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**Uso da terra, funcionamento ecossistêmico e degradação na Caatinga: O papel do clima
e fatores socioeconômicos**

Recife
2021

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Tese apresentada ao Programa de Pós-Graduação em Biologia Vegetal da Universidade Federal de Pernambuco, como requisito parcial para obtenção do título de doutor em Biologia Vegetal. Área de Concentração Ecologia e Conservação.

Orientador: Prof. Dr. Marcelo Tabarelli

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À todas e todos os profissionais de saúde do Brasil, que saem de casa todos os dias para conter encarar guerra contra a pandemia, seguindo a ciência e salvando vidas.

À todas e todos os cientistas brasileiros.

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Muito obrigado.

RESUMO

Globalmente, ecossistemas terrestres são ameaçados por duas principais forças resultantes de atividades humanas: mudança do uso e cobertura do solo e mudanças climáticas. Juntos, esses fatores agem sobre diversos níveis biológicos, do tamanho da população de espécies, estrutura e composição de comunidades à biodiversidade. Consequentemente, esse cenário tem impactado o funcionamento ecossistêmico e provisão de serviços ecossistêmicos, com consequente aumento da vulnerabilidade biológica e diminuição do bem-estar humano. Isso é especialmente verdadeiro em *drylands* em regiões em desenvolvimento, com grandes populações rurais altamente dependentes dos recursos naturais e do regime de chuva e, portanto, vulneráveis socioeconomicamente. Em diversas dessas regiões, repetidos ciclos de uso agrícola, sem uso de tecnologias, associado à extração de recursos dos remanescentes de vegetação, tem levado a degradação ecossistêmica e mudanças para estágios alternativos (sendo o extremo a desertificação). Nesse contexto, esse trabalho visa explorar como que a dinâmica de uso e cobertura do solo e a produtividade primária são afetados tanto por variáveis ambientais como por variáveis socioeconômicas em florestas secas. Assim, com uso de ferramentas de Sistema de Informação Geográfica e tomando as florestas secas do semiárido brasileiro (Caatinga) como modelo, objetivamos entender (1) quais os principais drivers de uso e cobertura do solo e suas contribuições para produtividade primária do ecossistema e; (2) quais as tendências espaço-temporais da produtividade da Caatinga e quais as contribuições de clima e perturbação humana para a dinâmica da vegetação (i.e., perda ou aumento de produtividade) nos últimos ca. 20 anos. Os resultados sugerem que (1) o uso da terra ainda é fortemente associado às variáveis ambientais, em especial climáticas, que representam áreas de maior aptidão agrícola, enquanto variáveis socioeconômicas são menos importantes; (2) áreas de pasto compõem significativa área da Caatinga, mas a produtividade é menor nesses ambientes do que em Caatinga tipo savânica e floresta, que apresentaram menor proporção, mas maior produtividade por área; (3) de 2001 a 2019, ca. 25% a Caatinga apresentou padrão de perda de produtividade que indica degradação, mas esse efeito é potencializado pela seca iniciada em 2012 e ocorre em maior intensidade e abrangência em regiões específicas (e.g., sudeste da Caatinga); (4) a produtividade é principalmente influenciada pela disponibilidade de água (i.e., chuva acumulada de 3 meses) em grande parte do ecossistema; e (5) existe um padrão espacial que indica significativa área da dinâmica da produtividade primária da Caatinga não sendo explicada pela chuva; mas nossos proxies de perturbação antrópica se correlacionam com variação da produtividade em menos de 10% da região. Em síntese, assim como é o caso em

outras *drylands*, fatores climáticos parecem ser drivers mais fortes da dinâmica da vegetação, sendo a aptidão agrícola um fator decisivo. No entanto, o papel de fatores socioeconômicos e atividades agrícolas é espacialmente relevante. Outros fatores não analisados, como culturais, podem ser peça importante para entendermos o futuro do uso do solo. Por fim, os cenários previstos de mudanças climáticas e aumento de pecuária intensiva na região aumentam a necessidade de aplicação de tecnologias agrícolas adaptadas ao semiárido.

Palavras-chave: Uso e cobertura do solo; sistemas socioecológicos; terras secas; desenvolvimento socioeconômico; mudanças climáticas; produtividade primária.

ABSTRACT

Globally, terrestrial ecosystems are threatened by two main forces resulting from human activities: land use and land cover change and climate change. Together, these factors act on several biological levels, from species population size, community structure and composition, to biodiversity. Consequently, this scenario has impacted ecosystem functioning and provision of ecosystem services, with a consequent increase in biological vulnerability and a decrease in human well-being. This is especially true in drylands in developing regions, with large rural populations highly dependent on natural resources and rainfall and, therefore, socioeconomically vulnerable. In several of these regions, repeated agricultural cycles, without proper technologies, associated with the extraction of resources from the remnants of vegetation, have led to degradation of the ecosystem and emerging alternative stages (the extreme being the desertification). In this context, this study aims to understand how land use and land cover and primary productivity dynamics are affected both by environmental and by socioeconomic variables in dry forests. Thus, using Geographic Information System tools and taking dry forests in the Brazilian semiarid region (Caatinga) as a model, we aim to understand (1) which are the main drivers of land use and land cover and their contributions to the primary productivity of the ecosystem and; (2) what are the spatio-temporal trends in Caatinga productivity and what are the contributions of climate and human disturbance to the vegetation dynamics (i.e., loss or increase in productivity) in the last ca. 20 years. The results suggest that (1) land use is still strongly associated with environmental variables, especially climatic ones, which represent areas of greater agricultural aptitude, while socioeconomic variables are less important drivers; (2) pasturelands represent a significant area of the Caatinga, but productivity is lower in these environments than in the savanna-like and forest inside Caatinga, which had a lower proportion, but higher productivity per area; (3) from 2001 to 2019, ca. 25% the Caatinga showed a pattern of productivity loss that indicates degradation, but this effect is enhanced by the drought that started in 2012 and occurs in greater intensity and coverage in specific regions (e.g., southeast of the Caatinga); (4) productivity is mainly influenced by water availability (i.e., accumulated rainfall of 3 months) in a large part of the ecosystem; and (5) there is a spatial pattern that indicates a significant area of the Caatinga primary productivity dynamics not explained by rainfall; but our anthropic disturbance proxies correlate with productivity variation in only less than 10% of the region. In summary, as in other drylands, climatic factors seem to be stronger drivers of vegetation dynamics, with agricultural suitability being a decisive factor.

However, the role of socioeconomic factors and agricultural activities is spatially relevant. Other factors not analyzed, such as cultural constraints, can play an important role in understanding the future of land use. Finally, the predicted climate change scenarios and the increase in intensive livestock farming in the region increase the need to apply agricultural technologies adapted to the semiarid region.

Keywords: land use and land cover; socio-ecological systems; drylands; socioeconomic development; climate change; primary productivity.

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1 INTRODUÇÃO

Com populações crescentes e uma maior necessidade de terras agricultáveis para produção de alimentos que supram essa demanda, as regiões tropicais têm passado por um intenso processo de conversão de áreas naturais em áreas de agricultura e pasto. Assim, as paisagens naturais dominadas pelo homem são cada vez mais comuns e representam risco à estrutura, biodiversidade e funcionamento ecossistêmico dos ambientes naturais. Nesse contexto, Florestas Tropicais Sazonalmente Secas (FTSS) representam quase metade das florestas tropicais no mundo e são historicamente e intensamente utilizadas pelo homem por apresentar características favoráveis à cultura agrícola. No entanto, apesar do crescimento da intensificação do uso da terra, a agricultura de subsistência representa o sustento de muitas famílias através de atividades como retirada de lenha, agricultura e pecuária, especialmente em países em desenvolvimento. Portanto, perturbação aguda (i.e., conversão de extensas áreas naturais para uso antrópico) e perturbação crônica (i.e., pequenas e constantes retiradas de biomassa da vegetação, como por exemplo madeira para lenha) representam duas facetas do impacto humano sobre ecossistemas terrestres.

Somado a isso, mudanças climáticas irão, resumidamente, alterar os padrões de temperatura e precipitação no planeta. Na verdade, se trata de um processo global já em andamento que já é responsável pelo abandono da terra de várias famílias em regiões mais vulneráveis. Essas mudanças se apresentam como uma ameaça à ecossistemas naturais, com impacto sobre biodiversidade, funcionamento ecossistêmico e qualidade de vida das pessoas. Apesar de que geralmente as mudanças climáticas estão associadas à aumento de temperatura média e diminuição de chuva, os efeitos em diferentes ecossistemas são complexos ou até contrários ao esperado, envolvendo modificações também, por exemplo, na intensidade de chuva em menor espaço de tempo e secas periódicas mais frequentes. Ademais, diferentes contextos socioecológicos, que refletem diferentes usos da terra em ambientes com vegetação com respostas variadas às mudanças de clima, podem resultar em ambientes com maior ou menor produtividade da vegetação.

Esse cenário de perturbação antrópica e mudanças climáticas representa uma alarmante ameaça à ecossistemas terrestres e à qualidade de vida das populações humanas. Isso é especialmente verdadeiro em regiões áridas e semiáridas (como FTSS), uma vez que nessas áreas geralmente estão localizadas em em países em desenvolvimento. É nesse contexto que existe uma grande interação entre grande dependência dos recursos naturais e de condições climáticas das populações de baixa renda e agrárias e maior disponibilidade de terras

agricultáveis para expansão agrícola. Portanto, é de grande importância que entendamos como que uso da terra está relacionado com condições socioeconômicas e climáticas e como isso se reflete no padrão espaço-temporal do funcionamento do ecossistema.

Na ciência atual, é crescente e evidente a necessidade de estudos que tragam uma maior abordagem multidisciplinar, que leve em consideração a conservação da biodiversidade e o bom funcionamento ecossistêmico, mas sempre considerando o bem-estar e a garantia das condições básicas de comunidades humanas. Nesse cenário, o grupo que compõe o PELD Catimbau (Projeto Ecológico de Longa Duração), além das diversas pesquisas desenvolvidas para avaliar como perturbações antrópicas e mudanças climáticas afetam a biota e funcionamento ecossistêmico da Caatinga, do nível populacional ao ecossistêmico, tem voltado também a entender esses processos e mecanismos em escalas mais amplas. Aqui, apresentamos alguns dos primeiros resultados dessa abordagem que visa avaliar como que mecanismos locais em associação com mecanismos mais amplos (e.g., clima) podem resultar num melhor entendimento sobre o futuro das florestas secas da Caatinga e as comunidades habitantes. Nesse ecossistema de clima semiárido localizado no nordeste brasileiro, muitas famílias de baixa renda ainda dependem da extração de recursos florestais, uso da terra e chuvas regulares para sobrevivência, representando a região socialmente mais vulnerável do país.

Em síntese, esse trabalho objetiva entender (1) como que o uso e cobertura do solo podem ser explicados por questões demográficas, socioeconômicas e ambientais e como isso se reflete na produtividade do ecossistema da Caatinga; e (2) qual o padrão espaço-temporal da produtividade primária do ecossistema Caatinga (i.e., degradando ou ficando mais produtivo) e qual o papel da chuva e perturbação humana nos caminhos da vegetação. Apresentamos então um manuscrito estruturado em três partes principais. Primeiramente, trazemos uma fundamentação teórica abordando os principais temas envolvidos na pesquisa. Em seguida, apresentamos dois manuscritos: o primeiro intitulado “*Vegetation cover and net primary productivity in the Caatinga dry forest: The role of socioeconomic, demographic, and environmental drivers*”, que será submetido ao periódico Landscape Ecology, onde discutimos o papel os principais drivers socioecológicos dos principais usos e cobertura do solo na Caatinga e qual a contribuição de cada classe dessa para a captura de carbono; e o segundo com o título “*Vegetation cover and net primary productivity in the Caatinga dry forest: The role of socioeconomic, demographic, and environmental drivers*”, a ser submetido na revista Land Degradation & Development, que por sua vez está mais voltado a entender as tendências de mudança da vegetação da Caatinga numa perspectiva espaço-temporal e analisando tendências

podem ser resultado de ações humanas. Por fim, apresentamos algumas breves conclusões dos principais resultados do trabalho e perspectivas futuras para a área de pesquisa.

2 FUNDAMENTAÇÃO TEÓRICA

2.1 FLORESTAS TROPICAIS SAZONALMENTE SECAS: IMPORTÂNCIA, AMEAÇAS E POPULAÇÕES HUMANAS

As Florestas Tropicais Sazonalmente Secas (FTSS) são caracterizadas por apresentar clara sazonalidade, com pluviosidade menor que 1600 mm por ano e com ao menos 5 a 6 meses com menos de 100 mm de chuva mensal. Apresenta uma vegetação dominada por árvores predominantemente decíduas na estação seca, com dossel relativamente contínuo e com gramíneas pouco abundantes (PENNINGTON; LAVIN; OLIVEIRA-FILHO, 2009). Além disso, quando comparadas às Florestas Tropicais Úmidas, são caracterizadas por menores valores de complexidade estrutural, riqueza de espécies, área basal, estrato de dossel, produtividade primária e, por outro lado, uma maior frequência de reprodução vegetativa do que florestas úmidas (LEBRIJA-TREJOS et al., 2008).

Numa classificação climática, FTSS são parte de um conjunto de terras áridas e semiáridas que compõem as *drylands* (“terras secas”) (BASTIN et al., 2017). Drylands compreendem as regiões onde a precipitação é contrabalanceada pela evapotranspiração e transpiração de superfícies, portanto apresentando índices de aridez (taxa da média anual de precipitação e evapotranspiração potencial) menor do que 0,65 (MIDDLETON; THOMAS; PROGRAM, 1997). Cobrindo mais de 40% de toda superfície terrestre (SORENSEN, 2009), abrigam cerca de 38% da população global. Algumas estimativas mostram que essas áreas estão em expansão globalmente (HUANG et al., 2016) e ao mesmo tempo que essas áreas apresentam até 7% mais cobertura florestal do que previamente pensado (BASTIN et al., 2017). No entanto, em geral representam terras inférteis, com baixa cobertura vegetal. Somado a isso, por serem altamente ameaçadas por atividades humanas e mudanças climáticas, são regiões bastante ameaçadas, apresentando inclusive diversas áreas em processo de desertificação (IPCC, 2014; MILES et al., 2006; REYNOLDS et al., 2007). Regiões semiáridas têm sido apontadas como importantes regiões para se entender a variabilidade interanual dos ciclos de carbono e que, no futuro, essas regiões vão ser mais importantes do que florestas úmidas para se entender essas variações interanuais de captura de carbono (POULTER et al., 2014).

Dentro das florestas tropicais, FTSS representam uma expressiva percentagem (aproximadamente 42%), com mais da metade nas Américas (PENNINGTON; LAVIN; OLIVEIRA-FILHO, 2009). São de grande importância biológica, com alta diversidade e taxa de endemismo (TREJO; DIRZO, 2000), assim como *turnover* florístico acentuado (inclusive mais elevado do que outros biomas neotropicais) (DRYFLOR, 2016). Adicionalmente, também

são de grande importância econômica e sociocultural, visto que apresentam características que facilitam bastante atividades de agropecuária. Isso gerou o estabelecimento de uma extensa população humana, que desenvolveram uma grande dependência dos recursos e serviços ecossistêmicos providos (PENNINGTON; LAVIN; OLIVEIRA-FILHO, 2009). Serviços esses que são bastante significativos nesses ecossistemas, como por exemplo a estocagem de carbono e provisão de água (BROCKERHOFF et al., 2017; DEXTER et al., 2015; HESKETH; SANCHEZ-AZOFEIFA, 2010). Estima-se, por exemplo, que sozinhos os ecossistemas florestais regulam um terço dos cursos d'água do mundo, impactando cerca de 5 bilhões de pessoas (MA, 2005).

No entanto, apesar desses fatores mencionados, as FTSS são altamente ameaçadas, seguindo o padrão que ocorre nas demais Florestas Tropicais (MILES et al., 2006). Perturbação antrópicas, especialmente causadas por mudanças do uso do solo (conversão de paisagens) e mudanças climáticas globais (com alteração do clima regional e no uso antrópico de recursos) representa a maior ameaça a esses ecossistemas florestais (WRIGHT, 2005). Assim, talvez as FTSS sejam o ecossistema terrestre mais ameaçado do mundo, onde predominam paisagens dominadas pelo homem, cada vez mais fragmentadas e imersas em matrizes agropecuárias e urbanas (DEXTER et al., 2015).

As FTSS estão particularmente expostas a pressões do tipo crônica, principalmente associados ao extrativismo e em países em desenvolvimento. Entre essas atividades, o uso de fogo, corte seletivo de madeira, sobrepastoreio de animais exóticos (a grande maioria de gado, caprinos e ovinos), caça e ciclos de corte e queima da vegetação são os mais comuns (MARTORELL; PETERS, 2009; SINGH, 1998). Apesar de os efeitos dessa perturbação serem aparentemente menos intensos, a constância dessas atividades torna essas atividades maléficas para diferentes níveis da organização biológica (SINGH, 1998). São capazes de desencadear processos como a homogeneização e simplificação das comunidades, bem como alterações no funcionamento do ecossistema e provisão de bens e serviços (MARTORELL; PETERS, 2009; SINGH, 1998). Essas perturbações parecem ter um impacto no ecossistema também em interação com a pluviosidade (RITO et al., 2017), onde os autores identificaram que a diversidade de espécies de lenhosas é positivamente impactada pela perturbação crônica em ambientes mais úmidos, mas negativamente em ambientes mais seco. Adicionalmente, perturbação crônica se mostrou um importante fator que pode levar florestas maduras na direção de vegetação secundária dominada por arbustos (RIBEIRO et al., 2015). No entanto, apesar desse particular tipo de perturbação em FTSS, perturbações agudas são atividades comuns

nessas regiões, variando desde uso em pequena escala ao uso em maiores escalas (relativo à presença de tecnologias, densidade humana, entre outros) (BALDI et al., 2014).

Como resultado desse processo, estimativas apontam para uma redução de aproximadamente entre dois terços (MILES et al., 2006) e metade (HOEKSTRA et al., 2005) da vegetação original das FTSS mundial. Considerando as FTSS apenas nas Américas, a perda de cobertura vegetal chega a 66% (PORTILLO-QUINTERO; SÁNCHEZ-AZOFEIFA, 2010), com muitos países apresentando menos de 10% dessa vegetação original (DRYFLOR, 2016). O impacto de diversos usos do solo é tão generalizado que praticamente não existem mais áreas não perturbadas em FTSS (TREJO; DIRZO, 2000). Quando associado à baixa renda, a atividade agrícola responsável pela perda de floresta é a de subsistência, principalmente baseada na técnica de corte e queima da vegetação (MURPHY; LUGO, 1986).

Cerca de um terço das florestas maduras nos neotrópicos passam por processo de sucessão secundária anualmente (AIDE et al., 2013). O processo de sucessão secundária em florestas tropicais é complexo, envolvendo diversos fenômenos e forças que operam na escala de tempo e espaço e, dependendo do contexto, a sucessão pode tomar diferentes caminhos (ARROYO-RODRÍGUEZ et al., 2015). Como resultado de todos esses processos, algumas regiões de FTSS estão em processo de conversão a uma formação arbustiva decídua, savanas secas e pastagens secas (Singh 1998). Essas áreas perturbadas tendem a favorecer espécies resistentes à perturbação (“vencedoras”) em detrimento de espécies menos resistentes (“perdedoras”) (TABARELLI; PERES; MELO, 2012).

Por um lado, existe uma concordância de que o cenário de degradação para FTSS tende a aumentar, como resultado do aumento da população nessas regiões e necessidade de terras agricultáveis (MILES et al., 2006; SÁNCHEZ-AZOFEIFA et al., 2005). Na América do Sul, por exemplo, foram encontradas as maiores taxas de perda de floresta seca (HANSEN et al., 2013). Por outro lado, no entanto, é importante ter em mente que é difícil generalizar padrões espaço-temporais de perda de cobertura vegetal devido à impacto humano. Nas FTSS das Américas do Norte e Central, na primeira década do século XXI, foi observado padrão de evolução da cobertura do solo em diferentes direções em diferentes contextos (PORTILLO-QUINTERO; SMITH, 2018). Algumas florestas secundárias neotropicais, por exemplo, mostraram ser bastante produtivas e resilientes, apresentando taxas de captura de carbono até 11 vezes maiores do que florestas maduras num período de apenas 20 anos (POORTER et al., 2016).

Por fim, o cenário de FTSS pode ser ainda mais preocupante se consideremos os eminentes efeitos das mudanças climáticas. É projetado que o efeito das mudanças climáticas

será mais acentuado em regiões mais secas e com clima sazonal do que em regiões úmidas (IPCC, 2014; MARENGO; TORRES; ALVES, 2017; NOBRE; BORMA, 2009). Assim, a cobertura florestal tende a diminuir mais rapidamente por causa, principalmente, de redução de precipitação. Esse cenário de mudanças climáticas ainda pode ser potencializado por um sinergismo com perturbação antrópica crônica, que pode levar à savanização (HIROTA et al., 2011) ou até desertificação (CHIDUMAYO; GUMBO, 2010). Adicionalmente, o cenário existente é de heterogeneidade no entendimento do efeito de mudanças climáticas e ciclo do carbono no mundo, onde América Latina e África apresentam uma maior quantidade de pesquisas, mas outras regiões ainda são bem defasadas (BLACKIE et al., 2014).

Para esclarecermos essas questões em FTTS mais atenção deve ser dada a esse ecossistema. Ainda é conflitante, por exemplo, quanto a capacidade de recuperação de FTSS comparativamente às florestas úmidas: de um lado, por ser um ambiente mais severo e menos previsível de chuva, alguns autores consideram que o processo sucessional em FTSS é mais suscetível a estresses (MURPHY; LUGO, 1986). Por outro lado, se defende que podem se recuperar mais facilmente pela sua relativa simplicidade estrutural (SÁNCHEZ-AZOFEIFA et al., 2005). Assim, uma das alternativas para se estimar o estado de áreas modificadas pelo homem é pela da mensuração dos serviços ecossistêmicos prestados, entre eles: suporte (e.g., produtividade primária), provisão (recursos), regulação (e.g., regulação climática, através da evapotranspiração das plantas) (DUARTE; RIBEIRO; PAGLIA, 2016).

2.2 FUNCIONAMENTO E SERVIÇOS ECOSSISTÊMICOS

2.2.1 Conceitos e classificações

Dentro da ecologia de ecossistemas, alguns conceitos são importantes de ser pontuados para se falar de um tema muito abordado recentemente na ciência, política e conservação, que é a temática dos serviços ecossistêmicos. Serviços ecossistêmicos podem ser conceituados como “as condições e processos através dos quais os ecossistemas naturais, e as espécies que os constituem, sustentam e realizam a vida humana” (DAILY, 1997).

Esses conceitos podem ser estratificados e seguir uma cadeia de interações: o primeiro conceito é o de processo ecológico, que diz respeito às relações entre o biótico e o abiótico que sustentam fluxo de energia, informação e matéria (e.g., fotossíntese); as funções ecossistêmicas estão mais associadas com os mecanismos que suportam a integridade dos ecossistemas e deriva das interações entre o ambiente e os processos ecológicos (e.g., produtividade primária, dispersão de sementes); mais no fim dessa cadeia, os serviços

ecossistêmicos são os benefícios que os humanos se beneficiam que são fruto das funções ecossistêmicas (e.g., biomassa vegetal) que irão gerar os bens (e.g., carvão) que são de grande importância para melhoria da qualidade de vida por permitir acesso a condições básicas de vida (BROCKERHOFF et al., 2017).

Um tema de pesquisa científica relativamente novo, que vem ganhando evidência nos últimos anos, o termo ‘serviço ecossistêmico’ ainda exhibe algumas divergências na literatura, mas a maioria dos conceitos concorda que o termo deve ser usado para descrever o benefício que o homem desfruta. (TRUCHY et al., 2015), por exemplo, se referem a serviços ecossistêmicos como “serviços ecossistêmicos finais”, ou aqueles serviços que diretamente afetam e beneficiam a vida do ser humano. Talvez aí resida uma das principais dificuldades de se classificar os serviços, que é avaliar se um funcionamento tem ou não, de fato, um benefício direto ao homem. Podemos tomar a dispersão de sementes em uma floresta como um exemplo dessa situação. Essa atividade desempenhada pelos dispersores pode não necessariamente trazer um efeito direto ao homem, mas por outro lado pode ser responsável pelo sucesso reprodutivo de algumas espécies de plantas que irão criar habitats adequados para polinizadores que irão visitar plantações que dependem de polinizadores (RICKETTS et al., 2008).

Assim, diversos trabalhos se propuseram a categorizar os serviços com base no que ele provê ao homem. Um dos principais trabalhos na área, desenvolvido pelo Millennium Ecosystem Assessment (MA, 2005), em parceria com centenas de especialistas na área, avaliou a prestação de diversos serviços e o impacto da ação humana. A classificação sugerida coloca os serviços em quatro grupos: (1) Serviços de Provisão, como água limpa e produção de alimentos; (2) Serviços de Suporte, como produtividade primária e ciclagem de nutrientes; (3) Serviços de Regulação, como purificação de água e regulação climática; e (4) Serviços Culturais, como uso recreacional e religioso. Como consequência também das divergências de conceitos, essas classificações apresentam algumas divergências. Para alguns autores, algumas funções ecossistêmicas acabam sendo classificadas como serviços de suporte, como a produtividade primária. Tendo isso em vista, serviços ecossistêmicos também são definidos como “o conjunto de funções do ecossistema que são úteis para os humanos” (KREMEN, 2005).

