológico, principalmente de seu componente ripário (FLORES et al., 2021; GOMES et al., 2020).

As savanas brasileiras caracterizam-se por apresentar vegetação xeromórfica de clima estacional (períodos de seca e de chuvas) ou, mais raramente, ombrófilo, disposta em solos bastante lixiviados, oligotróficos, aluminotóxicos, com sinúsias de hemicriptófitos, geófitos, fanerófitos de pequeno porte (IBGE, 2012). O Sistema Brasileiro de Classificação da Vegetação reconhece dois tipos savânicos, as savanas propriamente ditas e as savanas estépicas, ambas podem ser subdivididas em Savana Florestada, Savana Arborizada, Savana Parque e Savana Gramíneo-Lenhosa (IBGE, 2012). Na região amazônica, as savanas se fazem presentes quer como grandes e contínuas áreas, quer como pequenas e descontínuas manchas, perfazendo cerca de 5% dos quase 6 milhões de km² do bioma amazônico (CARVALHO; MUSTIN, 2017; PENNINGTON; LEHMANN; ROWLAND, 2018). Elas são o lar de cerca de 40 espécies de plantas produtoras de sementes exclusivas do Brasil (DEVECCHI et al., 2020).

Muitos incêndios têm substituído a floresta amazônica por uma vegetação graminosa monoespecífica, que não deve ser confundida com a vegetação de savana, pois esta é mais complexa florística e estruturalmente (VELDMANN; PUTZ, 2011; HOEVE et al., 2012). Por muito tempo acreditou-se que as savanas amazônicas seriam o resultado do avanço de savanas externas (dos Llanos ao norte e do Cerrado ao sul) para os espaços deixados pela floresta amazônica quando esta recuava durante episódios glaciais quaternários. Entretanto, evidências recentes indicam uma origem autóctone, pois elas já estavam presentes no bioma amazônico muito antes do quaternário e há mais similaridade genética e florística dos elementos das savanas amazônicas entre si, do que entre eles e seus vizinhos externos (VELOSO et al., 1975; DEVECCHI et al., 2020; RESENDE-MOREIRA et al., 2018).

A Savana da Guiana, situada na fronteira entre a Guiana, a Venezuela e o Brasil, é a segundo maior área de savana do Bioma Amazônico, totalizando 68145 mil km² (BARBOSA; CAMPOS, 2011). Aproximadamente 62% dessa área está no Brasil, no estado de Roraima, onde é conhecida por “Lavrado”, configurando-se na maior porção contínua de savana amazônica do país. Em Roraima, a divisão entre savana e savana estépica é mais geográfica do que fitofisionômica (Miranda e Absy, 2000), sendo reconhecidos para ambos os tipos de savana os subtipos Savana Arbórea Florestada, Savana Arbórea Aberta, Savana Parque e Savana Graminosa, podendo ou não apresentarem Matas de Galeria, Manchas de Floresta e Veredas de

Palmeiras, destacando-se as veredas de Mauritia flexuosa (Buritizais) ao longo de muitos igarapés (VELOSO et al., 1975; BARBOSA; MIRANDA, 2005; BARBOSA et al., 2007).

O interesse científico pelas savanas tem crescido principalmente pelo fato de serem importantes focos de biodiversidade e por albergarem inúmeras espécies endêmicas, mas também pelo reconhecimento de que são importantíssimas zonas de recarga de aquíferos e estabilização de regimes hídricos superficiais (MILLER et al., 2012; VILLALOBOS-VEGA et al., 2014; CARVALHO; MUSTIN, 2017; FURLAN et al., 2020). A despeito de toda essa importância, as savanas do mundo têm sido alvo de crescente e predatória pressão exploratória e no Brasil a situação não é diferente (VACCHIANO et al., 2019). Dentre os problemas que assolam as savanas é possível citar a perda ou exclusão de espécies, a desestruturação, fragmentação de hábitats e comunidades nativas e a perda de tipos funcionais, cujas causas principais são as mudanças antrópicas nos padrões de uso e cobertura do solo, a introdução de espécies exóticas, o sobrepastoreio, a contaminação dos solos e águas subterrâneas por nitritos e nitratos de fertilizantes e compostos orgânicos nocivos de agrotóxicos, a intensificação dos regimes de fogo, a exploração irracional dos recursos hídricos e as mudanças climáticas globais (OSBORNE et al., 2018). Dentre os principais agentes causadores destes problemas pode-se citar a mineração e agricultura predatórias, o comércio ilegal de madeiras, o florestamento mal projetado e o crescimento urbano desordenado (VELDMANN et al., 2015; DURIGAN; RATTER, 2015; FERNANDES et al., 2016; CARVALHO et al., 2019).

No Brasil, esses problemas têm se pronunciado nos últimos anos, em particular a partir de 2006, quando produtores de soja e carne voluntariamente comprometeram-se informalmente junto ao governo brasileiro a não mais desmatar a floresta amazônica para a produção de suas commodities, envolvendo nesse acordo, inclusive, os demais entes das respectivas cadeias produtivas (GIBBS, 2015). Conhecido como “Moratória da Soja e da Carne”, este acordo tinha por meta diminuir o desmatamento e destruição da floresta amazônica e de fato conseguiu atingir estes objetivos enquanto durou, porém, acabou por deslocar as pressões antrópicas para as savanas brasileiras, principalmente para o Cerrado. Assim, enquanto as áreas degradadas de floresta amazônica lentamente se recuperavam, novas áreas degradadas eram geradas no Cerrado brasileiro, a taxas muito maiores do que as de recuperação de floresta. Como resultado, as áreas de savana passaram a comportar mais da metade das fazendas brasileiras, sendo sua maioria no Cerrado (SOUZA et al., 2020).

Com o tempo, a moratória foi sendo lentamente subvertida, adiada ou mesmo abandonada, de tal modo que, atualmente não é mais observada por nenhum dos agentes inicialmente envolvidos. O atual cenário político brasileiro tem resultado não só no retorno das pressões exploratórias e irracionais sobre a amazônia brasileira, mas também seu incremento em níveis que ameaçam a resiliência da floresta, incluso aí seus componentes savânicos (BARBOSA; FEARNSIDE, 2005a,b; BARNI et al., 2015; ALIX-GARCIA; GIBBS, 2017; FLORES et al., 2021; GOMES et al., 2020). Atualmente, este incremento está diretamente ligado às políticas de extrema direita do governo Bolsonaro, que tem atendido acriticamente todas as demandas de ruralistas, garimpeiros, madeireiros e mineradores. Também tem enfraquecido os instrumentos governamentais de gestão, monitoramento e fiscalização ambientais. Esse enfraquecimento se dá quer através de discursos e posicionamentos oficiais aberta ou veladamente desfavoráveis à questão ambiental, quer através do controle destes instrumentos por militares de alta patente que não têm a formação técnico-científico necessária para lidar com as questões ambientais (CARVALHO et al., 2019; FERRANTE; FEARNSIDE, 2019; SCHMIDT; ELLOY, 2020).

As savanas amazônicas estão profundamente ameaçadas pela expansão da fronteira agrícola, minerária e urbana para dentro de seus domínios. Um importante vetor de transformação e destruição das savanas amazônicas tem sido a abertura de estradas tanto para fins de melhoria da infraestrutura urbana e rural, como para escoamento da produção. Independentemente das estradas em questão, elas atuam como cabeça de ponte para a expansão da colonização humana e/ou das suas atividades exploratórias, resultando em mais desflorestamento e pressão por recursos naturais (BARNI et al., 2009; BARBER et al., 2014; FEARNSIDE, 2015). Quando associadas à exploração agrícola e/ou mineral, essas pressões tornam-se ainda maiores e podem degradar irreversivelmente alguns ecossistemas, comunidades ou populações amazônicas, incluindo aquelas das comunidades originárias (BANERJEE et al., 2021).

Em se tratando de savanas amazônicas, as consequências de incêndios antrópicos podem ser até mesmo catastróficas se eles queimarem toda a área de uma ecorregião (ALVES; PÉREZ-CABELLO, 2017). O manejo com fogo está ligado à maioria das práticas agrícolas observadas na savana, uma vez que ele é empregado tanto para limpar o material derrubado, quanto para limpar os resíduos de colheitas. Em ambos os casos, é bastante grande o risco de o fogo escapar para além das fronteiras agrícolas e causar danos às formações mais sensíveis (como matas ripárias e buritizais). Antigamente, incêndios naturais na região amazônica eram mais numerosos do que incêndios antrópicos, porém, ultimamente estes últimos ultrapassaram em muito o número de incêndios naturais (DONG et al., 2021; KELLEY et al., 2021).

Roraima tem enfrentado um significativo aumento da exploração em seu território, seja devido à sua natureza pródiga quanto à existência de recursos naturais de interesse econômico (biológicos, geológicos e humanos), seja devido ao aumento populacional expressivo que o estado vem experimentando – principalmente devido à imigração venezuelana, que responde atualmente por praticamente um quinto da população (FURLEY, 1994; VERAS, 2009; VERAS et al., 2012; DINIZ; LACERDA, 2014; ARAÚJO Jr.; TAVARES Jr., 2017). Em um estudo de 2011, identificou-se 1.986 km² de áreas antropogenicamente perturbadas nas savanas de Roraima, dos quais 82,2% nas áreas de vegetação aberta (savanas típicas) e 17,8% em seus ecossistemas florestais associados, sendo a abertura de estradas o principal vetor de destruição (BARBOSA et al., 2007; BARBOSA; CAMPOS, 2011). Até o presente momento, as principais formas de destruição da savana estão associadas à expansão da infraestrutura urbana e rural e, mais importante, à expansão da fronteira agrícola pelo agronegócio, que já utiliza mais de 22% das áreas de savana para a produção de commodities de alto valor agregado e alta demanda internacional, como soja, milho, algodão, madeira e carne (DINIZ; LACERDA, 2018; LIMA, 2020; MAPBIOMAS, 2022).

Como membro signatário da Convenção sobre a Diversidade Biológica (internacional) e tendo a ratificado, o Brasil está comprometido a cumprir uma série de ações e protocolos dedicados a promover o desenvolvimento sustentável, o que inclui a criação e implementação de um plano nacional para alcançar estes objetivos. Conhecido pelo acrônimo “EPANB” (Estratégia e Plano de Ação Nacionais para a Biodiversidade), o plano brasileiro tem cinco objetivos estratégicos com várias metas cada um, dentre as quais estão a redução das perdas de hábitats nativos e a recuperação de ecossistemas que proporcionam serviços essenciais (BRASIL, 2022). A exemplo das demais savanas do país, o Lavrado proporciona também inúmeros serviços essenciais, como, por exemplo, conter grande diversidade de espécies de fauna e flora, muitas das quais endêmicas (BARBOSA et al., 2007), ser o local de recarga de águas subterrâneas do Sistema Aquífero Boa Vista, responsável por 70% do abastecimento público do estado (WANKLER; SANDER; EVANGELISTA, 2012), ser o local de vida e desenvolvimento de comunidades originárias e ser o local de lazer e turismo da população roraimense (BARBOSA et al., 2007). O cumprimento das metas do EPANB passa pelo entendimento da estrutura e dinâmica dos meios biótico, físico e antrópico do Lavrado, o que está ainda sendo construído.

Frente ao exposto, urge a necessidade de estudos que visem ajudar a compreender e descrever as características da savana roraimense, bem como dos processos geológicos, geomorfológicos, pedológicos, hidrológicos e ecológicos que atuam na criação e manutenção da biodiversidade savânica, com destaque à dinâmica de interação entre o meio biótico e abiótico. Embora existam muitos trabalhos sobre a savana de Roraima, muito ainda resta por saber sobre esse frágil ecossistema. Seu uso sustentável passa pelo entendimento das características, relações e histórico envolvidos, sem o qual toda e qualquer tentativa de preservação pode ser em vão. Entender a savana roraimense é importante também para garantir a segurança hídrica e alimentar de muitos municípios do estado, uma vez que é nela em que os principais cultivos agrícolas de larga escala são feitos e em particular, da capital Boa Vista, cuja principal fonte de água vem do Sistema Aquífero Boa Vista.

Neste contexto, a presente dissertação tem por objetivo quantificar os efeitos diretos e indiretos de alguns determinantes abióticos na variação espaço-temporal do Índice de Vegetação por Diferença Normalizada (NDVI), em um recorte da savana de Roraima, Brasil, englobando a Bacia Sedimentar do Tacutu. Os controles com um suposto efeito indireto são as Rochas, as Formas de Relevo, a Altitude e a Declividade. Controles com suposto efeito direto são: Temperatura, Precipitação, Frequência de Inundação, parâmetros dos solos relacionados à fertilidade Capacidade de Troca Catiônica (CEC) e Estoque de Carbono Orgânico (SOCS) e os parâmetros dos solos relacionados à textura Densidade Aparente e Percentagem de Areia. As principais hipóteses são o efeito positivo da precipitação, CEC, SOCS e percentual de areia, e o efeito negativo da inundação e da densidade aparente. Além disso, é provável que rochas e formas de relevo controlem indiretamente o NDVI, uma vez que a distribuição da vegetação tem sido relacionada à dinâmica sedimentar quaternária em outros locais da Amazônia.

2 ABIOTIC DRIVERS IN AN AMAZON SAVANNA USING MULTISENSOR REMOTE SENSING

Bruna Mendel
Stélio Soares Tavares Júnior
Pedro Aurélio Costa Lima Pequeno
PRONAT UFRR
brunamendeln@gmail.com

ABSTRACT

Savannas support great biodiversity and high levels of species endemism, occurring worldwide, including in the midst of the dense Amazon rainforest, where they play an important role as recharge areas for the Amazon watershed, which, given its continental dimensions, plays a central role in the hydrological cycle. Despite their importance, the ecological health of these ecosystems is threatened by the expansion of agribusiness and the advance of global warming. The parameters that control the large-scale distribution of savannas in the Amazon are still poorly understood. This paper presents the verification and quantification of direct and indirect controls of abiotic variables on the photosynthetic activity of the vegetation, represented by the Normalized Difference Vegetation Index (NDVI) in a time series of 5 years, in a clipping that includes the Tacutu Sedimentary Basin in Brazil, whose origin and deposition is associated with the evolution of the Guiana Savannas. The abiotic variables used were lithologies (rocks), landforms, altitude, slope, climate (precipitation and temperature), inundation frequency, and soil parameters: Cation Exchange Capacity (CEC), Soil Organic Carbon Stock (SOCS), bulk density, and sand percentage. A confirmatory Structural Equation Modeling (SEM) analysis was applied to investigate hypothesized causal relationships in a path diagram. Nine Sentinel-2 multispectral images from 2017 to 2021, ALOS PALSAR radar images and NASADEM digital elevation model were used to construct the Flood Frequency and relief shape of the river plains by means of Linear Spectral Unmixing (LSU) and fusion of optical and Synthetic Aperture Radar (SAR) images in open source software. The results showed that NDVI varied 60% between dry and wet periods. The current configuration of the landscape, expressed predominantly by the Sedimentary Formation Boa Vista and the products of its reworking, arranged in long planing surfaces, resulting from successive cycles of erosion and deposition, punctuated by residual reliefs (inselbergs) indirectly affect the NDVI, that is, rocks and relief forms affect the soils, which affect the NDVI. The variables with direct effect explained 48% of the variation in NDVI, with bulk density having the largest effect due to the presence of cohesive horizons that hinder root establishment and water drainage in soils. The fertility indicators (CEC and SOCS) had a negative effect because the soils are acidic and with high exchangeable aluminum content. The effect of precipitation is positive, and the effect of flood frequency is negative, and these hydroedaphic constraints are also evidenced by the positive effect of sand concentration in the soils. This approach demonstrated the relevance of landscape evolution, soil, and climate on the spatial and temporal distribution of vegetation cover.

Keywords: Tacutu Sedimentary Basin, SAR, LSU, SEM.

1. INTRODUCTION

Natural grassland vegetation is a common feature of the world, occurring from tropical climatic belt to temperate regions. Covering approximately 33 million km^2, savannas are a biome with xerophytic nature that is characterized by a mosaic of grass and forest ecological formations (Fernandes et al., 2016), with a predominance of C4 herbs and species tolerant to fire and light (Ratnam et al., 2011). In the Amazon, savannas occur within the Amazon Rainforest, generally as small discontinuous areas, like those of Suriname, French Guyana, and the Brazilian states of Amapá, and Pará, but also as a single, and large continuous area (68.145 km^2) on the triple border between Brazil, Guyana, and Venezuela. Of this triple frontier area, 62% is in Brazil, particularly in the Roraima state, where this ecoregion is known as “Lavrado” (Barbosa and Campos, 2011; Barbosa and Miranda, 2005; Barbosa et al., 2005; 2007).

Savannas are historically linked to regional climatic dry seasons and occurrences of natural and human-induced fire (Pivello, 2011; Walker, 1987). These conditions have selected tree species of cork bark, herbaceous species with dense and hairy sheaths buds, and species with physical and chemical deterrents to avoid herbivory (Mistry and Beradi, 2000). The occurrence of savannas is determined by complex interactions involving species functional characteristics, species coexistence, competition and facilitation, herbivory pressure, climate, resource availability, fire regimes (Hoffmann et al., 2012; Lehmann et al., 2011; Oliveras and Malhi, 2016), soil nutrients (Lloyd et al., 2008), cation exchange capacity and the balance between evaporation, and soil water storage (Veenendaal et al., 2015). Until now, remains unknown the exact relationships between these drivers, the order of importance of each variable, how growth rates occur across environmental gradients, and how the savanna transitions to another vegetation type (Archibald et al., 2020; Lehmann et al., 2014).

On a global scale not only the determinants of the occurrence of savannas vary, but also their magnitudes. Lehmann et al. (2014) believe that evolutionary history and regional environmental differences are the likely drivers of functional relationships between woody vegetation, fire, and climate across continents. In Amazonia, this evolutionary and biogeographic history of the biotic and abiotic drivers of savanna becomes even more evident when one considers its geological and geomorphological development through time, where the drivers are inextricably linked together through a sequence of ecological and evolutionary feedbacks whose history goes back at least to the Miocene, with emphasis on the Quaternary (Higgins et al. 2011; Rossetti et al. 2019a, b).

Savannas are largely ignored in the world's sustainable development agendas, despite being under serious threat from ongoing degradation, mainly by the expansion of agribusiness, urbanization, exploitation for natural resources and the rising of the atmospheric CO_2 due the climate change (Bardgett et al., 2021; Lehmann and Parr, 2016; Pennington et al., 2006; 2018). In Brazil, half of the arable land is in their savannas, and because of that, it is one of most threatened ecosystems of the country (Souza et al., 2020). In Roraima, the savannas have faced great anthropogenic pressure not only the urban and rural family farming development and urban expansion, but mainly for extensive agribusiness exploration which has already used 22% of the savanna areas for the to road construction, planting of soy, maize, cotton and meat, commodities of high added value and international demand (Araújo Jr. and Tavares Jr., 2017; Barbosa and Campos, 2011; Diniz and Lacerda, 2018; Lima, 2020; MapBiomas, 2022; Veras et al., 2012).

Due to their great biodiversity and their high levels of species endemism, as well as their fundamental role as aquifer recharge zones, the importance of the world's tropical savannas has been increasingly recognized (Carvalho and Mustin, 2017; Furlan et al., 2020; Miller et al., 2012; Villalobos-Vega et al., 2014; Wankler et al., 2012). Understanding how savannas shape themselves under different environmental constraints and in landscapes with different evolutionary histories has provided important insights into the distribution of species, especially in transition areas with forests, which are particularly sensitive to environmental changes (Murphy and Bowman, 2012). In this context, where the functioning of savanna ecosystems is deeply threatened by climate change (Matías et al., 2021; Ramos et al., 2021), efforts to quantify the drivers have been made at different scales, and for large areas, open databases and remote sensing are indispensable tools (Hill Sources, 2021).

Thus, although the savanna of Roraima has similarities with savannas elsewhere in the world and in Brazil, it is important to study its specific local and regional abiotic controls because its evolutionary history and elements is unique. To quantify the influence of abiotic determinants of the greenness in an Amazon savanna, this paper shows a qualy-quantitative methodology of measurement and comparison of some abiotic variables in the spatio-temporal variation of the Normalized Difference Vegetation Index (NDVI) in the region of Tacutu sedimentary basin (Roraima, Brazil). The variables with indirect effect analyzed were Rocks, Landforms, Altitude, and Slope, and the predictors with direct effect were Temperature, Precipitation, Flooding Frequency, and the soils parameters: Soil Cation Exchange Capacity (CEC), Soil Organic Carbon Stock (SOCS), Soil Bulk Density (Density) and Soil Sand Percentage.

The main hypotheses related to the analysis are: (1) There is a high variation of NDVI throughout the year (Xaud et al., 2009); (2) Geology and geomorphology affect indirectly the NDVI, since vegetation has been related to recent sedimentary deposition elsewhere in the Amazon (Cordeiro et al., 2016; Higgins et al. 2011; Rossetti et al. 2019a, b); (3) Although savannas in South America are not as affected by rainfall in the same way as in Africa and Australia are (Lehmann et al. 2014), a strong effect of precipitation is expected to be found here, as rainfall is voluminous and concentrated in a few months, followed by long dry periods (Barbosa et al., 1997); (4) Flooded areas exert a limiting effect on NDVI (negative relationship) (Tao et al., 2016; Oliveira et al., 2019) and (5) There is a high positive relationship between the soil fertility and NDVI (Lloyd et al., 2008; 2009).

