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PAULO AMADOR TAVARES

ANÁLISE DA DINÂMICA DA TRANSIÇÃO DO REGIME DE FOGO NA AMAZÔNIA BRASILEIRA

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Tese apresentada ao Programa de Pós-Graduação em Ciências Ambientais do Instituto de Geociências da Universidade do Estado do Pará em parceria com a Empresa Brasileira de Pesquisa Agropecuária/Amazônia Oriental e Museu Paraense Emílio Goeldi, como requisito para obtenção do título de Doutor em Ciências Ambientais.

Área de Concentração: Clima e Dinâmica Socioambiental na Amazônia.
Linha de Pesquisa: Ecossistemas Amazônicos e Dinâmicas Socioambientais.

Orientador: Dr. Bernard Josiah Barlow - Lancaster University

Coorientadora: Dra. Joice Nunes Ferreira - EMBRAPA

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Banca Examinadora:

Prof. Bernard Josiah Barlow – Orientador
Doutor em Ecology
Lancaster University

Profra. Ima Célia Guimarães Vieira
Doutora em Ecologia
Museu Paraense Emílio Goeldi

Prof. Everaldo Barreiros de Souza
Doutor em Meteorologia
Universidade Federal do Pará

Prof. Divino Vicente Silvério
Doutor em Ecologia
Universidade Federal Rural da Amazônia

Prof. Celso Henrique Leite Silva Junior
Doutor em Sensoriamento Remoto
Instituto de Pesquisa Ambiental da Amazônia

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RESUMO

O bioma Amazônico tem passado por mudanças significativas de formas de uso e ocupação do solo, sendo impactado também pelas mudanças climáticas globais. Em consequência, a ocorrência de queimadas e incêndios florestais tem se tornado mais recorrente na Amazônia. Assim, é importante conhecer como ocorre o regime do fogo nessa região e suas interações com o uso do solo e o clima. Por essas razões, este estudo analisa a transição do fogo na Amazônia brasileira. No Capítulo 1, foi investigado como ocorre a transição do fogo ao longo do tempo na Amazônia brasileira, considerando as mudanças no uso da terra e cobertura florestal. Foram coletados dados anuais de ocorrência de fogo, cobertura florestal, taxas de desmatamento e áreas de cultivo de soja. Utilizando modelos lineares mistos generalizados e modelos lineares, foram realizadas análises estatísticas para identificar os principais fatores que influenciam essa transição. Foi constatado que há um processo de transição do fogo na floresta, sendo que um modelo quadrático melhor predisse o comportamento da ocorrência de incêndios. Além disso, observou-se que o pico de ocorrência de incêndios está se deslocando para paisagens mais florestadas ao longo do tempo. As taxas de desmatamento e a expansão das áreas de cultivo mostraram-se relacionadas com essa transição, sendo que o desmatamento teve maior impacto na ocorrência de queimadas e a expansão das áreas de cultivo foi mais relevante para prever a transição para áreas mais florestadas. No Capítulo 2, foram investigadas as diferentes trajetórias de fogo nas paisagens florestais da Amazônia brasileira. Utilizando Análise de Trajetórias Latentes (LTA) e modelos lineares mistos generalizados, foram identificadas trajetórias latentes que representam diferentes padrões de ocupação do solo ao longo do tempo. Duas trajetórias latentes principais foram destacadas: a trajetória "Consolidada", caracterizada por um histórico mais antigo de desmatamento, e a trajetória "Transição", que apresentou um padrão mais recente de ocupação do solo. A cobertura florestal e o desmatamento foram as principais variáveis preditoras das queimadas florestais nas duas trajetórias, seguidas pelo déficit hídrico. A expansão da soja não mostrou ser significativa para nenhuma das trajetórias. Foi observado um aumento nas áreas de floresta queimada a partir de 2015 em ambas as trajetórias. Em conjunto, os resultados destacam a relação da transição do fogo na Floresta Amazônica brasileira com as mudanças no uso da terra e cobertura florestal. Essas descobertas ressaltam a necessidade do desenvolvimento políticas públicas que aumentem a cobertura florestal, por meio de iniciativas como a restauração florestal, e reduzam o desmatamento na região amazônica para garantir a conservação da biodiversidade e dos estoques de carbono.

Palavras-chave: transição do fogo; transição de uso do solo; desmatamento; agricultura mecanizada; secas severas.

ABSTRACT

The Amazon biome has undergone significant changes in land use and land cover, and it is also being affected by global climate change. Consequently, the fire occurrence has become more frequent in the Amazon. Therefore, it is important to understand how the fire regime in this region occurs and its interactions with land use and climate. For these reasons, this study analyses the fire transition in the Brazilian Amazon. In Chapter 1, we investigated the temporal fire transition in the Brazilian Amazon, considering changes in land use and forest cover. We collected annual data on fire occurrence, forest cover, deforestation rates, and soybean cultivation areas. Generalized linear mixed models and linear models were used to analyse the data and identify the key factors influencing this transition. We found that there is a fire transition process in the forest, and a quadratic model provided a better prediction of fire occurrence behaviour. Furthermore, the peak of fire occurrence is shifting towards more forested landscapes over time. Deforestation rates and the expansion of cultivation areas were found to be related to this transition, with deforestation having a greater impact on fire occurrence and cultivation expansion being more relevant in predicting the transition to more forested areas. In Chapter 2, we investigated the fire transition in forest landscapes of the Brazilian Amazon, aiming to understand how this transition occurs and which variables best explain the process. We used Latent Trajectory Analysis (LTA) and generalized linear mixed models to identify latent trajectories representing different patterns of land use over time. Two main latent trajectories were identified: the "Consolidated" trajectory, characterized by a longer history of deforestation, and the "Transition" trajectory, characterized by a more recent land occupation pattern. Forest cover and deforestation were the main predictors of forest fires in both trajectories, followed by water deficit. Mechanized agriculture did not show significant influence on either trajectory. An increase in burned forest areas was observed from 2015 onwards in both trajectories. Overall, these findings highlight the importance of the fire transition in the Brazilian Amazon and its relationship with land use changes and forest cover. They underscore the need to develop public policies that strengthen forest cover through initiatives like forest restoration and reduce deforestation in the Amazon region to ensure biodiversity conservation and carbon stocks.