Se diferentes ecossistemas ocorrem em diferentes escalas e de alguma forma são integrados, é compreensível que os serviços podem ser providos desde uma escala microscópica (e.g., purificação do ar por microrganismos) a uma escala global (e.g., estabilidade climática) (MA, 2005). A espacialidade é, então, um aspecto muito relevante para se entender a dinâmica de serviços ecossistêmicos. Se as populações humanas dependem da provisão de serviços, em

um cenário ideal de uso sustentável dos recursos, esse suprimento deveria suprir as demandas das sociedades. No entanto, demanda e suprimento nem sempre estão equilibrados, o que faz do mapeamento dessa dinâmica espaço-temporal de serviços uma atividade primordial para manejo de recursos naturais (BURKHARD et al., 2011).

Ao mesmo tempo em que os serviços são providos em diferentes escalas, múltiplos serviços podem ser providos ao mesmo tempo em um ecossistema. É relevante que um ecossistema, seja natural ou antrópico, possa prover diferentes tipos de serviços que se somem e supram necessidades de uso das populações humanas. Nesse contexto, o manejo humano para se priorizar quais serviços são mais relevantes para o contexto socioecológico é uma ferramenta que gera trade-offs, o que se torna um desafio. Trade-offs representam um ganho de um determinado serviço pode resultar na perda de um outro (DAW et al., 2015). Um ecossistema agrícola, por exemplo, pode apresentar altos valores de provisão de alimento, mas baixos valores de estoque de carbono. Eles podem ser gerados de escolhas explícitas, mas também podem emergir inesperadamente, quando por exemplo não conhecemos as interações entre os serviços (RODRÍGUEZ et al., 2006). Por outro lado, também podem ocorrer sinergias, o contrário de trade-off, onde ambos serviços aumentam ou diminuem conjuntamente (BENNETT; PETERSON; GORDON, 2009).

No entanto, vale registrar que é inegável que o conceito de serviços ecossistêmicos parte do ponto de vista de que a natureza está a serviço da espécie humana. Consequentemente, essa ideia antropocêntrica tem o poder de gerar ações humanas sempre voltadas para suprir suas próprias demandas. Quando as contribuições para a vida humana chegam a níveis não suficientes, medidas de adaptação e substituição (envolvendo o uso de tecnologia) são tomadas como forma de compensação. Essas medidas parcialmente cumprem seus objetivos, mas em geral não geram iguais benefícios dos gerados pela natureza e ainda possuem custos (e.g., eutrofização de cursos d'água devido à adição de fertilizantes num solo exaurido pela agricultura) (BRAUMAN et al., 2020).

2.2.2 Drivers e ameaças ao funcionamento ecossistêmico

Entender que existe uma grande variedade de processos ecossistêmicos que sustentam a provisão de serviços ecossistêmicos é um ponto chave. Fatores abióticos são importantes drivers do funcionamento ecossistêmico, uma vez que afetam os organismos que ocorrem num determinado ecossistema (TRUCHY et al., 2015). Nesse contexto, temperatura se apresenta como um desses principais drivers, ao alterar o metabolismo dos organismos (BROWN et al.,

2004). Em seguida, podemos citar luz e disponibilidade de nutrientes como outros fatores que alteram os processos ecossistêmicos, como aumento de produtividade e decomposição (CLOERN, 1999). Além do mais, esses drivers, em geral, não agem isolados, e processos sinérgicos ou antagonísticos regulam os processos, gerando mudanças não lineares no funcionamento ecossistêmico (WOODWARD et al., 2012).

O ecossistema também é modificado pelas espécies ali presentes à medida que elas consomem recursos para transformá-los em biomassa, seja por crescimento ou reprodução (HOOPER et al., 2005). Mas, diferentes espécies, com diferentes eficiências de captura desses nutrientes, irão apresentar produtividades variadas (TILMAN, 1996). Assim, é natural que um dos principais drivers de funcionamento ecossistêmico seja a biodiversidade (SEKERCIOGLU, 2010), ideia essa considerada por muitos como um consenso, baseado nas evidências até o momento (HOOPER et al., 2005).

É sabido, por exemplo, que a riqueza de espécies pode explicar em grande parte o nível de funções e serviços que uma comunidade provê (BROCKERHOFF et al., 2017). Essa abordagem é conhecida como BEF (do inglês Biodiversity and Ecosystem Function) (BANNAR-MARTIN et al., 2018). Numa escala regional, uma pesquisa encontrou uma relação positiva entre riqueza de árvores e serviços como biomassa arbórea, estoque de carbono e produção agrícola (GAMFELDT et al., 2013). Ademais, a diversidade de espécies é um dos principais determinantes da produtividade e dinâmica de nutrientes (TILMAN; ISBELL; COWLES, 2014), a diversidade filogenética aumenta a resiliência de serviços ecossistêmicos chave (MAZZOCHINI et al., 2019). Essa relação pode ser explicada por algumas teorias ecológicas. Pode se dar pelo efeito de amostragem, onde um ambiente com maior diversidade possui maior chance ter uma espécie com propriedades que aumentem sua produtividade (HUSTON, 1997); por complementaridade, em que uma maior diversidade de espécies com diferentes estratégias leva ao melhor uso dos recursos (HOOPER et al., 2005); ou pela facilitação, onde a presença de certas espécies torna o ambiente mais favorável ao estabelecimento de outras (BRUNO; STACHOWICZ; BERTNESS, 2003).

Esses processos refletem também na estabilidade e resiliência dos ecossistemas, visto que ecossistemas mais diversos provêm opções para um ecossistema frente a perturbações, como fluxo de energia e ciclagem de nutrientes (HOOPER et al., 2005; KOTSCHY et al., 2015), pelo menos em escalas locais. No entanto, essa relação de funcionamento ecossistêmico e biodiversidade não é tão simples, visto que as comunidades são estruturadas por vários fatores simultaneamente, desde perturbação e heterogeneidade ambiental a estocasticidade (MORI; ISBELL; SEIDL, 2018).

Assim, outros atributos da comunidade também são importantes para o funcionamento ecossistêmico, como a composição da comunidade e diversidade funcional (DÍAZ et al., 2013). Ao avaliar o sequestro de carbono, por exemplo, um dos principais serviços ecossistêmicos (relacionado a diminuir os impactos das mudanças climáticas globais), entender como os atributos funcionais estão relacionados com os processos de ganho de carbono (produtividade e alocação de carbono abaixo do solo) e perda de carbono (i.e., volatilização), é uma abordagem desafiadora (DE DEYN; CORNELISSEN; BARDGETT, 2008). Em cima dessa ideia, surgiu a abordagem CAFE (do inglês, Community Assembly and Functioning of Ecosystems), que se propõe a avaliar melhor como se dá a relação entre funcionamento ecossistêmico e estrutura da comunidade, considerando além da composição e atributos funcionais, a identidade das espécies envolvidas (BANNAR-MARTIN et al., 2018).

Nesse contexto, as maiores ameaças à biodiversidade, especialmente em ambientes tropicais, são de origem antrópica, relacionados a (1) mudança no uso e cobertura do solo para paisagens antrópicas e (2) mudanças climáticas (HOBBS et al., 2006, p. 200). Estima-se que as pressões antrópicas são responsáveis por uma redução de 13% da riqueza e 10% da abundância total. Ademais, estima-se que até 2100 a riqueza a de espécies diminua 3.4%, especialmente em países pobres e biodiversos (NEWBOLD et al., 2015). Portanto, a alteração da biodiversidade é um dos mecanismos pelo qual as atividades humanas impactam o funcionamento ecossistêmico. Em escala global, a perda de biodiversidade pode ter um efeito igual ou maior no funcionamento ecossistêmico do que outras variáveis amplamente avaliadas, como herbivoria, seca, fogo e fertilização.

Atividades antrópicas, no entanto, também geram mudanças no ecossistema com impactos diretos no seu funcionamento. Entre outros, podemos citar o uso desregulado de fertilizantes em algumas regiões agrícolas (podendo levar a eutrofização de corpos d'água caso haja escoamento inadequado), poluição de corpos d'água com esgotos de cidades. O uso da terra então está intimamente relacionado com o potencial da terra em ter suas funções em equilíbrio e prover serviços. Uma vez que diferentes usos e coberturas do solo (LULC, do inglês Land Use and Land Cover) prestam diferentes serviços, mudança do LULC são associadas a mudança na prestação de serviços (capítulo ALCARAZ-SEGURA & DI BELLA 2013). Ademais, a maioria dos usos do solo depende de valores mínimos de produtividade primária, o que reforça essa relação de dependência (HABERL et al., 2004).

2.2.3 Importância dos serviços ecossistêmicos

Apesar de ter se tornado um tema mais popular e estudado nas últimas décadas, a temática de funcionamento/serviços ecossistêmicos ainda não é tão bem compreendida pela sociedade (cada vez mais tecnológica), no que diz respeito a como somos dependentes do bom funcionamento do ecossistema e dos serviços providos por ele. Basicamente, a vida humana na terra se deve ao suprimento, por exemplo, de ar puro e água, bem como possibilita que tenhamos qualidade de vida (SEKERCIOGLU, 2010).

Uma das primeiras tentativas de dar evidência a essa importância para o bem-estar da nossa sociedade se deu pela publicação de um estudo onde o capital natural e 17 serviços ecossistêmicos de 16 biomas foram estimados em termos de contribuição para a economia. Os autores estimaram um valor entre 16 e 54 trilhões de dólares por ano (COSTANZA et al., 1997). Esse trabalho impulsionou outros estudos a valorarem os serviços (HÄYHÄ; FRANZESE, 2014). Entre as novas estimativas está uma atualização dos dados publicados em 1997, com valores estimados de 125 trilhões de dólares (COSTANZA et al., 2014). Essa abordagem de valoração é valiosa como forma de estratégia de convencimento de conservacionistas, auxiliando para que as tomadas de decisões por legisladores sejam baseadas também nesses serviços prestados e podendo assim garantir a manutenção da integridade desses serviços (REDFORD; ADAMS, 2009; SEKERCIOGLU, 2010). No entanto, há quem veja essa iniciativa como uma perigosa monetização do ecossistema, trazendo uma ideia implícita de que, se nós dependemos dos serviços prestados, a única ou melhor maneira de garantirmos essa contínua provisão é pagando por isso (REDFORD; ADAMS, 2009).

Independente de adotar a estratégia de valorar ou não, é necessário ter ferramentas que ajudem a mensurar o funcionamento e a prestação de serviços. As medições podem ser feitas numa escala local, com estudos in loco por medições diretas, como medições de serviços de polinização. No entanto, existe a necessidade de se extrapolar essas estimativas para uma escala maior e, nesse ponto, o uso de tecnologias é um grande aliado para o mapeamento de serviços (ALCARAZ-SEGURA; DI BELLA, 2013; CORD; SEPPELT; TURNER, 2015). O uso de sensoriamento remoto para o monitoramento da vegetação se apresenta como uma ferramenta bastante útil, viabilizando coletar dados em grandes escalas e em intervalos de tempo regulares (DEFRIES, 2008). Dentre vários parâmetros do ecossistema que podem ser estimados remotamente variáveis biofísicas, destaca-se componentes-chave em modelos ecológicos, como balanço de carbono e produtividade primária (HESKETH; SANCHEZ-AZOFEIFA, 2010). Fazer esse mapeamento é uma importante ferramenta para estimar suprimento e

demanda desses serviços, áreas prioritárias e relações entre diferentes serviços e outras partes envolvidas (BURKHARD et al., 2011).

Isso se torna especialmente importante se consideramos que a maioria dos ecossistemas terrestres já sofreu alguma alteração humana em virtude da mudança do uso do solo (MA, 2005). As avaliações das mudanças de cobertura e uso do solo representam a principal fonte de informação para estimativas de serviços que são calculados por modelos (CORD et al., 2017). Através de imagens de satélite, mapas de uso e cobertura do solo são utilizados para avaliar são gerados para avaliar as mudanças de prestação de serviços e as variações espaço-temporais. Atualmente, os modelos mais conhecidos são o InVEST e o ARIES que, além dos dados do LULC, utilizam variáveis biofísicas, como evapotranspiração e características do solo (ALCARAZ-SEGURA; DI BELLA, 2013). No entanto, é importante considerar que, obviamente, nem toda alteração antrópica no ecossistema é passível de ser detectada por sensoriamento remoto. Mudanças consideráveis no funcionamento ecossistêmico podem acontecer em função de ações como corte seletivo sem que deixe registros detectáveis pelo imageamento remoto (especialmente o óptico) (TANG et al., 2011).

Assim, ações conservacionistas e políticas que objetivem preservar o funcionamento ecossistêmico se fazem cada vez mais necessárias nesse cenário de aumento populacional e demanda por terras agricultáveis (DURO et al., 2020; GEIST; LAMBIN, 2001). Especialmente em regiões tropicais em regiões em desenvolvimento com tendências crescentes de perda de biodiversidade (NEWBOLD et al., 2015), manter floresta em pé é um grande desafio para legisladores e outros envolvidos. Assim, diversas ações têm sido aplicadas em diferentes regiões do planeta. Entre elas, as políticas baseadas no incentivo financeiro, ou os pagamentos por serviços ambientais, tem ganhado força nos últimos anos. Nas florestas tropicais secas do Brasil, exemplos como o projeto ‘Bolsa Verde’ que recompensa agricultores que preservem vegetação, e o programa ‘Pagamento por Serviços ecossistêmicos’ (MMA, 2012), são exemplos de políticas que poderiam ser amplificadas para se tentar mitigar os efeitos da mudança do uso do solo e de mudanças climáticas e, adicionalmente, prover renda às comunidades rurais. Obviamente, não é um cenário de fácil aplicação, necessitando que as políticas sejam bem planejadas, procurando promover envolvimento dos envolvidos e equidade na distribuição de benefícios aos envolvidos (LOFT et al., 2020).

2.2.4 Produtividade primária e a dinâmica da vegetação

Avaliar a dinâmica da vegetação em diferentes ecossistemas é crucial para entendermos as mudanças climáticas e ciclos biogeoquímicos (JARAMILLO; MARTÍNEZ-YRÍZAR; SANFORD, 2011). As plantas têm um papel muito importante no ciclo do carbono ao absorver parte do dióxido de carbono (derivado por exemplo das atividades humanas como queima de combustível fóssil) (DE DEYN; CORNELISSEN; BARDGETT, 2008). A produtividade primária é um atributo do funcionamento ecossistêmico que provê energia química e nutrição base para a maioria dos processos biológicos (POTTER et al., 2013), dando também suporte para a provisão de diversos serviços (TRUCHY et al., 2015). Portanto, justifica-se o uso desse processo ecossistêmico como um indicador de função ecossistêmica (MCNAUGHTON et al., 1989).

Em poucas palavras, produtividade primária é uma taxa da quantidade de carbono atmosférico fixado pelas plantas e acumulado como biomassa (MCNAUGHTON et al., 1989). Podemos classificar a produtividade primária em bruta (a quantidade de energia solar transformada em moléculas de açúcar na fotossíntese) e produtividade primária líquida (ou PPL, a produtividade primária bruta menos a perda de energia devido à respiração celular das plantas) (WILLIAMS et al., 1997). Portanto, é comum que a produtividade primária esteja diretamente correlacionada com biomassa acima do solo (BEER et al., 2010).

A PPL varia de ecossistema para ecossistema e é influenciada por diversos fatores, entre eles temperatura, umidade, dióxido de carbono atmosférico e nutrientes no solo (BARGER et al., 2002; MURPHY; LUGO, 1986; PENNISI, 2020). No nível biológico, diferentes composições de espécies e interações entre elas também afetam a produtividade. A herbivoria por insetos ou grandes mamíferos, por exemplo, representam drivers que diretamente afetam a PPL (MCNAUGHTON et al., 1989). Numa análise global, disponibilidade hídrica do solo e chuva são óbvios fatores limitantes da produtividade, uma vez que água é indispensável no processo de fotossíntese (BECKNELL; KISSING KUCEK; POWERS, 2012). No entanto, a disponibilidade de água também afeta a PPL indiretamente, por diversos mecanismos, entre eles a regulação de atividade microbiana, decomposição e mineralização de matéria orgânica e disponibilização de carbono e fósforo. Juntos, esses mecanismos contribuem para provisão de nutrientes orgânicos e inorgânicos após eventos de chuva (JARAMILLO; MARTÍNEZ-YRÍZAR; SANFORD, 2011).

Ao avaliarmos florestas tropicais úmidas e comparando diferentes áreas na superfície da terra (seja planícies ou planaltos), a temperatura média anual figura como o principal driver de produtividade. No entanto, em menores escalas (e.g., comparando apenas terras baixas), as evidências mostram que fósforo foliar e no solo também são os principais preditores da

produtividade (CLEVELAND et al., 2011). Ademais, no contexto de mudanças climáticas, o aumento de CO₂ atmosférico causa respostas diferentes nas plantas a depender da temperatura (MORISON; LAWLOR, 1999). Em ecossistemas áridos e semiáridos, por exemplo, o efeito do aumento de CO₂ tem sido apontado como um dos drivers do processo de aumento da produtividade (LU; WANG; MCCABE, 2016). Os autores observaram que maiores concentrações desse gás de efeito estufa induzem a planta a economizar água e que isso gera um aumento da disponibilidade da água no solo.

Em florestas secundárias em FTSS, ao contrário de florestas úmidas, disponibilidade hídrica é um limitante da produtividade. O acúmulo de biomassa é uma função da idade da vegetação, mas também pela precipitação anual média e riqueza de espécies (SOUZA et al., 2019). Áreas mais úmidas apresentam maior biomassa que áreas mais secas, mas não parece haver diferença entre o tempo necessário para se atingir esse máximo, indicando a produtividade aumenta com a umidade (BECKNELL; KISSING KUČEK; POWERS, 2012). No entanto, nessas regiões com clima sazonal, o NPP é regulado também pela distribuição da precipitação ao longo de toda estação chuvosa (JIAO et al., 2017).

A ação humana também exerce impacto sobre os padrões de PPL, justamente pelo fato de que apresentam grande potencial de alterar os mecanismos abióticos e bióticos mencionados acima. Ao longo do tempo, com a evolução da ocupação das populações humanas, o aumento de áreas urbanizadas e antropizadas se deu principalmente em áreas férteis. Se avaliarmos o processo de urbanização, por exemplo, o fato de terem ocupado áreas mais férteis e com disponibilidade de água torna o impacto antrópico tende a ser desproporcionalmente mais negativo sobre a produtividade primária líquida (IMHOFF et al., 2004). Em um estudo no sudeste da China, foi observada uma acentuada perda de produtividade devido à urbanização, mas com resultados que variavam para regiões com tamanho populacional que atingiam um determinado limiar (LU et al., 2010); nos EUA, estima-se que essa perda de NPP equivale ao requerimento energético de 6% da população do país (IMHOFF et al., 2004).

Assim, o uso da terra pelo homem está intimamente relacionado com a produtividade dos ecossistemas, o que levou a ciência a tentar melhor entender e quantificar essa relação. Nesse contexto, o termo Apropriação Humana da Produtividade Primária (ou HANPP, do inglês *Human Appropriation of Net Primary Productivity*) surge como uma linha de investigação científica para se responder, entre outras, à pergunta principal: “quanto da capacidade produtiva da Terra é utilizada pelos humanos?” (HABERL; ERB; KRAUSMANN, 2014). O conceito foi inicialmente sugerido em 1973, num estudo objetivando estimar o consumo de recursos naturais pelos humanos em ecossistemas terrestres (WHITTAKER; LIKENS, 1973). Uma das

abordagens práticas do HANPP, mais aplicada para estudos em áreas específicas, se apresenta como um indicador de intensidade de uso da terra (HABERL; ERB; KRAUSMANN, 2014). Outras estimativas mostram que globalmente as terras agrícolas apresentam 77% da produtividade potencial. No entanto, essa percentagem varia por biomas e situações socioeconômicas, onde a produtividade é muito menor do que o que poderia ser em regiões tropicais em desenvolvimento e muito maior do que o potencial em terras áridas e semiáridas irrigadas e também regiões temperadas. Os autores mostram que esse padrão pode ser atribuído, em geral, a uma relação linear com uso de fertilizantes na agricultura, apesar de terem ressalvas sobre a aplicação desse modelo em diferentes contextos socioecológicos (NIEDERTSCHEIDER et al., 2016).

Nesse contexto, o sensoriamento remoto é uma abordagem bastante útil para avaliar as dinâmicas da vegetação. Entre diversas ferramentas disponíveis para se avaliar como a vegetação se comporta no tempo e no espaço, os índices de vegetação são amplamente utilizados há bastante tempo como um proxy de produtividade primária (MYNENI et al., 1995). Índices de vegetação são taxas que representam uma relação entre a energia solar recebida pela superfície e a energia refletida. Para isso, os índices se valem das características de reflectância do espectro da luz de diferentes superfícies imageadas.

O espectro da luz compreende a energia eletromagnética que vai desde ondas com alto comprimento de onda e baixa energia (e.g., ondas de rádio) a ondas com pequeno comprimento de onda e alta energia (e.g., raios gama). Nessa escala, as ondas com comprimento de onda entre 780 e 380 nm, que vão do vermelho com menor energia ao azul-violeta de maior energia, compreendem o que conhecemos como luz visível do homem ou espectro da luz. Plantas, realizam fotossíntese ao absorver a energia solar na região espectral da Radiação Fotossinteticamente ativa (PAR, do inglês *photosynthetically active radiation*), que vai de 400 a 700 nm (MÖTTUS et al., 2012). As células das plantas, por exemplo, evoluíram para um padrão de alta reflectância de luz da região do infravermelho próximo (uma vez que possuem pouca energia para sintetizar moléculas orgânicas). Graças aos diferentes pigmentos das células (e.g., clorofila e carotenoides), a planta é capaz de absorver uma boa parte da luz visível para fotossíntese. No entanto, cada pigmento apresenta, dentro do PAR, comprimentos de onda específicos de pico de atividade fotossintética (i.e., absorvem mais ou menos regiões específicas do PAR). Assim, dentro dos grupos dos organismos fotossintetizantes, esses pigmentos ocorrem em diferentes concentrações, o que gera um padrão de reflectância da luz variado para cada espécie, gerando o que se chama de assinatura espectral (BAUERLE et al., 2004).

Entre diversos índices criados, o NDVI (*Normalized Difference Vegetation Index*) é o mais amplamente utilizado (TOMASELLA et al., 2018). Ele é baseado na proporção de luz refletida nas faixas do infravermelho próximo e do vermelho, gerando valores entre 0 e 1. Em geral, valores entre 0,3 e 0,8 representam vegetação densa, sendo 0,8 a vegetação com maiores taxas de fotossíntese. Corpos d'água geralmente apresentam valores positivos muito baixos ou negativos, enquanto solos expostos geralmente possuem valores entre 0,1 e 0,2. No entanto, o NDVI sofre algumas críticas, especialmente por aparentemente saturar em locais de alta densidade de vegetação, como florestas tropicais úmidas (HUETE, 1988). Com isso, outros índices foram criados ao longo da evolução do sensoriamento remoto, entre eles o SAVI (HUETE, 1988) e o EVI (BREDE et al., 2015), que buscam corrigir problemas como o da saturação em altas densidades de vegetação e a intensidade do efeito de solos expostos sobre as estimativas dos índices de vegetação para plantas.

Assim, o sensoriamento remoto trouxe a possibilidade de se estimar e espacializar a produtividade primária acima do solo (ANPP, *aboveground net primary productivity*) de toda a superfície do globo (terrestre e aquática). Os mapas globais de ANPP mostram o padrão de produtividade global, com valores mais elevados nas regiões tropicais, como já levantado pela ciência mesmo antes dessas medições remotas (PENG et al., 2012). É inegável como a mensuração espaço-temporal da ANPP se tornou um espectro chave no estudo de ecossistemas terrestres no mundo (FANG et al., 2003). A avaliação das tendências de produtividade da vegetação traz a possibilidade de se avaliar degradação, efeito de mudanças climáticas, sazonalidade e fenologia dos ecossistemas. Na região africana do Sahel, por exemplo, por muito tempo se tomou como certo de que essa região semiárida, caracterizada baixa pluviosidade e uso antrópico do solo, estava fadada ao cenário de desertificação generalizado (SEAQUIST et al., 2009). No entanto, análises espaciais no início do século das tendências espaço-temporais da vegetação mostrou um cenário inesperado de “*greening*” (i.e., aumento de produtividade) (OLSSON; EKLUNDH; ARDÖ, 2005), trazendo toda uma discussão atualizada sobre quais os processos (bióticos e abióticos) que podem estar envolvidos nessa reversão de desertificação (BÉGUÉ et al., 2011; HERRMANN; ANYAMBA; TUCKER, 2005).

2.3 DESENVOLVIMENTO SOCIOECONÔMICO, IMPACTO EM ECOSSISTEMAS E SUSTENTABILIDADE

Desde a revolução industrial do século XIX, a exploração de recursos naturais começou a se tornar um dos principais causadores de mudanças nos ecossistemas (LAMBIN;

MEYFROIDT, 2011). Esse momento também foi importante como o início do desenvolvimento econômico das nações, que se expandiu para países em desenvolvimento apenas após a Segunda Guerra Mundial. Assim, o crescimento populacional levou a um aumento da demanda por comida e energia, que por sua vez causaram extensas mudanças do uso e cobertura do solo, com a expansão de terras voltadas para agricultura e urbanização (SEPPÄLÄ; BUCK; KATILA., 2009).