2. MATERIAL AND METHODS

2.1. LOCATION AND SAMPLING

With 9,676 km², the study area is located along a SW-NE axis that extends from the capital Boa Vista to the city of Bonfim, Roraima state, Northern Amazonia. The study area was delimited by the extrapolation of the Brazilian portion of the Tacutu sedimentary basin, that extends to Guyana, according to the limits proposed by Hahn et al. (2012), being the limits of the first represented by a red polygon and the basin area represented by an orange filled polygon (Fig. 1). The present work proposes to measure the direct and indirect effects of abiotic variables in the vegetation vigor variation in this predominantly savanna region. The studied area included less than 10% of forest, but their effects on the analyses conducted here can be neglected, since the savanna-forest limits are not necessarily abrupt (many times they take place gradually), and there are many patches of forested savannas or even non-savannic forest inside the savanna area itself (IBGE, 2012; Meneses and Costa, 2012; Silva et al., 2022).

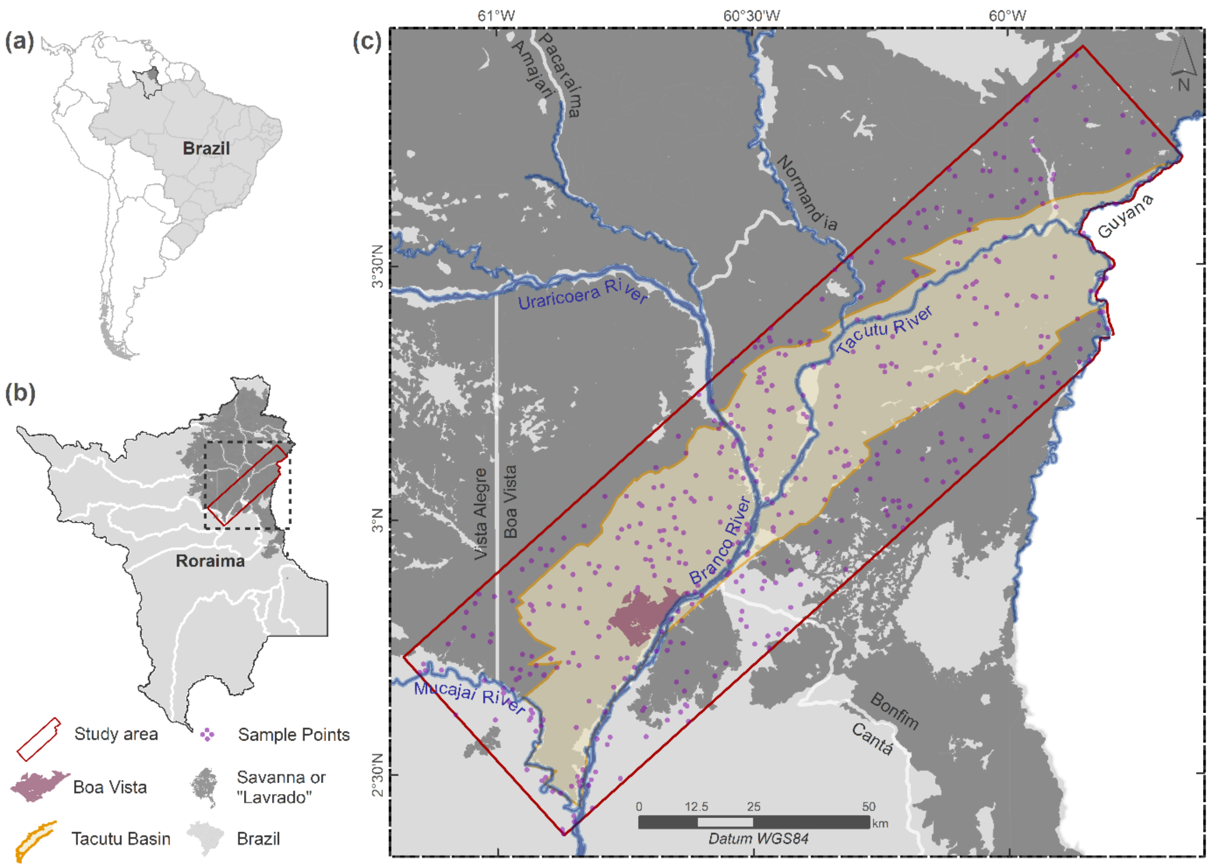

Fig. 1. Location Map: (a) Brazil, South America, (b) Roraima state and (c) Study area (red polygon) in the savannas (BDIA, 2021) of the Brazilian portion of the Tacutu Sedimentary Basin (Hahn et al., 2012), with emphasis on sample points indicated by the purple dots.

The analyzes conducted here were based on data extracted from 500 points randomly distributed in the studied area (Fig. 1), in a way that at least 25% of the points were representative of the floodplain and frequently flooded areas. To include the climatic seasonality through time, a historical series of nine dates between 2017 and 2021 were used, and in each one the same 500 points were used for extracted the data, totalizing 4.500 sampling units. For each one of the sample points, 18 variables were extracted, one NDVI biotic response variable, and 17 abiotic variables: precipitation lag times (4), temperature lag times (4), flood frequency (1), altitude (1), slope (1), geomorphology (1), geology (1), and soils parameters (4). The four lag times correspond to one to four months of accumulated precipitation and average temperature. The four soil parameters used were: soil bulk density, cation exchange capacity, sand, and soil organic carbon stock. Thus, the NDVI, flood frequency, precipitation, and temperature were time and space variables, while all other variables varied only in space. The extraction methods of each one of these variables will be described separately in the following topics.

2.2. SAVANNA VEGETATION

Two great savanna vegetation groups are recognized in Amazon Biome, the savanna itself and the steppe savanna, both with grassland, parkland, open woodland and woodland subgroups which may or may not present a gallery of palms along streams (Barbosa et al., 2007; IBGE, 2012). Miranda and Absy (2000) observed that the distinction between these two great groups is more geographical than phytosociological and they not described steppe savanna in Roraima.

In the area studied here, only the parkland and the grassland are recognized (Barbosa et al., 2007). The parkland savanna shows a physiognomy characterized by patches of woody elements and the grassland savanna is characterized by a predominant grassy stratus where may have wood and wood shrub species of small size in some cases. Besides, there are another vegetation formations too, as forest islands (usually circular), gallery forests at river and streams ("*igarapés*") and palm swamps of *Mauritia flexuosa ("Buriti")* along small seasonal streams (Barbosa and Miranda, 2005; Santos et al., 2013). The extrapolated study area ended up encompassing some tropical seasonal rain forests too (<10%).

For the analysis proposed here, the vegetation was represented by an index, and the savanna was treated as a unity, that is, no distinctions were made between their internal subgroups, mainly because there is not a good spatial resolution in the maps available and doing such mapping job is beyond the scope of this paper. By the same reasons, no distinctions were made between the woody and grassy elements of the savanna.

The Normalized Difference Vegetation Index (NDVI) was applied to the high spatial, spectral, and temporal resolutions Sentinel-2A images, acquired by multispectral instruments of identical satellites that operate in the same orbit and that went launched by the European Space Agency (ESA) on June 23, 2015 (Sentinel-2A) and on March 7, 2017 (Sentinel-2B). The images captured by the Sentinel-2 sensors have significantly contributed to the advance of the global vegetation knowledge, including pointing seasonal differences in savannas (ESA, 2018; Macintyre et al., 2020; Misra et al., 2020).

Whole images with low cloud interference were selected in each one of the four tiles needed to cover the area, namely the T20NQJ, T20NQH, T20NRK and T20NRJ from 2015 to 2021 temporal series. Although the satellites revisit interval is a few days, only nine dates fulfillment the low cloud cover condition for the complete mosaic of the area, an expected result to tropical regions, especially in the Roraima savanna, where the rainy season shows a bigger cloud dominance than the Central and South Amazon (Petri et al., 2019). Previous historical series studies in Roraima savanna showed that the higher and the lower NDVI values were closely related to wet and dry periods respectively (Gurgel et al., 2003; Xaud et al., 2009). The 32% variation in the NDVI of this phenoregion is the third highest already recorded in the whole Amazon region (Silva et al., 2013).

The nine Sentinel-2 images Level 1C used were: 02/15/2017, 02/20/2018, 09/18/2018, 10/08/2018, 04/01/2019, 09/13/2019, 03/26/2020, and 03/21/2021. The images were converted to surface reflectance (BOA) Level 2A through the SNAP 8.0

Sen2Cor plugin, an open platform developed by ESA for Sentinel products applications. The red and infra-red bands of Sentinel-2 are the B8 and B4 bands, with 10 m of spatial resolution and wavelength centered on 842 and 665 nm respectively. So, the NDVI calculus was realized according to the following equation: $NDVI = B8-B4/B8+B4$. Their product can be interpreted as the vegetation vigor measure or cover density, where values close to +1 correspond to dense and greenish vegetation covering.

2.3. DIGITAL ELEVATION MODEL

A Digital Elevation Model (DEM) was used to determine the drainage systems, altitude, and slope. To obtain a better DEM for the studied area comparisons were made between the Panchromatic Instrument ALOS AW3D30 DEM (Tadono et al., 2014) and the v.3 interferometric radar of Shuttle Radar Topography Mission (SRTM) DEM (Farr et al., 2007), and their derivations DEM ALOS PALSAR (PALSAR, 2015) and NASADEM (Crippen et al., 2016). This comparison was made by DEM subtraction to identify inconsistencies in the differences between the models, and the possible processing errors resulting from the application of global models to specific study areas, as pointed out by Grohmann (2018).

The biggest inconsistencies were in the ALOS PALSAR DEM, that is the SRTM pixels resampling from 30 to 12.5 m made originally to orthorectify the ALOS PALSAR radar images, whose vertical accuracy has not been tested. The AW3D30, SRTM and NASADEM models have similar vertical accuracy (proximately 5, 7, and 5.3 respectively), and AW3D30 seems to perform better in low relief areas, but in the area studied here, it shows some noises, as their optical sensor was probably affected by the frequent presence of clouds over this region (Mudd, 2020).

The SRTM and NASADEM showed little differences, and the latter was chosen because it is an improved DEM whose altimetric precision was reprocess and validated. NASADEM was project for Universal Transverse Mercator plan coordinates through cubic convolution interpolation (Mudd, 2020), and then it was used for drainage extraction on TerraHidro, an open-source tool developed in the C++ language for hydrologic modeling (Rosim et al., 2003; 2008).

2.4. SURFACE WATERS

The drainage system of the Roraima savanna region is composed of an intricate network of rivers, streams (igarapés), grassy swamps, buritizais (buriti palm streams), and lakes. The drainage system has a predominant dendritic pattern in the SW portion of the area and a parallel to a rectangular pattern in the central and NE portion, showing a clear tectonic influence, in the form of rivers and streams captured by the Mesozoic fault system associated with the formation of the Tacutu Basin and which were reactivated in the Pleistocene by the syneclise formation processes that gave rise to the Cenozoic covers of the area (Holanda et al., 2014, Nascimento et al., 2014). In addition to the predominant drainage patterns aforementioned, trellis, radial, and annular patterns are also observed.

The main rivers in the study area are the Tacutu, Uraricoera and Branco. The Tacutu river originates in the Uaçari Hills, Guyana, in the tropical forest region and goes North to the savanna region. Close to Conceição do Maú (3°33’ N, 59°52’ W), it receives the waters of the Maú River and curves to the Southwest. Approximately 60 km ahead (3°22’ N, 60°19’ W), it receives the waters of Surumu River and at 45 km ahead (3°01’ N, 60°29’ W) it joins the Uraricoera River to form the Rio Branco River, keeping the Southwesterly direction until reaching the Rio Negro River (1°23’ S, 61°50’ W), far from the Tacutu Basin Southwestern limit (2°26’ N, 60°50’ W).

The hydrological year of this drainage systems responds to seasonal climatic periods, with approximately one month interval of basin lag time. The Rio Branco discharge has high amplitude: in July (wet season), during the flooding period, the river reaches 7,000 $m^3 s^{-1}$ and in March (dry season), during the ebb period, reduces to 1,000 $m^3 s^{-1}$, and the linimetric quotas can oscillate up until 6 meters (Carvalho et al., 2021; Sander et al., 2008; 2015a, b).

Groundwater resurgences are very common and numerous, and it results in ponds or lakes. Most of these ponds are temporary, and the lakes are often perennial. In the wet season, the ponds and even some lakes can connect each other, forming an intricate network of small streams with shared springs. Most of these lakes are shallow, typically up to 2.5 m deep and their margins and other shallow parts used have aquatic sedges (Cyperaceae) while in the deepest parts can be found some floating leaves water lilies (Nymphaeaceae). Most of the lakes show an elevated central zone formed by the sedimentary substrate remobilization during the surge of the waters (Meneses et al., 2007; Sander et al., 2012; 2015a, b).

The studied area contains different sedimentary facies reworked and still in formation (Latrubesse and Nelson, 2001; Menezes and Wankler, 2020). From all environmental and sedimentary facies of an alluvial plain (Miall, 2006; Charlton, 2007), only the floodplains were discretized and used in the analyzes conducted in this work. For the objectives proposed here, the floodplains refer to the whole area of the river channel plus the area formed by alluvial deposits, whether or not flooded by the river overflow, the floodplains do not include areas flooded by lake overflow (lacustrine plains). On the other hand, Flooding Frequency rates were generated for all areas without distinction between their geomorphology unities.

2.5. FLOOD FREQUENCY

Considering the nonexistence of systematic mapping of the recurrent flooding areas, the Flood Frequency was mapped here. The same nine images of NDVI analyzes were used, and 12 bands were considered: blue, green and red of the visible spectrum, near-infrared with 10m of spatial resolution, the bands of the red edge, and the short-wave infrared with 20m. Initially, the 1C Level images were converted to 2A level images, next they were resampled from 10 m to 20 m to preserve the spectral information (Fig. 2). The Linear Spectral Unmixing (LSU) model was applied, and to their elucidating, it is necessary to consider that the instantaneous field of view projected by the optical system of the sensor determines the size of the smallest object that can be identified in an image since only objects with a size greater than the spatial resolution are identified by definition. The satellite sensors record the interaction of electromagnetic radiation with multiple components of the resolution elements of the terrain, geometrically expressed by the pixel, whose values vary within a gray level scale (2^n bits, where n is a function of the radiometric resolution) (Meneses and Almeida, 2012). So, each pixel shows the reflectance integrated sum of all contained objects, that is, the spectral responses of components are mixed in the pixel. If these responses are known and considering the mixture as a linear combination, then it is possible to estimate the proportion of the mixed objects (Holben and Shimabukuro, 1993; Shimabukuro and Ponzoni, 2017).

In each image endmembers were selected, that is, unmixed pixels containing exclusively vegetation, water or soil from which the LSU tool Unmix 1.1 of SNAP 8.0

returned three abundance images with the probable proportion (0 to 100%) of these components in each studied date. The 60% threshold was applied in the water abundance image to discretize the water (Fig. 2a, b), and the resulting binary image indicates the water absence (0) or presence (1). Sentinel-2's automatic cloud mask has been applied. The binary images of the nine dates were sum (Zani and Rossetti, 2012). The main NASADEM extracted drainage was added to this sum, so a flooding relative frequency gradient was obtained. For the product assessment, areas with high, average, low or zero flood frequency were represented by 20 plotting points each, totaling 80 points. These points were visually checked in the RGB color composition images, and the information about the water presence (Fig. 2c) or absence (Fig.2d) was tabulated, and their sum was compared to that of LSU product.

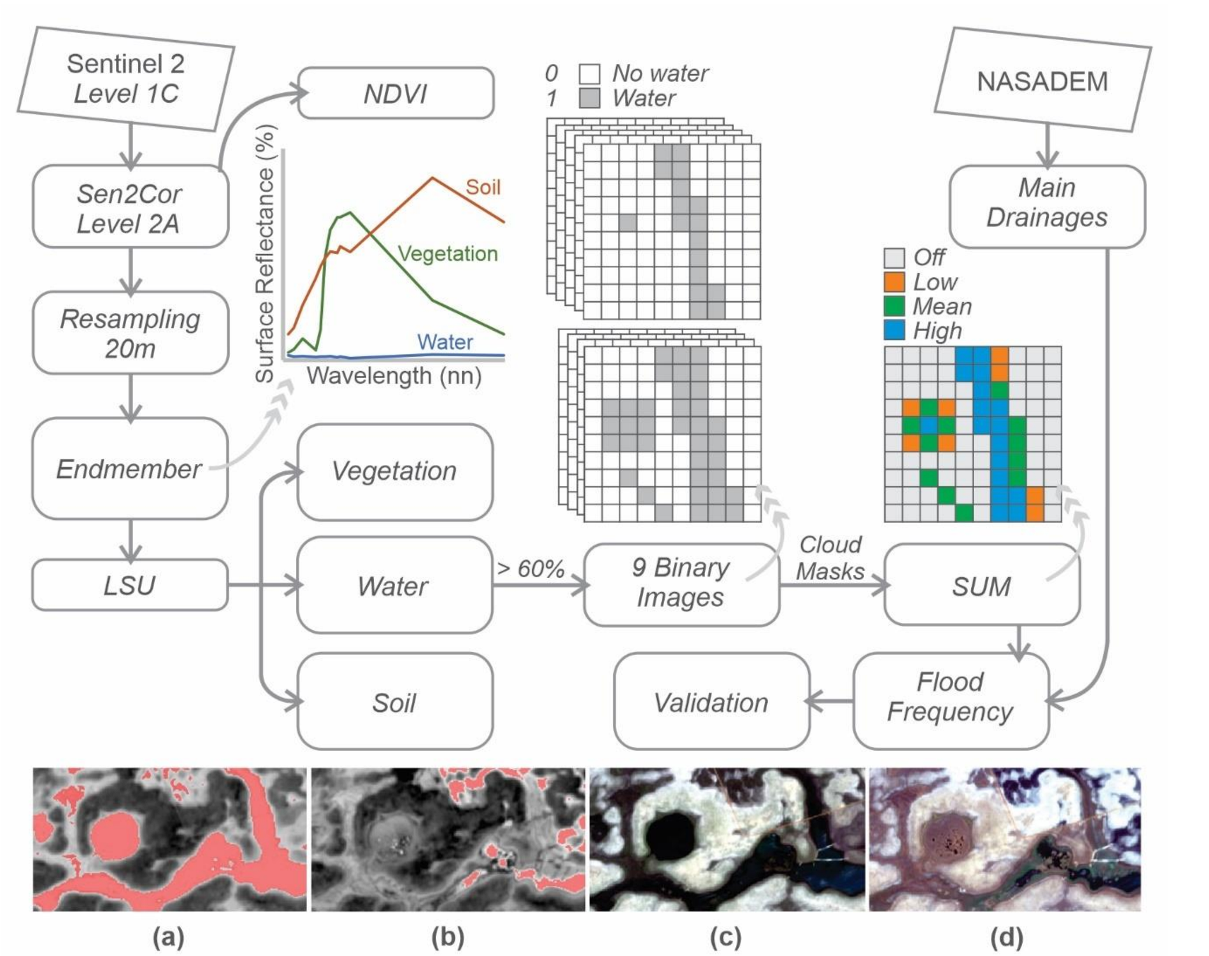

Fig. 2. Linear Spectral Unmixing flowchart applied to the determination of flood frequency. Water abundance in the wet (a) and dry (b) periods with 60% threshold for discriminating water (highlighted in pink). Example of the visual check performed for validation in wet (c) and dry (d) situations (notice the circular temporary lake).

2.6. FLOODPLAIN

Considering the importance of vegetation associated with floodplains, including those on smaller rivers (Drucker et al., 2008), these features were delineated here by merging optical and microwave images. Two images from different sensors were combined to form a new hybrid image via principal component analysis (Kulkarni and Rege, 2020; Mahyoub et al., 2019), with adaptations to the technique to highlight fluvial morphologies (D'Addabbo et al., 2016; Souza Filho and Paradella, 2005; Ward et al., 2014). SAR images can penetrate cloud cover and are independent of daylight

(Moreira et al., 2013; Shao et al., 2020), an alternative in the face of the difficulty in obtaining satellite images of tropical forests where high precipitation rates and cloud cover compromise optical multispectral images (Sanchez et al., 2020).

Alos Palsar and Sentinel-2A were employed as SAR and optical data, respectively. The Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) instrument operated in the L-band (1.27 GHz) producing day and night observations in a Japan Aerospace Exploration Agency (JAXA) mission between 2006 and 2011 that are available on the Alaska Satellite Facility platform (https://asf.alaska.edu/). In this study, the PALSAR images used are complex single look Level 1.1 data of Fine Beam Dual (FBD) imaging mode with HH and HV polarization (horizontal transmission with horizontal reception and horizontal transmission with vertical reception), 20m spatial resolution, acquired in 2009, date and orbit: 03/07:18322, 15/07:18497, 20/07:18570, 01/08:18745 and 18/08:18993. The pre-processing steps were performed in Sentinel Application Platform (SNAP) 8.0 software (Fig. 3a). Initially, deskewing was performed to bring the images to center doppler zero, multilooking to adjust the pixel dimensions, Lee filter with 5 x 5 window size to reduce speckle noise, Range-Doppler terrain correction with DEM ALOS PALSAR, radiometric calibration to obtain the scattering coefficients in dB ($\sigma H H$ 0 and $\sigma H V$ 0) and finally mosaicking and clipping of the study area. Sentinel-2A optical imagery was acquired on March 1, 2020, Level 2A, already at Bottom Of Atmosphere reflectance. SAR and optical images were registered in TerraView 5.5.2 software, with Root Mean Square Error (RMSE) less than one pixel.