Key words: fire transition; land use and land cover transition; deforestation; mechanised agriculture; severe droughts.

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1 INTRODUÇÃO GERAL

Paisagens intensamente ocupadas têm suas características naturais alteradas devido à exploração antrópica do território, resultando na redução da cobertura florestal, e sua fragmentação, e na diminuição da provisão de serviços ecossistêmicos (Foley *et al.*, 2005). Em um estudo global realizado por Andela *et al.* (2017), foi identificada uma forte relação entre os estágios iniciais de ocupação do território e o aumento na ocorrência de queimadas, enquanto paisagens mais ocupadas tendem a ter uma menor incidência de fogo. Essa dinâmica caracteriza uma transição no regime de fogo que parte de paisagens com dinâmica natural de fogo (floresta primária), passando pelo uso antrópico do solo com aumento da incidência de fogo nas paisagens (desmatamento, pastagem e agricultura) e, por fim, as produções agrícolas mecanizadas, que não utilizam fogo no seu processo produtivo.

Essa relação pode ser observada na Floresta Amazônica, como é apresentado no estudo de Aragão e Shimabukuro (2010), o qual mostra que as queimadas nas paisagens Amazônicas ocorrem principalmente nas áreas recentemente desmatadas desse território, tendo forte relação entre o uso do solo e o fogo. Ademais, no bioma Amazônico existem uma tendência de diminuição do uso do fogo em paisagens com maiores áreas de agricultura mecanizada (Morton *et al.*, 2008), reforçando o que é globalmente proposto por Andela *et al.* (2017).

Na Amazônia, a ocorrência de queimadas e incêndios florestais é principalmente resultado da interação entre a dinâmica de ocupação humana das paisagens e as mudanças climáticas (Bowman *et al.*, 2020; Nepstad *et al.*, 2008). A ocupação desse território intensificou-se a partir da década de 1970, quando os projetos brasileiros de desenvolvimento se voltaram para a floresta Amazônica com o objetivo de ocupar a região. A partir desse período, o desmatamento aumentou progressivamente (Garrett *et al.*, 2021; Pivello, 2011), o que também elevou a ocorrência de fogo nessa área (Barlow *et al.*, 2018; Kelly *et al.*, 2020). Assim, ressalta-se que o fogo no bioma Amazônico está intrinsecamente ligado à ocupação do território, ocorrendo principalmente durante a remoção da cobertura florestal (desmatamento), a limpeza das áreas agrícolas e de pastagem e quando há escape para áreas florestais (Barlow *et al.*, 2020).

Fatores externos, como as mudanças climáticas globais, também influenciam a ocorrência de fogo na Floresta Amazônia brasileira, principalmente com o aumento da frequência e intensidade dos períodos de seca (Brando *et al.*, 2020a; Staal *et al.*, 2020).

Durante os períodos de seca, nas paisagens de ocupação consolidada, os remanescentes florestais, que estão em sua grande maioria degradados, tem maior possibilidade de entrar em combustão, causando incêndios florestais (Matricardi *et al.*, 2020). Desta forma, com o aumento da recorrência e intensidade dos períodos de seca (Anderson *et al.*, 2018; Wigneron *et al.*, 2020), os fragmentos florestais entram em um ciclo no qual as florestas queimam pela redução frequente na precipitação e pelas pressões antrópicas no território (Staal *et al.*, 2020). Assim, as paisagens da floresta Amazônica acabam perdendo suas características originais, impactando na emissão de gases de efeito estufa devido ao fogo (Aragão *et al.*, 2018) e na perda de biodiversidade local (Barlow *et al.*, 2018; Gomes *et al.*, 2019). Essas ameaças podem fazer com que a floresta chegue a um ponto de não retorno ("*tipping-point*"), alterando seu estado original e tornando o fogo parte da dinâmica da paisagem (Nobre *et al.*, 2016).

Essa nova dinâmica tem consequências que impactam as formas de uso do território pelas populações, desde impactos nos meios de produção agrícola local até nas formas de vida das populações (Toledo *et al.*, 2017). As comunidades tradicionais e as populações indígenas, por exemplo, mesmo quando têm seu território regulamentado e protegido por lei, podem sofrer consequências indiretas devido ao escape do fogo para dentro de suas florestas ou diretas com conflitos pelo uso da terra (Villén-Pérez *et al.*, 2020). Além disso, os pequenos e médios produtores rurais, com baixo acesso à assistência técnica e equipamentos produtivos, utilizam técnicas como o corte e queima para limpeza do terreno e desenvolvimento de suas produções agrícolas, causando o uso de fogo e desmatamento no território (Morello *et al.*, 2017b; Garrett *et al.*, 2017).