Com a quantidade de terras férteis cada vez menor, a intensificação da agricultura, umas das alternativas para manter a produção, se apresenta como um processo que pode desencadear efeitos positivos ou negativos, se consideramos a globalização e seu impacto na produção local. Por um lado, quando o produto é consumido principalmente localmente, a intensificação pode diminuir a pressão sobre o uso do solo e a prática de corte e queima; por outro lado, se o insumo é de proveito para expansão de mercado global, a intensificação tende a levar a uma expansão de terras agrícolas (LAMBIN; MEYFROIDT, 2011). Mas, independentemente da intensidade, o uso humano é sempre voltado para se apropriar da produtividade primária do ambiente, de forma a obter os bens (IMHOFF et al., 2004). Portanto, o funcionamento ecossistêmico varia bastante em função das mudanças do uso do solo (BURKHARD et al., 2009), que assim impactam na capacidade do ecossistema em prover serviços (BURKHARD et al., 2011).

Assim, o desenvolvimento econômico global num contexto de globalização é apontado como uma ameaça para a provisão de serviços ecossistêmicos em florestas, já que é justamente nos países em desenvolvimento que ainda existem grandes remanescentes de floresta e são grandes alvos de fonte de terras agricultáveis (LAMBIN; MEYFROIDT, 2011). Essas mudanças no uso do solo em regiões em desenvolvimento merecem muita atenção não só pelo impacto causado na biodiversidade, que geralmente é o foco das atenções, mas também pela provisão de serviços ecossistêmicos (e.g., biomassa vegetal, suprimento e purificação de água, entre outros) (BROCKERHOFF et al., 2017). No entanto, é necessário ter em mente que uma grande parcela da população agrária em regiões pobres no mundo depende quase que exclusivamente da pecuária (FAO, 2011), trazendo mais uma camada de complexidade nas análises envolvendo uso da terra, degradação e qualidade de vida das pessoas.

A criação de gado representa um desses maiores agentes de mudança de uso do solo, especialmente em países em desenvolvimento. A implantação dessa cultura agropecuária tem sido apontada como responsável pela perda de biodiversidade e de espécies nativas, diversidade funcional de plantas, poluição de nascentes e corpos d'água, erosão do solo, compactação e redução da vida biológica no solo (BLACKMORE; VITOUSEK, 2000; CHILLO et al., 2017; HIERNAUX et al., 1999). Logicamente, esse impacto varia em função de diferentes contextos

socioecológicos, apresentando diversas estruturas, tipos de criação e manejo. A escolha de criar esses animais em altas densidades (i.e., uso intensivo) ou em grandes áreas de *rangelands* (i.e., criação extensiva) é também um dos principais fatores a serem considerados para se avaliar degradação pela pecuária (FAO, 2011). Além desses pontos, o desmatamento também é um efeito (talvez o mais aparente) da mudança do uso do solo para criação de gado (SEIDL; SILVA; MORAES, 2001).

No entanto, a proteção ambiental pode ser considerada um luxo para governos locais, como avaliado no contexto da China (um dos países em desenvolvimento com altos índices de degradação ambiental), visto que nem sempre a verba existente está disponível para políticas de compensação e conservação de ecossistemas (ZHAO; CURRIT; SAMSON, 2011). É sabendo disso que nações desenvolvidas tem interesse em financiar a conservação de florestas tropicais no mundo desenvolvido, não apenas para ajudar essas regiões a continuarem prestando serviços ecossistêmicos globais (e.g., sequestro de carbono), mas também para manter seus padrões elevados de vida sem mexer nas estruturas já existentes (LAMBIN; MEYFROIDT, 2011).

O crescimento econômico de uma região está intimamente atrelado ao acesso aos recursos naturais e, em geral, promove impactos negativos no ecossistema. Portanto, a interação entre capital natural e sistemas sociais é um ponto central nessa era da globalização (ZHAO; CURRIT; SAMSON, 2011), uma vez que torna possível ter uma melhor ideia de como as pressões antrópicas afetam os ecossistemas, considerando também a análise de fatores sociais e econômicos, subsistência das famílias, contexto espacial e cultural (SEPPÄLÄ; BUCK; KATILA., 2009).

No entanto, estudos que visem avaliar o impacto de desenvolvimento econômico de maneira um pouco mais precisa (i.e., avaliando variáveis socioeconômicas sobre o funcionamento ecossistêmico e serviços prestados) ainda precisam de mais atenção. Nos últimos 10 anos, alguns estudos se propuseram a avaliar esse contexto, especialmente em trabalhos na China. No Sudeste da China, (LU et al., 2010) mostraram que assentamentos humanos, tamanho da população e PIB (Produto Interno Bruto) apresentaram forte correlação negativa com a produtividade primária bruta. HOU et al. (2014) observaram que produtividade rural (um serviço de provisão) está positivamente relacionada com urbanização, industrialização, tecnologia agrícola e educação rural. LI; FANG (2014) abordando a valoração de serviços ecossistêmicos, mostraram que o valor dos serviços diminui com o aumento do PIB.

No entanto, essa avaliação deve considerar o contexto de nível socioeconômico prévio ao desenvolvimento. ZHAO; CURRIT; SAMSON (2011) observaram que pequenos aumentos

no PIB levam a inexpressivos ou efeitos nulos na produtividade primária da região e que aumentos maiores do PIB não necessariamente levam a maiores efeitos na produtividade. Os autores argumentam que (1) quando o nível socioeconômico é baixo, pequeno desenvolvimento econômico deve influenciar pouco o ecossistema; (2) o que afeta fortemente o ecossistema é o desenvolvimento intermediário, uma vez que aí existe capital natural e materiais para desenvolvimento; e (3) quando o nível socioeconômico é alto, os efeitos negativos no ecossistema são menores (menor dependência de recurso natural e maior dependência de ciência e tecnologia) (ZHAO; CURRIT; SAMSON, 2011).

Nesse contexto, manter produção de alimento para a população humana em crescimento ao mesmo tempo que serviços ecossistêmicos são mantidos é um grande desafio da sustentabilidade (LAMBIN; MEYFROIDT, 2011). Por um lado, ao desconsiderar outros fatores atrelados, o crescimento econômico não representa necessariamente melhores condições de vida para todos (KAISER; HENNESSY; SACHSER, 2015). Por outro lado, foi demonstrado que, em geral, há um aumento na qualidade de vida das pessoas ao mesmo passo que há uma supressão dos serviços ecossistêmicos. Os autores caracterizam esse processo como o “Paradigma do Ambientalista” (RAUDSEPP-HEARNE; PETERSON, 2016). No entanto, a própria definição de qualidade de vida é algo relativo a depender de que atributo é levado em consideração, assim como é ainda imprevisível saber por quanto tempo o impacto no ecossistema é capaz de manter retornos de bens que garantam qualidade de vida.

Do ponto de vista de tomadas de decisões, a maioria dos governos reconhecem a relação bem-estar e funcionamento do ecossistema e provisão de serviços, como está explícito em tratados internacionais como as Metas de Aichi e as Metas de Desenvolvimento Sustentável (Esmeralda book) e a Convenção da Diversidade Biológica. Na prática, a situação é outra. Assim, é necessário que procuremos um desenvolvimento sustentável, com crescimento econômico inclusivo, manutenção de funções ecossistêmicas chave, segurança alimentar e acesso à água limpa. Esse é o grande desafio de alcançarmos uma segurança de subsistência ambiental (sensu BIGGS et al., (2015)).

Além dessas políticas internacionais, conservar o funcionamento do ecossistema nesse cenário de crescimento econômico vai depender de políticas regionais e manejo (LI; FANG, 2014). Dentre as alternativas de políticas públicas de conservação, a criação de Unidades de Conservação (UCs) é uma das iniciativas mais conhecidas e utilizadas pelo mundo para proteger áreas ameaçadas.

2.4 CAATINGA, UM SISTEMA SOCIOECOLÓGICO

A Caatinga pode ser definida como um mosaico constituído por manchas de floresta seca e de vegetação arbustiva, representando a maior floresta seca da América do Sul (PENNINGTON; LAVIN; OLIVEIRA-FILHO, 2009; SAMPAIO, 1995). Localizada na região semiárida do Brasil, possui alta instabilidade climática, com chuvas irregulares, concentradas em poucos meses do ano (MARENGO; TORRES; ALVES, 2017). Vem sendo modificada pelo homem desde o início da colonização europeia (COIMBRA-FILHO; CÂMARA, 1996) e hoje é a região semiárida com maior densidade humana (MARENGO; TORRES; ALVES, 2017), com cerca de 28,6 milhões de pessoas exercendo uma pressão de uso dos recursos que ultrapassa a capacidade de suporte (LEAL et al., 2005) (Leal et al 2005). Apesar da paisagem transformada da Caatinga (91% dos remanescentes florestais são maiores do que 500 ha, mas os 720 com mais de 10000 ha representam 70% da vegetação), os fragmentos florestais ainda apresentam elevada conectividade (ANTONGIOVANNI; VENTICINQUE; FONSECA, 2018). Estima-se que dos mais de 820.000 km² do território original da Caatinga (ca. 8% do território nacional) restam apenas aproximadamente 40% desse total (SILVA; BARBOSA, 2017).

Do ponto de vista da biodiversidade, a Caatinga por muito tempo foi vista como um sistema com baixo número de espécies, de pouca importância para conservação (SANTOS et al., 2011). Mais recentemente, sabe-se que representa um sistema com elevada riqueza de espécies comparativamente a outras regiões semiáridas, inclusive com muitas espécies endêmicas. Se olharmos para relação do homem com o ecossistema, representa um sistema socioecológico (Sensu FU et al., 2013) com populações altamente dependente do extrativismo e dos serviços ecossistêmicos providos (KAUFFMAN et al., 1993). Estimativas apontam que aproximadamente 90% dos estabelecimentos relacionados à agropecuária são de agricultura familiar baseada na subsistência (ca. 8,5 milhões de pessoas) (IBGE, 2006). Apenas em nível de comparação, a África, frequentemente vista como um continente extremamente de agricultura familiar, apresenta cerca de 40% da renda familiar vinda de atividades não-agrícolas (BARRETT; REARDON; WEBB, 2001).

Dentre os diversos usos extrativistas na Caatinga, a pecuária extensiva de caprinos, extração de recursos florestais não madeireiros (MELO, 2017a) e os ciclos de agricultura de subsistência através de corte e queima da vegetação são frequentes na região (KAUFFMAN et al., 1993). Essas atividades levam a uma significativa perda de carbono e outros nutrientes do solo por produção agrícola e animal, quase nunca reintroduzidos no sistema por técnicas de manejo (KAUFFMAN et al., 1993), em especial nitrogênio e fósforo (MENEZES et al., 2012).

Segundo METZGER (2003) é uma técnica amplamente disseminada nos trópicos e seria sustentável se os tempos de descanso da terra fossem respeitados para restauração da terra.

Quando se avalia a paisagem da Caatinga nesse contexto de uso do solo, observa-se uma predominância de conversão de paisagens naturais por paisagens antropogênicas. A distribuição desse impacto na paisagem é heterogênea, onde o uso do solo se concentra em áreas mais produtivas e úmidas (e.g., brejos de altitude e proximidade de rios) (SILVA; BARBOSA, 2017). Esse padrão espacial heterogêneo acabou por gerar uma concentração de renda e desenvolvimento econômico na região semiárida (SAMPAIO et al., 2017). O que vemos hoje é uma região com elevada desigualdade social, com sucessivos planos de desenvolvimento malsucedidos, entre outros fatores que dificultaram o desenvolvimento da região (AB'SÁBER, 1999). Somado a isso, é projetado que as mudanças climáticas globais serão particularmente acentuadas na região da Caatinga, com significativo aumento de temperatura e diminuição de pluviosidade (IPCC, 2014). Outras estimativas também apontam para que essa instabilidade climática na região só tenda a aumentar com o tempo (MARENGO; TORRES; ALVES, 2017).

Portanto, nesse contexto de uma paisagem dominada pelo homem, podemos sintetizar que existem basicamente três grupos de perturbação na Caatinga: perturbação aguda para conversão do uso do solo, perturbação crônica e introdução de espécies exóticas (TABARELLI et al., 2017). Conservar então os serviços ecossistêmicos providos é uma forma de manter a qualidade de vida da população residente. Esse caminho parece ser mais facilmente alcançado através do desenvolvimento sustentável (SILVA et al., 2017a). Alcançar melhoria da qualidade de vida da população sem o comprometimento do capital natural é um objetivo desafiador e parece estar longe de acontecer ainda. No entanto, não é de se espantar que um sistema tão frágil socioeconomicamente, sendo um dos ecossistemas mais degradados e menos protegidos (menos de 1% é protegido por UCs de proteção Integral) (MELO; PINTO; TABARELLI, 2010), não esteja perto de alcançar um desenvolvimento sustentável. Um estudo lançado recentemente mostrou que grande parte dos municípios da Caatinga apresentam valores baixos ou muito baixos do que os autores consideraram como infraestrutura socioeconômica (Índice de desenvolvimento urbano utilizado como proxy) e infraestrutura verde (cobertura vegetal usada como proxy) (SILVA et al., 2017a). De fato, as cidades do nordeste brasileiro (onde se encontra o semiárido) são as que possuem municípios com menor infraestrutura e maior pobreza, o que as torna umas das cidades mais vulneráveis socialmente do país (DE LOYOLA HUMMELL; CUTTER; EMRICH, 2016).

Então, conservar o ecossistema ao mesmo tempo que se garante melhoria de qualidade de vida para a população residente (principalmente a rural mais dependente diretamente do

funcionamento ecossistêmico e serviços associados) exige tomada de decisões direcionadas. Essas ações podem ser voltadas para a expansão de políticas sociais que garantem condições mínimas de vida e facilitem a sobrevivência das pessoas em situações de seca; investimento em tecnologias agrícolas mais modernas (SAMPAIO et al., 2017).

Outra abordagem é a escolha de áreas-chave para restauração que permitam a prestação de serviços ecossistêmicos (Silva et al., 2018) e o estabelecimento de Unidades de Conservação que tanto protejam biodiversidade como serviços (MANHÃES et al., 2016, 2018). Estudos recentes mostraram que as UCs na Caatinga em geral não são capazes de garantir esses dois fatores e que as diferentes categorias de UCs garantem a prestação de diferentes serviços: as de proteção integral estão mais associadas a produtividade primária e estoque de carbono (ACOSTA SALVATIERRA et al., 2017) enquanto as de uso sustentável mais associadas a serviços de provisão (MANHÃES et al., 2016). Assim, saber então qual o capital natural associado a essas UCs, bem como serviços associados são um importante passo para a sustentabilidade, não apenas no seu interior, mas em todo seu entorno (TABARELLI et al., 2017).

3 ARTIGO 1 - VEGETATION COVER AND NET PRIMARY PRODUCTIVITY IN THE CAATINGA DRY FOREST: THE ROLE OF SOCIOECONOMIC, DEMOGRAPHIC, AND ENVIRONMENTAL DRIVERS

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Research paper – Landscape Ecology

Vegetation cover and net primary productivity in the Caatinga dry forest: The role of socioeconomic, demographic, and environmental drivers

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ABSTRACT

Context: Terrestrial ecosystems are threatened mainly by land use and land cover (LULC) and climate change. LULC is driven by different socio-ecological factors and is linked to net primary productivity (NPP).

Objectives: Here, we aim to detect the main drivers of the main LULC (i.e., forest, savanna-like vegetation, and pasture) and their productivity in a highly populated dryland (the Caatinga ecosystem in northeastern Brazil).

Methods: We first run two different machine learning models to identify the most important drivers between 26 candidates at the municipality level. Then, we compared the Normalized Vegetation Index values (proxy of NPP) for each LULC.

Results: We found that savanna-like vegetation predominates in the municipalities, as is the case for the whole Caatinga. Environmental factors are the most important to explain the three analyzed LULC in the region (e.g., temperature and precipitation). Savanna-like vegetation was explained by several drivers (e.g., temperature, and distance to cities and cattle), whereas forest and pasture presented single drivers with pronounced importance (i.e., annual precipitation and annual temperature, respectively). Although the models also selected socioeconomic drivers, they were less important. However, cattle density presents an important effect on savanna-like vegetation and pasture cover. Moreover, NPP is higher in the forest, followed by savanna-like vegetation and pasture.

Conclusions: Briefly, LULC and NPP are still driven by environmental variables, with no widespread land use intensification. The expansion of agricultural technologies use may substantially act as a new transforming landscape factor, both in underused and already degraded lands, which calls for well-planned landscape management.

Keywords: NPP, spatio-temporal analysis, socio-ecological systems, land use and land cover, drylands

INTRODUCTION

Worldwide, most of the terrestrial ecosystems are threatened by two major anthropogenic processes: land use and land cover (LULC) change and climate change (Hobbs et al. 2006; Foley et al. 2011). In tropical forests, these processes are considered responsible for modifying aspects at different levels of biological organization, such as reduction of the size of populations of specialist species, the proliferation of exotic species, changes in the taxonomic, phylogenetic, and functional composition of communities at different spatial scales (Gardner et al. 2009). Consequently, patterns of ecosystem functioning and the provision of services essential to human life (e.g., nutrient flow and storage, carbon sequestration, and storage and water supply) have also been negatively affected (Seppälä et al. 2009; Dantas De Paula et al. 2011). Under this context, it is important to note that LULC dynamics are ruled by a complex system of drivers acting in different temporal and spatial scales (Geist and Lambin 2002).

Hence, although different socio-ecological contexts reflect a different combination of factors acting on the LULC, demographic factors are often cited as the main drivers of land use change, since growing human populations and arable land demand led to deforestation growth in similar proportions (Geist and Lambin 2001). Therefore, deforestation may result in soil erosion, nutrient loss, and climate modifications, hence influencing LULC change. However, other studies have also shown that socioeconomic factors, as well as environmental (e.g., land and soil characteristics) and climatic factors influence land use dynamics (Geist and Lambin 2002; Krausmann et al. 2013). Gross Domestic Product (GDP, a measure of economic development), for example, may be closely related to vegetation cover (Silva et al. 2017a), biomass consumption (Haberl et al. 2012) and it also increases CO₂ emissions (Zheng et al. 2019). Moreover, in a dynamic LULC change scenario, common in developing regions, understanding the contribution of different types of vegetation to key ecosystem functioning

attributes (such as primary productivity), is an important tool to assess possible degradation scenarios.

Most of the land uses depend on primary productivity (Haberl et al. 2004) and this is especially important considering that productivity is an important ecosystem support service for several other services (Truchy et al. 2015). Land use change may impact NPP by altering C, N, and P soil stocks (Gava et al. 2021). However, when land use is done without proper management and good rural practices (e.g., the use of technologies or fertilization or fallow periods to renew land after harvest), it leads to decreasing land productivity over time (i.e., degradation) (Zika and Erb 2009; Sampaio et al. 2017). Thereby, forest dependency and farming may result in causal feedback looping, which leads to poverty traps (Tabarelli et al. 2017). At the same time, natural environments that suffer from human disturbance (e.g., firewood collection and hunting) may present more impoverished plant and animal communities (Fisher et al. 2014) and, consequently, less productive ecosystems. Moreover, in environments with no rainfall limitations like wet tropical forests, natural vegetation tends to have higher annual productivity than crops. Besides the fact those areas generally present considerable high levels of ecosystem functioning (e.g., nutrient cycling, presence of pollinators), they are evergreen and present a massive volume of trees in the case of old-growth forests (Beer et al. 2010). Even though traditional annual crops have high rates of photosynthesis (especially at the beginning of their development), as well as pasture present natural forage and other sparse vegetation types, these areas present overall lower productivity and, consequently, lower carbon storage over time (Meneses-Tovar 2011; He et al. 2017).

In this context, when we think of developing countries located in drylands, presenting irregular climatic regimes, this situation is enhanced. It is precisely in these environments where the human populations are most dependent on natural resources and precipitation regimes to supply their needs and develop their rural activities (Brockerhoff et al. 2017). In

dryland regions, however, it has been shown that agricultural plantations can be as much or more productive throughout the year as natural areas, which present a low productivity period due to climate seasonality (Bégué et al. 2011; Nutini et al. 2013). This may be related to irrigation systems, which allow the system to be productive even in lower rainfall years (Ferreira and García-Vila 2013). Drylands represent one of the most threatened terrestrial ecosystems in the world and semiarid ecosystems (Reynolds et al. 2007; Poulter et al. 2014). The Caatinga semiarid ecosystem in Northeastern Brazil represents one of the largest pieces of dry forest in the world and it is the most populated semiarid region worldwide. Over 27 million people, most of them poor and rural populations, spread across nearly one million km². Traditionally, farmers exhibit intense use of natural resources, from the ecosystem nutrients (slash-and-burn agriculture) to native vegetation as livestock forage (mainly exotic goats and cattle) (Gariglio et al. 2010; Sampaio et al. 2017). Moreover, Caatinga climatic models have predicted a one-third reduction in the precipitation levels for the next century, with more frequent and prolonged droughts (Marengo et al. 2017).

Hence, it is urgent that we better understand how the socioeconomic, demographic, and climate drivers are shaping LULC and hence how it is reflecting on the ecosystem integrity and related services. Tropical deforestation is more likely to be driven by multiple forces than by a single one, even if we consider more direct or more underlying variables (Geist and Lambin 2002), so we investigated a wide range of variables to detect the most important ones. We propose to assess this relationship by analyzing at the municipality level which are the main drivers of the three dominant LULC classes in the Caatinga dry forest, as was already assessed by some other studies (Bonilla-Moheno et al. 2012; Silva et al. 2017a). Therefore, we hypothesize that (1) climatic, demographic, and socio-economic drivers are evenly important to LULC dynamics, and (2) there is an evident difference in ecosystem functioning (i.e., primary productivity) for different land uses and land cover in the Caatinga.

METHODS

STUDY AREA

This study addresses the Caatinga ecosystem in northeast Brazil, a spatially well-delimited biota (862,818 km²) covering 10.1% of the Brazilian territory (Silva et al. 2017b). Despite being a geographically delimited region, the Caatinga has different ecoregions, with vegetation with varying levels of similarity to each other, as well as having different biogeographic histories with the Dry Forests (Pennington et al. 2009), the preponderant biome in the Caatinga (de Queiroz et al. 2017). Being the dominant ecosystem in the Brazilian semiarid area, it is exposed to 230-1000 mm of annual precipitation, elevated rates of evapotranspiration (i.e., a semiarid climate), and a very unpredictable interannual rainfall distribution, with several months without any rain (IBGE, 2019; Fig. 1a). It is a low-productivity ecosystem, due to reduced rainfall, frequent droughts, and overgrazing by livestock (Leal et al. 2005), with potential consequences for biomass and ecosystem services (Schulz et al. 2016). The water availability for natural environments and croplands is restricted not only by the factors mentioned above but also by soil factors (e.g., soil with low-to-medium nutrient availability, retention capacity) and the landscape (e.g., vegetation cover, the slope of the area) (Sampaio et al. 2017).

Certainly, the Caatinga is one of the most human-disturbed ecosystems in the neotropics, although it still extremely biodiverse (Silva et al. 2017b). It has been modified by humans since the beginning of European colonization (Silva and Barbosa 2017). The region has a general history of difficulty in establishing productive and profitable agriculture. The region has experienced several land uses types along the time. Initially, extensive cattle ranching supplied activities on the coast (except agriculture on more humid lands), and subsistence activities. Goats and sheep were just a small portion of livestock, in the harsher areas. It has also experienced arboreal cotton plantations, which led to great socioeconomic

development at the time. Some other wetter areas closer to the coast were able to develop other cultures, like cassava and sugar cane. In addition, two other crops were very notorious until the second half of the twentieth century: the first was the expansive culture of arboreal cotton, which leveraged several municipalities in the northeastern semiarid socioeconomically; the second was the introduction of the mesquite tree species (*Prosopis juliflora*, Fabaceae) for use as fodder for cattle, which today represents an invasive species in some places in the Caatinga, especially near water bodies. The former was virtually abandoned in the 1980s due to poor land use management, decreased productivity that was already low, and changes in the labor structure. As a result, it left a history of soil degradation, which, however, has not yet been well measured on a large scale. In the 21st century, a few infrastructure improvements were made in the region that, although it was not enough to well develop the region, allowed substantial changes and connection with the country (Sampaio et al. 2017). On the other side, industries that were born under this context (e.g., gypsum and iron), were responsible for a huge depletion of native vegetation due to the fuelwood need (Gariglio et al. 2010).

Nowadays, the Caatinga is populated mainly by rural people in a subsistence agriculture system. It also presents a few isolated regions with more productive and profitable agriculture, as the fruit production in the São Francisco River valley, cattle raising in the southeastern and a few growing irrigation agriculture spots. However, these anthropic activities may be higher than the carrying capacity in some regions (Leal et al. 2005). Although human disturbance is widespread in the most human-dense dry forest of the world, most of the big cities are placed in the eastern zone of the domain and play an important role in the socioeconomic dynamic (Silva et al. 2017b; fig 1a). It results in human-modified landscapes where low-income populations prevail, with farming relying on slash-and-burn agriculture, extensive livestock breeding, and firewood supply (Silva and Barbosa 2017).

Extensive goat breeding is widespread in the landscape, but cattle are still the most important single use of the area (Sampaio et al. 2017; Schulz et al. 2017). These activities often compose a mixed farming system, which means we cannot analyze their effects in isolation (Powell et al. 2004).

The Brazilian biomes limits were recently updated to a higher resolution, but some corrections were also made regarding phytophysionomies (hereafter vegetation types), especially for ecotone environments (IBGE, 2019). For the Caatinga, the main changes took place in the transition region from Caatinga to the Savanna region in Brazilian Cerrado (western Caatinga border). Moreover, the new shape of the Caatinga is very consistent with updated limits of neotropical dry forests based on plant phylogeny studies (DRYFLOR 2016).