In TerraView 5.5.2 the Sentinel 2A images were mosaicked and cropped, then PCA was applied to transform the multispectral images into new components with high spectral variance (Fig. 3b). The PCA was performed for the visible (PCA-1: bands 2 to

4), shortwave infrared (PCA-2: bands 11 and 12) and near-infrared and red edge (PCA 3: bands 5 to 8A) band sets, the first component of each was used to generate an RGB image, which was transformed to the IHS color space (intensity, hue and saturation) and in the inverse transform the vector I was replaced by the Alos Palsar image, thus resulting in the hybrid image. The hybrid image was segmented by region growth, the segments were sorted by k-means, and finally, the floodplain polygons were manually edited.

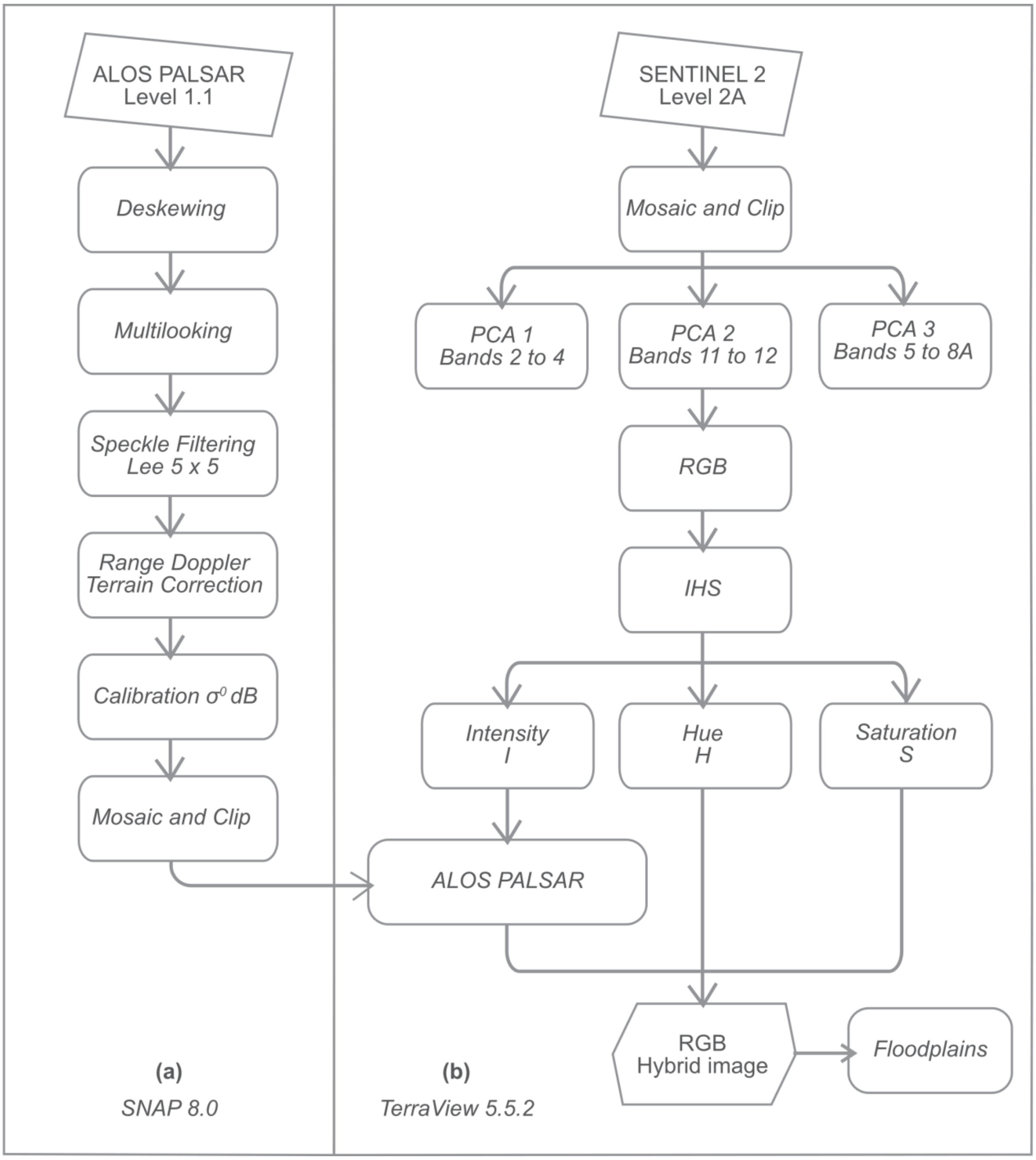

Fig. 3. Floodplains flowchart: (a) Preprocessing in SNAP 8.0. (b) Fusion in TerraView. 5.5.2.

2.7. CLIMATE

According to Köppen-Geiger, the climatic type of the region is the Savannic – Aw, which is characterized by dry (October-March) and wet (April-September) periods well distinct, locally known respectively as “summer” and “winter”. Only 10% of the annual rains (~1500 mm) occur during the dry period, the remaining 90% are concentrated in the wet period, being more than half during the May-July interval (Barbosa, 1997). The climate is hot and humid, with an average temperature of 25 °C, generally being January the driest month, with precipitations below 60 mm (Meneses et al., 2007). The cyclic Pacific warming (El Niño) and cooling (La Niña), as well as the global climate change caused by burning fossil fuels have affected the rainfall intensity and the water regime, in Roraima this effect also intensifies the risks of flooding and fire (Barni et al., 2022).

The climate data were obtained from the Global Land Data Assimilation System (GLDAS) by National Aeronautics and Space Administration (NASA), which uses advanced and robust modeling technics of assimilation and integration of remote and terrestrial meteorological data to give consistent temporal products of the Earth surface. The temporal resolution of the acquisition is three hour and daily, the months subproducts are generate by the temporal mean of three hour data and made available with 0,25° x 0,25° of spatial resolution, i.e., with a pixel of approximately 0.9 km (Beaudoing and Rodell, 2020).

The temperature and precipitation data were organized to consider the climatic annual and historical series, for which the dates used were the same those used to NDVI and Flood Frequency. In a 26 years interval for the all Amazon region, Silva et al. (2013) found the best correlations between precipitation and NDVI response in precipitation lag-times of three months, but to the specific regions of savanna the better responses occurred in lower lag-times. Thus, the accumulated precipitation for one, two, three and four months of precipitation lag-times were used, as well as the mean temperature (°C) for each one of these same lag-times.

2.8. GEOLOGY AND GEOMORPHOLOGY

The study area encompasses the entire Brazilian portion of the Tacutu sedimentary basin. With up to 300 km in length in the NE-SW direction and 50 km in width, the basin is in the central portion of the Guyana Shield being part of it in Brazil (4,500 km^2) and part of Guyana (7,000 km^2) – where is called North Savannas Rift Valley Basin (Silva and Porsani, 2006). Their origin is related to the rifting processes associated with the Pangea breakup in the Juro-Cretaceous that in the Central Atlantic region split the Northwest of the old Gondwana from the Southwest portion of the old Laurasia (Zalán, 2004). The breakup of Pangea also initiated the Andean orogeny, whose progressive uplift culminated in the reversal of the direction of vergence of the Amazonian watershed during the Miocene (Albert et al., 2018; Cediel et al., 2003). It is speculated that the Rio Branco then completely changed its drainage system, in which the rivers ceased to flow from the Guiana Shield towards the Caribbean Sea, to flow towards the Rio Negro and ultimately the Atlantic (Cremon et al., 2016).

During the initial Pangea breakup phase and establishment of the Tacutu Half-graben, tholeiitic basalts and andesites extruded around 150 Mya and formed what today is known Apoteri Formation (Eiras et al., 1990; Reis et al., 2006). This large space of accommodation generated gave rise to what is now known as the sedimentary Tacutu Basin, which from the base to the top was filled by the following sedimentary sequences: Manari Formation, Pirara Fm, Tacutu Fm and Tucano Fm (Vaz et al., 2007).

The Manari sits discordantly on the Apoteri, and it is constituted by fine siliciclastic materials as siltstones, shales and locally calcisiltstone and dolomites deposited in Thitonian lacustrine environments (Crawford et al., 1985; Eiras et al., 1990). The Pirara sits discordantly, and it is constituted by evaporitic halite in the central basin area and shales, siltstones and carbonates in the basin margins, deposited in lacustrine and sabkha plains (Silva and Porsani, 2006). The Tacutu sits discordantly, and it is constituted predominantly by siltstones, sometimes calciferous, sometimes clayish, and secondarily by sandstones, carbonates or shales, deposited in shallow lacustrine environments during the Berriasian-Barremian interval (Crawford et al., 1984; Santos et al., 2016; Souza et al., 2010; Hammen and Burger, 1966). The Tucano rest concordantly and it is constituted by sandstones with or without kaolinite and sometimes intercalated siltstones deposited in fluvio-lacustrine environments during the Barreminan-Albian interval (Reis et al, 1994; Cruz et al., 2019). Although the Tacutu formation outcrops along some portions of the Arraia and Tacutu rivers, only the Apoteri and Tucano formations are detectable at the map scale used here to the studied area, covering approximately 1.7 and 4.1% of the area, respectively (Holanda et al., 2014).

Long after the end of the Tacutu Basin infill, neotectonic reactivation of the faults during the Pleistocene gave rise to a shallow intracratonic basin (syneclise) filled by Boa Vista Formation in two stages, the lower succession being controlled by the structures of the Tacutu sedimentary basin, and the upper succession effected by the complete flattening of the relief from a low gradient alluvial plain (Menezes and Wankler, 2020). So, the Boa Vista Formation rest discordantly on Tucano Formation and are characterized by sandstones, laterite, sandy claystones and conglomerates deposited in fluvial, lacustrine and aeolian environments (Milani and Thomaz Filho, 2000; Montalvão et al., 1975; Reis et al., 2001; Vaz et al., 2007). Sandstones of the Quaternary Areias Brancas Formation and recent alluvial deposits can be found respectively over some parts of the Boa Vista Formation and along the beds or terraces river. The Areias Brancas Formation is believed to be the result of reworking Formation

Boa Vista during the Pleistocene-Holocene (Latrubesse and Nelson, 2001). The Boa Vista and Areias Brancas Formations cover 71% of the study area, respectively (Holanda et al., 2014).

Based on lithology, structural lineaments, and stream patterns the area was included in the Rio Branco-Rio Negro Pediplane Morphostructural Domain by Franco et al. (1975), and now two geomorphological units are recognized, the Boa Vista Depression and the North Amazon Dissected Highlands (Holanda et al., 2014), whose predominant features are landforms modeled by accumulation/aggradation, punctuated by dissection/denudation areas (Nascimento et al., 2014).

The accumulation modeled landforms included fluvial plains and an extensive planation surface, subdivided in Planation Surface and Erosional Planation Surface, this latter occurring as slightly elevated areas and being a result of smooth incision by the streams. These planation surface developed on Boa Vista and Areias Brancas sedimentary formations, and they are generally marked by smooth and low elevations (“tesos”) that are frequently associated to laterization processes. These areas are characterized by seasonal flooding, incipient drainage constituted by intermittent streamlets with associated M. flexuosa swamps (Franco et al., 1975; IBGE, 2009; Ladeira and Dantas, 2014).

The dissection modeled includes inselbergs resulting from the pediplanation process, and the Serra do Tucano hills and mounds, of the North Amazon Dissected Highlands. These remaining structural highs appear amidst the Planing Surfaces within the Tacutu sedimentary basin limits, or even as proterozoic residual highlands, configuring the basin shoulders (Costa and Falcão, 2011; Silva et al., 2010).

The geological and geomorphological maps were based on the Geodiversity of the State of Roraima vector maps (at a scale 1:1.000.000), available free of charge by the Brazilian Society of Geology (Holanda et al., 2014). Some adjustments were made in these vectors based on bigger scales works (Menezes and Wankler, 2020; Nascimento et al., 2014; Zular et al., 2019), and on the floodplain polygons obtained here according to the methodology described in the topic “2.2.4.1, Floodplain”. The geological units were synthesized as a variable called “Rocks”, and each one of its units was used to order them on a scale according to their hypothetical growing influence on NDVI.

Since the variable Rocks encompass both rocks itself and unconsolidated sedimentary material from alluvial plain, the scale is more related to the genesis than to the nature of each unit. Among the sedimentary group, the Areias Brancas shows higher reworking taxes, thus, lower NDVI values than the Boa Vista formation, while the Tucano formation probably presents highest values of the group due to its sheltered position from the floods. Metamorphic group, in turn, are likely to have higher values than those of the sedimentary group due their ability to transfer nutrients to the soil from their primary and secondary minerals. Similarly, the igneous group usually generates more fertile soils and is therefore more likely to have higher NDVI values, especially associated with the clay soils of the volcanic rocks. Finally, higher expected NDVI values are associated with alluvial deposits given the riparian vegetation. Thus, the Rock variable was ordered like this: Areais Brancas Fm (1), Boa Vista Fm (2), Tucano Fm (3), Metamorphics (4), Plutonics (5), Volcanis (6) and Alluvial deposits (7).

The geomorphological units were grouped in the “Landforms” variable. The modeled residual relief units on morphostructures formed in distinct tectonic episodes were not discretized because they are beyond the scope of this work, so the altitude was used to establish an ascending order for each one of the “Landforms” units in the following way: Floodplains (1), Planation Surface (2), Erosive Planation Surface (3), Tucano Hills (4), Inselbergs (5), and Mountains (6). The 1 to 3 features represent accumulation modeled areas and the 4 to 6 represent dissection modeled areas (IBGE, 2009; Nascimento et al., 2014). The altitude map was based on NASADEM. The declivity % map was extracted from NASADEM, and the percentage classes used to follow the EMBRAPA (1979) recommendations: 0 – 3% smooth; 3 to 8% smooth-way, 8 to 20% wavy, 20 to 45% strong-wavy, and >45% mountainous.

2.9. PEDOLOGY

The soils of Roraima have great pedological diversity, products of rock weathering and erosion and cyclic deposition in different biological and climatic conditions acting both in geological and current time scales. In general terms, the predominant soils are acid, aluminum saturated, with low cation exchange capacity, kaolinitic, with low base sum and saturation, i.e., dystrophic, organic matter and organic carbon poor. Considering the World Reference Base (WRB) for soil taxonomy of FAO (2015), the main soils under savanna can be classified as yellow Ferrasols and Acrisols, Ferralic Arenosols, Concretionary Plinthosols and Gleysols. Due to the practice of burning during dry periods, they all tend to have low natural fertility and a marked loss of organic matter (Vale Júnior and Sousa, 2005; Vale Júnior et al., 2014).

The yellow Ferrasols and Acrisols are deep and have a cohesive subsurface horizon and their origin is due to the weathering of the Boa Vista Formation. In the dry season, this cohesive horizon is especially hardened, making it difficult for the plants to establish roots, and in the wet season this previous hardening causes expressive laminar erosion by the intense runoff despite the low slope of the region. Associated to these soils occur the Ferralic Arenosols, which are quartz sands on plain to slightly wavy reliefs, with clay content below 15% and whose origin is due to the Boa Vista

Formation erosional reworking both in hydromorphic and aeolian environments (Latrubesse and Nelson, 2001; Vale Júnior and Schaefer, 2010). The grassland savanna is more expressive in these cohesive and sandy soils.

The red Ferrasols and Acrisols develop on positive residual reliefs of volcanic rocks and their color results from the presence of hematite even so the goethite (yellow) is the dominant iron oxide. Despite the general chemical characteristics described previously, these red soils are slightly more fertile than the yellows because they are less cohesive, more porous, and well drained, which allows better root development and, thus, the ability to sustain forest patches and parkland to woodland savannas (Vale Júnior and Sousa, 2005). The colluvium is commonly associated with positive residual reliefs both of Apoteri Formation volcanic rocks and of Guyana Shield metamorphic rocks.

The Concretionary Plinthosols developed from the weathering of the red Ferrasols and Acrisols by the groundwater fluctuations along the time, whose wet and dry cycles promoted the iron redox. If on the one hand the ferruginous concretions present in those soil decrease their permeability and difficult the root development, on the other they play an important role for occupying the landscape edges and giving slope sustaining, protecting these areas against erosion. Despite of their stoniness, Concretionary Plinthosols tend to hold parkland savannas (Benedetti et al. 2011; Feitosa et al., 2016).

Gleysols are found on flooded areas, large and small streams, gallery forest and palm swamps, and they are characterized by being deep, hydromorphic, and poorly drained. Their typical grey color came from the reduction of the iron minerals by stagnant waters. In fluvial plains there are also Umbric Fluvisols, characterized as young soils in which the sedimentary input from rivers is accompanied by nutrients and organic matter what gives to them the best fertility levels and the capacity to sustain a lush riparian forest (Benedetti et al. 2011; Vale Júnior and Schaefer, 2010).

The soil variables were Cation Exchange Capacity (CEC), Soil Organic Carbon Stock (SOCS), Soil Sand Percentage and Soil Bulk Density, all of them obtained from SoilGrids, with 250 m of spatial resolution, whose interpolations were made with satellite and field data (Henglt et al., 2017). The chemical CEC and SOCS variables are related to the soil fertility and to the nutrient availability to vegetation; sand percentage and bulk density are textural features and are related to soil drainage (Zuquim et al., 2020), although soil texture is not a physiologically important edaphic factor, it is correlated with other relevant environmental characteristics, such as nutrient and water retention (Zuquim et al., 2014). All soil parameters were extracted from the surface (<5 cm depth).

Fig. 4 synthesizes the study area characterization in a schematic section (out of scale) and illustrates the main geological, geomorphological, pedological, hydrological elements and the widely described and discussed savanna phytophysiognomies (Barbosa and Miranda, 2005; Barbosa et al., 2007; Benedetti et al., 2011; Carvalho et al., 2021; Feitosa et al., 2016; Franco et al., 1975; Latrubesse and Nelson, 2001; Menezes and Wankler, 2020; Reis et al., 2001; Vale Júnior and Sousa, 2005; Vale Júnior and Schaefer, 2010; Xaud and Carvalho, 1999; Vaz et al., 2007). It should be noted, however, that this scheme represents the units in their dominance occurrences and relations, but they are not so linear and regular, since different soils bear the same type of vegetational phytophysiognomy, as well as there are distinct phytophysiognomies that can be found on a same type of soil, geological or geomorphological unity.

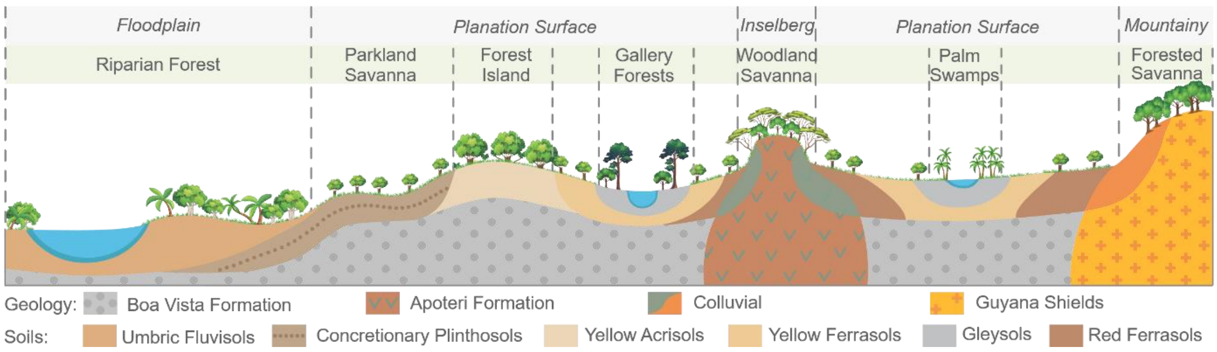

Fig. 4. Schematic section of the study area with the main soils and their environments.

2.10. STRUCTURAL EQUATION MODELING (SEM)

The linear model used was the multiple linear regression model, which seeks to separate the possible direct effects among the predictors and isolate the independent effect of each on the variation of the independent/response variable. The model was built assuming the direct effect of predictors temperature, precipitation, flood frequency and soil parameters on NDVI, assumed ecological relationships follow those proposed by Guisan and Zimmermann (2000), rocks and relief are in an indirect effects model, as they affect soil parameters, which affect NDVI. Then, a confirmatory analysis of Structural Equation Modeling (SEM) was applied to investigate the hypothetical causal relationships between the variables in a path diagram, in which indirect effects are estimated by multiplying the coefficients along a given path in the diagram (Magnusson et al., 2015; Shipley, 2016). All statistical analyses were performed in R environment (R Core Team, 2013).

3. RESULTS AND DISCUSSIONS

3.1. NDVI

The NDVI showed 60% variation on average between the nine analyzed dates. The lowest mean values occurred on March 26, 2020 (Fig. 5a, b) and were around

0.27 while the highest value occurred on September 18, 2018 and were around 0.48 (Fig. 5c, d). Besides this time variation, the NDVI also showed a wide spatial variation, whose highest values (77%) were recorded on the same dates of high contrast between vegetated and non-vegetated areas, i.e., on the same dates of lowest NDVI values. The lowest spatial variations (46%) were recorded on the same dates as the highest NDVI values – coinciding whit the period in which the vegetation was more homogeneous.

The photosynthetic activity and therefore the NDVI respond to climatic seasonality (Silva and Klink, 2001), that is, the wetter the period, the higher the NDVI and vice-versa. This occurs because the rain enhances in the soil the amount and quality of resources needed for plants, such as humidity, nutrients and organic matter (Ronquim, 2021). Although this relationship is positive along all savanna, it is controlled by different vegetational strategies for each sub environment. Thus, the increase in NDVI during the wet season occurs mainly in herbaceous plants due to the increase in leaf area and the speed of vegetation reproduction, in woody species, the NDVI responds to the increase in metabolism (Carrijo et al., 2021), common adaptation strategies in savannas, also seen in grasses (Costa el al., 2011;2014) and trees and shrubs (Ferreira et al., 2015) of Roraima's savannas.