Pelas razões expostas, acredita-se que a dinâmica de transição do regime fogo na floresta Amazônica brasileira está intrinsicamente conectada com as mudanças de uso do solo, podendo ser influenciadas também pelo regime de secas na Região. Por isso, as próximas subseções abordarão o regime de fogo nas paisagens da Floresta Amazônica, identificando e destacando as principais variáveis-chave que podem explicar esse fenômeno, como a relação do fogo com o desmatamento, as mudanças climáticas e com os métodos produtivos utilizados na paisagem.

1.1 Referencial Teórico

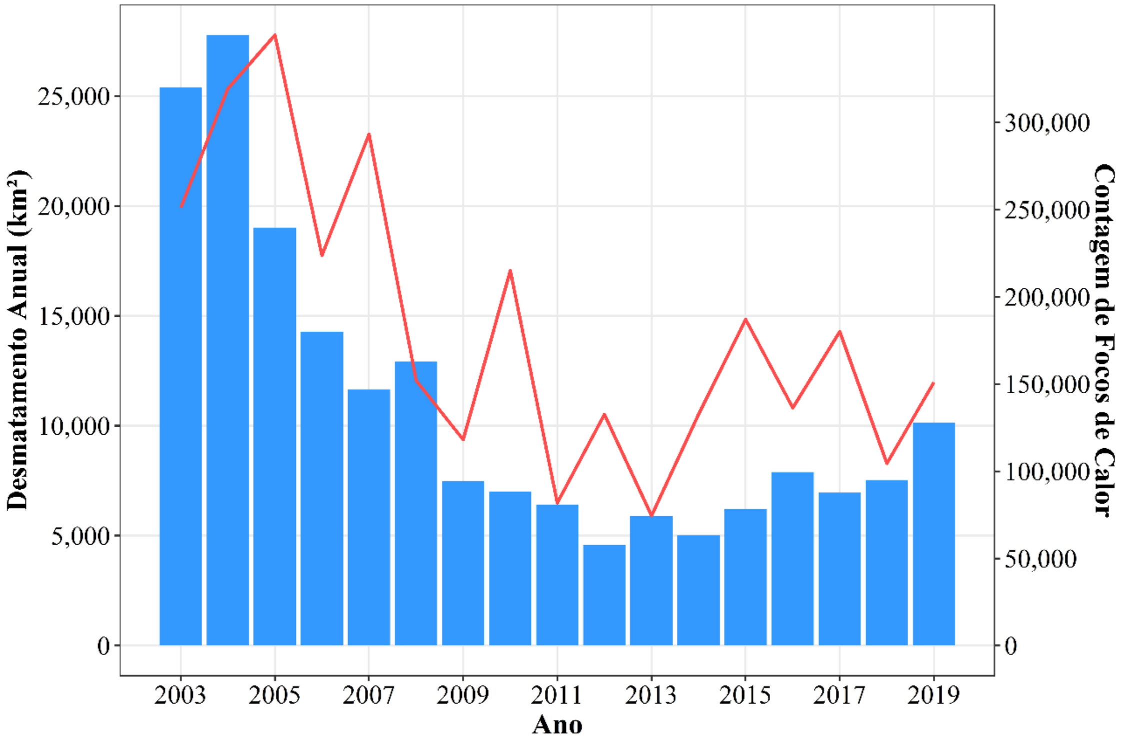
1.1.1 Os diferentes tipos de ocorrência de fogo na Amazônia Brasileira

Modelos de intervalos de retorno de fogo, indicam que para a Floresta Amazônica natural o intervalo de retorno de ocorrência de fogo varia de 400 a 900 anos (Thonicke *et al.*, 2001). Durante o período de ocupação pré-colombiana, as populações locais manejavam a paisagem de maneira sustentável, utilizando o fogo de forma estratégica para limpeza de terreno e produção de adubo para suas plantações (Pivello, 2011). Assim, o uso do fogo era feito de maneira racional e cuidadosa, mantendo a integridade da paisagem, como ainda é possível observar nas áreas de Terras Indígenas brasileiras, que são algumas das áreas mais preservadas do bioma Amazônico (Paiva *et al.*, 2020; Villén-Pérez *et al.*, 2020). Esse cenário mudou após a chegada das populações europeias na América do Sul.

No início da colonização europeia, durante um período que durou cerca de 250 anos, os registros de utilização de fogo apontam para uma redução no uso desse recurso, mesmo para fins de subsistência das populações locais, devido ao fato de que o território ainda estava sendo explorado pelos estrangeiros. Após esse período de grande transição, ocorreu uma modificação dos costumes locais e voltaram a surgir registros de uso do fogo para o manejo do solo na Amazônia (Pivello, 2011). Mais adiante, durante a década de 1970, ocorreu um processo de ocupação do território, fortalecido principalmente a partir das políticas de integração da Amazônia. Durante esse período, houve uma grande migração de pessoas para os estados do norte do Brasil em busca de melhores condições de vida (Garrett *et al.*, 2021; Pivello, 2011).

Esse processo de migração para o território Amazônico não foi acompanhado de subsídios financeiros, assistência técnica ou iniciativas preocupadas com o desenvolvimento sustentável da região. Por isso, a partir desse período, as taxas de desmatamento e de ocorrência de queimadas passaram a aumentar, tendo seu ápice no início dos anos 2000 (Figura 1). Entretanto, esse cenário teve tendência de redução entre os anos de 2003 e 2013, o que foi fortemente influenciado por políticas públicas visando a redução do desmatamento na região (Aragão *et al.*, 2018). As taxas de desmatamento voltaram a ter tendência de aumento a partir de 2013 (Fearnside, 2015) e retornaram à patamares muito elevados a partir de 2019 (Silva Junior *et al.*, 2021).