STUDY DESIGN

The municipality was adopted as the sampling unit to examine the potential relationship between social-ecological predictors (i.e., demographic, socioeconomic, and environmental variables, see Table 1), land use and land cover, and primary productivity. In Brazil, the municipality is the smallest political unit, with its own budget, and it is where development occurs, where national policies actually succeed or fail since you do not violate state/federal laws. A similar approach was also adopted for the Caatinga region (Silva et al. 2017a). From the 1,096 initial municipalities, we selected only those with at least 50% of their territory within the Caatinga limits (i.e., IBGE biome shapefile).

LAND USE AND LAND COVER SURVEY

We obtained the proportion of each LULC per municipality from collection 5 of the MapBiomas Project (MapBiomas, 2020). The MapBiomas is an innovative Brazilian project

involving a network of different organizations (academic, state, and private organizations) aiming to understand the land-use dynamics within Brazilian biomes (currently also outside borders). It provides an extensive temporal dataset (yearly, from 1985 to 2019), with 30m of spatial resolution (i.e., based on Landsat imagery) for every Biomes and has also adopted the new Brazilian biomes limits as we did (Souza et al. 2020).

The classification of land use and land cover was performed using the Random Forest algorithm, with an accuracy of 81.4% (Souza et al. 2020) . We selected three of the 19 LULC available classes because they are the main types covering Caatinga (i.e., together they account for 89% and 87% of the biome, for the years of 2000 and 2010, respectively; Fig. 1b-d). Despite representing a lower value than that found for other Brazilian biomes, it represents a high accuracy for semiarid environments. The Caatinga presents 13 different vegetational formations, as a result of natural vegetation heterogeneity, different land uses, terrain, and soil, ranging from woody and shrub-herbaceous dominant areas (Velloso et al. 2002; Prado 2003).

Mapbioma's project classifies the LULC classes based on previous LULC classifications nomenclatures, including one from an official federal agency (IBGE) and the FAO organization (Souza et al. 2020). Therefore, it is important to clearly define the selected LULC classes. The MapBiomias defines (1) *Forest* as a “Vegetation with a predominance of continuous canopy – [classes of] Forest Steppe Savanna, Seasonal Semi-Deciduous and Deciduous Forest”; (2) Savanna formation (hereafter *Savanna-like vegetation*) represents “Vegetation types with predominance of semi-continuous canopy species -Wooded Steppe Savanna and Wooded Savanna”; and (3) *Pasture* is the land used as pasture. However, we emphasize that although we refer to the original Mapbiomas nomenclatures, we have two concerns about it. First, it's well known that the Caatinga ecosystem is a tropical dry forest (*sensu* Pennington et al. 2009) and does not a Savanna as already proposed. The Savanna-like

vegetation nomenclature is then a way to describe a spatially widespread vegetation type that encompasses from sparse trees dominated to places with fewer trees and more shrubs and herbs presence, which may be structurally similar to savanna ecosystem, but not functionally (i.e., it is a vegetation not dominated by annual grasses and that catches fire regularly). The second point, strictly related to the former, is that as this LULC class covers the largest area of the Caatinga, it is prone to encompass areas that are both naturally savanna-like vegetation and also degraded areas with a greater history of land use (at least 30% of the classified native vegetation is secondary vegetation). Regardless of these inherent problems in a LULC classification in such a continental country like Brazil and a heterogeneous ecosystem like Caatinga, we still believe this is the best, most reliable and updated LULC source.

SOCIAL-ECOLOGICAL PREDICTORS

Based on the literature on human-environment interaction, social-ecological systems, and the data availability at the municipality level, we have chosen several variables that we expect to affect the ecosystem at different scales (Anastasopoulou et al. 2007; Tzanopoulos et al. 2013) and, hence, directly or indirectly affect the provision of ecosystem services (MA 2005). Briefly, we call the selected variables social-ecological drivers, which are related to social, economic, demographic, environmental, and geographical aspects.

We selected official public databases of socioeconomic variables from (1) the Federal Government Agency (IBGE) regarding the Demographic Census and other data collection with a more specific focus; and (2) the “Institute of Applied Economic Research” (in Portuguese, IPEA). We have selected 26 variables as potential predictors. More information about the data sets is listed in Table 1. We also selected those variables since they are freely available, so the analysis could be updated in future studies.

These agencies provide data for different years, but the years 2000 and 2010 are the ones with the most quantity of data since they are the two subsequent years of the last two demographic censuses with officially released results. Hence, we decided to use the available socioeconomic data for both years in the analysis.

NET PRIMARY PRODUCTIVITY ESTIMATION SURVEY

The estimative of Net Primary Productivity (NPP) for the Caatinga was obtained by assessing the Normalized Difference Vegetation Index (NDVI) data, a widely used proxy of the NPP in ecological research (Myneni et al. 1995), allowing the researcher to assess a very wide timeframe. Although there are some criticisms about the use of NDVI, it is mainly based on the idea that it saturates in highly productive environments (Nicholson et al. 1990) and, since the Caatinga dry forest does not fit this profile, we decided to use this index. In addition, we recognize that, in the chosen scale, NDVI will respond both to water availability (i.e., precipitation regarding regional-scale analysis) and to the ecosystem structure (i.e., vegetation cover, soil condition of each class). Therefore, our method does not allow us to identify which mechanisms explain productivity, but it allows us to comparatively assess in the productivity between the selected LULC classes. We assume that each LULC class presents specific ecosystem structure and, in turn, different conditions that may explain levels of photosynthesis. Finally, see the Statistical analyses section to see how we handled with different precipitation levels.

The data was taken from the Google Earth Engine platform (Gorelick et al. 2017). We downloaded the NDVI data from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor, with 250m of resolution, for the year 2010. To fit the MapBiomass data resolution with the NPP data, we reprojected the images to 250 meters. To get the NDVI

values for each LULC class, we extracted the NDVI values for every pixel inside the Caatinga.

LANDSCAPE DATA PREPARATION

Data processing and map elaboration were done in the QGIS v3.14 (QGIS 2021) and R language, with the *sf*, *raster*, *tidyverse*, and *ggplot2* packages (Pebesma 2018; Wickham 2019; Hijmans 2020). To deal with missing data, we did multiple imputations with the *missForest* package from R (Stekhoven 2013). In total, 18 missing data were replaced. We also excluded the municipality of Fortaleza, the capital of Ceará state since it has a very different social-ecological context that does not fit our study approach. In the end, 1,093 municipalities were selected for our analyses, including the years 2000 and 2010 ($n = 2,186$). The data of the predictor variables were centralized and scaled before the statistical analysis (Kuhn et al. 2020). After that, the data was spatial sign transformed to deal with outliers, where it projects the predictor values onto a multidimensional sphere, and it makes all the samples the same distance to the sphere's center.

STATISTICAL ANALYSES

To assess the relationship between the predictors and each of the three selected LULC classes, we run two different machine learning predictive models: Random Forest (RF) (Breiman 2001) and Multivariate Adaptive regression Splines (MARS) (Friedman 1991). In general, the RF algorithm is robust and one of the most used machine learning in ecology. It has few assumptions and data preprocessing and generating predictive models with high performance, designed to avoid overfitting (Breiman 2001; Lawler et al. 2006). Through decision tree algorithms, the RF produces both classifications and regression models (our

case). However, it is a type of “black box” algorithm, where the relationships between variables (e.g., direction and intensity of the relationship) are hard to interpret and visualize (Mouchet et al. 2014).

Therefore, to overcome this problem, we also run the predictive model through MARS. The algorithm is a non-linear regression analysis similar to regression analyzes (for example, GAM) (Elith and Leathwick 2007). Briefly, the algorithm creates a piecewise linear model, aiming to get the non-linearity aspect of polynomial regression, by assessing cut points called knots. Hence, it creates several linear regression lines for each predictor-response relationship. Each linear regression line segment can be synthesized by a function (basis function, see Table A2). Since the data from our response variable (proportion of land cover in the municipality) shows evident skewed distribution, with several occurrences of zero (especially for forest cover, see Fig. 1a), the use of this non-linear model is an interesting option. To avoid the overestimation of the model due to collinearity, we (1) analyzed the severity of multicollinearity between the independent variables by the Variation Inflation Factor (VIF), by excluding any variable with $VIF > 5$ (Jou et al. 2014); and (2) the correlation coefficients between drivers, excluding the variables with Spearman correlation > 0.7 . Of the 26 initial drivers, 21 of them left in our analysis (Table 1; Fig. A2).

For each chosen model, a model tuning of the parameters can be set to increase try to increase model performance, where each model presents its specific tuning parameters. For RF, the parameters are (1) `mtry` (the number of randomly selected predictors at each cut in the tree), (2) `splitrule` (different splitting rules), and 3) `min.node.size` (Minimal node size). For MARS, (1) `nprune` (the maximum number of terms in the tuned model), and 2) `degree` (the maximum degree of interaction). We executed the model for different configurations of the tuning parameters For RF, `mtry` = 2 to 23, `splitrule` = "gini" and "extratrees", and `min.node.size` = 10 to 20. For MARS, `degree` = 1 to 2, and `nprune` = 2 to 50.

Once the model tuning parameters are defined, the next step is to define the resampling method. Resampling is an important tool to generate models with reliable performances. While a large number of samples brings more robustness to statistical analysis, a statistical model based on a high sample number and with a large number of predictive variables tends to overfit (an overestimation of the predictive power of the model). To avoid it, resampling techniques are one of the main options available. Among the various techniques available, cross-validation analyzes are one of the most used. Since the model should not have its performance estimated based on the same data used to run the model (biasing the results), cross-validation divides the data into two parts: training and test data. It is common to divide the data in different proportions, but we choose a very robust technique that divides the data into different ‘folds’ (i.e., k-fold cross-validation). In short, the data is (1) randomized; (2) grouped in k-folds; (3) for each group one is held as test data and the remaining becomes training groups; (4) the algorithm runs the model with train data and tests it to obtain the evaluation score; and (5) summarizes all the models. Here, we use k-fold cross-validation with $k = 10$. To avoid overfitting due to spatial autocorrelation (training points spatially close to test points) (Valavi et al. 2019), we assigned the municipality microregion as an index to split the data locally (i.e., greater likelihood that folds present municipalities close to each other). All the analyses were done using the caret package in R (Kuhn et al., 2020).

To evaluate the model performance, we used the values of RMSE (Root Mean Square Error), R^2 , and the MAE (Mean Absolute error). We select the best model based on the `bestTune` and `finalModel` function in caret. In the end, the variables selected by the model are arranged in a ranking of importance. The variable importance is a value that measures the number of times that, when a specific predictor was included in the model, it increased the model’s performance. Therefore, it is closely related to model performance (Kuhn et al, 2020)

and the values are scaled to range from 0 to 100. Here, we chose to use the GCV (Generalized Cross-Validation) method.

All of these analyzes were performed using the R caret package (Kuhn 2020), using the train function. The function was developed to run the model tuning and resampling for a diverse range of predictive models, allowing several other packages to be imported to the caret. In our case, earth packages have been incorporated, for MARS and the ranger package for the RF model.

Finally, to assess if the NPP differs in the chosen LULC classes, aiming to highlight their specific contributions to the ecosystem functioning, we compared the NDVI values for each class by running an Analysis of Variance in R and Tukey's test to assess difference for each pair. To get the NDVI values, we randomized 150 points per class, from pixels that presented the same LULC classification from 2000 to 2010. To identify the differences between each group, we computed a post hoc T-test with Bonferroni correction. Considering that the NDVI strongly responds to the spatio-temporal precipitation variation, (1) the NDVI values we considered were the mean annual NDVI (2001 - 2010); and (2) we assessed the mean annual precipitation values (Fig. 5b) for the randomized points, aiming to better understand the contributions of the precipitation and the ecosystem structure to NDVI differences that may exist in different LULC.

RESULTS

REPRESENTATIVENESS AND SPATIAL DISTRIBUTION OF VEGETATION TYPES OR LAND-USE CLASSES

The proportion of each LULC class per municipality presented a specific spatial distribution pattern within the Caatinga ecosystem (Fig. 1b-d). The Savanna-like vegetation is the most common physiognomy, covering a proportion of 0.484 ± 0.245 (mean $\pm$ standard

deviation) of the municipalities. The municipalities with the highest savanna-like vegetation cover are located above the São Francisco River, mainly in the western, middle northern, and western Caatinga (Fig. 1b). The municipality of Lagoa do Sítio presented the highest savanna-like vegetation cover (i.e., more than 95% of its land both in 2000 and 2010), while the municipality of Lamarão has no savanna-like vegetation cover. Forest represents the lowest proportion of land cover, covering on average a proportion of 0.063 ± 0.139 of the municipalities, with a clear patchy spatial distribution (Fig. 1c). It is possible to see a concentration of municipalities with a higher forest cover in the southeastern Caatinga, in the hilly ecoregion known as the Chapada Diamantina Complex, but also in the northern area. Finally, pasture cover 0.281 ± 0.257 of the municipality's territory, with a higher concentration covering from the southern region to the eastern border (Fig. 1d).

LULC-DRIVER RELATIONSHIP

For the effect of social-ecological on LULC, we found different sets of explanatory variables that had a significant effect on each of the three analyzed classes. We also obtained different final models (i.e., selected predictors) for the MARS and RF analyzes. Additionally, no correlation was found between the size of the municipalities and the proportion of each of the three classes of land cover analyzed.

For the savanna formation in the RF algorithm, several drivers were important to the model in different magnitudes, but only four of them were clearly more important (Fig. 2a), namely distance to a big city, MAT, CWD, and CET (all environmental variables). The best model was the one with the parameters $mtry = 21$, $splitrule = extratrees$ and $min.node.size = 10$ (Fig. A1), with robust values of model performance ($R^2 = 0.716$, $RMSE = 0.130$ e $MAE = 0.104$). Next, the MARS model selected ten predictor variables (Fig. 2; Table A1). Although cattle density was the most important driver, from the first five in the ranking of importance,

four were related only to climate, soil, and terrain properties. The other less important drivers describe demographic conditions (population density and rural population density), livestock (density of goat), and location of the municipality (longitude and distance to a big city) (Fig. 2; Table A1). The cattle density, the most important variable, showed an effect on savanna-like vegetation cover that is divided into two parts, with an initial negative effect (Fig. 3a). Additionally, Table A1 shows the basis function for each LULC-predictor relationship. The variable distance to a big city, although figured as the less important variable for savanna-like vegetation cover in MARS analysis, is figured as the most important one for RF. The best model tuning parameters setup for MARS was with degree = 1 (meaning that the best model does not have any interactive effect of the predictors) and nprune = 18. The best model had a $R^2 = 0.648$, RMSE = 0.144 and MAE = 0.115.

For the forest land cover, only the RF algorithm selected significant drivers (Fig. 2c). Regardless of the driver's group, all the top five selected drivers are environmental variables, with precipitation as the far most important one, followed by three other climates and one terrain predictor. The RF model with a higher performance presented the parameters mtry = 21, splitrule = extratrees and min.node.size = 10 (Fig. A1), with a $R^2 = 0.391$, RMSE = 0.083 and MAE = 0.059.

Lastly, the RF algorithm also showed environmental variables as the most important drivers of pasture cover (Fig. 2d). The temperature was much more important than the other ones (e.g., the other climatic variable, CWD). The best parameters were mtry = 21, splitrule = extratrees and min.node.size = 10 (Fig. A1), with a $R^2 = 0.436$, RMSE = 0.272 and MAE = 0.207. For MARS, the model selected four predictor variables (MAT, Cattle_dens, MAP, CWD; Fig. 2e; Table A1). From the 4 variables selected by the model (although CWD has almost zero importance), three are climatic, and only cattle density represents the socioeconomic predictors of pasture cover. The temperature was picked up as the most

important driver in both models (Fig. 2d,e) and presented a relationship in “z” with pasture cover (Fig. 4a). Meanwhile, cattle density strongly influences pasture areas, but it reaches a level where the land used as pasture does not fluctuate. The best model tuning parameters setup was with degree = 1 and nprune = 5. The model had a $R^2 = 0.565$, RMSE = 0.188 and MAE = 0.145.

PRIMARY PRODUCTIVITY PER LULC CLASS

We found that the three selected LULC classes present different rates of NDVI ($F(2,441) = 92.58$, $p < 0.005$) (Fig. 5). As expected, the forest was the most productive physiognomy (average NDVI = 0.661 ± 0.0919), presenting mean NDVI values greater than savanna-like vegetation (0.564 ± 0.081) and pasture (0.522 ± 0.096). In turn, savanna-like vegetation presented a significantly higher NDVI value than pasture (Fig. 5a). Additionally, the same pattern was found for the historical annual precipitation, where the forested areas received more precipitation (941 ± 202) than savanna-like vegetation (728 ± 166) and pasture (692 ± 155), the last two with no significant difference (Fig. 5b).

DISCUSSION

Our findings emphasize the spatial dominance of savanna-like vegetation in the Caatinga region, followed by pasture and forest stands, at the municipality level. Forests apparently cover only a small percentage of municipal areas and consequently the entire region. Moreover, vegetation cover considering these three major types is not uniformly distributed but spatially organized, particularly by physical environmental variables. In fact, our results suggest that LULC is influenced by a myriad of variables, with a specific and varied effect depending on the LULC type. Overall, LULC is driven mainly by environmental variables (edaphic, climatic, and geographic), with forest cover rates across municipalities being the most unpredictable variable. However, some social-economic variables associated to rural activities are also important drivers or correlates with patterns of LULC, including cattle and goat density and density of rural people. Surprisingly, a myriad of classical socioeconomic variables, such as income, GDP, population above poverty, and education variables, play no role or only a minor one on the patterns of LULC in the Caatinga region/biota. Additionally, the relationships are non-linear exposing how complex is the scenario of land use and land cover at the regional level. Finally, NPP is higher across lands covered by forest, followed by savanna-like vegetation and pastures. In synthesis, land use, vegetation cover, and land-use productivity in the Caatinga region are spatially organized and persist to a great extent influenced by climatic and soil conditions rather than reflecting social-economic contexts posed by municipalities.

Our findings also confirm the protagonism of environmental variables on patterns of LULC across human-modified landscapes, as already documented for other drylands (Cho et al. 2015; Huang et al. 2016), particularly in the case of regions still not completely encroached by human populations; i.e., low-density regions. We refer to regions or biotas still supporting a high level of cover by natural vegetation, where precipitation is by far the most

important variable associated to the predominant vegetation types across the tropics (Hirota et al. 2011). In addition to precipitation, the Caatinga LULC also respond or correlates to average temperature, water availability, and soil attributes as already mentioned as drivers for natural vegetation cover, including the Caatinga dry forest at multiple spatial scales (Cleveland et al. 2011; Redo et al. 2013; Rito et al. 2017; Souza et al. 2019).

Although here we are not able to identify the underlying mechanisms, we shall mention that precipitation and temperature respond to potential evapotranspiration and, consequently, to vegetation type as does CWD (Matin and Bourque 2013). Accordingly, forest cover was positively associated to precipitation and temperature (what is highly expected), while savanna-like respondent negatively to increments in soil fertility and increments in water availability beyond a threshold (Redo et al. 2013; Beuchle et al. 2015). In the perspective of an environmental-driven pattern of LULC, pastures correlated negatively with increments in precipitation and temperature; i.e the less water-demanding “vegetation type” as compared to forest and even savanna-like vegetation (Sampaio et al. 2017). In some extent, LULC still reflects the physical environmental conditions regardless of five centuries of occupation by resident farmers (Pereira et al. 2003; Silva et al. 2017b). Such a protagonism by a reduced set of environmental variables has been documented elsewhere, at least in terms of initial land occupation: environmental variables were more significant than socioeconomic variables (or a mix of variables) in describing deforestation and regeneration in the Mexican dry forests (Bonilla-Moheno et al. 2012).

However, there is evidence that LULC also reflects other variables such as the natural agropastoral potential as it correlates to the physical environment (Bruinsma 2003). We refer to (1) savanna-like and pastures occurring into climatic envelopes able to support forest (i.e. zones of high precipitation, see figure 1b and 1dc, (2) pasture concentration in the climatic envelopes with lower potential (low precipitation and increased temperature) for agriculture,

(3) the positive relationship between savanna-like and free-ranging goats, and (4) pasture (natural or introduced) positively correlated with cattle. In this perspective, eastern and southern Caatinga provide better conditions for livestock, including grass production to sustain livestock. We also refer to spots where rocky/shallow or infertile soils limit agropastoral activities regardless of precipitation level (Sampaio et al. 2017).

Additionally, the occurrence of climatic envelopes able to support pastures (and other agricultural activities) but still devoted to natural forest cover suggest that agropastoral potential (and associated physical conditions) is not the only variable defining LULC. Precisely, the spatial concentration of the remaining forest in the Caatinga western border suggests the influence of remoteness and historical development on LULC patterns. By far, rural and urban development have been more intense and it started closer to the coastal region (east border) and its big cities (the most important market for Caatinga products) rather than inland areas along the Caatinga border with Cerrado vegetation; i.e. an east-west vector of development (Silva et al. 2017b). Moreover, the few and small areas with a visible higher concentration of forest, particularly those located north of the São Francisco River and also one to the south, are associated with protected areas; i.e., protected areas and their determinants as drivers of LULC patterns, such as remoteness or low agropastoral potential, the marginal lands (Joppa and Pfaff 2009).

Such a protagonism of environmental drivers (particularly precipitation and temperature) and the connections with natural agropastoral potential, but also a lack of intense land use where naturally or technologically it could be possible (e.g. irrigation, chemical fertilization, etc.) partially explain the low scores of human, economic and social development of the Caatinga region as a whole and at municipality level (see Silva et al. 2017a). Note that in the Caatinga region our LULC categories are associated to reduced agropastoral productivity/revenue by a combination of slash-and-burn agriculture, free-ranging goat and

cattle production, and exploitation of forest products such as firewood; i.e. extractivism-based farming (Gariglio et al. 2010; Melo 2017). Although the agribusiness system has been changing since the 1980s in the Caatinga region (Sampaio et al. 2017), with technological advances and social safety programs increasing the ability of the rural population to maintain their economic activities (Buainain and Garcia 2013), such advances are still associated to particular sites (i.e. higher water availability) and/or have not supported more intense and profitable farming activities (Araújo-Filho 2013; Sampaio et al. 2017). It becomes visible in the case we consider socioeconomic scores: 60% of the Caatinga municipalities still support very low to low HDI scores, 39% lack reasonable socioeconomic infrastructure and only 1% have high levels. In turn, the highest rural populations occur in places with low levels of vegetation cover and low socioeconomic conditions (Silva et al. 2017a).

However, in contrast to what was been proposed, we did not find strong correlations between key socioeconomic attributes and LULC (Geist and Lambin 2002). In fact, our results do not offer strong evidence that is caused by a variety of different socioeconomic forces acting together (e.g. Geist and Lambin 2001; Raudsepp-Hearne et al. 2010) although we did not assess the same drivers of the mentioned studies. Even when socioeconomic variables are important in our models, their significance is low overall. In fact, on a global scale, there is no consistent relationship between the Human Development Index and non-food services like forest cover (Raudsepp-Hearne et al. 2010). Similarly, in the Caatinga regions, the use of rural credit by the municipalities reduced the grazing area, but by only less than 0.1% (Souza et al. 2020); and only a 0.6 percent difference in vegetation coverage was noted at the city level as a result of poverty alleviation policies (Dyngeland et al. 2020). Moreover, socioeconomic variables did not explain degradation levels exhibited by the Caatinga ecoregions (Silva et al. 2017a). Such a lack of correlation implies that social-economic development at the municipality level is neither a driver nor completely a result of

surrounding LULC in the Caatinga dry forest. In other words, LULC does not reflect the economic potential for rural development posed by municipalities or its lack, with LULC persisting into low revenue categories regardless of the municipality profile.

Moving to LULC productivity, lands covered by forest appears to be the most productive. It is reasonable that denser vegetation like forested areas presents a larger leaf area and therefore a higher productivity per area (He et al. 2017). As forested areas experience higher precipitation levels it is likely that vegetation structure and precipitation act synergistically on chlorophyll density and the carbon intake in the Caatinga region. Accordingly, lands covered by pasture support the lowest productivity level followed by savanna-like vegetation. Additionally, the savanna-like vegetation category here encompasses secondary vegetation across degraded areas (30% of native vegetation is secondary vegetation), which may represent impoverished and less productive plant assemblages (Sá and Angelotti 2009; Rito et al. 2017; Souza et al. 2019; Brun et al. 2019). Precisely, high-diversity plant assemblages can be two times more productive than monocultures and the difference gets greater over time (Tilman et al. 2014). A recent finding has connected average precipitation, woody plant species richness, and aboveground biomass in the Caatinga dry forest (Souza et al. 2019). Similarly, pastures in the Caatinga dry forest usually cover degraded areas in terms of soil conditions with few or inexistent technical inputs such as fertilization; i.e. pastures covering marginal lands without the benefit of inputs (Sampaio et al. 2017). As a third underlying mechanism, pasture and savanna-like categories shall contain much more infrastructure/facilities per area such as roads, fences, dams, among others. Finally, we shall consider that NDVI is estimated through optical images, thereby, it captures only the canopy layer supported by forest and savanna-like, but not the productivity associated to shrubs and herbs beneath crow trees (Fang et al. 2013).