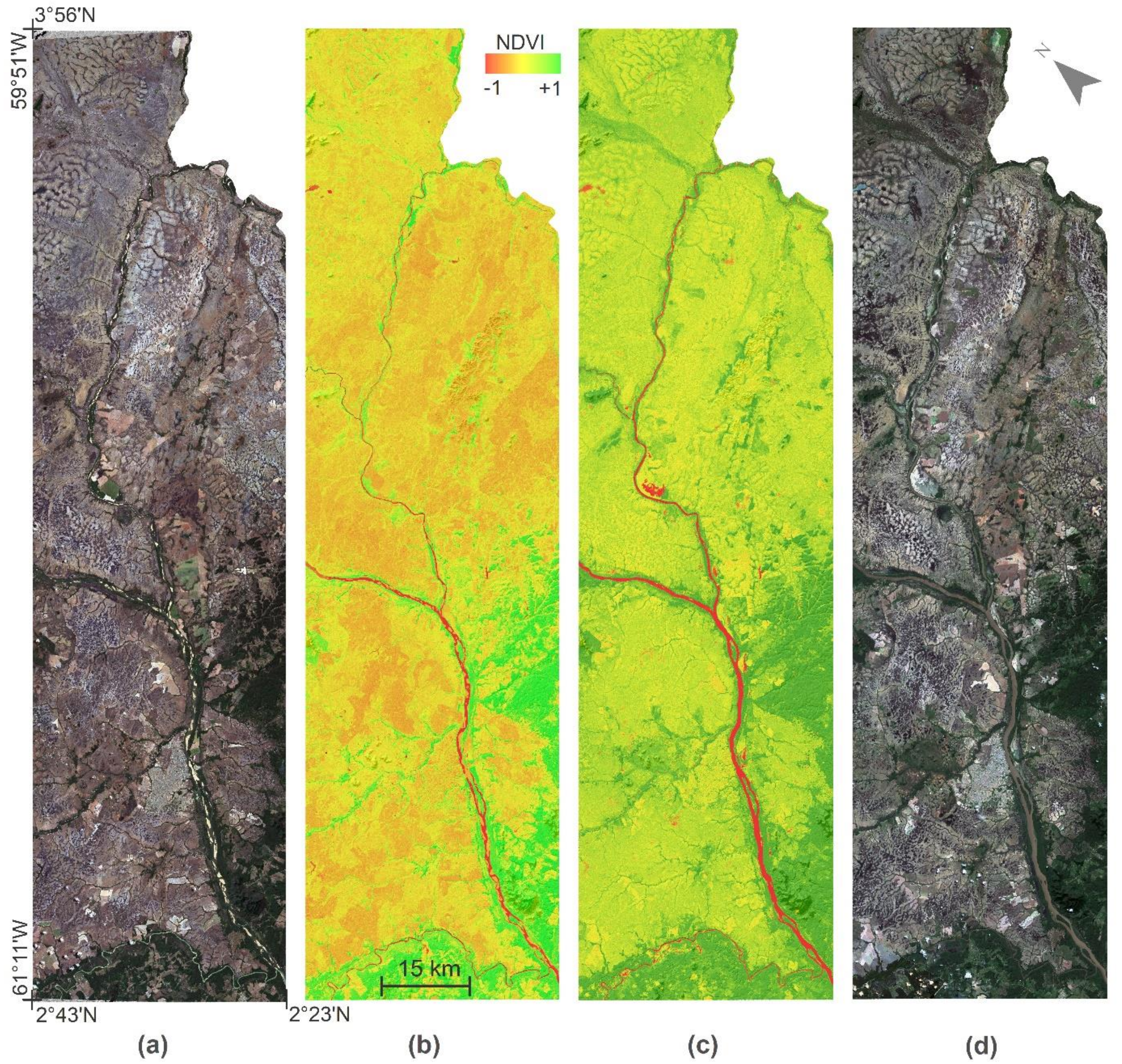

Fig. 5. Sentinel 2A real color composition and corresponding NDVI. (a) Dry season image; (b) the lowest mean NDVI value on March 26, 2020; (c) the highest mean NDVI value on September 18, 2018, and (d) wet season image. The maps displayed in this section present the study area (Fig. 1) slightly rotated for better visualization of its different variables.

3.2. FLOOD FREQUENCY

The automatic extraction of streams from DEM did not adequately represent the streams because the area is very flat and the NASADEM, although robust, does not have a detailed resolution to capture such small variations in slope. With a low threshold, the automatic extraction creates streams where they do not actually exist

(Fig. 6a) and with a high threshold only the main streams are revealed (Fig. 6b). On the other hand, the LSU does not recognize the “igarapés” (small drainage) because the riparian vegetation is dense in these locations throughout the year, regardless of the season (Fig. 6c), so the main drainages extracted from the DEM were added to the areas delimited by LSU to compose vectors that represent the complex drainage system of the study area (Fig. 6d). The areas with low, medium and high flooding frequency reached 472, 215 and 225 km² respectively, corresponding to 9.3% of the total area analyzed and the mean NDVI of these areas was 0.25. The map in Fig. 6e represents the "Flood Frequency", for the statistical analysis this predictor entered as 0 or 1, indicating absence or presence of flooding, since the 500 points (Fig. 1) were extracted from each of the 9 images/dates in the time series.

The LSU fundamentally separates water or vegetation, and this is a technical limitation to characterize the drainage system, as it makes impossible the discretization of water bodies covered by vegetation, as is the case of some small streams and the shorezone of lakes during the dry period (Meneses et al., 2007). These problems were solved by the addition of the main small streams extracted from NASADEM and by the lake identification through the temporal series. The validation of the LSU showed $r^2 = 0.9$ ($p < 0.001$) (Fig. 6f).

The flood frequency mapping made here highlighted the parallel river pattern in the Tacutu River-Tucano Hills region and the dendritic river pattern in the Boa Vista region (Fig. 6g and 6h), as proposed by Latrubesse e Nelson (2001). These differences can be associated not only to the structural geology and geomorphology features but with the climatic factors acting in both regions. The results obtained here also allowed us to differentiate the two regions in terms of the scars left behind by the runoff, being more biaxial opposite on the Tacutu River-Tucano Hills region and slightly radial in the

Boa Vista region. The higher and better precipitation distribution recorded to the Uraricoera and Mucajaí river catchments when compared to those recorded to the Tacutu river catchment explains why this latter lowers further in the dry season and contributes less to the Branco River than the two first (ANA, 2020).

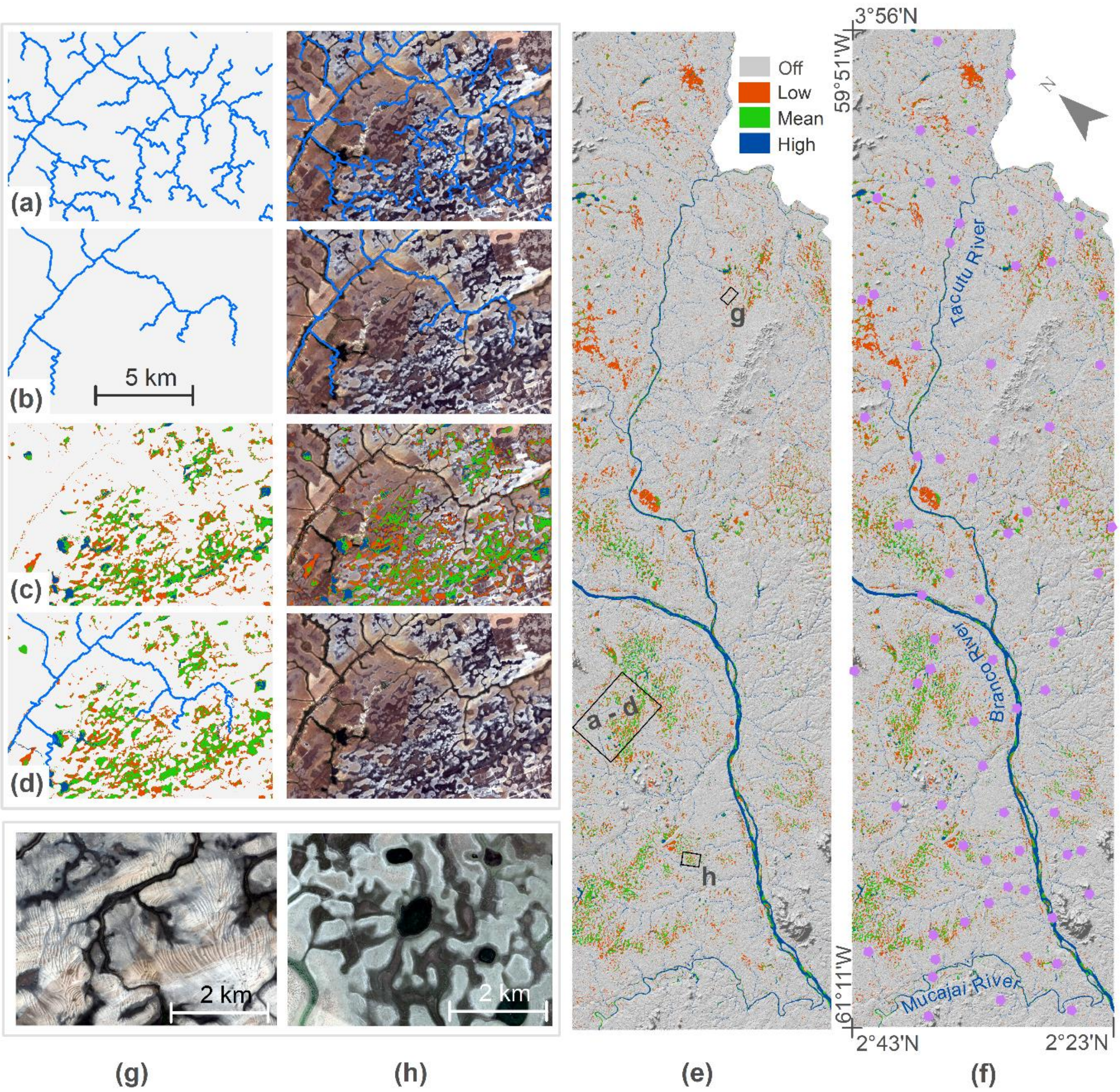

Fig. 6. Drainages extracted from NASADEM with (a) low and (b) high threshold. (c) Flood areas delimited by the LSU. (d) Integration of b and c. (e) Flood frequency. (f) Distribution of points for LSU validation. Different surface runoff patterns associated with predominantly parallel (g) and dendritic (h) drainages.

3.3. FLOODPLAIN

The fusion of the Sentinel 2A multispectral image (Fig. 7a) with the ALOS PALSAR SAR image (Fig. 7b) generated the hybrid image (Fig. 7c) from which it was possible to extract the floodplains, and small streams (Fig. 7d), whose area of 1,305 km² constitutes 13.3% of the total area, allowing a better detailing in relation to the 484 km² obtained by the Brazilian Geological Survey made at 1:1,000,000 scale (Holanda et al., 2014). The prominence of the floodplains was given by the double jump effect in radar images, the signal return is enhanced by the flooded areas (Pierdicca, 2013). The signal return is enhanced by flooded areas (Moreira et al., 2013) made manual separation difficult, but since they occur in less than 10% of the total area, it only required more attention during the process of dividing floodplains by forest. The area of the river plain is larger (1,305 km²) than the flooded areas (912 km) because it also considered the discrimination of alluvial deposits, which are not necessarily periodically flooded.

The sediments of the Branco River floodplain are richer in illite and potassium than those further away (Meneses et al., 2007), which favors the development of vegetation. The smaller floodplains also have associated riparian vegetation. In fact, NDVI in the studied area were on average higher in the floodplain (0.56) than outside (0.32), coinciding with the higher concentration of tree vegetation in the savanna area.

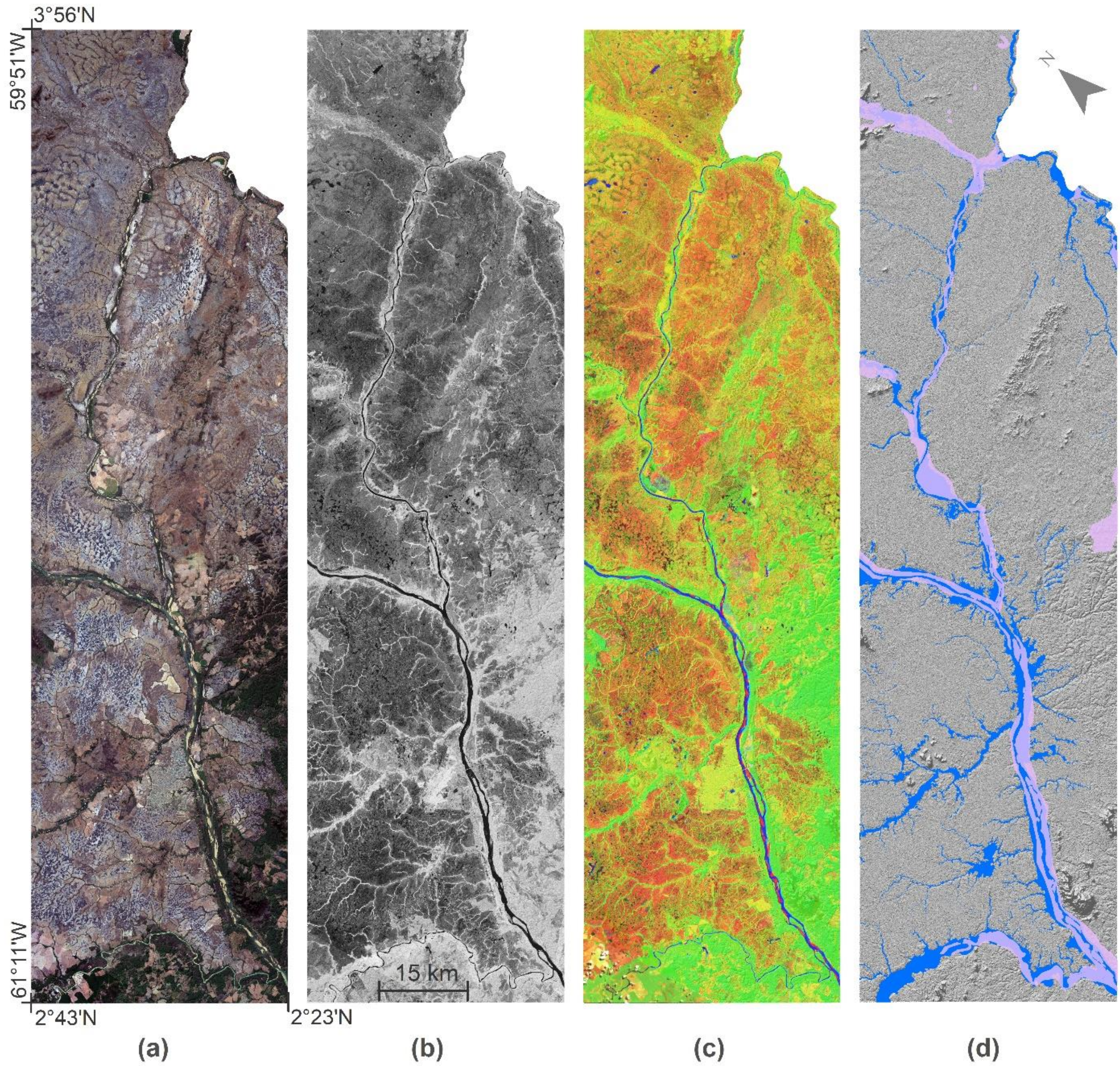

Fig. 7. (a) Sentinel 2A multispectral image. (b) ALOS PALSAR image. (c) Hybrid image. (d) Floodplain extracted from the hybrid image (blue), and floodplain overlay from the Brazilian Geological Society (pink).

3.4. TEMPERATURE AND PRECIPITATION

Ranging around 5%, the temperature did not fluctuate much, which is expected for the hot climate of the region – with average temperatures between 28°C and 32°C (Fig. 8a, b). In space, the temperature varied on average by 2%. Precipitation showed 95% variation over time, confirming the expected well-demarcated seasonality, so that the minimum accumulated rain was 14 mm on March 26, 2020, in the “summer” period, while the maximum was 222 mm on September 18, 2018, in the “winter” period (Fig.

8c, d). The precipitation variation in space was 30% on average, with a minimum of 20% on September 13, 2019 and a maximum of 53% on April 1, 2019. As the predictive power of the different lag-times (30, 60, 90, and 120 days) was similar, 30 days were used for the temperature and precipitation variables, since this is the interval commonly observed between the maximum rain volume and curve pike in the hydrograph of these rivers (ANA, 2020; Sander et al., 2015a, b).

Precipitation is one of the main drivers of savanna distribution (Lehmann et al., 2014). In tropical savannas, the peak of vegetative growth coincides with the rainy season because the temperature is not a limiting factor (Archibald et al., 2020). The lack of rain, the high evapotranspiration and the elevated temperatures during the dry season decrease the water availability in the more surficial layers of the soil (Borghetti et al., 2019), resulting in the photosynthetic pigment lost by the herbaceous stratum, while in the rainy season there is an increase in the vegetation reproduction and a concomitant greenness increase (Eamus et al., 2016). Thus, the herbaceous stratum's predominance in the study area and its greater sensitivity to water deficit explain the conspicuous NDVI responses to dry and wet seasons in the savannas.

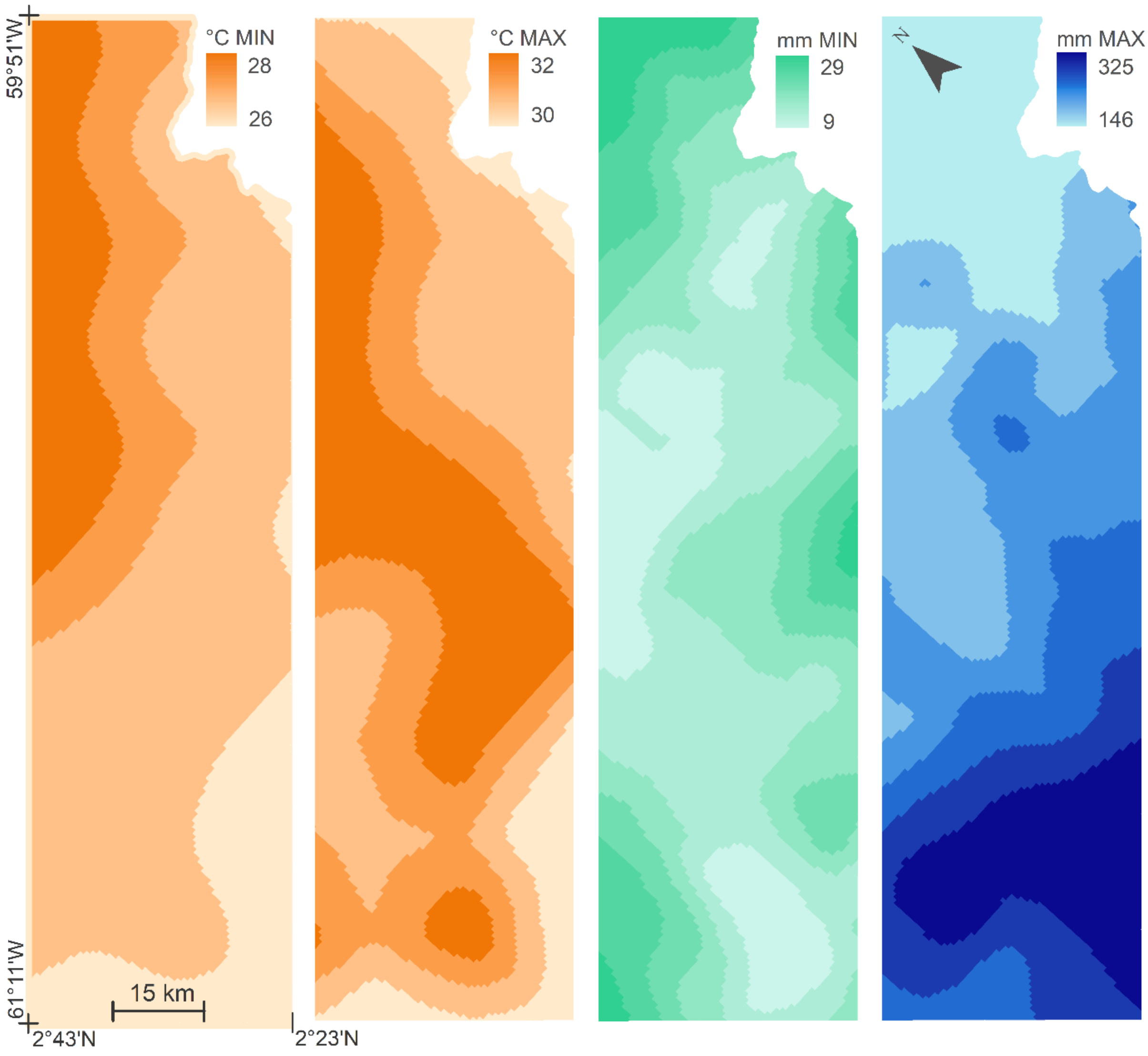

Fig. 8. Average variation of temperature and precipitation over time. (a) The minimum temperature on February 15, 2017. (b) The maximum temperature on April 1, 2019. (c) Minimum accumulated precipitation on March 26, 2020. (d) Maximum accumulated precipitation on September 18, 2018.