Figura 1 - Taxa de desmatamento e contagem de focos ativos de calor por ano na floresta Amazônica brasileira, representadas pelas barras azuis e linha vermelha, respectivamente



Fonte: Taxa anual de desmatamento (INPE, 2022) e focos ativos de calor (FIRMS, 2022).

A maior parte do desmatamento para a produção de pastagem na Floresta Amazônica brasileira é feita por meio de práticas que utilizam o fogo como ferramenta principal de limpeza do solo (Barlow *et al.*, 2020; Staal *et al.*, 2020). Já nos estágios mais avançados da transição de uso do solo, como na agricultura mecanizada, não há uso direto do fogo como método produtivo, mas sim o uso de maquinários de alta tecnologia (Sauer, 2018). Entretanto, os incentivos financeiros para que grandes produtores aumentem a produção mecanizada na Amazônia podem pressionar a criação de novas fronteiras agrícolas, resultando em novos desmatamentos (Toledo *et al.*, 2017; Morton *et al.*, 2008; Sauer, 2018). Assim, ainda que o fogo não faça parte desse processo produtivo, ele se faz necessário para a limpeza das áreas de floresta e a consolidação das áreas de monocultura. Dessa forma, é possível que a transição de ocorrência de fogo na Floresta Amazônica brasileira tenha relação com a transição de uso do solo. No entanto, ainda não se sabe em que escala essa relação ocorre e nem em que medida a ocorrência de períodos de seca pode contribuir para a transição do fogo.

Os autores Barlow *et al.* (2020) caracterizam três principais tipos de ocorrência de fogo na Amazônia. Primeiramente, as queimadas para desmatamento são as mais comuns nesse território, essas acontecem durante a primeira fase de ocupação do território, quando o fogo é utilizado como ferramenta primária para remoção da vegetação. Em seguida, fogo é comumente utilizado para limpeza das áreas de pastagem, de modo a não permitir a degradação do pasto e remover a vegetação secundária. Por fim, o fogo utilizado para desmatamento ou pastagem, pode acabar escapando para áreas florestais. As queimadas florestais têm maior chance de ocorrer durante os períodos de seca na região Amazônica, quando essas florestas úmidas se tornam mais vulneráveis ao fogo.

Assim, é possível notar que as altas taxas de ocorrência de fogo e a elevada intensidade desses eventos na Amazônia tem como principal origem as atividades humanas, seja pelo uso para limpeza de terreno ou pelo escape desse fogo para áreas previamente degradadas pelo ser humano. Entretanto, fatores globais podem influenciar o regime de fogo, destacando-se as mudanças climáticas que causam a redução no intervalo entre períodos de seca para essa Região, além de aumentar a sua intensidade (Anderson *et al.*, 2018; Wigneron *et al.*, 2020). Para compreender a relação do regime de transição do fogo e o clima, o tópico a seguir irá tratar das variáveis globais que podem influenciar na ocorrência de queimadas e incêndios florestais na floresta Amazônica brasileira.

1.1.2 A susceptibilidade da floresta ao fogo e às mudanças climáticas

Na Floresta Amazônica brasileira, o aumento na frequência eventos extremos de seca é um dos principais responsáveis pelo aumento da flamabilidade das florestas (Nepstad *et al.*, 2004). Em uma análise paleológica, os autores Mayle e Power (2008) identificaram evidências de que a maior parte da Floresta Amazônica se mostrou resiliente à ocorrência de períodos secos por vezes mais drásticos do que os atuais. Isso se deve ao fato de que, apesar de serem mais intensos, esses eventos de seca não aconteciam com frequência, dando tempo para a floresta se recuperar. Em contrapartida, com a intensificação da consolidação antrópica dos territórios e com a emissão exacerbada de gases causadores do efeito estufa, esses eventos têm redução no seu intervalo de recorrência, causando maiores impactos ambientais relacionados ao fogo (Anderson *et al.*, 2018; Wigneron *et al.*, 2020).

Em se tratando de um bioma com extensões continentais, os períodos de seca, e os consequentes eventos de fogo, variam espacial e temporalmente. Na Colômbia e na

Bolívia, por exemplo, os picos de fogo são notados em fevereiro, enquanto no Peru e no Brasil isso ocorre em setembro, e no Equador em janeiro e outubro são os meses com maior ocorrência de fogo (Armenteras *et al.*, 2017). Analisando-se especificamente o bioma amazônico brasileiro, é possível notar que diferentes regiões também têm regime de fogo diferenciado. Na região central e oriental da Amazônia brasileira, os picos de ocorrência de fogo ocorrem principalmente entre os meses de agosto e dezembro, enquanto nas demais áreas, que são afetadas com menores incidências de focos de calor, esse pico ocorre entre os meses de janeiro a abril (Schroeder *et al.*, 2009). Deste modo, há um indicativo de que o regime de queimadas na Amazônia segue um padrão vinculado com o regime de secas na região.