In synthesis, we shall be conservative in our interpretations as human potential drivers acting at multiple administrative levels do not necessarily pose ecological impacts on the same spatial scales (Tzanopoulos et al. 2013). Despite such caution, patterns of LULC and associated primary productivity in the Caatinga region appear to respond to a large extent to a combination of physical variables with impact on biomass while defining the natural agropastoral potential. Other variables, including the socioeconomic profile exhibited by municipalities, play a minor role. Land use and agropastoral activities limited by natural conditions rather than technology have resulted in extractivism-based rural activities, such as livestock production based on native vegetation as fodder; i.e. a causal connection between LULC patterns, rural revenues, and socioeconomic conditions at the regional level. In fact, socioeconomic scores at the municipality level have been widely defined by the presence of federal-supported services and social programs; i.e. the main sources of revenues (Silva et al. 2017a). As Caatinga is expected to experience decreasing levels of precipitation due to climate changes (up to one-third, Marengo et al. 2017)), forest and savanna-like vegetation represent valuable assets in terms of ecosystem services, biodiversity persistence, and economic opportunities (Araujo et al. 2021).

However, their persistence and sustainable use probably require a land-sparing approach (Sunderland et al. 2015; Meli et al. 2019), with more intense and productive use of those areas devoted to agropastoral activities, particularly in the case we considered that the Caatinga is one of the most-populated semiarid regions globally. As socioeconomic conditionings at municipality fail to explain patterns of LULC, we need further hypotheses to explain why rural activities remain constrained by natural conditions rather than experiencing transitions towards more productive land uses with technology able to reduce environmental limitations (i.e., reduced water supply). Agricultural/rural development has proven to occur everywhere (Stewart 2016) without necessarily leading to degradation when properly

managed (Noorka 2011). In other words, the Caatinga region, like other dry forests globally, appears to have achieved a “cross-road” where alternatives appear not to be completely associated to socio-economic contexts (at least at the municipal level) limiting or favoring the adoption of new technologies and approaches able to “release” rural activities from natural constraints and thus support socioeconomic development. Whatever the trajectory followed (traditional/low-input approach vs. modern/high-input land use), both can potentially alter current patterns of LULC and consequently the Caatinga resilience/vulnerability to climate change.

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Table 1. List of the predictors with potential impact in the ecosystem and that were used to predict the land use / land cover

Predictor	Description	Abbreviation	Unit	Mean	SD	Data source
Cattle density	Number of cattle heads in a given area	Cattle_dens	Heads / km ²	22.50	23.68	IBGE, 2000, 2010
Goat density	Number of goat heads in a given area	Goats_dens	Heads / km ²	8.89	14.66	IBGE, 2000, 2010
Sheep density	Number of sheep heads in a given area	Sheep_dens	Heads / km ²	10.24	13.33	IBGE, 2000, 2010
GDP per capita	The average Gross domestic product (a measure of the market value of all the final goods and services produced in a year) per person for a municipality	GDP_cap	R\$ * 1,000 Reais / inhabitant	3.43	3.41	IBGE, 2000, 2010
GDP of agriculture per capita	Contribution of Agriculture to Gross domestic product (GDP) of municipalities per capita	GDP_agric_cap	R\$ * 1,000 Reais / inhabitant	0.32	0.61	IBGE, 2000, 2010
Population density	Density of the population in the area of a municipality	Pop_dens	People / km ²	53.00	237.06	IBGE, 2000, 2010
Rural population density	Density of the population in the rural area of a municipality	Rural_pop_dens	People / km ²	20.37	28.36	SADes, 2019
Income per capita	The average income per person in a given area	Income_cap	R\$	216.61	82.69	IPEA, 2020
Rural population below the poverty line	Rural population that receives less than a half minimum wage (i.e., R\$ 151,00 in 2000 and R\$ 510,00 in 2010)	RPBPL	Percent	28.52	12.74	IBGE, 2000, 2010
Gini coefficient	A measure of inequality inside a population (1 is the highest and 0 is the lowest inequality)	Gini_coef	Unitless	0.54	0.06	IPEA, 2020
Human Development Index (HDI)	A statistic at the municipality level, composed of a index of life expectancy, education, and per capita income indicators	HDI	Unitless	0.51	0.10	IPEA, 2020

Primary school education	Percentage of the total municipality population that finished the Elementary school	Prim_school	Unitless	23.28	10.63	IBGE, 2000, 2010
Secondary school education	Percentage of the total municipality population that finished the Secondary school	Sec_school	Unitless	13.34	7.47	IBGE, 2000, 2010
Rural illiteracy	Percentage of the rural municipality population that cannot read or write	Rural_illiteracy	Unitless	50.54	21.55	IBGE, 2000, 2010
Mean Annual Precipitation	Historical Mean Annual Precipitation (1970 – 2000)	MAP	Milimeters	826.97	242.45	Fick and Hijmans, 2017
Mean Annual Precipitation – 5 years	Mean Annual Precipitation for the last five years	MAP_5yrs	Milimeters	793.98	237.59	Funk et al., 2015
Precipitation seasonality	A measure of the variation in monthly precipitation totals in a year	Prec_season	Percent	86.96	22.81	Fick and Hijmans, 2017
Mean Annual Temperature	Mean annual Temperature	MAT	Celsius degrees	33.47	2.39	Fick and Hijmans, 2017
Soil Nitrogen	Total nitrogen (N) at 0-5 cm soil depth	Nitr_05	cg/kg	156.81	47.20	Hengl et al., 2017
Cumulative Water Deficit	Cumulative water deficit	CWD	mm	-10113.20	210.60	Chave et al., 2014
Urban Population Influence	Mean value of the kernel density values (raster), based on the centroid of urban areas and with intensity proportional to the urban population	Pop_inf	hab/km ²	10922.05	17683.51	SADes, 2019
Cation Exchange Capacity	Cation Exchange Capacity at soil 0-5 cm depth, a measure of soil's ability to hold charged ions (influencing, for example, soil structure, nutrient availability)	CET	mmol(c)/kg	183.44	33.73	Hengl et al., 2017
Distance to a big city	Nearest distance to city with 500,000 inhabitants or more	Dist_big_city	Meters	214.65	113.82	IBGE, 2019
Slope	Mean slope of the municipality terrain	Slope	Degrees	1.15	0.76	Jarvis et al., 2008

Latitude	Latitude from the centroid of the municipality	Latitude	Meters (UTM)	2644451	298298.10	IBGE, 2019
Longitude	Longitude from the centroid of the municipality	Longitude	Meters (UTM)	2278541	258020.7	IBGE, 2019

Table 2. List of basis functions of the MARS model for the Savanna-like vegetation cover and their coefficients c_i . Summary of the results of the Multi Adaptative Regression Splines (MARS) showing the effect of several predictors in the prediction of the proportion of the land covered by the three major land use / land cover in the Caatinga dry forest (Savanna-like vegetation, forest and pasture).

Basis function	Definition	Coefficients
B1	(Intercept)	0.54968111
B2	$h(-0.868957\text{-Longitude})$	-0.15920417
B3	$h(\text{Longitude}- -0.868957)$	-0.03374527
B4	$h(1.70266\text{-Cattle_dens})$	0.05230695
B5	$h(-0.486249\text{-Goat_dens})$	-0.21137962
B6	$h(\text{Goat_dens}- -0.486249)$	0.01689211
B7	$h(0.345286\text{-Pop_dens})$	0.09424956
B8	$h(0.705761\text{-Rural_pop_dens})$	0.08347599
B9	$h(\text{Rural_pop_dens}-0.705761)$	-0.01228854
B10	$h(-0.606539\text{-Slope})$	-0.23435716
B11	$h(\text{Slope}- -0.606539)$	0.02161975
B12	$h(0.967291\text{-MAP})$	-0.06103887
B13	$h(\text{MAP}-0.967291)$	-0.18561688
B14	$h(-0.912427\text{-CWD})$	-0.18880159
B15	$h(\text{CWD}- -0.912427)$	-0.06593036
B16	$h(\text{Dist_big_city}-0.0248796)$	0.0273237
B17	$h(-0.605744\text{-CET})$	0.09812758
B18	$h(\text{CET}- -0.605744)$	-0.09392576

Table 3. List of basis functions of the MARS model for the Pasture cover and their coefficients c_i .

Basis function	Definition	Coefficients
B1	(Intercept)	0.64867454
B2	$h(1.05684 - \text{Cattle_dens})$	-0.1264201
B3	$h(\text{MAP} - -0.77875)$	-0.08774778
B4	$h(\text{CET} - -0.496976)$	0.11717421
B5	$h(\text{CET} - 1.03314)$	-0.26222683
B6	$h(\text{MAT} - -1.21729)$	-0.21308116
B7	$h(\text{MAT} - 0.112807)$	0.21709088

FIGURE LEGENDS

Figure 1. Map of the Caatinga territory, exposing the main river of the region and the big cities (500,000 inhabitants or more) (a) and the maps of the Savanna-like vegetation cover (b), Forest cover (c) and Pasture cover (d). The values are classified based on the Natural break (Jenks) classification in order to optimize the spatial visualization.

Figure 2. The importance rank graph for the three analyzed land use and land cover. The graphs on the left represent the driver's importance rank for Random Forest algorithm and on the right the ones selected by MARS. Only the forest presents no variable importance for the MARS algorithm, since the model did not select any driver for this land cover. The ranking was based on the GCV (Generalized Cross-Validation) method and are scaled to get values between 0 and 100. To see the scaled values, please refer to the Table A1 in the Appendixes.

Figure 3. The drivers of savanna-like vegetation cover selected by the MARS model in the Caatinga dry forest. The graphs are ordered by their importance rank (see Fig. 2).

Figure 4. The drivers of savanna-like vegetation cover selected by the MARS model in the Caatinga dry forest. The graphs are ordered by their importance rank (see Fig. 2).

Figure 5. Mean annual Normalized Difference Vegetation Index values in the year of 2010 (a) and annual mean precipitation values (mm) for the last 11 years (2000-2010) for the main classes of land use and cover in the dry Caatinga dry forest. * = significant difference for each pair of LULC class, n.s. = not significant.

Figure 1.

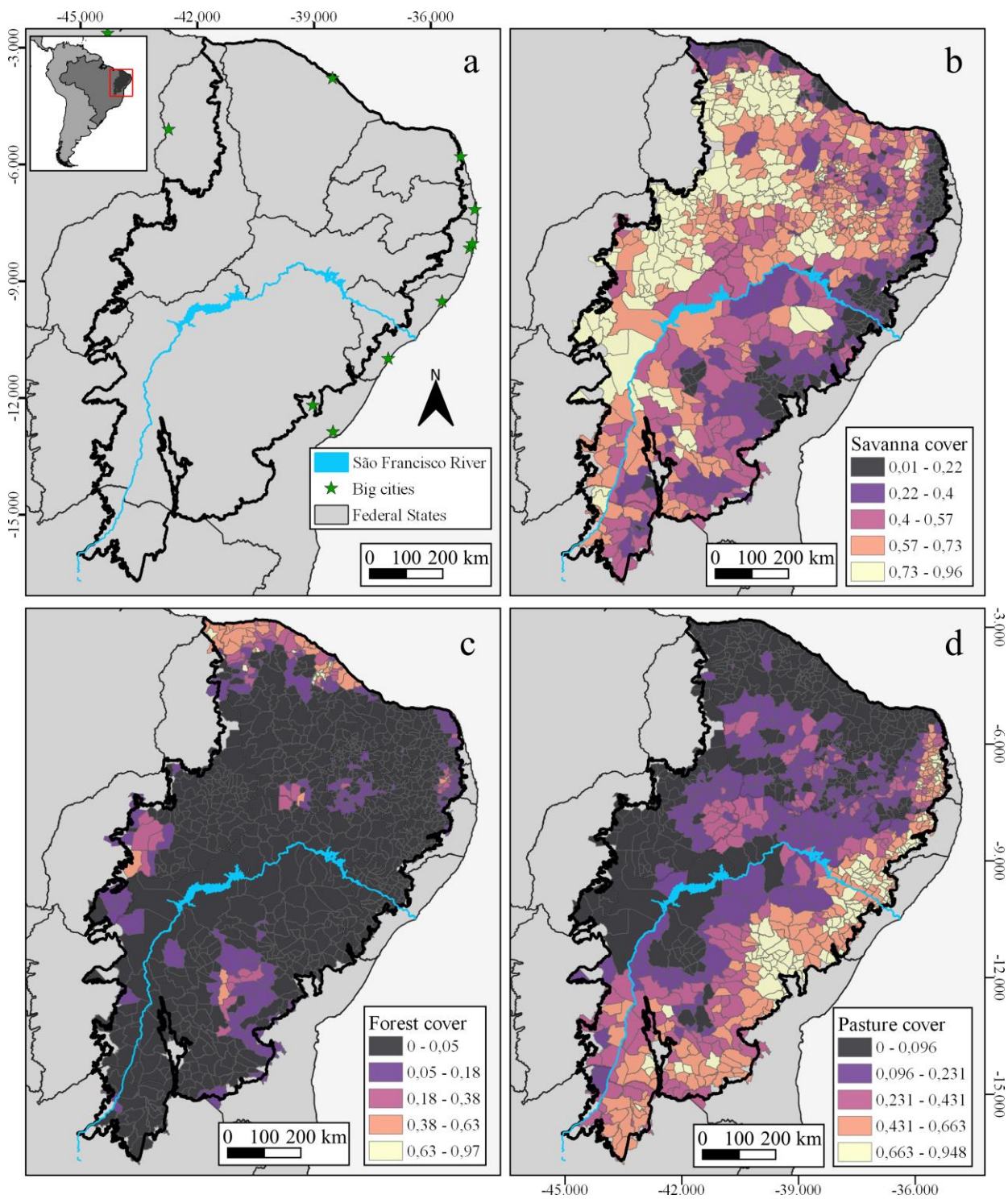


Figure 2.

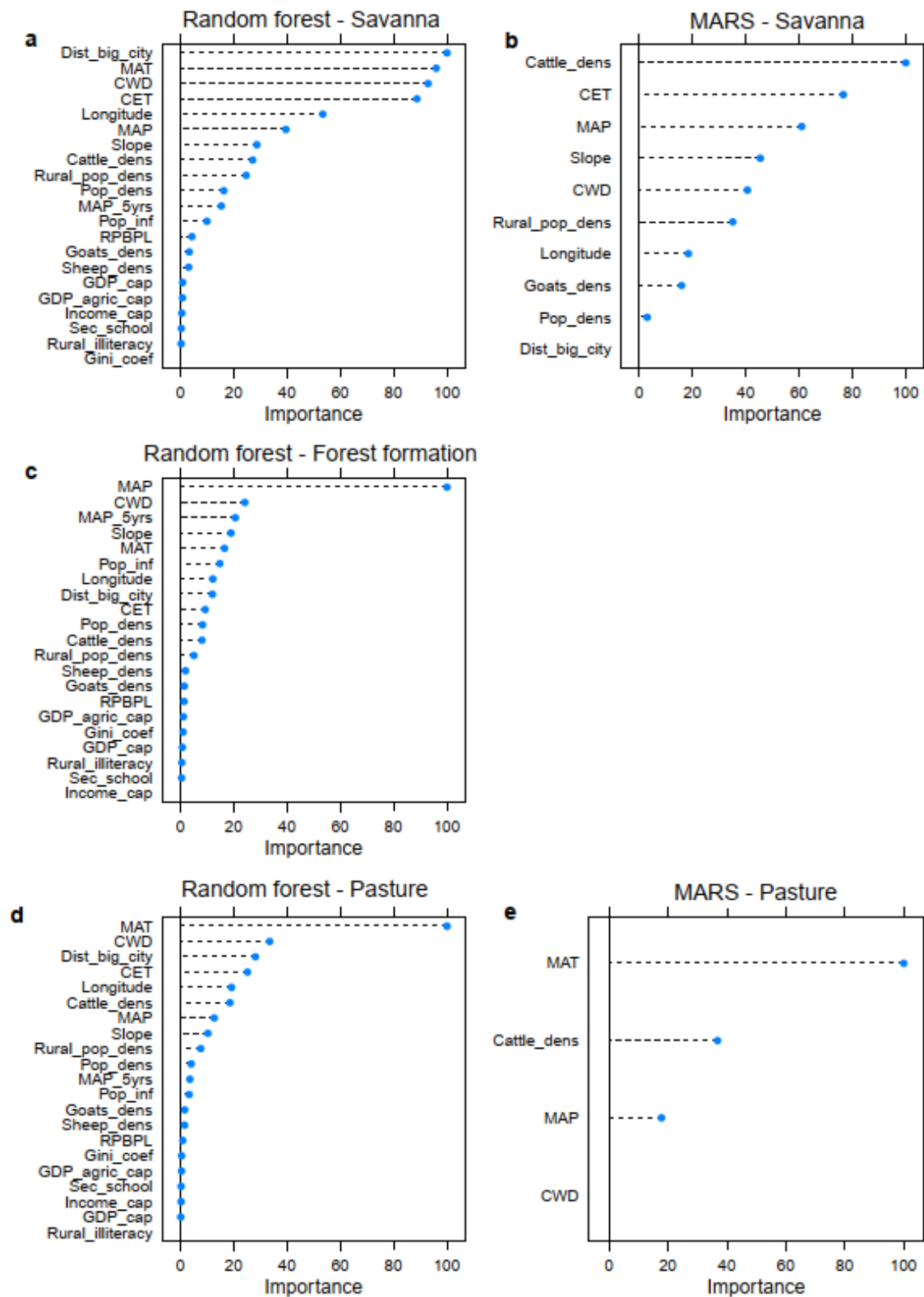


Figure 3.

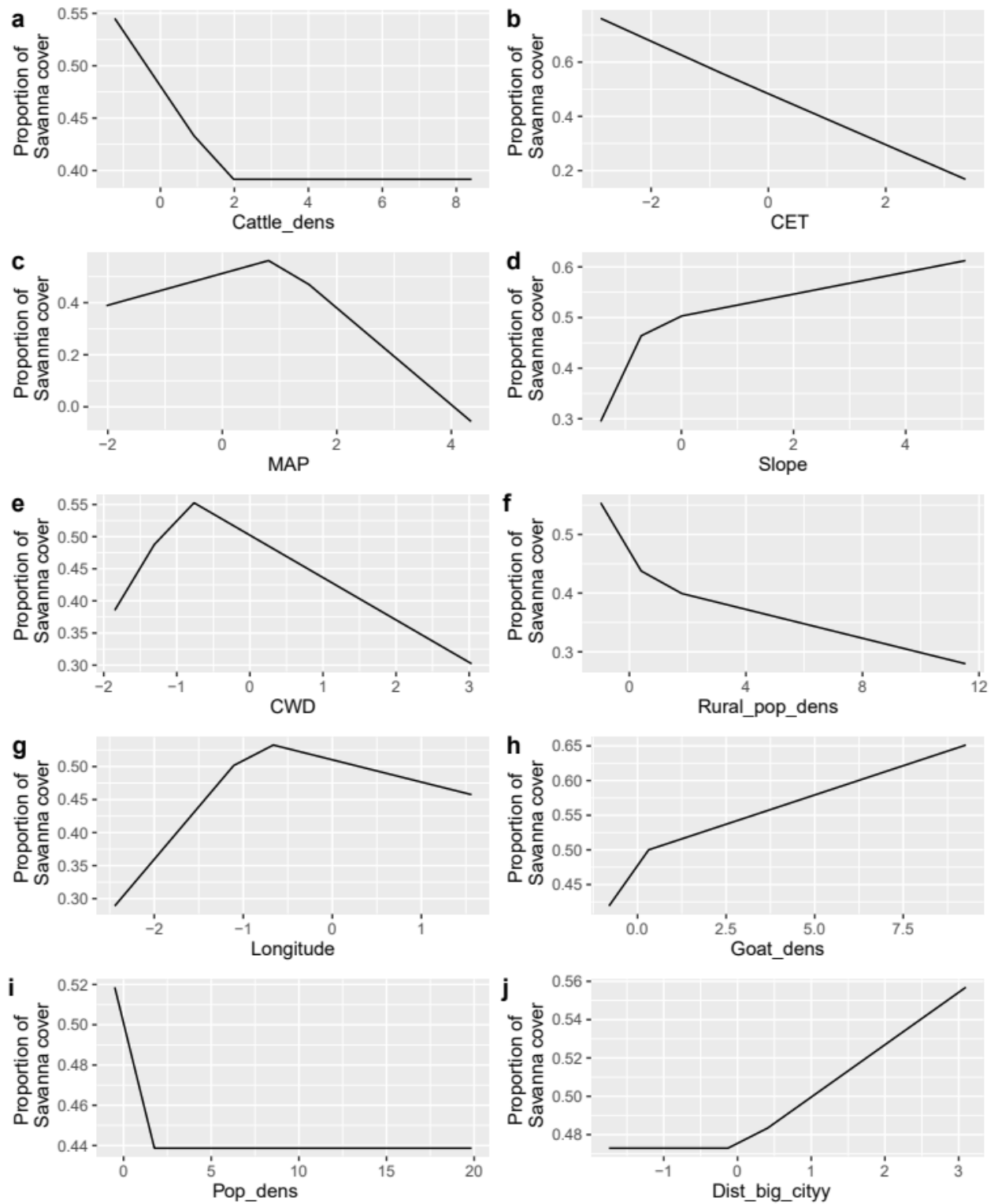


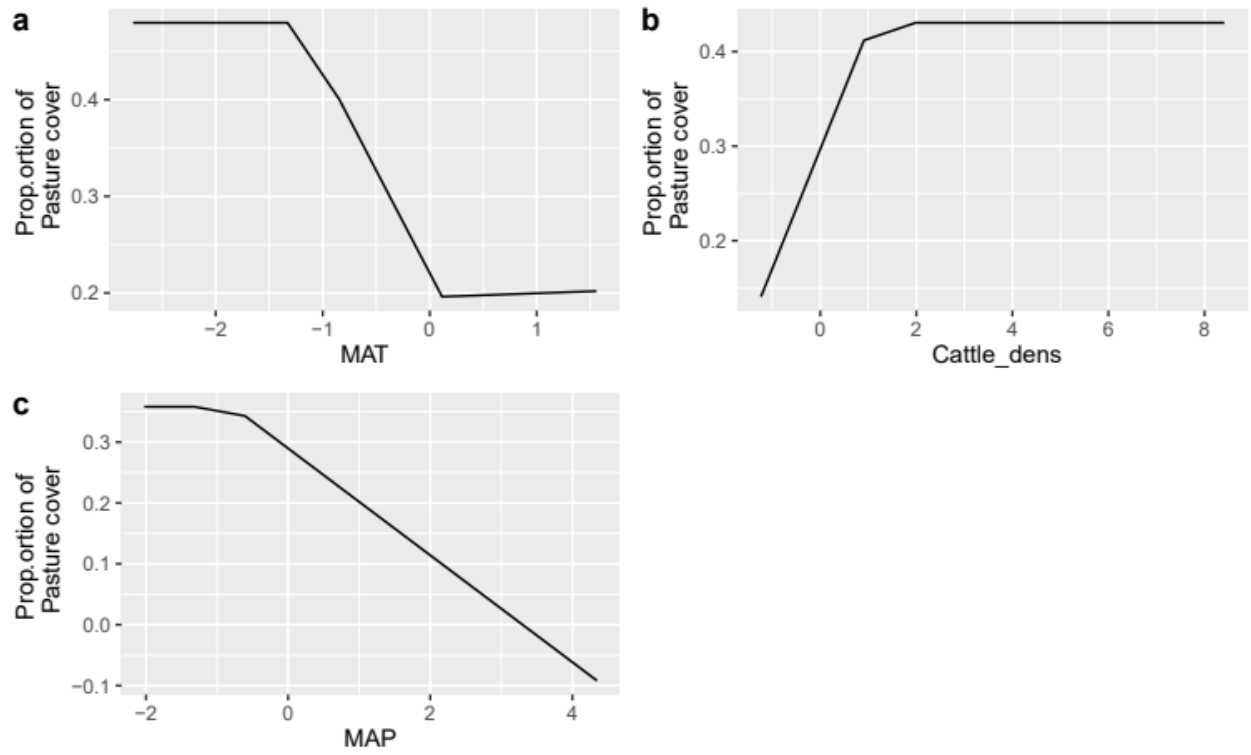
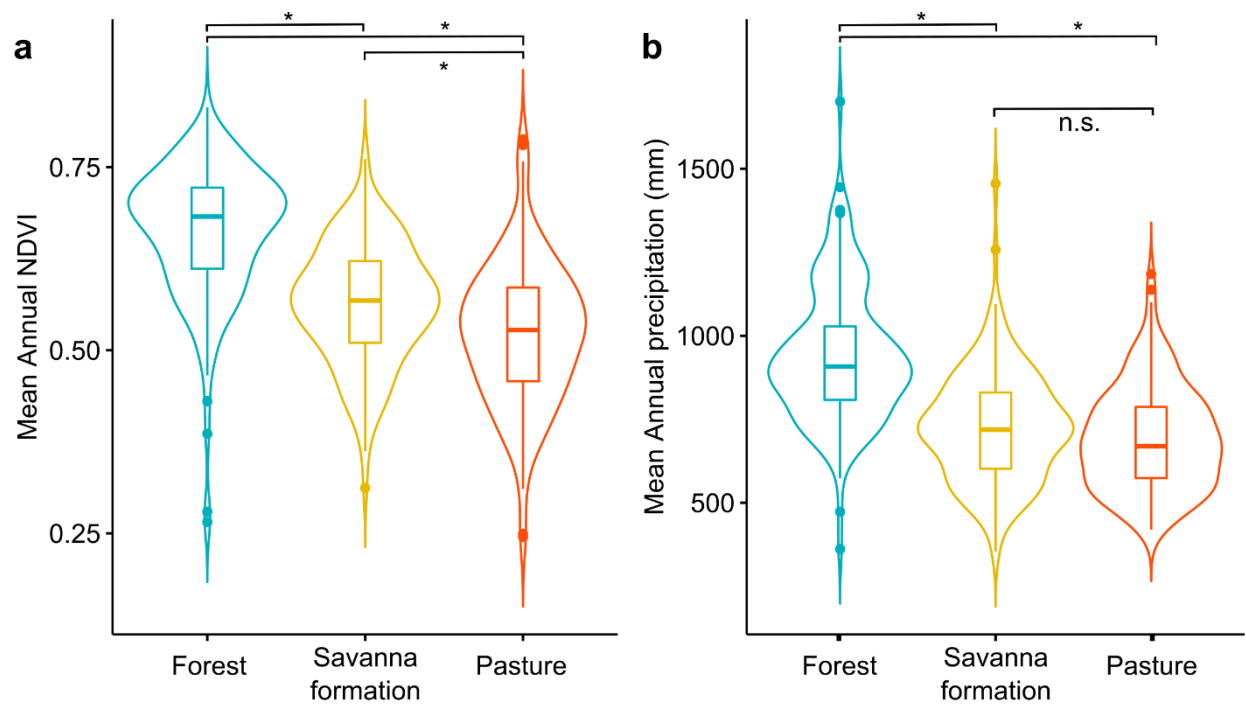
Figure 4.