Fig. 9 shows the NDVI responses related to the climatic seasonality, with the numbers in circles indicating the image year in the historic series. Generally, low precipitation values (blue bars) are equivalent to the low NDVI values of the dry seasons and the high precipitation values are equivalent to the high NDVI values of the wet seasons. On average, the NDVI was 0.30 in the dry season and 0.47 in the wet season. The red values indicate the years that showed a different pattern, that is, there was a high NDVI during the dry seasons. In these cases, the precipitation accumulated in one month was similar to those recorded for the other years (ΔP ≈ 10 mm), but when observed the precipitation accumulated in four months, these years showed significantly higher precipitation values (>100 mm). Finally, important climatic variables were not considered in this analysis, such as evapotranspiration, La Niña/El Niño events and consecutive days of drought or rain (Hoyos et al., 2022), could ensure a greater predictive power than the average and accumulated monthly of the temperature and precipitation used here.

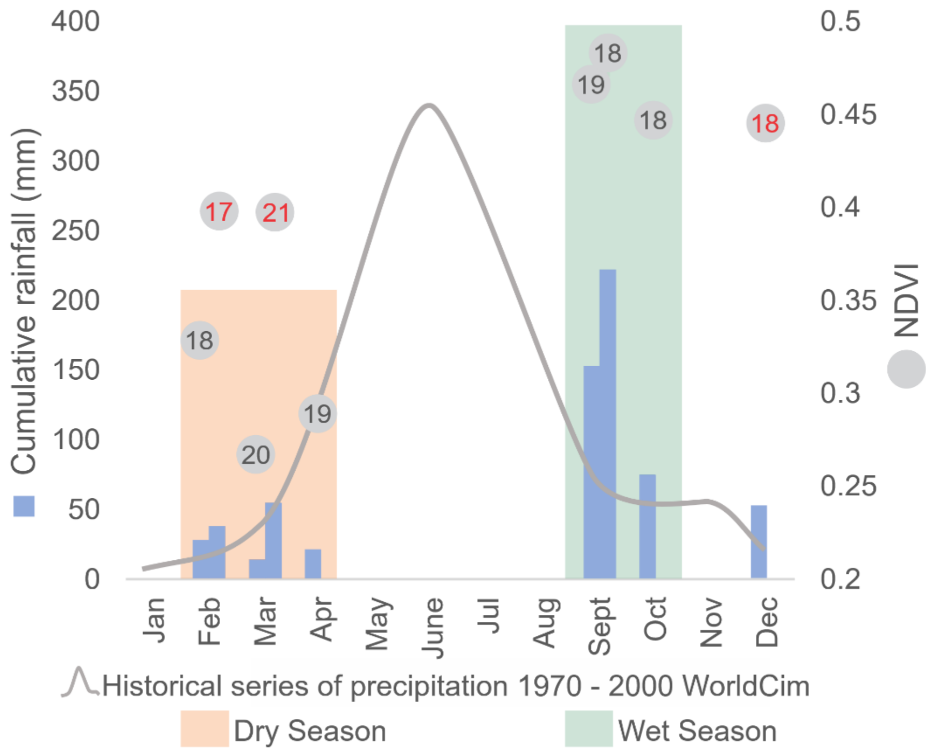

Fig. 9. NDVI is controlled by the climatic seasonality (dry and wet seasons). Cumulative rainfall curve derived from historical series from 1970-2000 (Fick and Hijmans, 2017) and monthly cumulative rainfall frequencies (blue bars) for each image date (numbers inside the circles) and the NDVI value associated to each one.

3.5. LANDFORMS AND ROCKS

Considering the Slope variable, the area is predominantly smooth, about 92% of its surface has a slope of less than 8%, except for the occasional presence of residual plateaus with slopes higher than 45% (Fig. 10a). For the variable Altitude, values between 75 and 90 m occur in 55% of its extension, while altitudes above 115 m appear only in the residual plateaus, making up 6% of the area (Fig. 10b). The coefficient of variation for Landforms and Rocks was 39 and 65, respectively, indicating greater geological variation than geomorphological (Fig. 10c and 10d).

On average, landforms showed the following NDVI values: Floodplains (0.56), Planation Surface (0.29), Erosive Planation Surface (0.38), Tucano Hills (0.20), Inselbergs (0.70), and Mountains (0.71). The forest vegetation of structural highs (metamorphic and intrusive rocks) showed NDVI values higher than floodplains. The lower values occurred in the Tucano Hills maybe are perhaps due to the intense rust oxidation of their quartz rich sandstones (Cruz et al., 2019). The high NDVI values of the Erosive Planation Surface are perhaps due to fact that it has higher areas (100 m) and less flooding areas (170 km²) in relation to the Planation Surface (82 m and 518 km² respectively).

The Rocks variable showed the following NDVI mean values: Areias Brancas Fm (0.28), Boa Vista Fm (0.32), Tucano Fm (0.30), Metamorphics (0.45), Plutonics (0.45), Volcanics (0.32), and Alluvial deposits (0.56). The relations between geologic materials and NDVI don’t follow the expected order made here. Contrary to expected, Tucano Fm, and Volcanic areas showed lower NDVI values than Boa Vista Fm. Each of these non-expected results is an average of spatially distinct behaviors within their respective areas. Thus, while the high parts of the Tucano Fm areas showed lower NDVI values, their lower parts showed comparatively higher NDVI values. In contrast, the Vulcanic areas showed high NDVI in the highest altimetric quotas and low in their basin areas. On the other hand, although metamorphic and igneous units showed high NDVI values as expected, perhaps they would show even higher values if a distinction had been made between the lithological types (Urubu and Mucajaí units) associated with the forests in the southwest of the area from those (Cauarane and Saracura units) associated to the savanna in the northeast (Holanda et al., 2014). These discrepancies perhaps are because most of the spatial distribution of each unit is based on interpolations and their nature itself is based on simplistic generalizations of a vast and complex range of lithological types. Large-scale geological surveys and more detailed petrographic and geochemical units would most likely result in more realistic results.

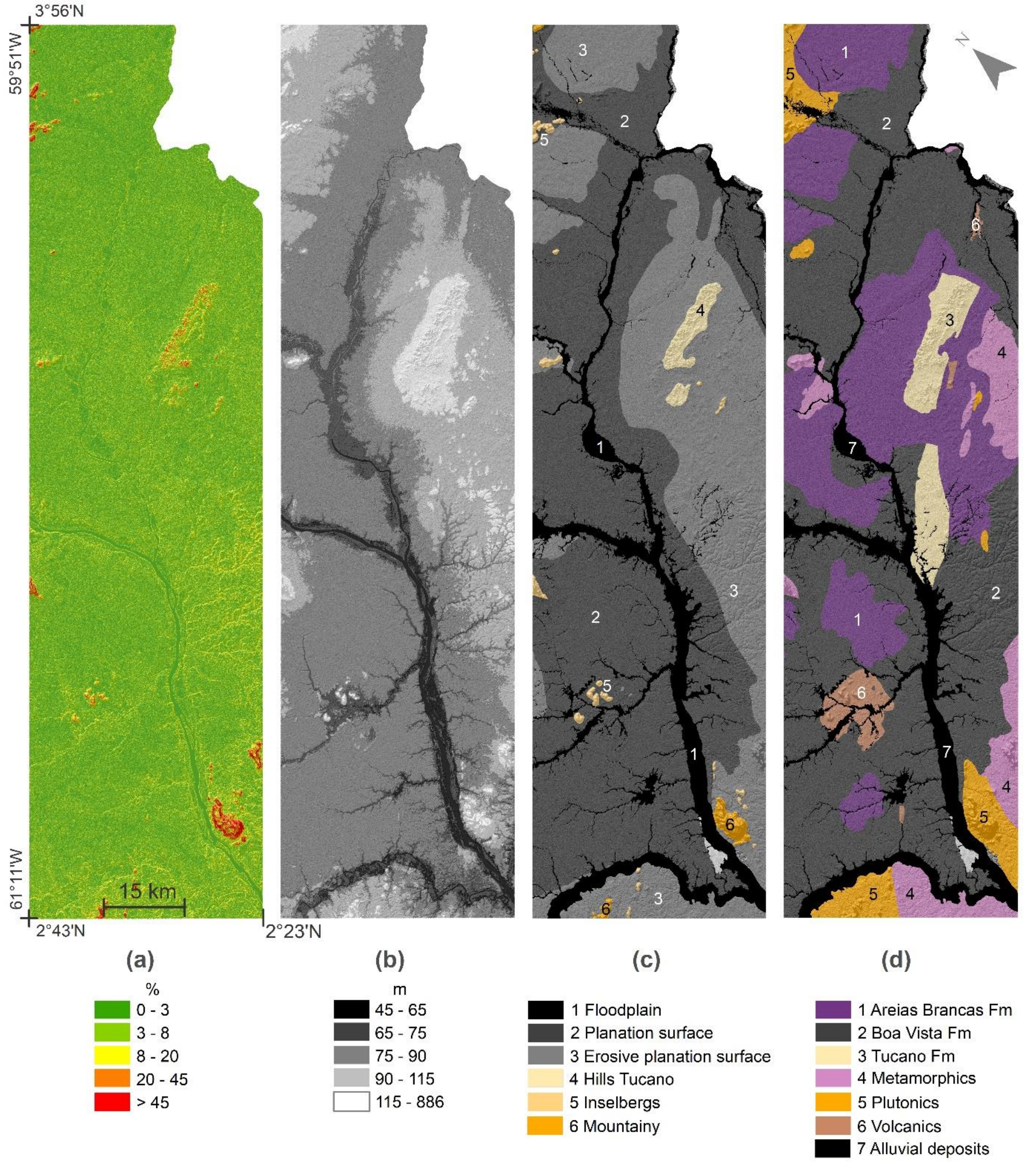

Fig. 10. Spatial distribution of variables (a) Slope, (b) Altitude, (c) Landforms and (d) Rocks.

3.6. SOILS PARAMETERS

The spatial distribution of soil parameters (Fig. 11) did not vary substantially, and the mean values and percentage of variation found were: Bulk Density 1.3 kg/dm³ - 3%, CEC 17.7 $cmol_c$/kg - 20%, Sand 53.2% - 12% and SOCS 4.5 kg/m² - 13%. The Soilgrids variables reflect the soil characteristics described for the region, the soil Bulk

Density are compatible with the values obtained by Feitosa et al. (2016) in field measurements made in savanna and forest patches surfaces, these values tend to increase in subsurface due the cohesive horizons of yellow ferrasols and acrisols (Vale Júnior and Schaefer, 2010). With 53% of sand and 24% of clay, the sandy clay loam texture is due to the source material predominantly sedimentary and are commonly described to the region (Vale Júnior and Schaefer, 2010). The low clay and organic matter content and the hot and humid tropical climate favors weathering and so the soils have low CEC, which is associated to the organic carbon dynamics. The savanna organic carbon dynamics is characterized by a low soil accumulation of organic matter due the lower litter supply, the high decomposition rates, and the sandy soil texture, what results in low SOCS (Simões et al., 2010; Vale Júnior and Sousa, 2005).

The Bulk Density is influenced by the amount of organic matter present in the soil. Considering that the organic matter has a density lower than the minerals and acts as a biophysical conditioner to porosity recovering (decreasing the porosity), thus a high density soil implies in low organic matter concentration, and lower carbon input (Ronquim, 2021; Grüneberg et al., 2013).

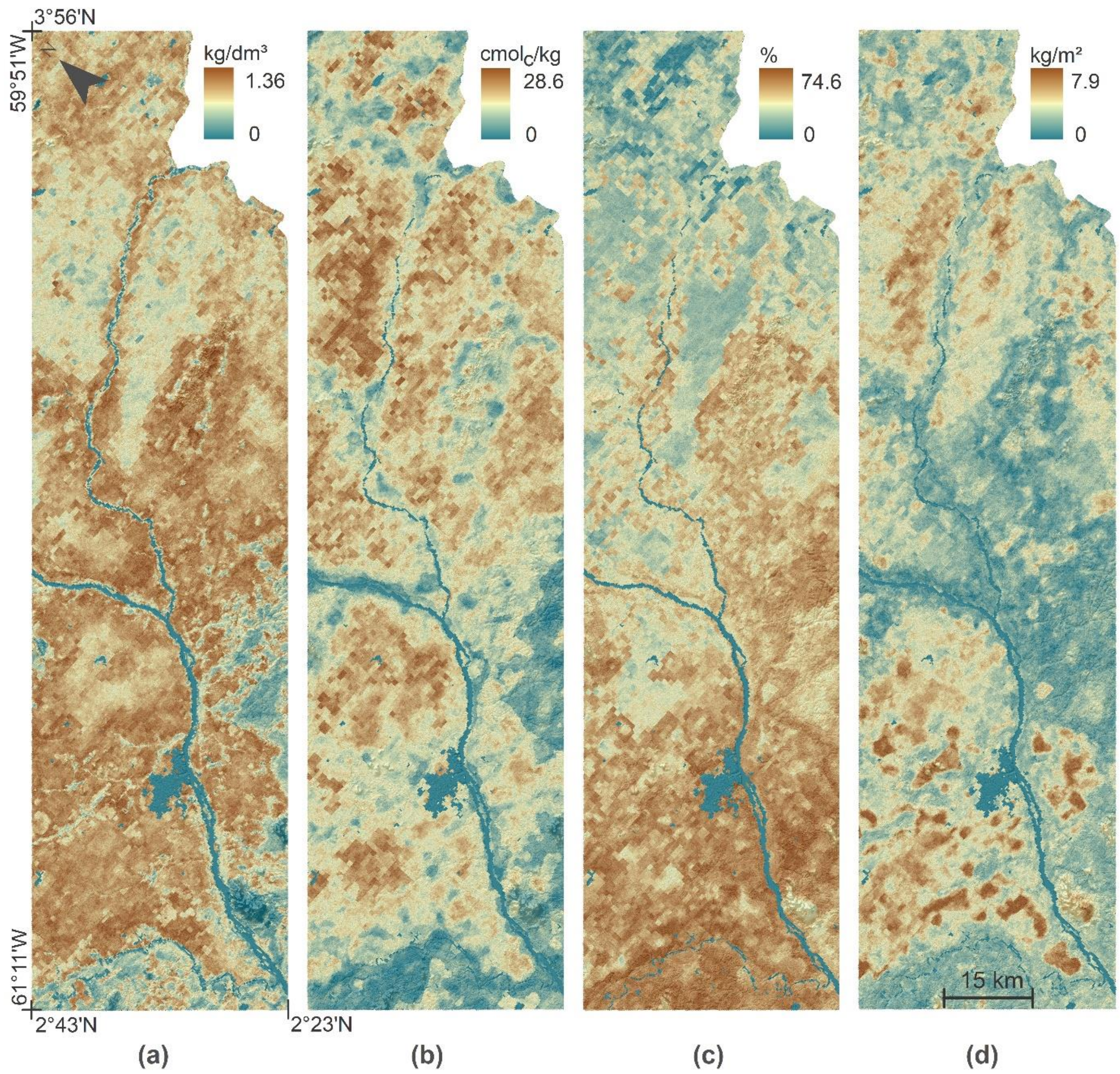

Fig. 11. Spatial distribution of Soilgrids variables (a) Bulk Density (b) CEC. (c) Sand. (d) SOCS.

3.7. SEM

The residuals of the linear multiple regression models showed no spatial autocorrelation, the graphs with the partial regressions of the direct effect on NDVI are in Fig. 12, where the variable Bulk Density showed the highest correlation. The SEM revealed that the indirect effects of rocks and landforms on NDVI were 0.33 and 0.16, respectively (Fig. 13). This result is intrinsically related to the ordering of the groups within the geology and geomorphology variables. Relief could have been grouped based on different combinations of all the characters it represents, however, the number of possible combinations makes this alternative unfeasible for the purposes proposed here. Similarly, the geology variable would be better grouped on a geochemical gradient base, but this is not possible since these data are not available for the scale of the study. Some tests of different ways of ordering were performed here. When grouped by age, the Rock variable lose their indirect effect, i.e., the variation in vegetation showed no relationship to the age of the rocks. Thus, the order presented here was based on the alleged favorability of the geological unit to the development of vegetation and the relief units was ordered by altitude. Rocks showed a greater indirect effect than relief, reinforcing the fact that altitude does not have such a relevant effect. The effect of rocks is due to the relationships between this variable and soils, since rocks are the primary source of macronutrients, and so playing an important role in soil fertility (Gray et al., 2016).

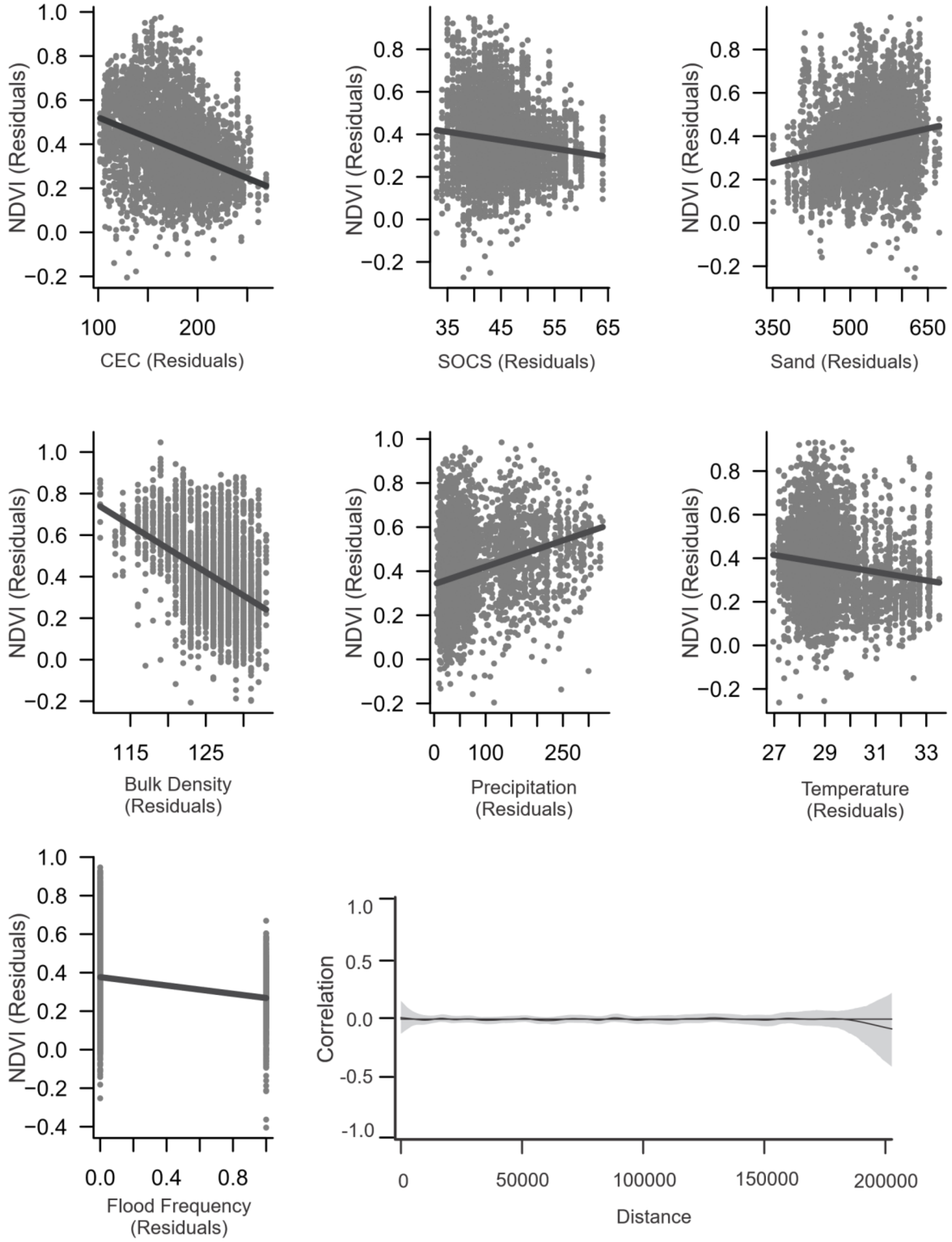

Fig. 12. Partial regressions of the direct effect on NDVI.