A ocorrência de secas mais intensas no bioma amazônico brasileiro está associado com eventos climáticos globais, como é o caso do El Niño Oscilação Sul (ENOS), caracterizado pelo aquecimento de águas no oceano pacífico, e o Dipolo do Atlântico, durante o qual há o aquecimento das águas do oceano atlântico (Aragão *et al.*, 2018; Thonicke *et al.*, 2001; Zeng *et al.*, 2008). Destaca-se então que a ocorrência de seca é fundamental para o aumento nas áreas impactadas por incêndios florestais. Entretanto, ressalta-se que para que os incêndios florestais aconteçam na Amazônia, é necessário que existam fontes de ignição de fogo.

As fontes de ignição de fogo nas paisagens Amazônicas são geradas ocupação desordenada do solo, a redução da cobertura florestal, o aumento do efeito de borda nas florestas e à degradação e fragmentação florestal (Brando *et al.*, 2020a; Silva Junior *et al.*, 2019). A recorrência de fogo e degradação florestal, por si só já causam alterações nas características microclimáticas da floresta, tornando a floresta mais vulnerável à incêndios. Quando esses fatores locais se unem aos fatores climáticos globais, nota-se uma espécie de ciclo em que o desmatamento e as secas ocorrem recorrentemente, reduzindo a capacidade de resposta das florestas aos eventos de seca (Staal *et al.*, 2020).

Deste modo, reforça-se a tese de uma transição de regime de fogo na Amazônia relacionada principalmente com as formas de uso do solo e as condições climáticas globais. Isso porque, apesar de os períodos de secas serem os principais momentos nos quais há a elevação na ocorrência de fogo na Floresta Amazônica, é somente a partir da ocupação antrópica do território que as florestas se tornam susceptíveis aos incêndios florestais. Assim, percebe-se a existência de uma relação entre a transição de uso do solo nesse território e a sua susceptibilidade ao fogo das florestas.

Nas últimas décadas, as discussões sobre a preservação das florestas e a redução do desmatamento na Amazônia tem ganhado força. Esses debates, que ocorrem em âmbitos globais, nacionais e locais, impactaram no surgimento de ações governamentais, refletidas em políticas públicas, voltadas a redução nas taxas do desmatamento e queimadas nesse território. A seguir, são destacadas políticas públicas com implicações no regime de queimadas na Amazônia brasileira.

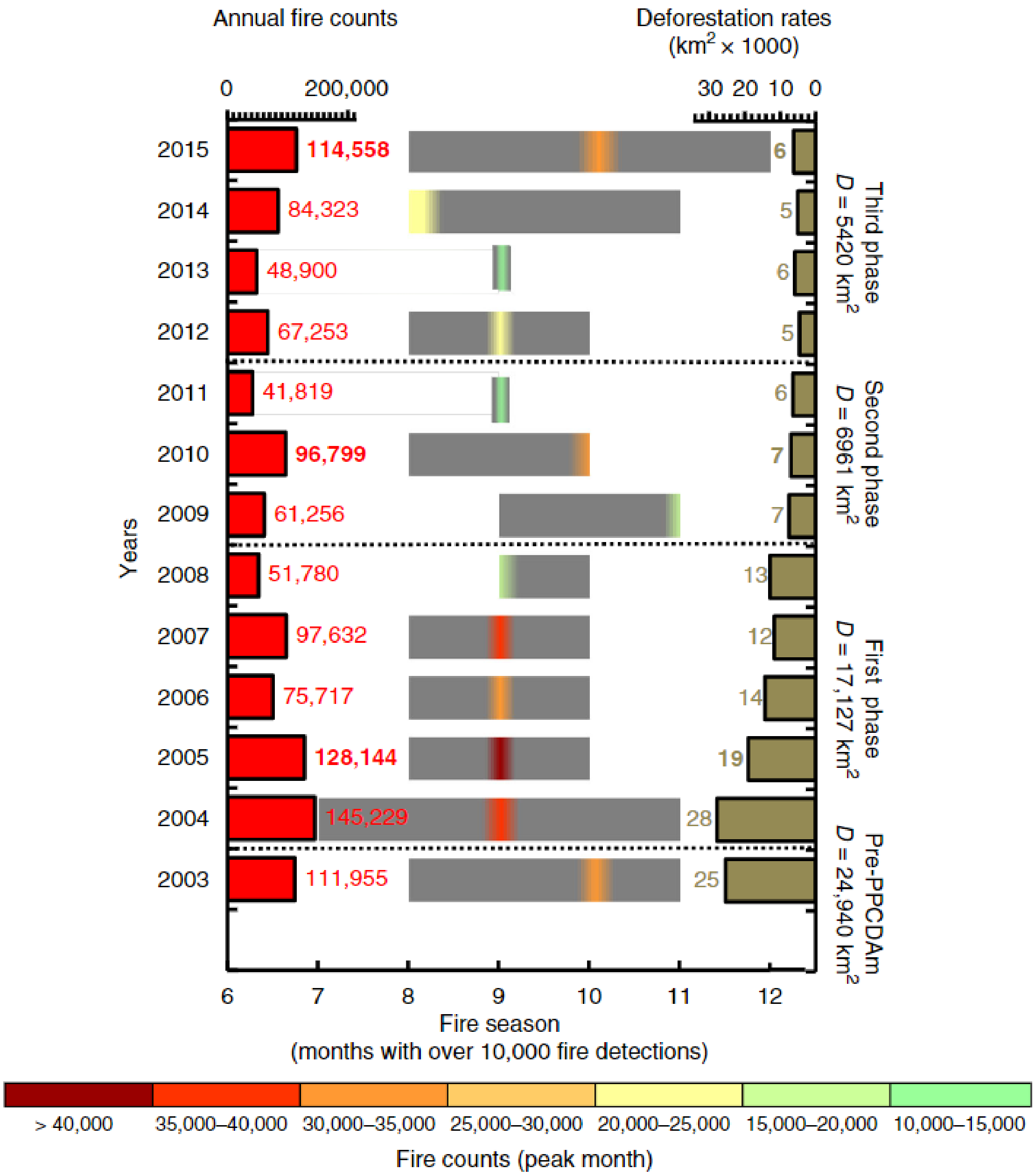
1.1.3 As políticas públicas com implicações nas queimadas na Amazônia brasileira