Figure 5.

Supporting Information for:

Vegetation cover and net primary productivity in the Caatinga dry forest: The role of socioeconomic, demographic, and environmental drivers

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Table A1. Importance values for Savanna-like vegetations in RF.

Predictor	Importance
Savanna formation – RF	
Dist_big_city	100
MAT	96.7675
CWD	92.7766
CET	88.7289
Longitude	53.5618
MAP	39.5246
Slope	28.519
Cattle_dens	26.9933
Rural_pop_dens	24.4693
Pop_dens	16.2095
MAP_5yrs	15.1537
Pop_inf	9.7651
RPBPL	4.1121
Goat_dens	3.199
Sheep_dens	2.9012
GDP_cap	0.6077
GDP_agric_cap	0.514
Income_capita	0.3612
Sec_school	0.1426
Rural_illiteracy	0.1225
Savanna-like vegetation – MARS	
Cattle_dens	100
CET	76.539
MAP	60.919
Slope	45.368
CWD	40.52
Rural_pop_dens	35.021
Longitude	18.336
Goat_dens	15.79
Pop_dens	2.868
Distance_big_city	0
Forest – RF	
MAP	100
CWD	21.2781

MAP_5yrs	18.9745
Slope	18.0897
Pop_inf	16.1022
MAT	13.684
Longitude	11.3094
Dist_big_city	10.8765
CET	8.2866
Cattle_dens	8.2189
Pop_dens	7.6173
Rural_pop_dens	3.4133
Sheep_dens	1.7589
Goat_dens	1.3326
GDP_agric_cap	1.0082
Gini_coef	0.948
RPBPL	0.9045
GDP_cap	0.5073
Sec_school	0.3254
Rural_illiteracy	0.2672
Pasture – RF	
MAT	1.00E+02
CWD	3.35E+01
Dist_big_city	2.81E+01
CET	2.50E+01
Longitude	1.91E+01
Cattle_dens	1.85E+01
MAP	1.26E+01
Slope	1.02E+01
Rural_pop_dens	7.49E+00
Pop_dens	3.90E+00
MAP_5yrs	3.41E+00
Urban_pop_influence	3.14E+00
Goat_dens	1.47E+00
Sheep_dens	1.40E+00
RPBPL	7.64E-01
Gini_coef	3.15E-01
GDP_agric_cap	3.09E-01
Sec_school	1.43E-01
Income_capita	1.42E-01
GDP_cap	9.74E-03
Pasture – MARS	
MAT	100
Cattle_dens	36.75
MAP	17.71
CWD	0

Table A2. Basis functions for the best model by the Multivariate Adaptive Regression Splines (MARS), showing the relationship between the selected drivers for each of the three analyzed land use and land cover classes in the Caatinga dry forest.

Savanna-like vegetation		
Basis function Definition		Coefficients
B1	(Intercept)	0.54968111
B2	h(-0.868957-Longitude)	-0.15920417
B3	h(Longitude- -0.868957)	-0.03374527
B4	h(1.70266-Cattle_dens)	0.05230695
B5	h(-0.486249-Goat_dens)	-0.21137962
B6	h(Goat_dens- -0.486249)	0.01689211
B7	h(0.345286-Pop_dens)	0.09424956
B8	h(0.705761-Rural_pop_dens)	0.08347599
B9	h(Rural_pop_dens-0.705761)	-0.01228854
B10	h(-0.606539-Slope)	-0.23435716
B11	h(Slope- -0.606539)	0.02161975
B12	h(0.967291-MAP)	-0.06103887
B13	h(MAP-0.967291)	-0.18561688
B14	h(-0.912427-CWD)	-0.18880159
B15	h(CWD- -0.912427)	-0.06593036
B16	h(Dist_big_city-0.0248796)	0.0273237
B17	h(-0.605744-CET)	0.09812758
B18	h(CET- -0.605744)	-0.09392576
Pasture		
B1	(Intercept)	0.64867454
B2	h(1.05684-Cattle_dens)	-0.1264201
B3	h(MAP- -0.77875)	-0.08774778
B4	h(CWD- -0.496976)	0.11717421
B5	h(CWD-1.03314)	-0.26222683
B6	h(MAT- -1.21729)	-0.21308116
B7	h(MAT-0.112807)	0.21709088

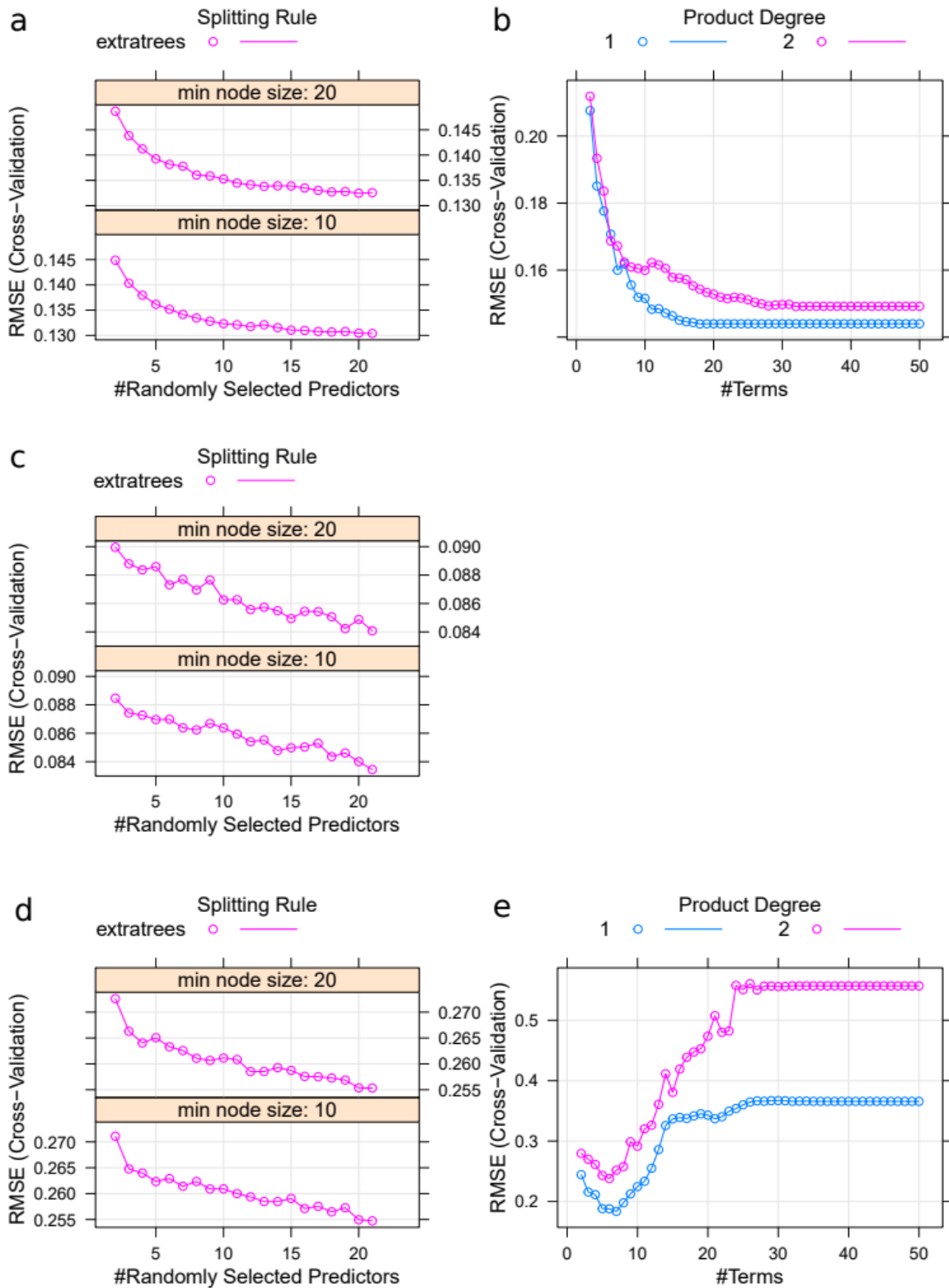
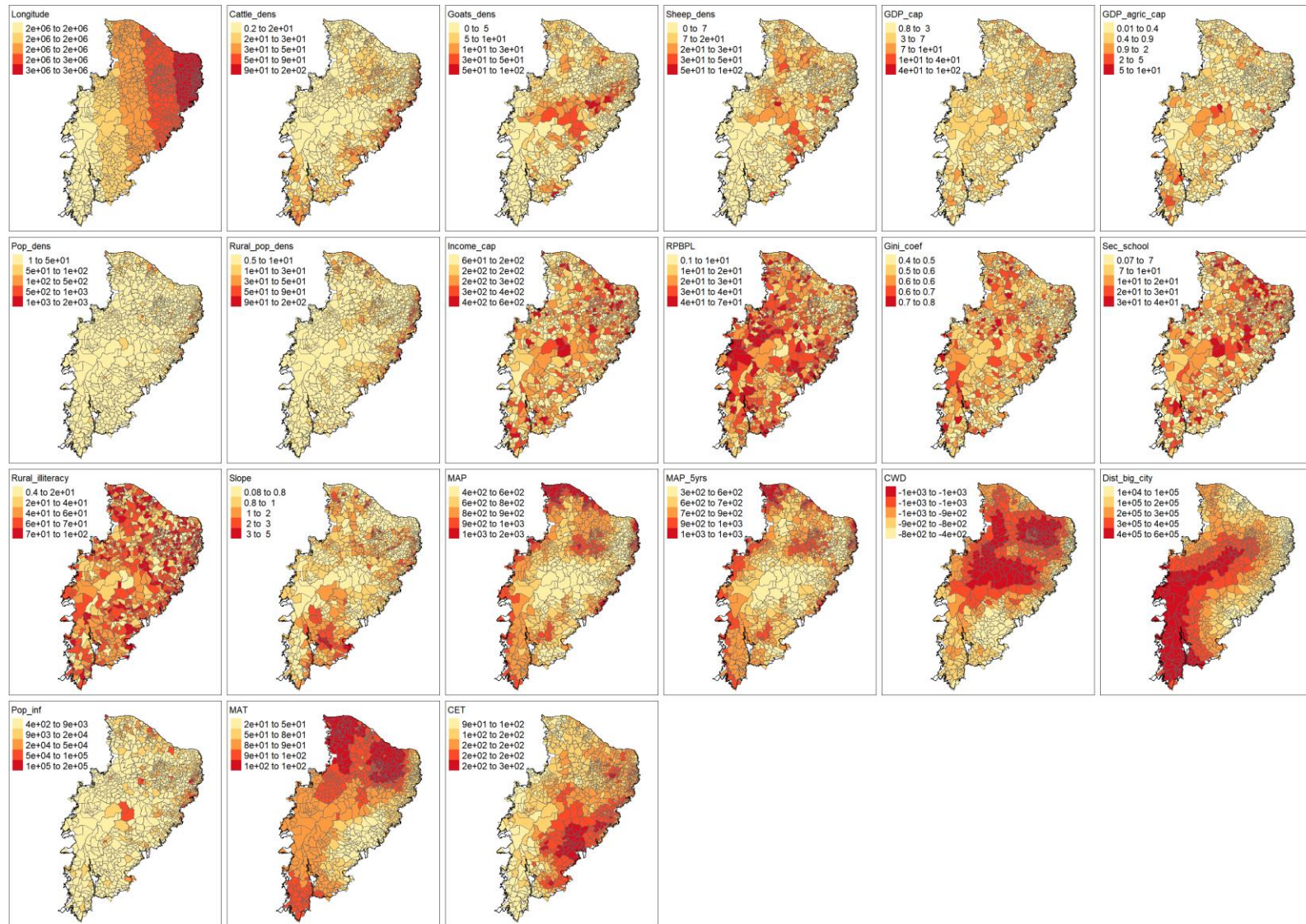


Figure A1. RMSE (Root Mean Square Error) values for the different values of the hyper parameters for each Land Use and Land Cover class analyzed.



4 ARTIGO 2 - VEGETATION TRENDS IN THE CAATINGA DRY FOREST (2001-2019) AND POTENTIAL HUMAN IMPACT ON VEGETATION DYNAMICS

Manuscrito a ser submetido ao periódico *Land Degradation & Development*. Formatação segue a formatação exigida pelo periódico.

Research paper – *Land Degradation & Development*

Vegetation trends in the Caatinga dry forest (2001-2019) and potential human impact on vegetation dynamics

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ABSTRACT

Land degradation in drylands is an ongoing threat to ecosystem functioning, driven by anthropic and climate drivers. Understanding how the vegetation dynamic responds to such drivers is, therefore, an important tool to plan land use sustainably. Here, we analyzed the spatio-temporal productivity dynamic in the Brazilian dry forest (Caatinga). With pixel-wise linear regressions, we assessed trends of precipitation, primary productivity, and their relationship in three different periods from 2001 to 2019 (to consider the drought event). The residuals trend of productivity-

precipitation regression and two proxies of human disturbance were used to identify human contribution to productivity dynamics. We found that in the long term the region received less rainfall and almost a quarter of the Caatinga is degrading (mainly in the northeastern region), with virtually greening areas only in the post-drought period. Rainfall is the main productivity driver and 90% of the region was responsive to annual rainfall (mean $R^2=0.49$), with some areas less responsive. Moreover, 16.6% presented significant residuals trend (i.e., vegetation becoming less or more productive than expected by rain), but only a small percentage of residuals were correlated to human disturbance. In synthesis, the degrading evidence matches with studies in other drylands, including Caatinga. However, patterns are spatially heterogeneous and may emerge depending of time scale. Precipitation stands as the main driver of NDVI, although substantial variation is unexplained. Human disturbance (i.e., agriculture) is also a driver, but in a much smaller extent. Physical conditions, land use and ecosystem functioning constitute a complex framework and claims for more specific studies, especially considering the ongoing climate changes.

Keywords: Desertification; drylands; socio-economic development; vegetation dynamic; NDVI

INTRODUCTION

The accelerated and unstoppable increase of the human population is one of the greatest challenges to natural ecosystem maintenance worldwide (Tilman & Lehman, 2001). It is leading to increasing demand for food and energy and acting as a major factor in land use and land cover (Lambin & Meyfroidt, 2011; Seppälä *et al.*, 2009). Recently, the United Nations (2019) predicted that the world population is expected to grow to around 9.7 billion by 2050 and ca. 10.9 billion people by 2100. In order to meet such demand, it is estimated that at least one-third of the earth's land surface should be used as cropland or pastures (FAO, 2018). However, even though it is the land use that supports the well-being and economic development of the human population, the resulting degradation of these activities ends up affecting various aspects of the ecosystem, such as biodiversity, ecosystem functioning, and service provision (Foley *et al.*, 2005).

Since the availability of fertile land in developed countries is low, developing regions tend to be the most affected by this global quest for croplands and its negative outcomes (Lambin & Meyfroidt, 2011). We talk about an increase in demand for agricultural land of 25% in middle-income and 78% in low-income countries, compared to negative trends in wealthier countries (Duro *et al.*, 2020). As the fertile areas for cropland expansion are mainly located in developing countries where most of the forest remains, these became one of the most threatened ecosystems. Among several other consequences, they have lost habitat, the landscape is fragmented (Gibbs *et al.*, 2010) and the remnants may be depleted, particularly in rural areas that support low-income populations (Antongiovanni *et al.*, 2018; Fisher *et al.*, 2014). Thus, although land use efficiency has increased, to different degrees, in developing countries, rising food requirements can lead to a more unequal and less sustainable system if land use efficiency is not properly addressed (Duro *et al.*, 2020).

The relationship between land use and degradation deserves serious attention, especially in developing regions and drylands (Brockerhoff *et al.*, 2017). In fact, most of the drylands are located in less developing countries and it is in these regions where human populations are highly dependent on natural resources (Gariglio *et al.*, 2010; Wang *et al.*, 2012), such as rainfall for agricultural activities (Stewart, 2016). These regions present a combined effect of anthropic disturbance and unpredictable climate, which may act in synergism and potentialize the impact on ecosystems (Zika & Erb, 2009). For example, the precipitation regime drives the effect of human disturbance on the plant community (Rito *et al.*, 2017) and tropical dryland ecosystems are changing vegetation-precipitation sensitivity mainly due to anthropic activities (Abel *et al.*, 2021). Even though those environments have evolved to withstand variations in precipitation such as drylands, this ongoing degradation process can also be influenced by extreme drought events greatly, which reduce the availability of water in the soil and, therefore, the potential of vegetation to regenerate (Stringer *et al.*, 2009).

This is especially true for the Caatinga ecosystem, located in the Brazilian semiarid. Despite historically suffering from a scarce and irregular rainfall regime, it is the most populated semi-arid regions in the world, on which 27 million people (most of them from poor rural populations) rely for natural resources and agriculture (Gariglio *et al.*, 2010; Silva *et al.*, 2017b). Traditionally, local farmers intensively use natural resources, from ecosystem nutrients (slash and burn agriculture) to native vegetation such as cattle fodder (mainly cattle and goats) (Melo, 2017). More recently, the region experienced a rapid increase in socioeconomic development, with greater results than the rest of the country (IBGE, 2016; Silva *et al.*, 2017a), and yet remains one of the poorest and socially vulnerable Brazilian regions (de Loyola Hummell *et al.*, 2016). Moreover, the climatic models for Caatinga predict an increase of up to 4°C and a reduction of 33% (in magnitude) in precipitation

levels for the next century, with more frequent and prolonged droughts (IPCC, 2014; Marengo *et al.*, 2017). As a result of land use and climatic conditions, at least a quarter of the entire region has turned into desertification areas (Menezes *et al.*, 2012). Although the Caatinga flora presents a clear resilience to environmental stressors (as drought and biological invasion) (de Andrade *et al.*, 2017), the indiscriminate increase of human pressure may lead to a non-return point of the ecological succession. Thus, understanding how the vegetation has been behaving in the last few decades is a key question to predict future strategies of balance in the forest's productivity improvement and increase of socioeconomic quality of the region.

While some studies point to a vegetation cover increase within Caatinga (e.g., Redo *et al.*, 2013), others observed a reversal in the pattern of vegetation cover gain in recent years (Beuchle *et al.*, 2015). Also, it has been reported both an increase in vegetation productivity and an ecosystem with most of the vegetation with negative productivity (Barbosa *et al.*, 2019; Schulz *et al.*, 2017; Tomasella *et al.*, 2018). Even in the absence of desertification, the collapse of biomass associated with the replacement of old forests by agricultural fields and secondary forests (Souza *et al.*, 2019) may affect the provision of ecosystem services related to biomass (e.g., soil protection, nutrient absorption, and water storage and supply) (Foley *et al.*, 2005; Pandit & Thapa, 2003).

In a scenario of dynamic socioeconomic transformation and reported degradation such as the Brazilian semiarid region, monitoring biophysical and socioeconomic is an essential activity to understand degradation and address sustainability (Reynolds *et al.*, 2007). Therefore, we took advantage of the Normalized Difference Vegetation Index (NDVI), a widespread proxy of net primary productivity to better understand the spatiotemporal primary productivity dynamic in the Caatinga ecosystem and how it is related to precipitation and human presence. To address that, we applied a similar methodology used by other studies assessing vegetation trends in drylands (e.g.,

Herrmann *et al.*, 2005). In a nutshell, we first assessed if the vegetation is mainly degrading (becoming less productive) or greening (more productive) in the last few years and analyzed if the spatial pattern matches with the precipitation trend for the same period. Second, we evaluated how much of the vegetation trend may be human-induced. Therefore, based on the presented framework, we expect that (1) regardless of the possible drivers, the Caatinga vegetation is mainly degrading, with a noticeable spatial degradation pattern in the most populous regions; (2) the vegetation is positively affected by precipitation, but it is possible to identify hotspots of human-induced degradation; and (3) these hotspots are correlated with human development measurements.

MATERIALS AND METHODS

GEOGRAPHIC AND ECOLOGICAL SETTING

This study took place in the Caatinga region, the largest seasonally dry tropical forest in the new world, comprising ca. 912 thousand km² (Fig. 1A). The Caatinga is characterized as patchy vegetation, exhibiting at least 13 different physiognomies summarized into 8 main ecoregions (see Fig. 1.3 in Silva *et al.*, 2017b). This domain presents a variate plant diversity, comprises a mosaic of xerophytic, deciduous, semiarid thorny shrubs and seasonally dry tropical forests (Rito *et al.*, 2017). The average annual temperature is 23 °C, with irregular rainfall ranges from 480 to 1,100 mm/yr (de Andrade *et al.*, 2017). In general, it is a low-productivity ecosystem due to a combination of reduced/erratic rainfall, frequent droughts, soil with low-to-medium nutrient availability, and overgrazing by livestock (Prado 2003; Leal *et al.*, 2005). Despite the semi-arid climate, the Caatinga is crossed by several rivers, with a focus on the São Francisco River (Fig. 1), which is responsible for supplying much of the region, both for domestic use and subsistence agriculture, as well as for the agricultural sector. Such water provision by the São Francisco River, associated with irrigation, for example, was crucial to the recent development of one of the largest productive areas of wine and fruit trees of Brazil, but it may also have aggravated degrading scenarios (Silva *et al.*, 2017b).

CAATINGA SOCIOECONOMIC DATASET

The Caatinga ecosystem is a socio-ecological system, presenting human-modified landscapes where low-income populations prevail, with farming relying on slash-and-burn agriculture, extensive livestock breeding, and firewood supply (Silva *et al.*, 2017b). Nowadays, it

is the most human-dense semiarid region of the world (Marengo *et al.*, 2017), transpassing its ecological carrying capacity (Leal *et al.*, 2005). Despite Caatinga's relevance as a repository of biodiversity, less than 1% of its territory has been declared protected by restricted use (Melo *et al.*, 2010). The socioeconomic situation in the semi-arid region has changed only in the last two decades, with the establishment of public policies to address hunger, extreme poverty, and the periodic moments of water scarcity (Silva *et al.*, 2017b). As a consequence, if on the one hand, these actions improved the life of the 'sertanejos' (as the inhabitants of that region are known), the increase in purchasing power and production capacity may have decreased vegetation cover in some regions (Dyngeland *et al.*, 2020).

SPATIOTEMPORAL DYNAMICS OF PRIMARY PRODUCTIVITY IN THE CAATINGA

Because spatially and temporally complete information at high resolution is crucial to understand the Caatinga vegetation dynamic and its possible correlation to precipitation and human activities, we first estimated the Caatinga productivity using the NDVI as a proxy for vegetation greenness, as commonly done (Tong *et al.*, 2017; Zewdie *et al.*, 2017). NDVI is a unitless ratio representing a balance between the reflected and the incoming radiation of the plant's leaf. Thus, it is based on the relation of the near-infrared (NIR), which is reflected in a great proportion, and the red surface reflectance values (Red), following the equation below:

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)}$$

We assessed NDVI data for the whole Caatinga with the MODIS (Moderate Resolution Imaging Spectroradiometer) Terra products (MOD13Q1.006), for 250 m of resolution. The MODIS Vegetation Indexes products have been used by several other researches in drylands, being

calculated from atmospherically corrected bi-directional surface reflectance masked for water, clouds, heavy aerosols, and cloud shadows (Didan *et al.*, 2015; Herrmann *et al.*, 2005; Schulz *et al.*, 2017; Tong *et al.*, 2017). We evaluated data from January 2001 to December 2019 in a monthly format (a total of 239 images) and then calculated the maximum monthly value every time there were two images for the same month. We used the Google Earth Engine platform to download the images (Google, 2020) and we preprocessed the images following the protocol from Eckert *et al.* (2015). Although some studies point to saturation of NDVI index in the regions with high biomass (Huete, 1988), its use on dry forests is recommended, since the dry forest vegetation is, in general, less productive and presents lower biomass (especially when compared to rainforests).

PRECIPITATION DATA SURVEY

We selected the modeled precipitation data from the CHIRPS project (Climate Hazards Group InfraRed Precipitation with Station data), a database that encompasses more than 35 years of precipitation information, with a resolution of 0.05 arc degrees (~ 5.5 km) (Funk *et al.*, 2015; 20). It has been created to supply, among other topics, trend analysis, and seasonal drought monitoring. The CHIRPS is an important appliance to fill a rainfall data gap for more isolated rural regions, being useful to Caatinga, since its region is historically neglected, it has a low number of stations and also a low scale of data collected in the field (Barbosa *et al.*, 2019; Funk *et al.*, 2015; Santos *et al.*, 2011). Due to CHIRPS dataset having a coarser resolution than the NDVI, we reprojected the NDVI raster files to the CHIRPS resolution to run the overlaying spatial analysis.