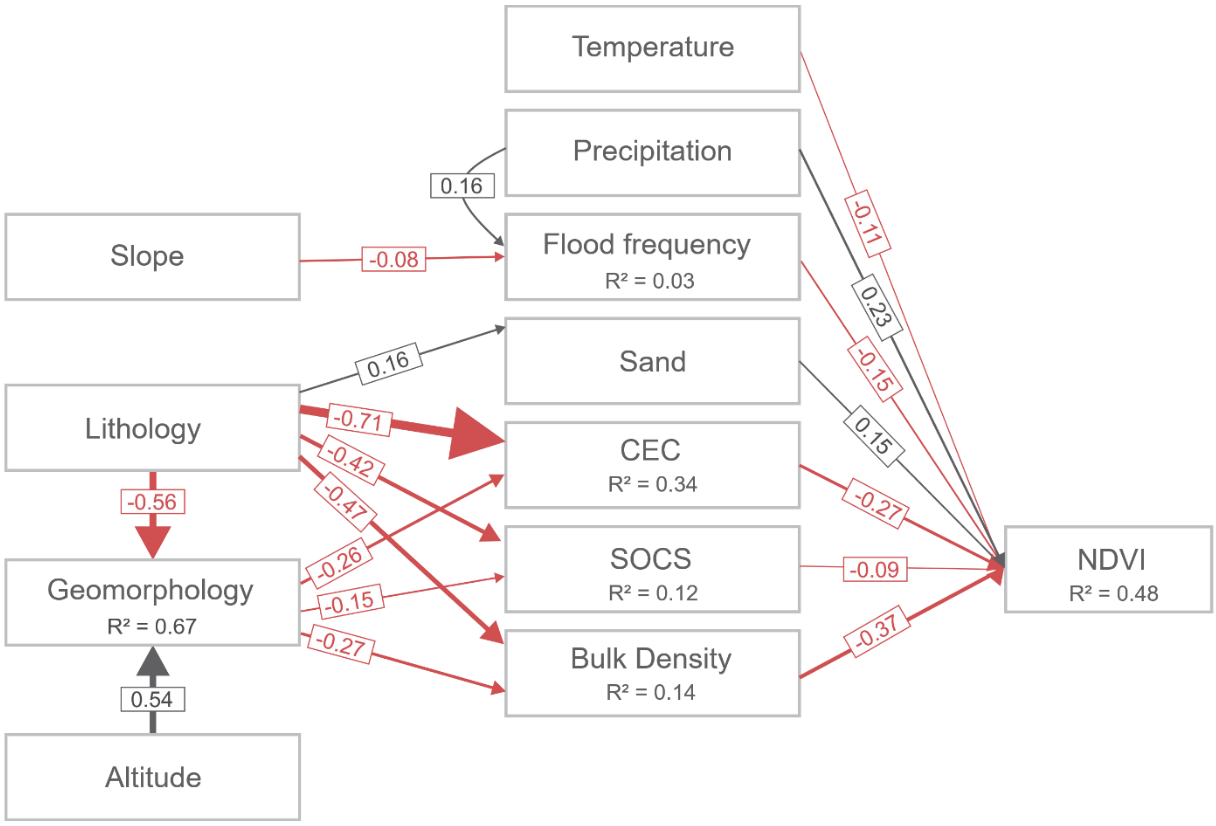

Fig. 13. Structural equation model quantifying the direct and indirect effects of abiotic predictors on NDVI. The arrows represent significant ($P < 0.05$), direct and unidirectional relationships between the variables, the arrows that point to other variables before reaching the NDVI express the paths of indirect effects. Black arrows indicate positive effects and red arrows indicate negative effects. The thickness of the arrows is directly proportional to the standardized regression coefficient, that is, to the effect size. R^2 corresponds to the linear models of multiple regressions used in the construction of the SEM.

As expected, the variables Rocks and Altitude explain much of the landforms (R^2=0.67), but relative to NDVI, altitude had a low indirect effect (0.1), probably because the area is very smooth and the NASADEM spatial and vertical resolutions is not so fine to capture such subtle differences in terrain, and/or because the plants are quite sensitive to the soil hydrological gradients (Cavagnaro, 2016; Silverton et al., 1999; 2015).

Bulk density, CEC and SOCS had negative effects on NDVI, of -0.37, -0.27 and -0.09, respectively. For the Bulk Density variable this negative effect was expected, since denser soils hinder root development and water infiltration (Vale Júnior and Schaefer, 2010). As for the variables CEC and SOCS, a positive effect was expected, but negative results between vegetal development and these variables are not uncommon (Goodlee et al., 2021; Sana et al., 2014; Silveira et al., 2018). Although the presence of cations in the soil is crucial for the distribution and formation of vegetation (Lloyd et al., 2009), CEC is a measure of how well the soil is able to retain cations, if most of the CEC is occupied by cations essential for plant development, such as calcium, magnesium and potassium, the soil will be fertile, on the other hand, if a large part of the CEC is occupied by potentially toxic cations, such as hydrogen and aluminum, the soil will be poor (Ronquim, 2021). The CEC of Amazonian soils is notoriously occupied by aluminum (Quesada et al., 2011), and high concentrations of hydrogen, and the consequent acidity are described for soils in the studied region (Vale Júnior and Schaefer, 2010). Miranda et al. (2003) reported the influence of these variables on the occurrence and distribution of tree species in the savanna of Roraima. Thus, the negative relationship found here between CEC and NDVI is believed to be due to aluminum toxicity. CEC and SOCS correlate ($R = 0.45$), which may explain the slight negative effect of SOCS on NDVI, when a positive effect would be expected.

Regarding the Flood Frequency, slope and precipitation did not explain well this phenomenon ($R^2=0.03$), contrary to the expected. Water flows more on slopes and less on flat land, so the relationship between slope and flooding is negative, here this effect was very small (-0.08) probably because these gradients are very subtle and NASADEM has insufficient resolution to capture them. Precipitation also had a smaller effect on flood frequency (0.16), suggesting that flooded areas are more related to the infiltration capacity of soils, the presence of cohesive horizons, and the level of the water table (Franco et al., 1975).

Regarding the NDVI, precipitation showed a positive effect (+0.23) and flood frequency a negative effect (-0.15), both expected results. Precipitation is the principal source of water in the study area, and its effects on vegetation goes beyond simply providing water for plants. The correlation between NDVI and precipitation was 0.27 for overall area, 0.32 for non-flooded areas and 0.38 for the flooded areas, while the NDVI on average was higher in the non-flooded areas (0.41) than in those flooded (0.25). These results show that there are minimum and maximum thresholds of precipitated water volume, whose extrapolations imply difficulties for plant development (Tao et al., 2016). Too much water increases the likelihood of the formation of stagnant waters, which reduces oxygen availability to soil microorganisms and plant roots, and can lead to physiological drought, i.e., the inability of roots to absorb resources, so that plants poorly tolerant to flooding suffer marked reductions in photosynthetic capacity and ultimately the intolerant species die (Banach et al., 2009). Too little water, in turn, can cause drought-sensitive plants to lower their metabolism and vigor to avoid reaching the point of permanent wilting (Mosa et al., 2017), and a good example of this is the occurrence in the savannas of Roraima of plants endemic to hydromorphic soils of poorly drained and constantly flooded areas - such as some herbaceous legumes recorded by Cavalcante et al. (2014).

Temperature had a small negative effect (-0.11) on NDVI, possibly due to reduction in vegetative productivity to avoid significant water lost with the increased respiration at high temperatures (Sullivan et al., 2020).

The positive effect found here between Sand and NDVI (+0.15) can be attributed to the drainage conditions of the soils, in the sense that the greater the amount of sand, the greater its permeability. The hydromorphic character of the soils, that is, long periods of water stagnation followed by dry periods, higher toxicity by exchangeable aluminum and higher acidity are described as hydro-edaphic constraints in field studies in the study area (Araújo et al., 2017; Cavalcante et al., 2014; Feitosa et al., 2016; Xaud and Carvalho, 1999), while better drainage conditions of soils, in the mentioned studies, are associated with forest fragments, wooded savannas, and higher herbaceous legumes species richness and diversities. Together all the direct predictors explain 48% of the variation in NDVI.

4. CONCLUSIONS

The NDVI showed 60% of temporal variation through the five years analyzed, responding to climatic seasonality, confirming what was expected. These results are specifically related to the foliar area increase and of the vegetative growth efficiency of their herbaceous elements during the rainy season. Altitude and slope showed no indirect effect on NDVI, while rocks and landforms showed an indirect effect of 0.33 and 0.16, respectively. The high value of geology confirmed the validity of the criteria used to order this variable, namely, its favorability to vegetation development based on the probability of inorganic nutrient inputs.

The evolutionary history of savannas around the world has conditioned specificities in their abiotic determinants, and in the Amazon the recent sedimentary dynamics have been related to the distribution of vegetation. This study quantified the indirect effect of rocks and reliefs on NDVI, showing that the current landscape configuration in the study area, expressed predominantly by the Sedimentary Formation Boa Vista and the products of its reworking (White Sands Formation and alluvial deposits) arranged in long planing surfaces, resulting from successive cycles of erosion and deposition, punctuated by residual reliefs in the form of inselbergs and mountains, coming mainly from volcanic rocks of the pre-rift phase of the Tacutu

Sedimentary Basin and from crystalline and metamorphic rocks, even older, of the Guiana Shield, contributes to the distribution of savannas, that is, the evolutionary history of this landscape has an indirect effect on the variation of NDVI.

Considering the variables with direct effect on NDVI, a strong positive effect was expected with the indicators of soil fertility (CEC and SOCS), but the relationship was negative because the soils are acidic and with high exchangeable aluminum. A stronger effect of moisture-related predictors (precipitation and flooding frequency) than of soil-related predictors was expected, as occurs in savannas on a global scale, but this was not confirmed. Although flooding has a negative effect and precipitation a positive effect, this is a complex relationship, given the presence of herbaceous-shrub matrix with hygrophytes elements specially adapted for soil hypersaturation conditions. Thus, precipitation and flood frequency did not have a high effect as the soil variables, but the soil variable with the highest effect is Bulk Density, which is precisely linked to water drainage in soils. The positive effect of the concentration of sand reinforces the hydroedaphic restrictions; periodically flooded areas hinder the establishment of tree species, which is favored in areas with better drainage conditions.

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6. REFERENCES

Albert, J. S., Val, P., Hoorn, C. (2018). The changing course of the Amazon River in the Neogene: center stage for Neotropical diversification. Neotropical Ichthyology, 16.

ANA. Agência Nacional de Águas HIDROWEB v3.1.1. Accessed through <http://www.snirh.gov.br/hidroweb/serieshistoricas>. Access in: mar. 2020.

Araújo, M. A. M., Rocha, A. E. S. D., Miranda, I. D. S., Barbosa, R. I. (2017). Hydro-edaphic conditions defining richness and species composition in savanna areas of the northern Brazilian Amazonia. Biodiversity Data Journal, (5), e13829.

Araújo Júnior, A. C. R., Tavares Júnior, S. S. (2017). Land use and cover for urban planning, Boa Vista, Roraima, Brasil. Boletim Goiano de Geografia 37(1), 36-55.

Archibald, S., Bond, W. J., Hoffmann, W., Lehmann, C., Staver, C., Stevens, N. (2019). Distribution and determinants of savannas. Savanna woody plants and large herbivores, 1-24.

Banach, K., Banach, A. M., Lamers, L. P., De Kroon, H., Bennicelli, R. P., Smits, A. J., Visser, E. J. (2009). Differences in flooding tolerance between species from two wetland habitats with contrasting hydrology: implications for vegetation development in future floodwater retention areas. Annals of botany, 103(2), 341-351.

Barbosa, R. I. (1997). Distribuição das chuvas em Roraima. In: Barbosa, R. I., Ferreira, E. F. G., Castellon, E. G. (Eds.), Homem, Ambiente e Ecologia no Estado de Roraima. Editora INPA, Manaus, Amazonas, pp. 325-335.

Barbosa, R. I., Campos, C. (2011). Detection and geographical distribution of clearing areas in the savannas (‘Lavrado‘) of Roraima using Google Earth web tool. Journal of Geography and Regional Planning, 4(3): 122-136.

Barbosa, R. I., Campos, C., Pinto, F., Fearnside, P. M. (2007). The “Lavrados” of Roraima: biodiversity and conservation of Brazil’s Amazonian Savannas. Functional Ecosystems and Communities, 1(1), 29-41.

Barbosa, R. I., Miranda, I. D. S. (2005). Fitofisionomias e diversidade vegetal das savanas de Roraima. Savanas de Roraima: Etnoecologia, Biodiversidade e Potencialidades Agrossilvipastoris, FEMACT, Boa Vista, 61-77.

Bardgett, R. D., Bullock, J. M., Lavorel, S., Manning, P., Schaffner, U., Ostle, N., ... Shi, H. (2021). Combatting global grassland degradation. Nature Reviews Earth & Environment, 2(10), 720-735.

Barni, P. E., Barbosa, R. I., Xaud, H. A. M., Xaud, M. R., Fearnside, P. M. (2022). Precipitation in northern Amazonia: spatial distribution in Roraima, Brazil. Sociedade & Natureza, 32, 420-436.

BDIA Banco de dados de informações ambientais IBGE. Accessed through <https://bdiaweb.ibge.gov.br/#/home>. Access in: jan. 2021.

Beaudoing, H., Rodell, M. NASA/GSFC/HSL (2020). GLDAS Noah Land Surface Model L4 3 hourly 0.25 x 0.25 degree V2.1, Greenbelt, Maryland, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC).

Benedetti, U. G., Vale Júnior, J. F. D., Schaefer, C. E. G. R., Melo, V. F., Uchôa, S. C. P. (2011). Gênese, química e mineralogia de solos derivados de sedimentos pliopleistocênicos e de rochas vulcânicas básicas em Roraima, Norte Amazônico. Revista Brasileira de Ciência do Solo, 35(2), 299-312.

Bond, W. J. (2010). Do nutrient-poor soils inhibit development of forests? A nutrient stock analysis. Plant and soil, 334(1), 47-60.

Borghetti, F., Barbosa, E., Ribeiro, L., Ribeiro, J. F., Walter, B. M. T. (2019). South American Savannas. Savanna Woody Plants and Large Herbivores, 77-122.

Carrijo, J. N., Maracahipes, L., Scalon, M. C., Silvério, D. V., Abadia, A. C., Fagundes, M. V., ... Lenza, E. (2021). Functional traits as indicators of ecological strategies of savanna woody species under contrasting substrate conditions. Flora, 284, 151925.

Carvalho, T. M., Maia, R. P., Sander, C. (2021). Inserção do rio Branco nas áreas úmidas da Amazônia, estado de Roraima, Amazônia Setentrional.

Cavagnaro, T. R. (2016). Soil moisture legacy effects: impacts on soil nutrients, plants and mycorrhizal responsiveness. Soil Biology and Biochemistry, 95, 173-179.

Cavalcante, C. D. O., Flores, A. S., Barbosa, R. I. (2014). Edaphic factors determining the occurrence of herbaceous legumes in Amazonian savannas. Acta Amazonica, 44, 379-386.

Cediel, F., Shaw, R. P., Cceres, C. (2003). Tectonic assembly of the northern Andean block.

Charlton, R. (2007). Fundamentals of fluvial geomorphology. Routledge.

Cordeiro, C. L., Rossetti, D. F., Gribel, R., Tuomisto, H., Zani, H., Ferreira, C. A., Coelho, L. (2016). Impact of sedimentary processes on white-sand vegetation in an Amazonian megafan. Journal of Tropical Ecology, 32(6), 498-509.

Costa, J. A. V., Falcão, M. T. (2011). Compartimentação morfotectônica e implicações de evolução do relevo do hemigráben do Tacutu no Estado de Roraima. Revista Brasileira de Geomorfologia, 12(1).

Costa, N. D. L., Moraes, A., Gianluppi, V., Bendahan, A. B. (2014). Avaliação da rebrota natural de pastagens de Trachypogon plumosus nos cerrados de Roraima. Scientia Agraria Paranaensis, 13(1), 57-64.

Costa, N. D. L., Gianluppi, V., Moraes, A., Bendahan, A. B. (2011). Produtividade de forragem e características morfogênicas e estruturais de Axonopus aureus nos cerrados de Roraima. Amazônia Ciência & Desenvolvimento, 6(12), 7-22.

Crawford, F. D., Szelewski, C. E. (1984). Geology and exploration in the Takutu graben of Guyana. Oil & gas journal, 82(10): 122-129.

Crawford, F. D., Szelewski, C. E., Alvey, G. D. (1985). Geology and exploration in the Takutu graben of Guyana Brazil. Journal of Petroleum Geology, 8(1): 5-36.

Cremon, É. H., de Fátima Rossetti, D., de Oliveira Sawakuchi, A., Cohen, M. C. L. (2016). The role of tectonics and climate in the late Quaternary evolution of a northern Amazonian River. Geomorphology, 271, 22-39.

Crippen, R. E., Buckley, S., Agram, P. S., Belz, J. E., Gurrola, E. M., Hensley, S., ... Tung, W. (2016). NASADEM global elevation model of earth: Methods for the refinement and merger of SRTM and ASTER GDEM. In AGU Fall Meeting Abstracts (Vol. 2016, pp. IN43B-1692).

Cruz, C. M., Holanda, E. C., Evangelista, T. A. (2019). Composição florística do cretáceo inferior da Formação Serra do Tucano, Bacia do Tacutu, RR. In: Anais Do Xxvl Congresso Brasileiro De Paleontologia. Anais eletrônicos... Galoá. Accessed through <https://proceedings.science/cbp-2019/papers/composicao-floristica-do-cretaceo-inferior-da-formacao-serra-do-tucano--bacia-do-tacutu--rr?lang=en>. Access in jun. 2021.

D'Addabbo, A., Refice, A., Pasquariello, G., Lovergine, F. (2016). SAR/optical data fusion for flood detection. In 2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS) (pp. 7631-7634). IEEE.

Diniz, A.M.A., Lacerda, E.G. (2018). The complexities of the Brazilian Amazon frontier and its most recent chapter: soybean expansion in Roraima. In.: Roy Jones and Alexandre M. A. Diniz, Twentieh Century Land Settlement Schemes, (1st ed.), NY: Routledge, pp: 178-204

Drucker, D. P., Costa, F. R. C., Magnusson, W. E. (2008). How wide is the riparian zone of small streams in tropical forests? A test with terrestrial herbs. Journal of Tropical Ecology, 24(1), 65-74.

Eamus, D., Huete, A., Yu, Q. (2016). Savannas. In Vegetation Dynamics: A Synthesis of Plant Ecophysiology, Remote Sensing and Modelling (pp. 383-414). Cambridge: Cambridge University Press.

Eiras, J. F., Kinoshita, E. M. (1990). Geologia e perspectivas petrolíferas da Bacia do Tacutu. Origem e Evolução das Bacias Sedimentares: PETROBRAS, Anais, 197-220.

Empresa Brasileira De Pesquisa Agropecuária – EMBRAPA. (1979). Serviço Nacional de Levantamento e Conservação de Solos. In: Reunião Técnica De Levantamento De Solos. Súmula...Rio de Janeiro. 83p.

FAO. (2015). World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. IUSS Working Group WRB, Rome.

ESA. (2018). Sentinel-2 User Guide. Accessed through <https://sentinel.esa.int/web/sentinel/technical-guides/sentinel-2-msi>. Access in jan. 2020.

Farr, T. G., Rosen, P. A., Caro, E., Crippen, R., Duren, R., Hensley, S., ... Alsdorf, D. (2007). The shuttle radar topography mission. Reviews of geophysics, 45(2).

Feitosa, K. K. A., Vale Júnior, J. F. D., Schaefer, C. E. G. R., Sousa, M. I. L. D., Nascimento, P. P. R. R. (2016). Relações solo-vegetação em" ilhas" florestais e savanas adjacentes, no nordeste de Roraima. Ciência Florestal, 26(1), 135-146.

Fernandes, G.W. Coelho, M.S. Machado, R.B. Ferreira, M.E. Aguiar, L.M.S. Dirzo, R. Scariot, A., Lopes, C.R. (2016). Afforestation of savannas: an impending ecological disaster. Brazilian Journal of Nature Conservation, 14: 146-151.

Ferreira, C. S., Carmo, W. S. D., Graciano-Ribeiro, D., Oliveira, J. M. F. D., Melo, R. B. D., Franco, A. C. (2015). Leaf anatomy of eleven dominant woody species in the savannas of Roraima. Acta Amazonica, 45, 337-346.

Fick, S. E., Hijmans, R. J. (2017). WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. International journal of climatology, 37(12), 4302-4315.

Furlan, L. M., Rosolen, V., Salles, J., Moreira, C. A., Ferreira, M. E., Bueno, G. T., ... Mounier, S. (2020). Natural superficial water storage and aquifer recharge assessment in Brazilian savanna wetland using unmanned aerial vehicle and geophysical survey. Journal of Unmanned Vehicle Systems, 8(3): 224-244.

Franco, E. M. S., Del'arco, J. O., Rivetti, M. (1975). Folha NA. 20 Boa Vista e parte das Folhas NA. 21 Tumucumaque, NB. 20 Roraima e NB. 21. Geomorfologia. BRASIL. Projeto RADAMBRASIL. Geomorfologia. Rio de Janeiro. DNPM, 139-180.

Godlee, J. L., Ryan, C. M., Bauman, D., Bowers, S. J., Carreiras, J. M., Chisingui, A. V., ... Dexter, K. G. (2021). Structural diversity and tree density drives variation in the biodiversity–ecosystem function relationship of woodlands and savannas. New Phytologist, 232(2), 579-594.

Gray, J. M., Bishop, T. F., Wilford, J. R. (2016). Lithology and soil relationships for soil modelling and mapping. Catena, 147: 429-440.

Grohmann, C. H. (2018). Evaluation of TanDEM-X DEMs on selected Brazilian sites: Comparison with SRTM, ASTER GDEM and ALOS AW3D30. Remote Sensing of Environment, 212, 121-133.

Grüneberg, E., Schöning, I., Hessenmöller, D., Schulze, E. D., Weisser, W. W. (2013). Organic layer and clay content control soil organic carbon stocks in density fractions of differently managed German beech forests. Forest Ecology and Management, 303, 1-10.

Guisan, A., Zimmermann, N. E. (2000). Predictive habitat distribution models in ecology. Ecological modelling, 135(2-3), 147-186.

Gurgel, H. D. C., Ferreira, N. J., Luiz, A. J. (2003). Estudo da variabilidade do NDVI sobre o Brasil, utilizando-se a análise de agrupamentos. Revista Brasileira de Engenharia Agrícola e Ambiental, 7(1), 85-90.

Hahn, P. Y. S., Júnior, S. S. T., Neta, L. C. B., Gauger, A. P. (2012). Caracterização das unidades morfoestruturais do Hemigraben Tacutu, Norte de Roraima. Revista Geonorte, 3(5), 1378-1383.