Como destacado anteriormente, a relação entre o fogo e o desmatamento tem sido amplamente discutida na literatura científica (Aragão *et al.*, 2018; Aragão; Shimabukuro, 2010). Essa relação é bem apresentada no estudo de Aragão *et al.* (2018), o qual mostra que as políticas públicas voltadas para o combate e redução do desmatamento têm desempenhado um papel importante na redução das ocorrências de queimadas na Amazônia brasileira.

Nas últimas décadas, o Plano de Ação para Prevenção e Controle do Desmatamento na Amazônia Legal (PPCDAm) foi a principal intervenção em políticas públicas na região. Por meio desse plano, diversas atividades foram desenvolvidas, dentre elas o ordenamento fundiário e territorial, fomento a atividades agrícolas sustentáveis, investimentos em monitoramento controle e infraestrutura (Mello; Artaxo, 2017). Essas atividades ressaltam a importância do manejo sustentável do solo e uso de técnicas agrícolas sem fogo, de tal modo que seria esperada uma redução nas taxas de queimadas, além do desmatamento, objeto alvo do plano.

O PPCDAm plano ocorreu em três fases principais, durante os anos de 2004 e 2015, e teve resultados expressivos na redução do desmatamento, como evidenciado nas Figuras 1 e 2. Entretanto, sua continuidade na fase IV, que deveria ter ocorrido a partir de 2016, não foi efetivada. É esperado que haja uma retomada do plano na sua fase V (Brasil, 2023), a partir do ano de 2023.

Figura 2 - Comportamento anual do fogo e do desmatamento na Amazônia brasileira. As barras da esquerda representam a contagem de focos ativos de calor e as barras da direita o desmatamento anual registrado. O gráfico é subdividido em pré-PPCDam e as fases 1, 2 e 3



Fonte: Imagem retirada do trabalho de Aragão *et al.* (2018).

O PPCDAm também incentivou o desenvolvimento de planos estaduais para redução do desmatamento e queimadas. Esse eixo foi particularmente importante nos últimos seis anos, uma vez que em decorrência da interrupção do PPCDAm, as iniciativas em nível estadual puderam continuar atuando na linha de frente da preservação da Amazônia. De maneira geral, os planos ativos (Quadro 1) para o controle do desmatamento nos estados da Amazônia Legal abrangem os eixos principais do

PPCDAm, concentrando suas ações de acordo com a realidade local (Brasil, 2023). No entanto, é natural que esses planos tenham suas ações limitadas se o plano federal não estiver em vigor.

Quadro 1 - Planos Estaduais de Prevenção e Controle do Desmatamento e Queimadas

Estado	Nome do Plano	Vigência	Meta de Redução	Status
Acre	Plano Estadual Prevenção e Controle do Desmatamento e Queimadas – PPCDQ/Acre	2017-2020	80%	Nova fase em elaboração
Amapá	Plano de Prevenção e Controle de Desmatamento, Queimadas e Incêndios Florestais do Estado do Amapá – PPCDAP	2022-2025	36%	Vigente
Amazonas	Plano Estadual de Prevenção e Combate ao Desmatamento do Amazonas – PPCDQ/AM	2020-2022	15%	Nova fase em elaboração
Maranhão	Plano de Ação para Prevenção e Controle do Desmatamento e das Queimadas no Estado do Maranhão – PPCD – MA	2011-2015	42%	Informações não disponíveis
Mato Grosso	Plano de Ação para Prevenção e Controle do Desmatamento e Incêndios Florestais do Estado do Mato Grosso – PPCDIF/MT	2021-2024	15% a.a. e 85%	Vigente
Pará	Plano Estadual Amazônia Agora 2021 – 2023 (PEAA)	2021-2023	37% até 2030 e 43% até 2035	Vigente
Rondônia	Plano de Prevenção, Controle e promoção de alternativas sustentáveis ao desmatamento e queimadas de Rondônia – PPCASD/RO	2023-2026	75%	A ser lançado
Roraima	Plano Estadual de Prevenção e Controle ao Desmatamento e Queimadas de Roraima – PPCDQ/RR	2020-2023	15% a.a.	Vigente
Tocantins	Plano de Prevenção e Combate aos Desmatamentos e Incêndios Florestais do Tocantins – PPCDIF/TO	2021-2025	100%	Vigente

Fonte: Quadro retirado de Brasil (2023).

As ações integradas realizadas pelos Estados brasileiros, apesar de contribuir com o controle das taxas de desmatamento e queimadas, tem impacto limitado quando não são acompanhadas de ações federais. Por isso, o aumento dessas duas taxas (Figura 1) é mais perceptível a partir de 2016, quando o PPCDAm começa a ter as suas ações limitadas. Por isso, é importante considerar o papel que as ações governamentais para controle do desmatamento e das queimadas exercem na transição do regime de fogo na Amazônia, uma vez que as dinâmicas de uso do território impactam esse regime.