HUMAN DEVELOPMENT DATA

To assess the potential human role on vegetation dynamic, we selected two data sources that provide yearly data for the timeframe we are analyzing. Therefore, we first chose to use the Version 4 of DMSP-OLS Nighttime Lights Time Series from the Defense Meteorological Program. Its sensors detect visible and near-infrared emission sources during the night (NOAA, 2020) and provide a measurement of human development over time. This kind of approach is being more widely used recently since it is an effective way to map degradation and its intensity in remote zones (Yuan *et al.*, 2019), while also presenting a high correlation, at the provincial level, with a few socioeconomic drivers (e.g., gross regional product, power consumption).

In the second place, we selected the fire occurrence dataset from the Brazilian National Space Research Institute (INPE, 2020). The annual dataset was obtained from 2001 to 2012 and it is part of the *Programa Queimadas* (“Burnt Program”). After downloading the georeferenced fire detection points, we run a Kernel density analysis in QGIS v3.16.4 (QGIS, 2021) to generate a matrix data for the whole Caatinga for each year and in the same spatial resolution of the NDVI and precipitation datasets. Since spontaneous fire is a very uncommon phenomenon in the Caatinga dry forest and that slash and burn activities are still a quite common practice to clear vegetation for agricultural purposes, we are assuming that fire detection is a coherent proxy of human activity and degradation.

COMPLEMENTARY DATABASES

Additionally, we assessed three variables that may help us to better understand the spatial pattern of vegetation dynamic in the Caatinga dry forest. Namely, the variables are 1) Areas vulnerable to desertification (MMA, 2007), which are classified in four graduated levels of vulnerability (moderate, serious, very serious and desertification nuclei); 2) Elevation in meters (Jarvis *et al.*, 2008); and 3) Protected areas boundaries (MMA, 2021).

DATA ANALYSIS

To evaluate the spatiotemporal vegetation dynamic in the Caatinga and how it is related to precipitation and human presence, we first assessed the direction and vegetation change over time from the mean annual NDVI and total annual precipitation. The trends were estimated by fitting pixel-wise simple linear regressions (i.e., one fit for each pixel in our study area). Pixel-wise regression represents an interesting approach to account for the local variability in the NDVI-precipitation relationship due to soil and vegetation heterogeneity (Nicholson and Farrar, 1994). Also, because monthly data are very likely autocorrelated over time, which can lead to a skew of the parameter estimates (Abdulhafedh, 2017), we have aggregated the monthly data for each year.

Since there was an intense drought in the region starting from around 2012 (Barbosa *et al.*, 2019), we decided to split our analysis into three different periods, to avoid the general pattern's misinterpretation due to the drought's effect. For that, the trend analysis was made from 2001-2019 and additionally from 2001-2012 and 2013-2019. We are aware that the drought did not end in 2013, but it was the best way we found to at least provide a perspective of vegetation dynamics after the most abrupt drought year. For the NDVI analysis, we performed an overlay analysis where we selected only the pixels that presented the same results (i.e., negative or positive significant trend) in different analyzed time frames.

Second, to assess the response of the Caatinga vegetation to the precipitation, we performed a simple pixel-wise linear regression using the NDVI as the response variable and precipitation as the explanatory one. Since the precipitation-NDVI relationship varies in space and time due to different land cover responses to rainfall, we divided the precipitation dataset into five components: (1) precipitation of the current month; (2) precipitation of the previous month; (3) precipitation

from two months before the current one; (4) two months accumulated precipitation (current and previous month); and (5) three months accumulated precipitation. Then, we considered the strongest predictor by analyzing the output with the highest average R^2 of every pixel with significant values ($p < 0.05$) and the proportion of the Caatinga area with significant pixels.

Based on the precipitation-NDVI regression analysis, we extracted the residuals values for each analyzed year. The residuals represent the difference between the modeled values and the observed values, thus serving as an estimate of how much NDVI is not explained by the precipitation. Such an approach has been used by other studies addressing vegetation dynamics (Archer, 2004; Herrmann *et al.*, 2005). Then, we ran simple pixel-wise linear regressions with the annual residuals as the dependent variable and time as the independent one. Here, a positive trend means that the vegetation is becoming green more than it would be expected from the precipitation values over time; and negative trends indicate degradation, where the vegetation is browning over time.

To test whether the residuals trends are correlated by the anthropogenic disturbance, we ran pixel-wise Pearson's correlation analysis of the residuals and a proxy of human development (i.e., the annual night lights values and fire detection density, session 2.5). We decided to restrict our analysis to the period of 2001-2012, fitting the time frame before the intense drought period and thus avoiding more uncertainties due to such a strong precipitation variation. Finally, to have a better picture of the spatial pattern of the vegetation, we overlayed the NDVI trends (for the whole period) with the three complementary variables (i.e., vulnerable areas to desertification, elevation, and protected areas). Specifically for the desertification areas, we tested if the NDVI slope means differed between the vulnerability classes by running an ANOVA, aiming to verify if desertification areas are decreasing productivity more than non-desertification areas. We performed all the spatial

analyses in the R environment, with the raster, sf, and tidyverse packages (Wickham, 2019; Hijmans, 2020; Pebesma, 2018), as well as the graphs which were made with the ggpubr package (Kassambara, 2020). The final maps were generated in QGIS v3.16.4 (QGIS, 2021).

RESULTS

PRECIPITATION TRENDS IN THE CAATINGA REGION

From 2001 to 2019 (the total focal period for this analysis), 7.5% (64,480.35 km²) of the Caatinga region exhibited a trend of decreasing precipitation (Fig. 1A), with a slope average of -222.4 ± 64.4 mm). Drying spots concentrated in the mid to mid-east zone, next to the São Francisco River, but two highly negative spots occurred in the mid-northern area and the southern area (Fig. 1A). The only spot with precipitation increase was on the northwestern border.

In the pre-drought period, only 0.03% of the Caatinga experienced precipitation reduction (-180.52 ± 22.07 mm) and no precipitation increment; i.e., precipitation stability. However, from 2013 to 2019 (post-drought period), there was a precipitation increment across 17.7% (152,989.6 km²) of the whole region (486.2 ± 171.0 mm), mainly in the northern region; and just 1.4% (12,100.9 km²) with precipitation reduction (-177.5 ± 59.7 mm) on a specific area in the mid-eastern region (Fig. 1C).

NDVI TRENDS AND NDVI RESPONSE TO PRECIPITATION

Over 19 years (from 2001 to 2019) the Caatinga region has suffered tangible changes in primary productivity, with ca, 25.3% of the whole Caatinga (218,766.4 km²) exhibiting a negative trend on NDVI values (mean slope of -0.12 ± 0.04 of standard deviation). Only 1.3% of the area (11,236.5 km²) experienced greening (i.e., NDVI increments (0.08 ± 0.04)) (Fig. 2A). Altered spots were widely distributed but concentrated less across northern and northeastern Caatinga zones.

However, in the pre-drought period (2001-2012) the productivity drop covered much less area in the region as compared to the whole period (218,766.4 km² vs. 27,659.1 km²). ~~On the other hand, in those areas experiencing productivity increment, the increment was 150% higher in pre-drought than in the entire period.~~ Precisely, the NDVI trend pre-drought indicated that only 3.2% of the Caatinga (27,659.1 km²) was becoming less productive (-0.13 ± 0.04), whilst 1.87% (16,163.3 km²) was becoming more productive (0.12 ± 0.04 , Fig. 2B). Negative spots are concentrated in the northeastern region, while positive ones in the northern region. Moving to the post-drought period (2013-2019), only 0.60% of the Caatinga (5,186.1 km²) presented negative trends (-0.12 ± 0.06), while 13.8% (119,279.93 km²) presented a positive trend (0.13 ± 0.04) (Fig. 2C). Changing spots were clearly concentrated at the north of the São Francisco River.

By regressing NDVI against the 3-months precipitation scores, 90% (777,913.1 km²) of the Caatinga region was significantly responsive during the whole assessed period (mean $R^2 = 0.49$), with less responsive spots in portions in the southeastern, North center, and west zones (Fig. 3A). In the pre-drought period, the rainfall responsive area was slightly smaller (84.9% or 732,967 km², Fig. 3B), but with considerably higher R^2 values (0.59 on average). In the post-drought, however, only 19.7% (170,276.5 km²) of the Caatinga NDVI was explained by the precipitation (mean $R^2 = 0.72$, Fig. 3C).

RESIDUALS TRENDS, HUMAN DISTURBANCE EFFECTS, AND SPATIAL PATTERNS

Over the whole focal period, 16.6% of the Caatinga region (143,481.7 km²) presented a significant change in the residuals derived from the correlation between precipitation and NDVI scores. Precisely, 8.2% exhibited a negative trend and 8.4% a positive trend (Fig. 4A). Significant negative and positive trends were both widespread, but negative trends were more concentrated

in the southeastern, western, and northern areas, whereas positive trends tend to be found in the northeastern and southern areas.

Moreover, the correlation analysis between annual residuals and the human-disturbances proxies revealed spatially distinct spots with positive and negative trends. The fire density correlated to 7.5% (64,998.9 km²) of the whole Caatinga region, where 3.3% presented a negative correlation (mean Pearson coefficient = -0.66 ± 0.072) and 4.2% a positive correlation (0.66 ± 0.06) (Fig. 4B). On the other side, the night light scores were correlated with residuals across only 2.9% of the pixels, where 1.4% was negatively correlated (mean Pearson coefficient = -0.67 ± 0.07) and 1.54% positively correlated (0.66 ± 0.06) (Fig. 4C).

Finally, considering the total assessed period, spots exhibiting either positive or negative trends in productivity (1) extrapolated the spots classified as vulnerable to desertification and those considered as established desertification nuclei (Fig 5A), (2) visually, decreasing NDVI spots preferentially occurred across lowlands, while increasing spots located across highlands (Fig 5B), and (3) even protected areas exhibited NDVI trends that exceeded changes on precipitation (Fig.5C). Relative to the NDVI trends (increment or decrease) and desertification vulnerability, although all of them presented negative NDVI trend mean values, no differences were observed across classes of desertification vulnerability, including the desertification nuclei ($F(3,196) = 1.866$, $p = 0.137$) (Fig. A1). However, classes presented mean historical annual NDVI that varied according to desertification vulnerability, i.e., an increment from desertification nuclei to areas of medium vulnerability ($F(3,596) = 35.64$, $p < 0.001$) (Fig. A2).

DISCUSSION

Regardless of time interval and climatic conditions, our results suggest that some particular portions of the Caatinga region are experiencing changes in both precipitation levels and ecosystem productivity inferred from NDVI. Overall, a higher proportion of the Caatinga region is experiencing precipitation and productivity decline rather than increments (i.e., up to a quarter of the whole region). Ecosystem productivity responds primarily and positively to precipitation, particularly strongly following a severe drought, but a substantial proportion of productivity remains unexplained (ca. 30% on average). In this context, some variables related to human disturbance play a secondary/minor role by explaining a small proportion of productivity variation, with both positive and negative impacts over restricted areas. Preliminarily, it is possible to speculate that productivity-changing spots, particularly those experiencing decreasing trends, are concentrated on low altitude flatlands. Moreover, these spots are not spatially restricted to areas considered vulnerable or represent current desertification spots, although productivity performance and vulnerability categories are consistent. In fact, even protected areas are experiencing productivity trends. Such an alarming perspective, however, depends on the period addressed (i.e., it is time-scale dependent) with contrasting trends emerging from short-period approaches.

Our findings support the notion the Caatinga region is experiencing long-term precipitation changes, as already documented for other drylands, which in turn may increase fire frequency (Huang *et al.*, 2016; IPCC, 2014). Apparently, the Caatinga region is experiencing a long-term trend of precipitation decrease across particular but extensive areas as already predicted and observed (Barbosa *et al.*, 2019; Marengo *et al.*, 2017). Even considering potential drought effects (i.e., the post-drought period), the Caatinga rainfall reduction is spatially limited. In fact, the last

drought and its impacts in the region were spatially and temporally varied (Rebello *et al.*, 2020), with some areas/spots recovering faster than others (e.g., the northern area, despite the limitation of our post-drought analysis) (Mariano *et al.*, 2018). Biomass change restricted to particular areas was also documented, with a predominance of biomass decline regionally considering the drought period (Mariano *et al.*, 2018). Yet, it was recorded that productivity has also declined regionally, mainly in pasturelands areas (Tomasella *et al.*, 2018).

Although long-term precipitation changes appear to occur across particular areas/spots and the precipitation drop achieves a maximum of 7.5%, a significant portion of the Caatinga region is losing productivity. Our regional score (25%) is slightly greater than a recent study evaluating the degradation in the Brazilian northeastern where Caatinga is the dominant biome (17%); although visually most of the areas degrading pre- and post-drought are inside Caatinga (Mariano *et al.*, 2018). The same study also found a significant match between desertification areas and degrading prone areas, while we offer evidence for a strict correlation between vulnerability to desertification and productivity performance (i.e., average annual NDVI). However, our findings suggest that productivity decline, although occurring in particular areas, extrapolated the desertification spots, occurs across protected areas, with a potential association with lowland spots across the region (i.e. Depressão Sertaneja).

Furthermore, the Caatinga productivity appears to be in some extension correlated to precipitation as already evidenced for most terrestrial ecosystems, since water availability practically controls the plant photosynthetic activity (Nicholson, 2000). Yet, in drylands, the annual summed precipitation mainly drives primary productivity, but the number of rainy days in the wet season is also an important metric (Zhang *et al.*, 2018). Following these patterns, in the Caatinga rainfall also impacts productivity and, consequently, aboveground forest biomass (Barbosa *et al.*,

2019; Souza *et al.*, 2019). However, patterns of precipitation/productivity trends and correlations in the Caatinga region are time-dependent/drought-dependent; i.e. contrasting patterns in response to differences relative to the extension and addressed period. This is particularly relevant in the case of the Caatinga greening trend. Precisely, it has been noticed that some Caatinga spots may experience vegetation greening, especially in the center and north of the region, mainly related to precipitation increase even considering the drought period (Barbosa *et al.*, 2019). Our findings suggest that the Caatinga greening is a post-drought, but an ephemeral phenomenon that follows the ecosystem collapse caused by droughts. In fact, drought events have been referred to explain up to 73% of the biomass degradation in the region, including productivity loss (e.g., Mariano *et al.*, 2018; Rebello *et al.*, 2020). Moreover, vegetation response to precipitation is expected to experience a time lag associated with water availability, particularly in the soil (Barbosa *et al.*, 2019; He *et al.*, 2021; Herrmann *et al.*, 2005; Huang *et al.*, 2016). Particularly in semiarid regions, vegetation response may require intense/frequent droughts as species evolved to cope with water deficit (Vicente-Serrano *et al.*, 2013). In this perspective, not only historical precipitation but also drought events emerge as important (but not exclusive) primary productivity drivers (Barbosa *et al.*, 2019; Marengo *et al.*, 2017), but with distinct time-lasting effects on the Caatinga dry forest. Despite such a protagonism, precipitation explained little or did not correlate with productivity across several spots in the Caatinga dry forest and this must be examined.

In this context, proxies of human disturbance also contribute to changes in ecosystem productivity in the Caatinga dry forest, but they play a marginal role as already documented in other dry forests (Seaquist *et al.*, 2009). Although Caatinga desertification (i.e., the collapse of ecosystem productivity) has been considered a human-driven process, particularly due to soil degradation by agriculture/livestock (Vieira *et al.*, 2015), here we failed to document relevant

correlations between human-disturbance related variables and long-lasting trends in ecosystem productivity at the regional scale. However, some patterns emerged such as positive and negative effects from nocturnal light intensity and fire on ecosystem productivity. Light in the Caatinga region can be positively associated with rural population and patterns of land use (Yuan *et al.*, 2019), while fire is particularly due to slash-and-burn agriculture and renovation of pasturelands (Schulz *et al.*, 2017; Tabarelli *et al.*, 2017). The responsive spots (i.e. higher or lower productivity scores as expected by precipitation) are widely concentrated in the Caatinga region, where the negative correlation with fire occur mainly in the southeastern and northern region. By the way, the northern region is known for smallholder agriculture and vulnerability to desertification (Sietz *et al.*, 2006). Thus, it reinforces potential connections between human populations/disturbance and ecosystem productivity as takes into account the historical development of this sector.

The fact that the precipitation in the Caatinga is scarce, unpredictable, and spatially variable has led to the occupation of specific areas by human populations. Spots with greater agricultural aptitude are also the most used and inhabited by humans (Sampaio *et al.*, 2017). Moreover, Caatinga has been historically used as rangeland to supply the food demand by the eastern coastal region devoted to sugar cane plantations (Sampaio *et al.*, 2017), Caatinga still supports large rural populations with populations concentrated across the eastern sector (Silva *et al.*, 2017b). Accordingly, human activities concentrated into the southeastern sector of the Caatinga region has been referred to causal mechanism behind: (1) the lack of productivity gain in the face of different areas of the semiarid with greening (Barbosa *et al.*, 2019); (2) presence of degradation nuclei with severe biomass losses (Mariano *et al.*, 2018); most of the municipalities with the highest density of cattle (IBGE, 2001, 2010); and (3) the largest amounts of pasturelands (Mapbiomas, 2020). In this spatial context, our results point to three important scenarios: (1) a stable pattern of degradation

in the last 20 years (please refer to Fig. 2), (2) spots with low vegetation response to rainfall (Fig. 3), and (3) evidence that other variables (e.g., soil, rainfall variability, and human activities) have made this sector less productive than expected by rainfall (see Fig. 4A).

Collectively, however, our disturbance-related correlations covered less than 8% of the Caatinga region. This reinforces the notion that anthropogenic activities or proxies of human disturbance explain degradation much less than the rainfall in the case correlations are examined at the regional level and by adopting proxies from satellite imagery (Mariano *et al.*, 2018; Seaquist *et al.*, 2009). On the other hand, 16.7% of Caatinga region experiencing productivity changes (not explained by precipitation) represent 144,346.1 km², i.e., the double of Republic of Ireland territory. The paradox of human-driven Caatinga desertification and the low explanation power of human-related variables relative to productivity trends remains to be explained. In the search for the drivers of ecosystem productivity, we shall do not forget soil/topography and other climatic variables. In fact, the availability of water depends not only on the precipitation but also on other climatic factors, such as evapotranspiration and temperature (Sampaio *et al.*, 2009). The natural topography and the soil's ability to retain water also define the types of cover or land use. Sandy soils or crystalline rock soils present different degrees of water and nutrient retention, as well as regions with high declivity, favor the flow of these elements (Sampaio *et al.*, 2017). Soil attributes responsible for ecosystem productivity (water and nutrients) also respond to rural activities such as slash-and-burning agriculture and livestock production, which in many situations are considered soil degrading (Metzger, 2003). Unfortunately, the spatial scale of our analyses does not permit addressing this small-scaled drivers.

In synthesis, the Caatinga dry forest appears to be experiencing a long-lasting trend of changes on both precipitation and ecosystem productivity. Decreasing precipitation and

productivity prevails but increments are also observed across particular areas. Ecosystem productivity responds to precipitation and human disturbance, but across a significant proportion of the Caatinga territory, productivity is higher or lower than expected. Despite such a spatial uncertainty, a significant area of the Caatinga region moves towards degradation by a combination of precipitation decline and increased human disturbances. Degrading trends spatially extrapolate current desertification nuclei, concentrate in the eastern sector of Caatinga region and are also present in protected areas. At regional scale, physical conditions, land use and ecosystem productivity emerge as complex patchwork not easily understood at first glance. Similar to other dry forests, Caatinga has been considered highly vulnerable to climate changes due (1) an expectative of increasing aridity, (2) a socioecological context marked by low green and socioeconomic infrastructure, (3) a high dependence of forest products and ecosystems services, and (4) the predominance of degrading and low-revenue activities. To provide a better understanding the drivers of Caatinga productivity and provide sounding guidelines and better practices toward Caatinga adaptation to global changes, much more research is required including (1) those looking for productivity drivers at finer spatial/socioecological scales (2) those catching those that encompass a longer post-dry period.

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FIGURE LEGENDS

Figure 1. The annual precipitation trends (in mm units) overtime, indicating precipitation increase (positive slope values) and decrease (negative slope values), for the three assessed periods: (a) the total focal period (2001-2019), (b) the pre-drought period (2001-2012), and (c) the post-drought period (2013-2019). The São Francisco River, the main one in the region, as well as its dams, can be seen in light blue. All the maps are showing only the significant pixels.

Figure 2. The annual NDVI (Normalized Difference Vegetation Index) trends overtime, indicating productivity increase (positive slope values) and decrease (negative slope values), for the three assessed periods: (a) the total focal period (2001-2019), (b) the pre-drought period (2001-2012), and (c) the post-drought period (2013-2019). The São Francisco River, the main one in the region, as well as its dams, can be seen in light blue. As it is an index, the NDVI is unitless, and it ranges from -1 to 1. All the maps are showing only the significant pixels.

Figure 3. The predictive power (R^2 values from the pixel-wise linear regression) of 3-months accumulated precipitation on the NDVI (Normalized Difference Vegetation Index) values, for the three assessed periods: (a) the total focal period (2001-2019), (b) the pre-drought period (2001-2012), and (c) the post-drought period (2013-2019). The São Francisco River, the main one in the region, as well as its dams, can be seen in light blue. All the maps are showing only the significant pixels.

Figure 4. a) The annual residuals trend from the pixel-wise linear regression of NDVI (Normalized Difference Vegetation Index) ~ 3-months accumulated precipitation (2001-2012, the period of highest precipitation stability through the region), indicating a vegetation becoming more productive than would be expected by the precipitation (positive slope values) and a vegetation becoming less productive than would be expected by the precipitation (negative slope values); b)

the Pearson's correlation coefficient values of the annual residuals values and the fire density values and c) the night light values. The São Francisco River, the main one in the region, as well as its dams, can be seen in light blue. All the maps are showing only the significant pixels.

Figure 5. The annual NDVI (Normalized Difference Vegetation Index) trends overtime (2001-2019) overlayed with a) the areas vulnerable to desertification, b) the elevation model (m) and c) the protected areas databases.

Figure 1.

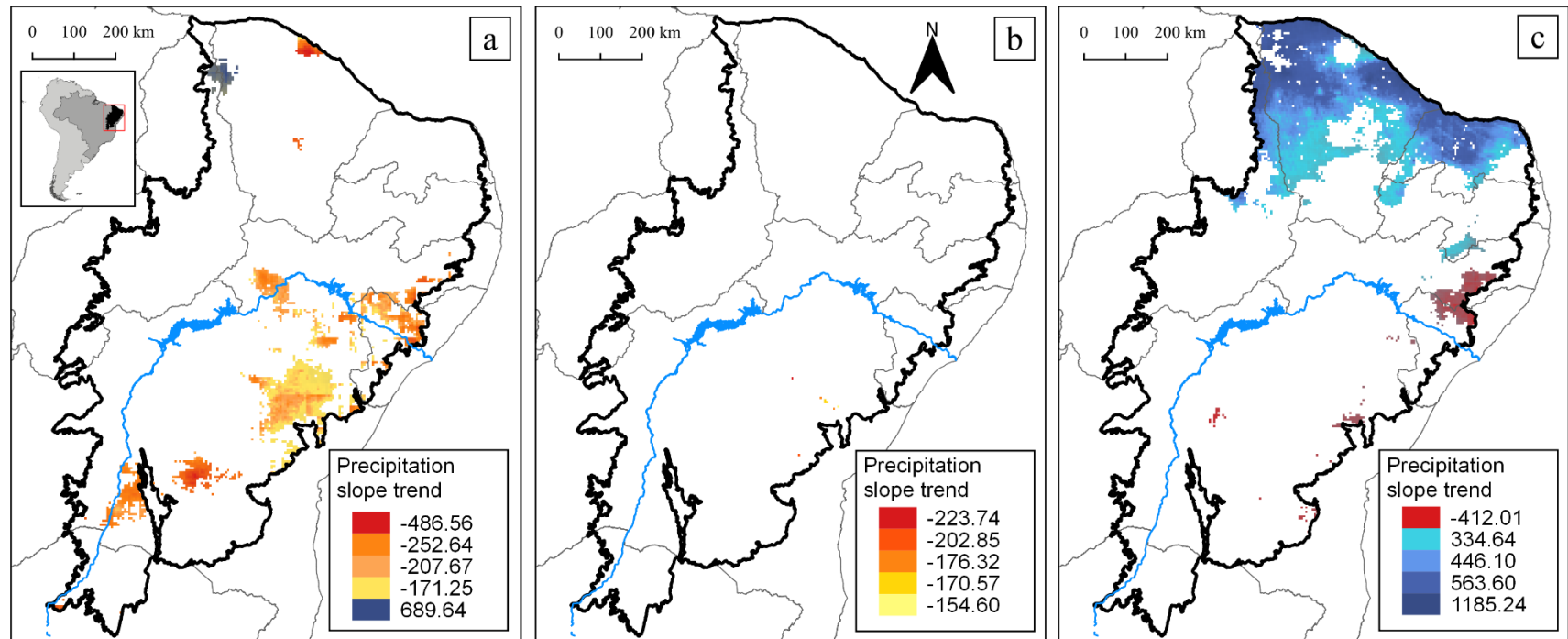


Figure 2.