Hengl, T., Mendes de Jesus, J., Heuvelink, G. B., Ruiperez Gonzalez, M., Kilibarda, M., Blagotić, A., ... Kempen, B. (2017). SoilGrids250m: Global gridded soil information based on machine learning. PLoS one, 12(2), e0169748.

Higgins, M. A., Ruokolainen, K., Tuomisto, H., Llerena, N., Cardenas, G., Phillips, O. L., ... Räsänen, M. (2011). Geological control of floristic composition in Amazonian forests. Journal of biogeography, 138(11), 2136-2149.

Hill MJ. (2021). Remote Sensing of Savannas and Woodlands: Editorial. *Remote Sensing*. 13(8):1490.

Hoffmann, W. A., Geiger, E. L., Gotsch, S. G., Rossatto, D. R., Silva, L. C., Lau, O. L., ... Franco, A. C. (2012). Ecological thresholds at the savanna-forest boundary: how plant traits, resources and fire govern the distribution of tropical biomes. Ecology letters, 15(7), 759-768.

Holanda, J. L. R., Marmos, J. L., Maia, M. A. M. (2014). Geodiversidade do estado de Roraima. CPRM.

Holben, B. N., Shimabukuro, Y. E. (1993). Linear mixing model applied to coarse spatial resolution data from multispectral satellite sensors. Remote Sensing, 14(11), 2231-2240.

Hoyos, N., Correa-Metrio, A., Jaramillo, C., Villegas, J. C., Escobar, J. (2022). Effects of consecutive dry and wet days on the forest–savanna boundary in north-west South America. Global Ecology and Biogeography, 31(2), 347-361.

IBGE (2009). Manual Técnico da Geomorfologia Brasileira. Rio de Janeiro, 2.

IBGE (2012). Manual Técnico da Vegetação Brasileira. Rio de Janeiro, 1.

Kulkarni, S. C., Rege, P. P. (2020). Pixel level fusion techniques for SAR and optical images: A review. Information Fusion, 59, 13-29.

Ladeira, L. F. B., Dantas, M. E. (2014). Compartimentação geomorfológica. Holanda, Jl.

Latrubesse, E. M., Nelson, B. W. (2001). Evidence for Late Quaternary aeolian activity in the Roraima–Guyana region. Catena, 43(1), 63-80.

Lehmann C.E.R., Parr C.L. (2016). Tropical grassy biomes: linking ecology, human use and conservation. Phil. Trans. R. Soc. B 371: 20160329.

Lehmann, C. E., Anderson, T. M., Sankaran, M., Higgins, S. I., Archibald, S., Hoffmann, W. A., ... Bond, W. J. (2014). Savanna vegetation-fire-climate relationships differ among continents. Science, 343(6170), 548-552.

Lehmann, C. E., Archibald, S. A., Hoffmann, W. A., Bond, W. J. (2011). Deciphering the distribution of the savanna biome. New Phytologist, 191(1), 197-209.

Lima, M.S.B. (2020). Expansão da cadeia da soja na Amazônia Setentrional: os casos de Roraima e Amapá. Boletim de Geografia da Universidade Estadual de Maringá, 38(2): 79-93.

Lloyd J, Goulden ML, Ometto JP, Patiño S, Fyllas NM, Quesada CA. (2009). Ecophysiology of forest and savanna vegetation. In Amazonia and global change (eds Keller M, Bustamante M, Gash J, Silva Dias P), pp. 463–484. Washington, DC: American Geophysical Union.

Lloyd, J., Bird, M. I., Vellen, L., Miranda, A. C., Veenendaal, E. M., Djagbletey, G., ... Farquhar, G. D. (2008). Contributions of woody and herbaceous vegetation to tropical savanna ecosystem productivity: a quasi-global estimate. Tree physiology, 28(3), 451-468.

Macintyre, P., Van Niekerk, A., Mucina, L. (2020). Efficacy of multi-season Sentinel-2 imagery for compositional vegetation classification. International Journal of Applied Earth Observation and Geoinformation, 85, 101980.

Magnusson, W. E., Mourão, G., Costa, F. R. C. (2015). Estatística sem matemática: a ligação entre as questões e as análises.

Mahyouba, S., Fadilb, A., Mansour, E. M., Rhinanea, H., Al-Nahmia, F. (2019). Fusing of optical and synthetic aperture radar (SAR) remote sensing data: A systematic literature review (SLR). International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 42(4/W12), 127-138.

MapBiomas (2022). Statistics. Accessed through <https://mapbiomas.org/en/statistics>. Access in fev. 2022.

Matías, L., Hidalgo-Galvez, M. D., Cambrollé, J., Domínguez, M. T., Pérez-Ramos, I. M. (2021). How will forecasted warming and drought affect soil respiration in savannah ecosystems? The role of tree canopy and grazing legacy. Agricultural and Forest Meteorology, 304, 108425.

Meneses, M. E. N. D. S., Costa, M. L. D. (2012). Caracterização mineralógica e química dos regolitos de uma área de transição savana-floresta em Roraima: uma análise da evolução da paisagem.

Meneses, M. E. N. D. S., Costa, M. L. D., Costa, J. A. V. (2007). Os lagos do lavrado de Boa Vista-Roraima: fisiografia, físico-química das águas, mineralogia e química dos sedimentos. Brazilian Journal of Geology, 37(3), 478-489.

Meneses, P. R., Almeida, T. D. (2012). Introdução ao processamento de imagens de sensoriamento remoto. Universidade de Brasília, Brasília.

Menezes, F. B., Wankler, F. L. (2020). Sistemas deposicionais fluviais: análise estratigráfica das unidades sedimentares da Formação Boa Vista, nordeste da bacia do Tacutu, RR. Revista Geográfica Acadêmica, 14(1), 69-93.

Miall, A. D. (2006). The Geology of Fluvial Deposits. Sedimentary Facies, Basin Analysis, and Petroleum Geology. Berlin: Springer, 4th. ed., 599 pp.

Milani, E.J., Thomaz Filho, A. (2000). Sedimentary Basins of South America. In: Cordani, U.G., Milani, E.J., Thomaz Filho, A. Campos, D.A. (eds.). Tectonic Evolution of South America. Rio de Janeiro, 31st. IGC, 389-449.

Miller, G. R., Cable, J. M., McDonald, A. K., Bond, B., Franz, T. E., Wang, L., ... Scott, R. L. (2012). Understanding ecohydrological connectivity in savannas: a system dynamic modelling approach. Ecohydrology, 5(2), 200-220.

Miranda, I. S., Absy, M. L. (2000). Fisionomia das savanas de Roraima, Brasil. Acta Amazonica, 3, 423-440.

Miranda, I. S., Absy, M. L., Rebêlo, G. H. (2003). Community structure of woody plants of Roraima savannahs, Brazil. Plant Ecology, 164(1), 109-123.

Misra, G., Cawkwell, F., Wingler, A. (2020). Status of phenological research using Sentinel-2 data: A review. Remote Sensing, 12(17), 2760.

Mistry, J., Beradi, A. (2000). The Savanna ecosystem. In.: J. Mistry and A. Beradi (eds.), World Savannas - Ecology and Human Use, Routledge Ed., 1st. ed., NY, USA, 1-25 pp.

Montalvão, R. M. G., Muniz, M. B., Issler, R. S., Dall'Agnol, R., Lima, M. I. C., Fernandes, P. E. C. A., Silva, G. G. (1975). Folha NA. 20 Boa Vista e parte das Folhas NA. 21 Tumucumaque, NB. 20 Roraima e NB. 21. Geoogia. BRASIL. Projeto RADAMBRASIL. Geomorfologia. Rio de Janeiro. DNPM, 15-136.

Moreira, A. (2013). Synthetic aperture radar (SAR): Principles and applications.

Mosa, K. A., Ismail, A., & Helmy, M. (2017). Plant stress tolerance: an integrated omics approach. Cham: Springer, 1-19.

Helmy, M. (2017). Introduction to plant stresses. In Plant stress tolerance (pp. 1-19). Springer, Cham.

Mudd, S. M. (2020). Topographic data from satellites. In Developments in Earth Surface Processes (Vol. 23, pp. 91-128). Elsevier.

Murphy, B. P., Bowman, D. M. (2012). What controls the distribution of tropical forest and savanna? Ecology letters, 15(7), 748-758.

Nascimento, S. O., Junior, S. T., Neta, L. B. (2014). Mapeamento geomorfológico da região do Gráben do Tacutu, por meio de análise de morfoestruturas. Revista Geonorte, 5(16), 218-224.

Oliveras, I., Malhi, Y. (2016). Many shades of green: the dynamic tropical forest–savannah transition zones. Philosophical Transactions of the Royal Society B: Biological Sciences, 371(1703), 20150308.

Oliveira, P. C., Parolin, P., Borghetti, F. (2019). Can germination explain the distribution of tree species in a savanna wetland? Austral Ecology, 44(8), 1373-1383.

PALSAR (2015). Radiometric Terrain Corrected low res Includes Material © JAXA/METI 2007. Accessed through <https://asf.alaska.edu/>. Access in: jan. 2020.

Pennington, R. T., Lehmann, C. E. R. Rowland, L. (2018). Tropical savannas and dry forests. Current Biology, 28, pp: R527-R548.

Pennington, R. T., Lewis, G. P. Ratter, J. A. (2006). An overview of the plant diversity, biogeography and conservation of Neotropical Savannas and seasonally dry forests. In.: R. Toby Pennington and James A. Ratter (eds.), 1st. ed., Boca Raton FL: CRC Press, pp 1-30.

Petri, C. A., Galvão, L. S., Lyapustin, A. I. (2019). MODIS BRDF effects over Brazilian tropical forests and savannahs: A comparative analysis. Remote Sensing Letters, 10(2), 95-102.

Pierdicca, N., Pulvirenti, L., Chini, M., Guerriero, L., Candela, L. (2013). Observing floods from space: Experience gained from COSMO-SkyMed observations. Acta Astronautica, 84, 122-133.

Pivello, V. R. (2011). The use of fire in Cerrado and Amazonian Rainforests of Brazil: Past and Present. Fire Ecology, 7(1): 24-39.

Quesada, C. A., Lloyd, J., Anderson, L. O., Fyllas, N. M., Schwarz, M., Czimczik, C. I. (2011). Soils of Amazonia with particular reference to the RAINFOR sites. Biogeosciences, 8(6), 1415-1440.

Ramos, I. M. P., Álvarez-Méndez, A., Wald, K., Matías, L., Hidalgo-Galvez, M. D., Navarro-Fernández, C. M. (2021). Direct and indirect effects of global change on mycorrhizal associations of savanna plant communities. Oikos, 130(8), 1370-1384.

R Core Team (2013) R: A language and environment for statistical computing. R Foundation for Statistical Computing.

Ratnam, J., Bond, W. J., Fensham, R. J., Hoffmann, W. A., Archibald, S., Lehmann, C. E., ... Sankaran, M. (2011). When is a ‘forest’a savanna, and why does it matter? Global Ecology and Biogeography, 20(5), 653-660.

Reis, N. J., Nunes, N. D. V., Pinheiro, S. D. S. (1994). A Cobertura Mesozóica do Hemigraben Tacutu-Estado de Roraima. Uma abordagem ao Paleo-ambiente da Formação Serra do Tucano. SBG, Congr. Bras. Geol, 38, 234-235.

Reis, N. J., Faria, M. D., Maia, M. A. M. (2001). O quadro Cenozoico da porção norte-oriental do Estado de Roraima. Contribuição à Geologia da Amazônia, 3, 259-272.

Reis, N. J., Szatmari, J., Wanderley Filho, J. R., York, D., Evensen, N. M., Smith, P. E. (2006). Dois eventos de magmatismo máfico mesozóico na fronteira Brasil-Guiana, escudo das Guianas: enfoque à região do rifte Tacutu-North Savannas. SBG, Congr. Bras. Geol., 43, 459-464.

Ronquim, C. C. (2021). Fertility concepts and adequate management for soils in tropical regions. Embrapa Territorial-Boletim de Pesquisa e Desenvolvimento (INFOTECA-E).

Rosim, S., Monteiro, A. M. V., Rennó, C. D., Oliveira, J. R. F. (2008). Uma ferramenta open source que unifica representações de fluxo local para apoio à gestão de recursos hídricos no Brasil. IP. Informática Pública, 10, 29-49.

Rosim, S., Monteiro, A. M. V., Rennó, C. D., Souza, R. D., Soares, J. V. (2003). TerraHidro - Uma plataforma computacional para o desenvolvimento de aplicativos para a análise integrada de recursos hídricos. XI Simpósio Brasileiro de Sensoriamento Remoto-SBSR, 2589-2596.

Rossetti, D. F., Gribel, R., Cohen, M. C. L., Valeriano, M. M., Tatumi, S. H., Yee, M. (2019a). The role of Late Pleistocene-Holocene tectono-sedimentary history on the origin of patches of savanna vegetation in the middle Madeira River, southwest of the Amazonian lowlands. Palaeogeography, Palaeoclimatology, Palaeoecology, 526, 136-156.

Rossetti, D. F., Moulatlet, G. M., Tuomisto, H., Gribel, R., Toledo, P. M., Valeriano, M. M., ..., Ferreira, C. A. (2019b). White sand vegetation in an Amazonian lowland under the perspective of a young geological history. Anais da Academia Brasileira de Ciências, 91(4): e20181337.

Sana, R. S., Anghinoni, I., Brandão, Z. N., Holzschuh, M. J. (2014). Variabilidade espacial de atributos físico-químicos do solo e seus efeitos na produtividade do algodoeiro. Revista Brasileira de Engenharia Agrícola e Ambiental, 18, 994-1002.

Sanchez, A. H., Picoli, M. C. A., Camara, G., Andrade, P. R., Chaves, M. E. D., Lechler, S., …, Queiroz, G. R. (2020). Comparison of Cloud cover detection algorithms on sentinel–2 images of the amazon tropical forest. Remote Sensing, 12(8): 1-16.

Sander, C., Gasparetto, N. V. L., Santos, M. L., Carvalho, T. M., Wankler, F. L. (2015a). Aspectos da dinâmica morfológica do Alto Rio Branco, adjacências da cidade de Boa Vista, Roraima. In: Gorayeb, P. S. S., Lima, A. M. M. (Org.). Contribuições à Geoecologia da Amazônia, 1. ed., v. 9., Belém: SBG - Núcleo Norte, p. 15-31.

Sander, C., Gasparetto, N., Santos, M. (2015b). Variações da carga sedimentar de fundo e morfologia dos perfis transversais batimétricos no trecho inferior da bacia do Alto rio Branco, Roraima. Revista Geográfica Acadêmica, 9(1), 130-145.

Sander, C., Wankler, F. L., Evangelista, R. A. O., Santos, M. L., Quinonez Fernandez, O. V. (2012). Intervenções antrópicas em canais fluviais em áreas urbanizadas: rede de drenagem do Igarapé Caranã, Boa Vista-RR. Acta Geográfica, 6(12): 59-84.

Sander, C., Wankler, F. L., Tonello, M. F., Sousa, V. P. (2008). Levantamento hidrológico da bacia do igarapé Carrapato, Boa Vista, RR: dados preliminares. Acta Geográfica, 2(3), 119-129.

Santos, Â. C. S., Holanda, E. C., Souza, V., Guerra-Sommer, M., Manfroi, J., Uhl, D., Jasper, A. (2016). Evidence of palaeo-wildfire from the upper lower Cretaceous (Serra do Tucano Formation, Aptian–Albian) of Roraima (North Brazil). Cretaceous Research, 57, 46-49.

Santos, N. M. C., Vale Junior, J. F., Barbosa, R. I. (2013). Florística e estrutura arbórea de ilhas de mata em áreas de savana do norte da Amazônia brasileira. Boletim do Museu Paraense Emílio Goeldi-Ciências Naturais, 8(2), 205-221.

Shao, Z., Wu, W., Guo, S. (2020). IHS-GTF: A fusion method for optical and synthetic aperture radar data. Remote Sensing, 12(17): 2796.

Shimabukuro, Y. E., Ponzoni, F. J. (2017). Mistura Espectral: modelo linear e aplicações. Rio de Janeiro: Oficina de Textos, 1a. Ed., 87 pp.

Shipley, B. (2016). Cause and Correlation in Biology: A User's Guide to Path Analysis, Structural Equations and Causal Inference with R. Cambridge: Cambridge University Press, 2th. Ed., 314pp.

Silva, D. A. D., Klink, C. A. (2001). Dinâmica de foliação e perfilhamento de duas gramíneas C4 e uma C3 nativas do Cerrado. Brazilian Journal of Botany, 24: 441-446.

Silva, M. G., Porsani, M. J. (2006). Aplicação de balanceamento espectral e DMO no processamento sísmico da Bacia do Tacutu. Revista Brasileira de Geofísica, 24(2), 273-290.

Silva, D. A., Nascimento, F. A., Silva, L. D., Neta, L. C. B., Júnior, S. S. T. (2010). Características Geomorfológicas e a Atuação Antrópica na Formação da Atual Paisagem em Boa Vista, Bonfim e Pacaraima. Acta Geográfica, 3(6): 55-64.

Silva, F. B., Shimabukuro, Y. E., Aragao, L. E., Anderson, L. O., Pereira, G., Cardozo, F., Arai, E. (2013). Large-scale heterogeneity of Amazonian phenology revealed from 26-year long AVHRR/NDVI time-series. Environmental Research Letters, 8(2), 024011.

Silva, L. J. D., Dick, D. P., Neckel, D., Nóbrega, G. N., Rodrigues, R. D. A. R., Barbosa, R. I., Cordeiro, R. C. (2022). Effects of fire on soil organic matter in northern Amazonian forest fragments. Acta Amazonica, 52: 13-22.

Silveira, H. L. F., Galvão, L. S., Sanches, I. D. A., de Sá, I. B., Taura, T. A. (2018). Use of MSI/Sentinel-2 and airborne LiDAR data for mapping vegetation and studying the relationships with soil attributes in the Brazilian semi-arid region. International Journal of Applied Earth Observation and Geoinformation, 73: 179-190.

Silvertown, J., Dodd, M. E., Gowing, D. J., Mountford, J. O. (1999). Hydrologically defined niches reveal a basis for species richness in plant communities. Nature, 400(6739): 61-63.

Silvertown, J., Araya, Y., Gowing, D. (2015). Hydrological niches in terrestrial plant communities: a review. Journal of Ecology, 103(1): 93-108.

Simões, S. M. O., Zilli, J. É., Costa, M. C. G., Tonini, H., Balieiro, F. D. C. (2010). Carbono orgânico e biomassa microbiana do solo em plantios de Acacia mangium no Cerrado de Roraima. Acta Amazonica, 40(1): 23-30.

Souza, V., Vieira, C. E. L., Costa, J. A. V., Matos, S. C., Soares, V. M. A. (2010). Ocorrência de Lenhos Fósseis na Bacia do Tacutu-Roraima. Acta Geográfica, 3(5): 73-77.

Souza, A. A., Galvão, L.S., Korting, T. S., Prieto, J.D. (2020). Dynamics of savanna clearing and land degradation in the newest agricultural frontier in Brazil. Geoscience and Remote Sensing, 57(7): 965-984.

Souza Filho, P. W. M., Paradella, R. W. (2005). Use of RADARSAT-1 fine mode and Landsat-5 TM selective principal component analysis for geomorphological mapping in a macrotidal mangrove coast in the Amazon Region. Canadian Journal of Remote Sensing, 31(3): 214-224.

Sullivan, M. J., Lewis, S. L., Affum-Baffoe, K., Castilho, C., Costa, F., Sanchez, A. C., Vargas, P. N. (2020). Long-term thermal sensitivity of Earth's tropical forests. Science, 368(6493): 869-874.

Tadono, T., Ishida, H., Oda, F., Naito, S., Minakawa, K., Iwamoto, H. (2014). Precise global DEM generation by ALOS PRISM. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 2(4): 71-76.

Tao, S., Guo, Q., Li, C., Wang, Z., Fang, J. (2016). Global patterns and determinants of forest canopy height. Ecology, 97(12): 3265-3270.

Vale Júnior, J. F. D., Sousa, M. I. L., Barbosa, R. I., Xaud, H. A. M., Souza, J. M. C. (2005). Savanas de Roraima: Etnoecologia, biodiversidade e potencialidades agrosilvopastoris. Boa Vista, FEMACT, 2005. p.79-91.

Vale Júnior, J. F. D., Schaefer, C.E.G.R. (2010). Guia de solos sob savanas de Roraima. Boa Vista. Ioris, 219 p.

Vale Júnior, J. F. D., Sousa, M. I. L., Nascimento, P. P. R. R. (2014). Solos e Ambientes. In: Holanda, J. L. R., Marmos, J. L., Maia, M. A. M. (Org.). Geodiversidade do Estado de Roraima, 1. ed., Manaus: CPRM, p. 65–86.

Hammen, T., Burger, D. (1964). Pollen flora and age of the Takutu Formation (Guyana). Leidse Geologische Mededelingen, 38: 173-180.

Vaz, P. T., Wanderley Filho, J. R., Bueno, G. V. (2007). Bacia do Tacutu. Boletim de Geociências da Petrobras, Rio de Janeiro, 15(2): 289-297.

Veenendaal, E. M., Torello-Raventos, M., Feldpausch, T. R., Domingues, T. F., Gerard, F., Schrodt, F., ... Lloyd, J. (2015). Structural, physiognomic and above-ground biomass variation in savanna–forest transition zones on three continents–how different are co-occurring savanna and forest formations? Biogeosciences, 12(10): 2927-2951.