Com essa revisão de literatura, foi possível notar as diferentes interações antrópicas, de mudança nos padrões de ocupação do solo, do clima, de como os regimes de seca influenciam nas queimadas, e do papel que as políticas públicas podem ter nas alterações no regime de fogo no território Amazônico.

1.2 Justificativa, Questões Científicas e Interdisciplinaridade da Pesquisa

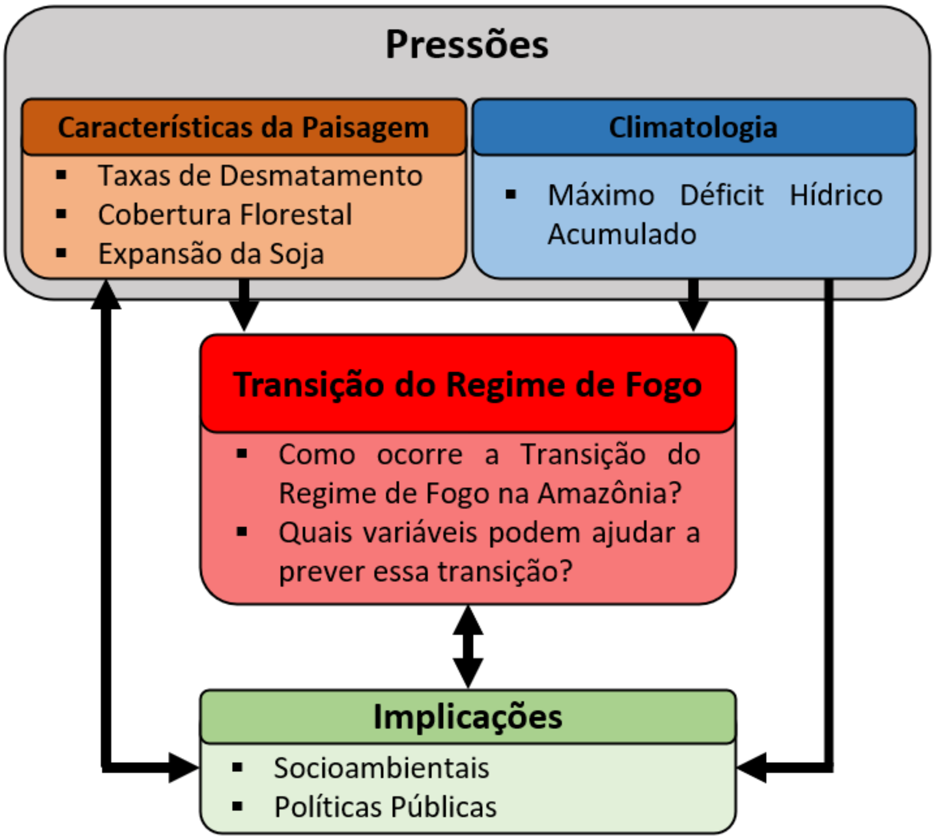
Como apresentado nos tópicos anteriores, a relação das queimadas com a ocupação antrópica do território e as mudanças climáticas vem sendo fortemente investigada na Amazônia brasileira. A ocorrência de queimadas nesse bioma não ocorre de maneira natural, sendo geralmente introduzida durante o processo de desmatamento e em seguida, durante a limpeza do solo para fins agropecuários. A ocorrência de secas severas, as quais estão se tornando mais frequentes e intensas por causa das mudanças climáticas, amplifica esse processo, tornando as florestas mais vulneráveis à ocorrência de queimadas e incêndios florestais. Além disso, nas últimas décadas, políticas públicas voltadas para a redução do desmatamento na Amazônia mostraram-se eficazes também na redução da ocorrência de fogo.

No entanto, ainda é necessário aumentar o entendimento sobre a relação entre a transição do regime fogo com a ocupação humana do território ao longo do espaço e do tempo na Floresta Amazônica. Além disso, é fundamental entender como essa relação pode ser influenciada por questões climáticas e a interação dessa transição com o desenvolvimento de política públicas de combate ao desmatamento e às queimadas. Por essa razão, essa pesquisa questiona como ocorre o processo de transição do regime fogo na Floresta Amazônica brasileira, quais variáveis podem ajudar a prever essa transição e quais são as principais implicações da transição do fogo para políticas públicas de preservação desse bioma.

Para facilitar a compreensão da relação entre as variáveis ambientais, sociais e econômicas envolvidas na transição do regime de fogo na Floresta Amazônica brasileira, este estudo adotou uma abordagem interdisciplinar. Primeiramente, foram utilizados conceitos da geografia para identificar as características da paisagem e investigar as interações humanas com o uso e a cobertura do solo na região. Além disso, informações sobre climatologia foram empregadas para entender como as dinâmicas climáticas e as mudanças climáticas podem afetar a transição do regime de fogo nessas paisagens. Adicionalmente, utiliza-se de disciplinas das ciências humanas para entender as implicações dos resultados no meio socioambiental e como as políticas públicas se relacionam com transição do fogo pensando na preservação da Amazônia brasileira.

O arcabouço interdisciplinar (Figura 3) mostra de maneira centralizada a transição do regime de fogo e as perguntas centrais dessa Tese. Nesse arcabouço, é possível identificar como as diferentes disciplinas do conhecimento interagem para o entendimento da transição do regime de fogo. Ademais, possíveis implicações relacionadas às ciências humanas são destacadas.