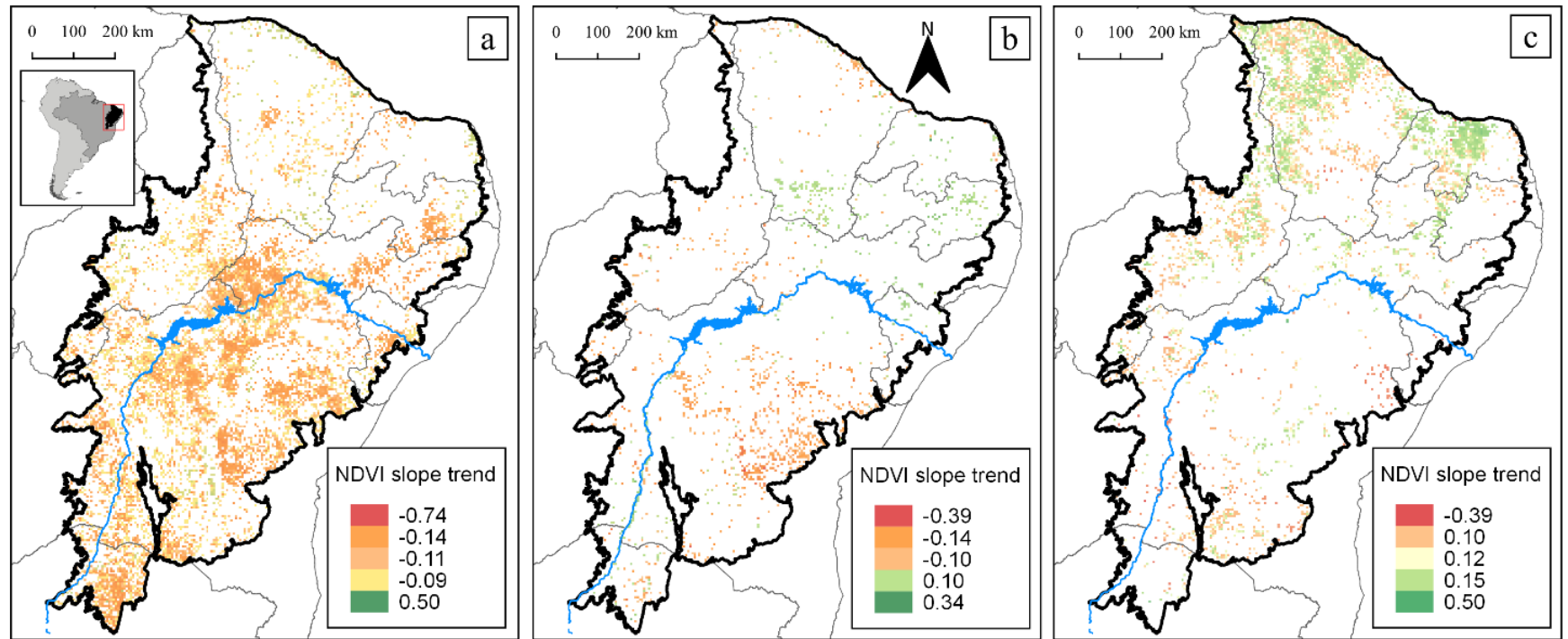


Figure 3.

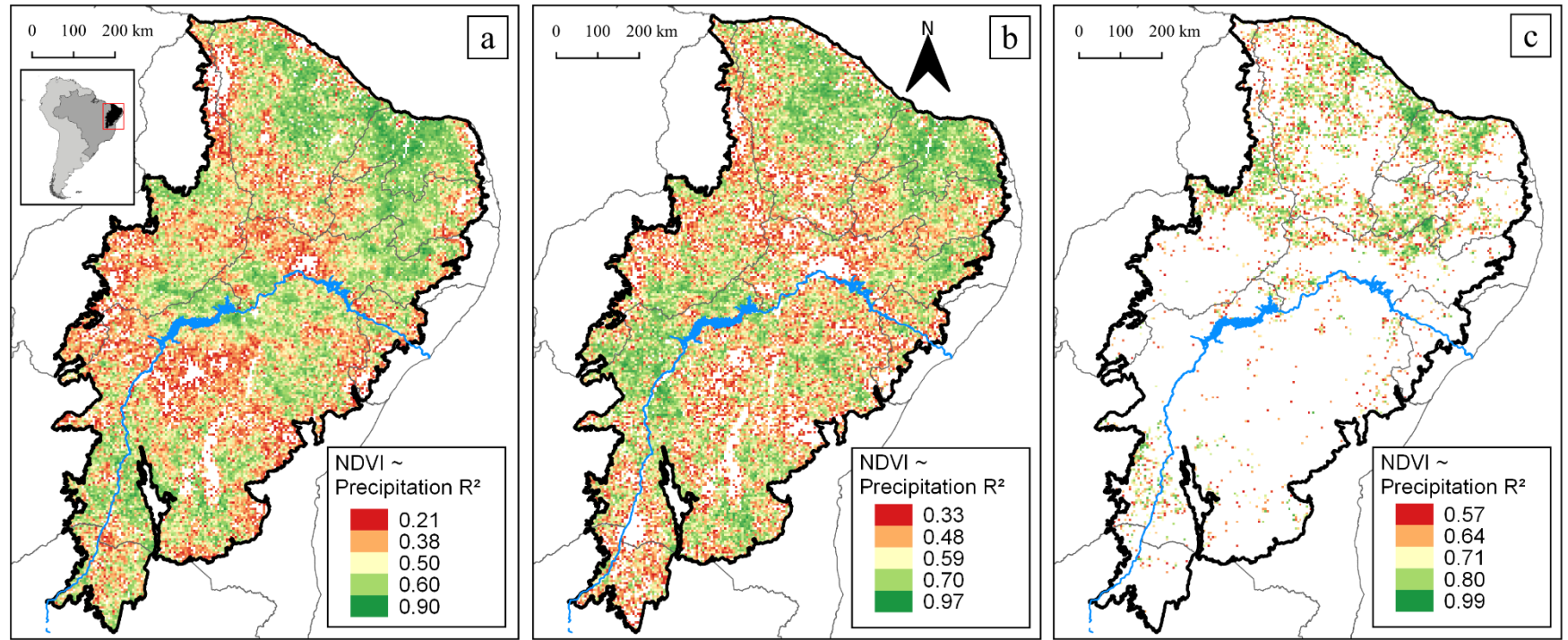


Figure 4.

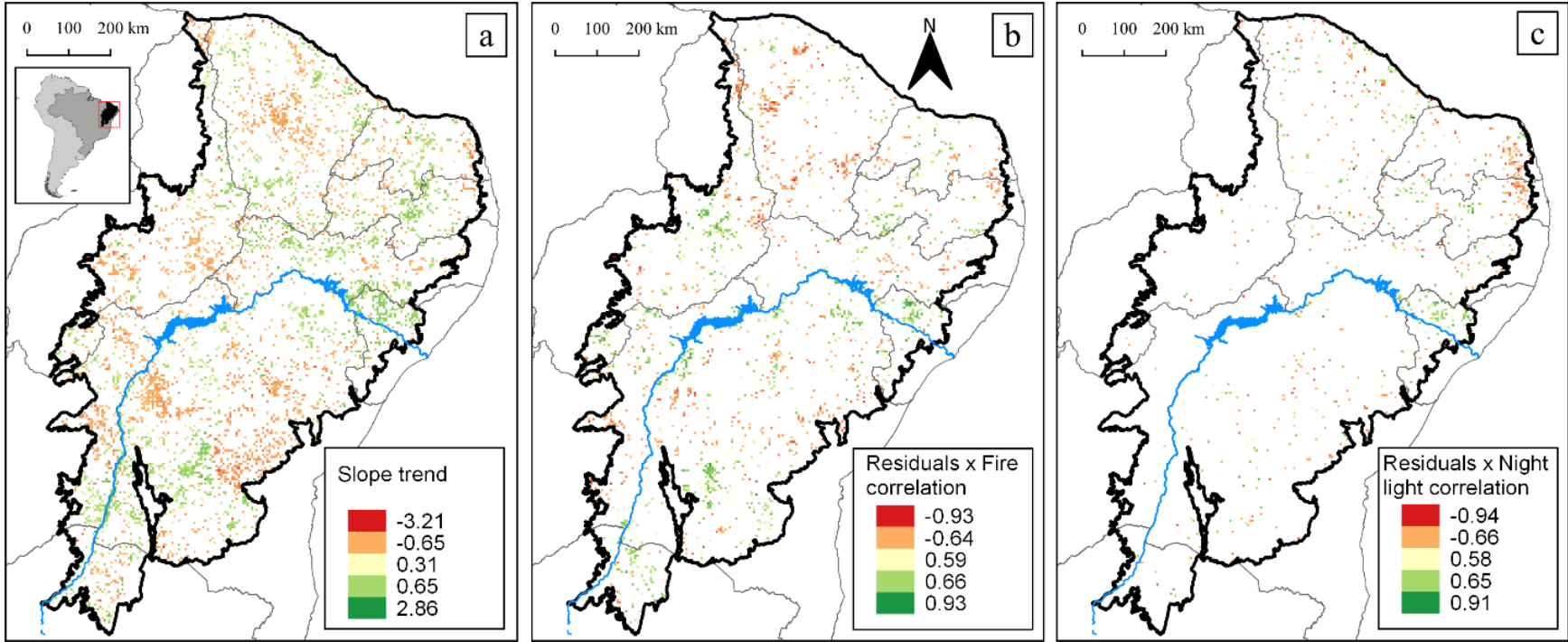
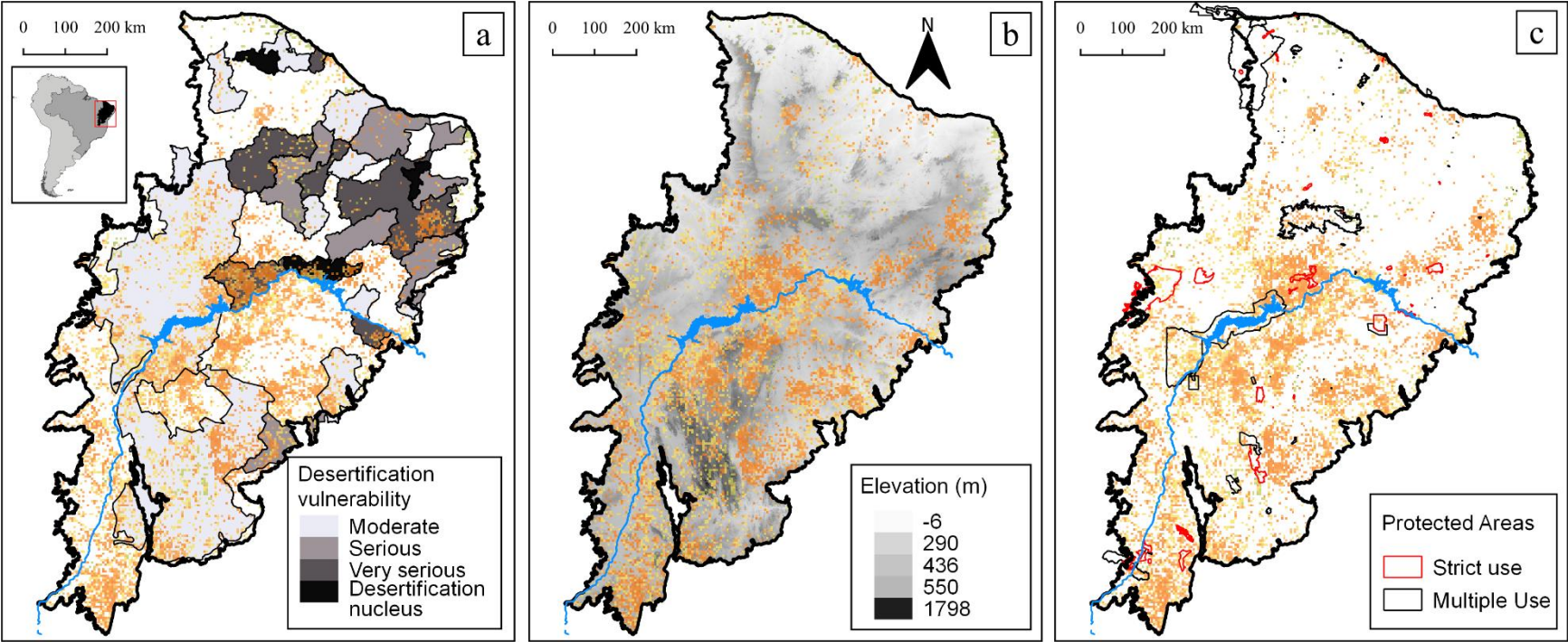


Figure 5.



Supporting Information for:

Vegetation trends in the Caatinga dry forest (2001-2019) and potential human impact on vegetation dynamics

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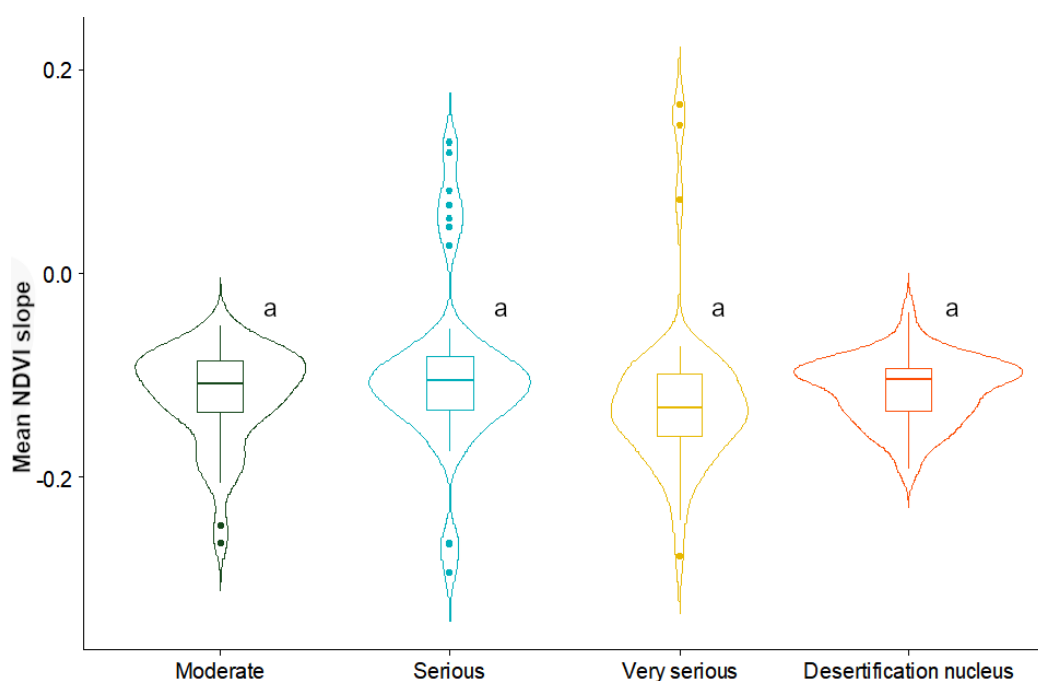


Figure A1. Comparison of the mean NDVI slope trend values (2001-2019) of several areas, classified according to the degree of vulnerability to desertification in the interior of the Caatinga. Statistics were obtained by running an ANOVA ($F(3,196) = 1.866$, $p = 0.137$)

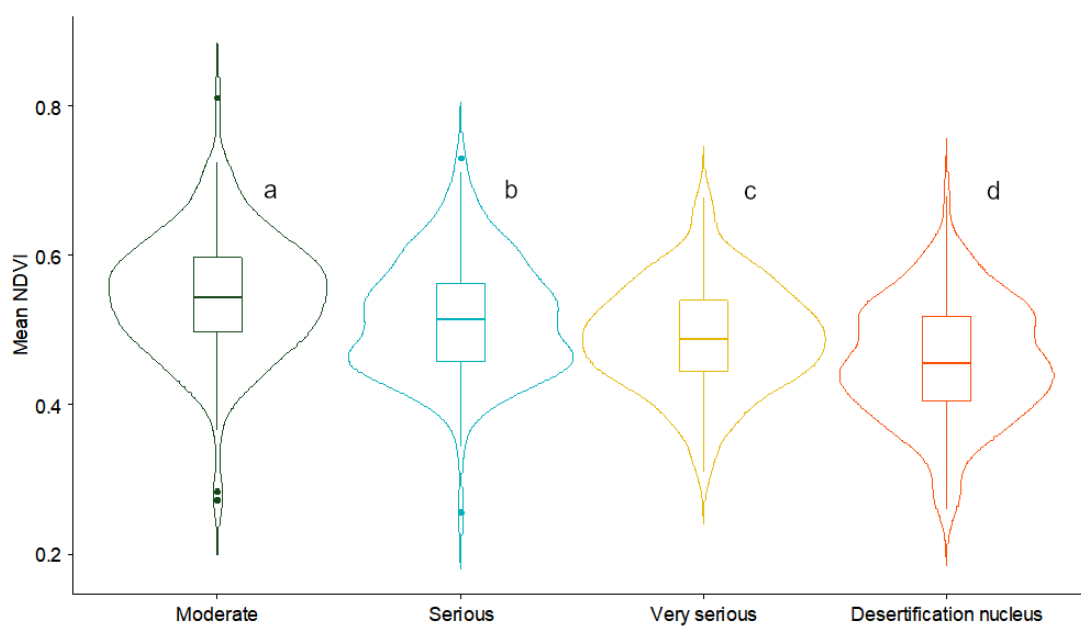


Figure A2. Comparison of the mean annual NDVI (2001-2019) of several areas, classified according to the degree of vulnerability to desertification in the interior of the Caatinga. Statistics were obtained by running an ANOVA ($F(3,596) = 35.64$, $p < 0.001$) and a pair-wise post-hoc test to identify differences between each pair.

5 CONSIDERAÇÕES FINAIS

Nosso trabalho indica que o uso e cobertura da terra em florestas secas como a Caatinga ainda está fortemente condicionado às variáveis ambientais, que definem aptidão agrícola e, por consequência, produtividade agrícola. Como esperado para ambientes semiáridos, as variáveis climáticas (em especial precipitação e temperatura) se destacam como drivers da dinâmica da vegetação (i.e., uso e cobertura do solo e produtividade). Ao mesmo tempo, a disponibilidade hídrica (reflexo do acúmulo de chuva em meses anteriores) é responsável por ditar a dinâmica de produtividade ecossistêmica na escala regional, apesar desse padrão não se aplicar à todas as regiões (e.g., sudeste da Caatinga). Secas severas também impactam na resposta da vegetação à chuva, mesmo em ecossistemas adaptados à sazonalidade.

Adicionalmente, variáveis socioeconômicas, apesar de contribuírem para essa dinâmica do ecossistema, apresentaram contribuições inferiores quando comparadas às variáveis ambientais. Entre elas, a pecuária tradicional (no caso, gado) se destaca como provável driver de degradação ecossistêmica (capítulo 2) e driver da presença de Caatinga savânica e pasto (capítulo 1). E, entre os usos da terra, o de menor produtividade é justamente o para pastagem, que também representa a segunda maior cobertura do solo desse ecossistema. Portanto, com base nesses achados, é razoável concluirmos que a dinâmica da vegetação sistemas socioecológicos como a Caatinga é condicionado principalmente por condições climáticas, mas com um efeito mediado pelas atividades antrópicas.

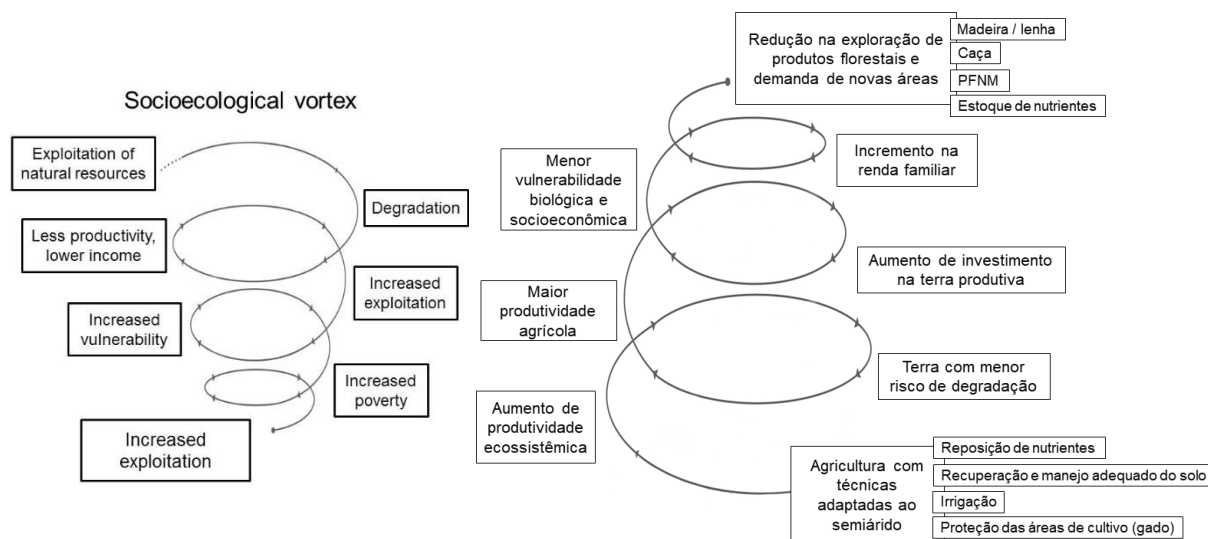
Na Caatinga, onde o uso da terra geralmente é misto, com agricultura e pecuária, nossos resultados demonstram que esse uso extensivo preponderante na região, em termos de produtividade por área, é regionalmente desvantajoso. Como demonstrado no nível global, a produtividade em ambientes agrícolas de fato é bem mais baixa em ambientes tropicais e subtropicais do que seria esperado pelo seu potencial. Diante desse contexto, a Caatinga parece ter duas trajetórias possíveis bem estabelecidas: o primeiro seria de continuar nesse cenário de uso da terra associado às melhores condições ambientais. A segunda trajetória seria de intensificação de uso do solo, ampliando o uso de tecnologias adequadas. Obviamente, ambos os cenários podem ser deletérios para a esse complexo sistema socioecológico, que acumula séculos de aumento de desigualdade e pouco investimento. No entanto, no contexto da Caatinga, onde as propriedades rurais são muito pequenas (ca. 2/3 possuem menos de 5 ha e menos de 5% possuem mais de 100 ha), a intensificação do uso pode trazer benefícios às populações rurais. Se o processo de intensificação for adequadamente implantado, com uso de

diversas tecnologias agrícolas já disponíveis e em uso no semiárido brasileiro e em outras regiões secas (porém ainda em pequena escala), como reposição de nutrientes, recuperação e manejo do solo e irrigação, a modernização e intensificação do uso do solo em terras secas pode trazer ganho de produtividade. Adicionalmente, aumentar produtividade por área pode gerar uma menor pressão sobre os remanescentes de Caatinga que já são cronicamente perturbados. Portanto, é razoável concluirmos que o potencial produtivo da Caatinga ainda permanece pouco explorado, embora boa parte do ecossistema já tenha sido degradado.

O modelo hipotético mostrado na Figura 1 representa o cenário atual da maioria das paisagens antropizadas na Caatinga, onde a contínua retirada de biomassa do ecossistema por atividade humanas tem levado o ecossistema a estados alternativos, inclusive a um ponto de não retorno (i.e., desertificação). A existência de diversas áreas abandonadas e degradadas representam exemplos desse sistema em geral improdutivo, degradante e com pouca geração de renda. De forma a evitar que esse cenário permaneça capturando famílias de baixa renda em um ciclo de pobreza, modelos socioecológicos alternativos devem ser propostos para falarmos de sustentabilidade concreta. Dentro do exposto, é razoável então que um cenário de uso dessas tecnologias agrícolas adaptadas ao semiárido gerem um efeito em cascata inverso ao proposto pelo vórtex socioecológico. Ecossistemas mais produtivos podem diminuir o risco de uma terra degradar, permitindo maior produtividade agrícola, renda e investimento. Esse quadro pode gerar um sistema de pessoas menos vulneráveis biológica e socioeconomicamente, onde apresentam uma redução da exploração sucessiva. Logicamente, tudo isso passa por uma mudança de empenho dos tomadores de decisão que há décadas tem negligenciado a situação socioecológica da região.

Adicionalmente, nosso padrão espaço-temporal encontrado sugere que os esforços de conservação e manejo do uso do solo devem ser focados em algumas regiões-chave que apresentaram dinâmica da vegetação que apontam degradação. Uma vez que esses padrões parecem ser um reflexo de uma relação entre vegetação e chuva moduladas pelo uso da terra, o cenário estimado de mudanças climáticas e aumento do uso da terra nos leva a acreditar que as tendências de degradação aumentem caso medidas adequadas de manejo de uso do solo não sejam implementadas.

Figura 1 - À esquerda, o vórtex socioecológico sintetizando um modelo hipotético da resposta do ecossistema frente a perturbação crônica a longo prazo (TABARELLI et al., 2017). À direita, uma proposta de vórtex socioecológico reverso, apresentando o uso de agricultura com uso de tecnologias adaptadas ao semiárido como um caminho à redução de degradação e ciclo de pobreza em ecossistemas semiáridos.



Fonte: O autor (2021)

Por fim, é possível que aspectos culturais, ou outras variáveis socioeconômicas não acessadas poderiam explicar o porquê de a Caatinga ainda não ter dado esse passo no caminho da intensificação, a semelhança de outros ecossistemas brasileiros. A Caatinga possui um histórico de 500 anos de uma postura extrativista dos recursos naturais (basicamente agricultura de corte e queima e pecuária extensiva), onde poucas mudanças significativas no modo de uso da terra aconteceram. Esse padrão de uso extensivo da terra é recorrente em outras terras secas ao redor do globo, com exemplos bem claros na África, com contextos socioecológicos de uso extensivo da terra e pobreza crônicas bastantes semelhantes à Caatinga. Esse processo precisa ser melhor entendido, em escala regional e local, para que iniciativas de conservação e manejo do uso do solo sejam adequadas ao contexto socioecológico de terras secas frente ao cenário de mudança do uso do solo e mudanças climáticas.

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