Veras, A. T. R., Galdino, L. K. A., Oliveira Jr, Z. (2018). Occupation of urban space and legal evolution of the app's of the water courses of Law No. 12.651/2012: temporal reflections in the city of Boa Vista-Roraima. Direito da Cidade, 10(3): 1761-1788.

Villalobos-Vega, R., Salazar, A., Miralles-Wilhelm, F., Haridasan, M., Franco, A. C., Goldstein, G. (2014). Do groundwater dynamics drive spatial patterns of tree density and diversity in Neotropical savannas? Journal of vegetation science, 25(6), 1465-1473.

Walker, B. H. (1987). Determinants of Tropical Savannas. Oxford, UK: IRL Press Ltd., 1st. ed., 167 pp.

Wankler, F. L., Evangelista, R. A. O. Sander, C. (2012). Sistema Aquífero Boa Vista: "Estado da Arte" do conhecimento e perspectivas. ACTA Geográfica, Boa Vista, 6(12): 21-39.

Ward, D. P., Petty, A., Setterfield, S. A., Douglas, M. M., Ferdinands, K., Hamilton, S. K., Phinn, S. (2014). Floodplain inundation and vegetation dynamics in the Alligator Rivers region (Kakadu) of northern Australia assessed using optical and radar remote sensing. Remote Sensing of Environment, 147: 43-55.

Xaud, M. R., Xaud, H. A. M., Ferreira, N. J., Kampel, M., Santos, J. R. (2009). Análise de padrões de vegetação através de séries temporais de NDVI-NOAA e suas relações com o clima em Roraima. Anais XIV Simpósio Brasileiro de Sensoriamento Remoto, Natal, Brasil. INPE, p. 3143-3150

Xaud, H. A. M., Carvalho, V. C. (1999). Definição de unidades de paisagem natural através de cruzamentos entre mapas: abordagem crítica e aplicabilidade. In: Congresso e Feira para Usuarios de Geoprocessamento da America Latina, 5, Salvador. Anais... Salvador: INPE. p.1-18.

Zalán, P. V. (2004). Evolução fanerozóica das bacias sedimentares brasileiras. In: Geologia do Continente Sul-Americano: Evolução da obra de Fernando Flávio Marques de Almeida. São Paulo, Beca: 595-613.

Zani, H., Rossetti, D. F. (2012). Multitemporal Landsat data applied for deciphering a megafan in northern Amazonia. International Journal of Remote Sensing, 33(19), 6060-6075.

Zular, A., Sawakuchi, A. O., Chiessi, C. M., d'Horta, F. M., Cruz, F. W., Demattê, J. A. M., ... Soares, E. A. A. (2019). The role of abrupt climate change in the formation of an open vegetation enclave in northern Amazonia during the late Quaternary. Global and planetary change, 172, 140-149.

Zuquim, G., Tuomisto, H., Jones, M. M., Prado, J., Figueiredo, F. O., Moulatlet, G. M., ..., Emilio, T. (2014). Predicting environmental gradients with fern species composition in Brazilian Amazonia. Journal of Vegetation Science, 25(5), 1195-1207.

Zuquim, G., Costa, F. R., Tuomisto, H., Moulatlet, G. M., Figueiredo, F. O. (2020). The importance of soils in predicting the future of plant habitat suitability in a tropical forest. Plant and Soil, 450(1), 151-170.

2.1 NORMAS DA REVISTA

Manuscrito elaborado para submissão ao periódico *Remote Sensing of Environment*. A escolha desse periódico deve-se ao seu alto fator de impacto interdisciplinar, não apenas no âmbito do sensoriamento remoto, mas também das ciências ambientais, geociências e biodiversidade. Guia aos autores em: https://www.elsevier.com/journals/remote-sensing-of-environment/0034-4257/guide-for-authors.

3 CONCLUSÃO

Na área estudada, o vigor da vegetação variou consideravelmente tanto em termos espaciais (77%), quanto temporais (>60%), ou seja, por um lado as diferenças de NDVI registradas dentro da área variaram desde a completa ausência de qualquer tipo de vegetação, até densas manchas florestais e, por outro lado, quando comparadas imagens de distintas épocas, houve também uma significativa variação do NDVI, particularmente quando se comparam imagens de épocas de chuvas com épocas de secas.

Considerando-se que de todos os caracteres abióticos aqui analisados, apenas a precipitação e a temperatura têm a capacidade de variar significativamente nas escalas de tempo analisadas, é possível atribuir à precipitação grande parte da responsabilidade por esta variação. De fato, os resultados do Modelo de Equações Estruturadas apontaram um efeito positivo significativo no NDVI da precipitação (0,23) e um efeito secundário e inverso da temperatura (-0,11). A precipitação variou mais no tempo (0,95%) do que no espaço (30%). Dado o caráter xeromórfico da vegetação de savana, a maior proximidade a corpos d'água perenes explica a variação espacial e o aporte de água durante as épocas de chuva explica a variação temporal.

Essa influência, no entanto, não é linear, pois em casos onde as chuvas geram acumulações expressivas de água, a concomitante ausência de ar nos poros dos solos decorrente da sua saturação pode afogar as raízes e matar as plantas, exercendo assim, um efeito negativo no NDVI. De fato, inundações mostraram efeitos negativos na vegetação (-0,15), ainda que não tão elevados quanto o esperado.

Para a savana roraimense, a altitude e a declividade do terreno não se mostraram muito importantes para o comportamento e distribuição da savana, ao contrário da geologia e da geomorfologia, cujos efeitos indiretos no NDVI da vegetação foi de 0,33 e 0,16, respectivamente. O maior valor da geologia deve-se a dois fatos, o primeiro, de que ela é a fonte primária da química das partículas minerais dos solos, e o segundo, de que a geomorfologia foi ordenada pela atitude.

Os solos se fazem mais influentes quanto ao seu grau de compactação, conforme pode-se observar pela magnitude do efeito obtido para a Densidade Aparente (-0,37). Os valores para a CEC, Areia e SOCS foram, respectivamente, -

0,27, 0,15 e -0,09. É fácil entender o resultado da Densidade Aparente, já que, quanto maior ela for, menor será a capacidade de infiltração do solo e maior será o escoamento superficial, implicando que, após cessada a chuva, as plantas podem ter dificuldade de obter a água necessária, quer porque a água já tenha escoado, quer porque suas raízes não conseguem receber ou capturar água no solo impermeabilizado.

Por outro lado, esperava-se uma influência positiva da CEC, relativa a capacidade do solo trocar cátions importantes ao desenvolvimento vegetal. Sua influência negativa deve-se ao fato de que muitos solos da savana roraimense costumam apresentar altas concentrações de cátions de alumínio, tóxicos ao desenvolvimento vegetal. O efeito positivo da concentração de areia reforça as restrições hidroedáficas da região, áreas periodicamente inundadas dificultam o estabelecimento de espécies de árvores, o que é favorecido em áreas com melhores condições de drenagem.

REFERÊNCIAS

ALIX-GARCIA, J.; GIBBS, H. K. Forest conservation effects of Brazil's zero deforestation cattle agreements undermined by leakage. **Global Environmental Change**, Amsterdan, v. 47, p. 201-217, nov. 2017.

ALVES, D.B.; PÉREZ-CABELLO, F. Multiple remote sensing data sources to assess spatio-temporal patterns of fire incidence over Campos Amazônicos Savanna Vegetation Enclave (Brazilian Amazon). **Science of the Total Environment**, Amsterdan, v. 601-6021, p. 142-158, dez. 2017.

ARAÚJO JÚNIOR, A. C. R.; TAVARES JÚNIOR, S. S. Land use and cover for urban planning, Boa Vista, Roraima, Brasil. **Boletim Goiano de Geografia**, Goiana, v. 37, n. 1, p. 36-55, jan-abr. 2017.

BANERJEE, O.; CICOWIEZ, M.; MACEDO, M.; MALEK, Z.; VERBURG, P. H.; GOODWIN, S.; VARGAS, R.; RATTIS, L.; BRANDO, P. M.; COE, M. T.; NEIL, C.; MARTI, O. D. An Amazon Tipping Point: The Economic and Environmental Fallout. **IDB Working Paper Series** N° IDB-WP-01259, 107 pp. 2021.

BARBER, C.P.; COCHRANE, M. A.; SOUZA JR., C. M.; LAURENCE, W. F. Roads, deforestation, and the mitigating effect of protected areas in the Amazon. **Biological Conservation**, Amsterdan, v. 177, p. 203-209, set. 2014.

BARBOSA, R. I.; CAMPOS, C.; PINTO, F.; FEARNSIDE, P. M. The “Lavrados” of Roraima: biodiversity and conservation of Brazil’s Amazonian Savannas. **Functional Ecosystems and Communities**, Tokyo, v. 1, n. 1, p. 29-41, jan. 2007.

BARBOSA, R. I.; CAMPOS, C. Detection and geographical distribution of clearing areas in the savannas (‘Lavrado‘) of Roraima using Google Earth web tool. **Journal of Geography and Regional Planning**, London, v. 4, n. 3, p. 122-136, fev. 2011.

BARBOSA, R. I.; FEARNSIDE, P.M. Above-ground biomass and the fate of carbon after burning in the savannas of Roraima, Brazilian Amazonia. **Forest Ecology and Management**, Amsterdan, v. 216, n. 1–3, p. 295-316, dez. 2005a.

BARBOSA, R. I.; FEARNSIDE, P.M. Fire frequency and area burned in the Roraima savannas of Brazilian Amazonia. **Forest Ecology and Management**, Amsterdan, v. 204, n. 2-3, p. 371–384, jan. 2005.

BARBOSA, R. I.; MIRANDA, I. D. S. Fitofisionomias e diversidade vegetal das savanas de Roraima. In: BARBOSA, R. I.; XAUD, H. A. M.; COSTA E SOUZA, J. M. (ORG.). **Savanas de**

Roraima: Etnoecologia, Biodiversidade e Potencialidades Agrossilvipastoris. 1 ed. Boa Vista: FEMACT, 2005. p. 61-78.

BARNI, P.E.; FEARNSIDE, P.M.; GRAÇA, P.M.L.A. Deforestation and Carbon Emissions in Amazonia: Simulating the Impact of Connecting Brazil's State of Roraima to the "Arc of Deforestation" by Reconstructing the BR-319 (Manaus-Porto Velho) Highway. In: XII Congreso Forestal Mundial, 12., 2009, Buenos Aires. **Anais...** Buenos Aires: UBA, 2009. p. 1-16.

BARNI, P. E.; PEREIRA, V. B.; MANZI, A. O.; BARBOSA, R. I. Deforestation and forest fires in Roraima and their relationship with phytoclimatic regions in the Northern Brazilian Amazon. **Environmental Management**, Berlin, v. 55, n. 5, p. 1124-1138, jan. 2015.

CARVALHO, W.D.; MUSTIN, K.; HILÁRIO, R.R.; VASCONCELOS, I.M.; EILERS, V.; FEARNSIDE, P.M. Deforestation control in the Brazilian Amazon: A conservation struggle being lost as agreements and regulations are subverted and bypassed. **Perspectives in Ecology and Conservation**, Amsterdan, v. 17, n. 3, p. 122–130, jul-set. 2019.

CARVALHO, W. D.; MUSTIN, K. The highly threatened and little known Amazonian savannahs. **Nature Ecology & Evolution**, California, v. 1, n. 4, p. 1-3, mar. 2017.

DEVECCHI, M. F., LOVO, J., MORO, M. F., ANDRINO, C. O., BARBOSA-SILVA, R. G., VIANA, P. L., ...; ZAPPI, D. C. Beyond forests in the Amazon: biogeography and floristic relationships of the Amazonian savannas. **Botanical Journal of the Linnean Society**, Oxford, v. 193, n. 4, p. 478-503, ago. 2020.

DINIZ, A.M.A.; LACERDA, E.G. The Colonization of Roraima State, Brazil: an Analysis of its Major Migration Flows (1970 to 2010). **Espace Populations Sociétés**, Paris, v. 2-3, p. eps5817, jul. 2014.

DINIZ, A.M.A.; LACERDA, E.G. The complexities of the Brazilian Amazon frontier and its most recent chapter: soybean expansion in Roraima. *In*.: JONES, R.; DINIZ, A. M. A. (Org.). **Twentieh Century Land Settlement Schemes**, 1 ed. Nova York: Routledge, 2018. p. 178-204.

DONG, X.; LI, F.; LIN, Z.; HARRISON, S.P.; CHEN, Y.; KUNG, J.-S. Climate influence on the 2019 fires in Amazonia. **Science of The Total Environment**, Amsterdan, v. 794, p. 148718, dez. 2021.

DURIGAN, G.; RATTER, J.A. The need for a consistent fire policy for Cerrado conservation. **Journal of Applied Ecology**, London, v. 53, n. 1, p. 11-15, out. 2015.

FEARNSIDE, P.M. Highway construction as a force in the destruction of the Amazon Forest. In.: REE, R.; SMITH, D. J.; GRILO, C. (Org.). **Handbook of Road Ecology**, 1 ed., Nova York: John Willey and Sons Ltd., 2015. p. 414-424.

FERNANDES, G.W.; COELHO, M.S.; MACHADO, R.B.; FERREIRA, M.E.; AGUIAR, L.M.S.; DIRZO, R.; SCARIOT, A.; LOPES, C.R. Afforestation of savannas: an impending ecological disaster. **Brazilian Journal of Nature Conservation**, Rio de Janeiro, v. 14, p. 146-151, mar. 2016.

FERRANTE, L.; FEARNSIDE, P.M. Brazil's new president and 'ruralists' threaten Amazonia's environment, traditional peoples and the global climate. **Environmental Conservation**, Cambridge, v. 46, n. 4, p. 261 –263, dez. 2019.

FLORES, B.M.; DECHOUM, M.S.; SCHMIDT, I.B.; HIROTA, M.; ABRAHÃO, A.; VERONA, L.; PECORAL, L.L.F.; CURE, M.B.; GILES, A.L.; COSTA, P.B.; PAMPLONA, M.B.; MAZZOCHINI, G.G.; GROENENDIJK, P.; MINSKI, G.L.; WOLFSDORF, G.; SAMPAIO, A.B.; PICCOLO, F.; MELO, L.; LIMA, R.F.; OLIVEIRA, R.S. Tropical riparian forests in danger from large savanna wildfires. **Journal of Applied Ecology**, London, v. 58, n. 2, p. 419-430, 2021.

FURLAN, L. M., ROSOLEN, V., SALLES, J., MOREIRA, C. A., FERREIRA, M. E., BUENO, G. T., …; MOUNIER, S. Natural superficial water storage and aquifer recharge assessment in Brazilian savanna wetland using unmanned aerial vehicle and geophysical survey. **Journal of Unmanned Vehicle Systems**, Ottawa, v. 8, n. 3, p. 224-244, set. 2020.

FURLEY, P.A. **The Forest Frontier**. 1 ed. London: Routledge, 1994. 260 p.
GIBBS, H.K.; RAUSCHA, L.; MUNGER, J.; SCHELLY, I.; MORTON, D.C.; NOOJIPADY, P.; SOARES-FILHO, B.; BARRETO, P.; MICOL, L.; WALKER, N.F. Brazil's Soy Moratorium. **Science**, Washington, v. 347, n. 6220, p. 377-378, jan. 2015.

GOMES, L.; MIRANDA, H.S.; SOARES-FILHO, B.; RODRIGUES, L.; OLIVEIRA, U.; BUSTAMANTE, M.M.C. Responses of Plant Biomass in the Brazilian Savanna to Frequent Fires. **Frontiers in Forest and Global Change**, Lausanne, v. 24, p. 1-11, nov. 2020.

HOEVE, J.E.T.; REMER, L.A.; CORREIA, A.L; JACOBSON, M.Z. Recent shift from forest to savanna burning in the Amazon Basin observed by satellite. **Environmental Research Letters**, Bristol, v. 7, p. 024020, jun. 2012.

IBGE. **Manual Técnico da Vegetação Brasileira**. 1 ed. Rio de Janeiro: IBGE, 2012. 271 p.
KELLEY, D.I.; BURTON, C.; HUNTINGFORD, C.; BROWN, M.A.J.; WHITLEY, R.; DONG, N. Technical note: Low meteorological influence found in 2019 Amazonia fires. **Biogeosciences**, Berlin, v. 126, n. 18, p. 787-804, mar. 2021.

LEHMANN, C. E.; ANDERSON, T. M.; SANKARAN, M.; HIGGINS, S. I.; ARCHIBALD, S.; HOFFMANN, W. A.; ... BOND, W. J. Savanna vegetation-fire-climate relationships differ among continents. **Science**, 1109 343(6170), 548-552, set. 2014.

LIMA, M.S.B. Expansão da cadeia da soja na Amazônia Setentrional: os casos de Roraima e Amapá. **Boletim de Geografia da Universidade Estadual de Maringá**, Maringá, v. 38, n. 2, p. 79-93, out. 2020.

MAPBIOMAS. Statistics. 2022. Disponible in: https://mapbiomas.org/en/statistics. Last accessed: 04/19/2022.

MILLER, G. R.; CABLE, J. M.; MCDONALD, A. K.; BOND, B.; FRANZ, T. E.; WANG, L.; …; SCOTT, R. L. Understanding ecohydrological connectivity in savannas: a system dynamic modelling approach. **Ecohydrology**, Hoboken, v. 5, n. 2, p. 200-220, mai. 2012.

MIRANDA, I. S.; ABSY, M. L. Fisionomia das savanas de Roraima, Brasil. **Acta Amazonica**, Manaus, v. 3, p. 423-440, set. 2000.

MISTRY, J., BERADI, A. (2000). The Savanna ecosystem. In.: MISTRY, J.; BERADI, A. (Org.). **World Savannas - Ecology and Human Use**. 1 ed. Nova York: Routledge, 2000. p. 1-25.

OSBORNE, C. P.; CHARLES- DOMINIQUE, T.; STEVENS, N.; BOND, W. J.; MIDGLEY, G.; LEHMANN, C. E. Human impacts in African savannas are mediated by plant functional traits. **New Phytologist**, Hoboken, v. 220, n. 1, p. 10-24, jan. 2018.

PENNINGTON, R.T.; LEHMANN, C.E.R.; ROWLAND, L.M. Tropical savannas and dry forests. **Current Biology**, Cambridge, v. 28, p. R527-R548, abr. 2018.

RESENDE- MOREIRA, L. C.; KNOWLES, L. L.; THOMAZ, A. T.; PRADO, J. R.; SOUTO, A. P.; LEMOS- FILHO, J. P.; LOVATO, M. B. Evolving in isolation: genetic tests reject recent connections of Amazonian savannas with the central Cerrado. **Journal of Biogeography**, Hoboken, v. 46, n. 1, p. 196-211, jan. 2019.

SCHMIDT, I. B.; ELOY, L. Fire regime in the Brazilian Savanna: Recent changes, policy and management. **Flora**, Amsterdan, v. 268, p. 151613, jul 2020.

SIMIONI, P. F.; EISENLOHR, P. V.; PESSOA, M. J. G.; DA SILVA, I. V. Elucidating adaptive strategies from leaf anatomy: do Amazonian savannas present xeromorphic characteristics?. **Flora**, Amsterdan, v. 226, p. 38-46, jan. 2017.

SOUZA, A. A.; GALVÃO, L.S.; KORTING, T. S.; PRIETO, J.D. Dynamics of savanna clearing and land degradation in the newest agricultural frontier in Brazil. **Geoscience and Remote Sensing**, Nova York, v. 57, n. 7, p. 965-984, ago. 2020.

VACCHIANO, M. C.; SANTOS, J. W.; ANGEOLETTO, F.; SILVA, N. M. Do Data Support Claims That Brazil Leads the World in Environmental Preservation?. **Environmental Conservation**, Cambridge, v. 46, n. 2, p. 118-120, mai. 2019.

VELDMAN, J. W.; BUISSON, E.; DURIGAN, G.; FERNANDES, G. W.; LE STRADIC, S.; MAHY, G.; ...; BOND, W. J. Toward an old- growth concept for grasslands, savannas, and woodlands. **Frontiers in Ecology and the Environment**, Washington, v. 13, n. 3, p. 154-162, out. 2015.

VELDMAN, J.W.; PUTZ, F. E. Grass-dominated vegetation, not species-diverse natural savanna, replaces degraded tropical forests on the southern edge of the Amazon Basin. **Biological Conservation**, Amsterdan, v. 144, n. 5, p. 1419-1429, ago. 2011.

VERAS, A.R.T. **A produção do espaço urbano e Boa Vista – Roraima**. 2009. 235 f. Tese (Doutorado em Geografia) – Universidade de São Paulo, São Paulo, 2009.

VERAS, A.R.T.; GALDINO, L.K.A; OLIVEIRA JR., Z. Occupation of urban space and legal evolution of the APP's of the water courses of law, no. 12.651/2012. **Direito da Cidade**, Rio de Janeiro, v. 10, n. 3, p. 1761+, abr. 2012.

VILLALOBOS- VEGA, R., SALAZAR, A., MIRALLES- WILHELM, F., HARIDASAN, M., FRANCO, A. C., GOLDSTEIN, G. Do groundwater dynamics drive spatial patterns of tree density and diversity in Neotropical savannas? **Journal of vegetation science**, Hoboken, v. 25, n. 6, p. 1465-1473, set. 2014.

WANKLER, F. L.; EVANGELISTA, R. A. O.; SANDER, C. Sistema Aquífero Boa Vista: "Estado da Arte" do conhecimento e perspectivas. **ACTA Geográfica**, Boa Vista, v. 6, n. 12, p. 21-39, ago. 2012.