Figura 3 - Arcabouço interdisciplinar da Tese



Desta forma, justifica-se a relevância do desenvolvimento pesquisa científica e seu potencial de contribuição para o entendimento do regime de fogo na Amazônia brasileira. Ademais, o caráter interdisciplinar desse estudo permite uma compreensão mais completa da complexidade do problema, contribuindo para a proposição de ações mais efetivas para a redução dos impactos negativos do fogo na região.

1.3 Objetivos

1.3.1 Objetivo Geral

A presente pesquisa tem como objetivo principal investigar o processo de transição do regime de ocorrência de fogo na Floresta Amazônica brasileira, identificando seus principais causadores e implicações para políticas públicas.

1.3.2 Objetivos Específicos

- Identificar a transição do regime de fogo nas paisagens Amazônicas analisando a relação entre a ocorrência de fogo, a cobertura florestal e o uso e ocupação do território na Amazônia brasileira, destacando seus principais causadores.
- Determinar trajetórias de transição do regime de ocorrência das queimadas florestais ao longo do tempo na Amazônia brasileira e diagnosticar quais fatores contribuem para a caracterização dessas trajetórias.
- Discutir a relação da transição do fogo na Amazônia brasileira em termos das implicações socioambientais e de políticas públicas dessa transição.

1.4 Estrutura da Tese

Essa tese investiga o processo de transição do fogo na Floresta Amazônica brasileira, analisando também as diferentes trajetórias em que as queimadas florestais ocorreram nesse bioma nas últimas três décadas. Além disso, faz-se o levantamento das possíveis implicações desses resultados para as políticas públicas de preservação das florestas amazônicas. Para isso, essa pesquisa está subdividida em dois capítulos, sendo cada um correspondente a um artigo científico desenvolvido com as análises feitas.

No Capítulo 1, investiga-se o processo de transição do fogo na relação da ocorrência de fogo na paisagem e a porcentagem de cobertura florestal em cada grade. Além disso, investiga-se quais variáveis-chave são fundamentais para entender esse processo de transição. Analisa-se também implicações socioambientais que os resultados podem ter. Nesse capítulo, foi possível constatar o processo de transição do fogo na Floresta Amazônica brasileira. Nesse processo, o desmatamento teve forte relação com a ocorrência de fogo nas paisagens, enquanto a expansão da agricultura mecanizada foi chave para a transição do fogo para áreas com maior cobertura florestal.

Em seguida, no Capítulo 2, analisa-se as trajetórias de queimadas florestais na Floresta Amazônica brasileira. Nesse capítulo, as implicações em políticas públicas para a conservação da floresta Amazônica contra as queimadas florestais são também abordadas. Nessa investigação, foi possível caracterizar duas distintas trajetórias de queimadas florestais na Amazônia brasileira, ambas com fortes influências do desmatamento e da cobertura florestal, seguidas pelo déficit hídrico.

Por fim, apresentam-se as considerações finais. Nessa seção, além das conclusões sobre os dois capítulos e suas relações, faz-se um breve levantamento sobre as implicações para políticas públicas que esses resultados têm. Além disso, são apontadas questões relevantes para pesquisas futuras na temática estudada nessa tese.

2 EXPLORING THE ROLE OF DEFORESTATION AND CROPLAND EXPANSION IN DRIVING A FIRE-TRANSITION IN THE BRAZILIAN AMAZON [1]

Resumo: A Floresta Amazônica Brasileira passou por mudanças significativas no uso da terra e na cobertura vegetal nas últimas décadas. Essa transição no uso da terra, junto com as mudanças climáticas, pode ser responsável pela mudança no regime de queimadas nesse território. Portanto, esse estudo objetivou investigar como ocorre a transição do fogo ao longo do tempo na Floresta Amazônica Brasileira e identificar os principais parâmetros que podem ajudar a prever essa mudança. Para isso, foram coletados dados anuais sobre a ocorrência de incêndios, cobertura florestal, taxas de desmatamento e áreas de cultivo. Utilizou-se uma grade espacial de 0,45° e, com esses valores anuais, foram produzidos: (i) modelos lineares mistos generalizados de ocorrência de incêndios em relação à cobertura florestal, usando anos e grades como fatores aleatórios; (ii) modelos lineares anuais de ocorrência de incêndios em relação à cobertura florestal; (iii) modelos lineares dos valores máximos em relação aos anos; e (iv) modelos lineares generalizados desses valores máximos em relação ao desmatamento e às áreas de cultivo. Descobriu-se que que há um processo de transição do fogo na Floresta Amazônica Brasileira, uma vez que um modelo quadrático previu melhor o comportamento da ocorrência de incêndios. Além disso, o ponto máximo de ocorrência de incêndios está se deslocando para paisagens mais florestadas, passando de 50,7% em 2003 para 55% em 2019 ($R^2 = 0,3$). As taxas de desmatamento e a expansão das áreas de cultivo tiveram relações importantes com a transição do fogo, sendo que o desmatamento está relacionado com a ocorrência de incêndios na paisagem ($R^2 = 0,62$), enquanto a expansão das áreas de cultivo melhor prediz a transição para áreas mais florestadas ($R^2 = 0,38$). Assim, identificou-se que a transição do fogo na Floresta Amazônica Brasileira está fortemente relacionada com as etapas de transição no uso da terra nessa região.

Palavras-chave: transição do fogo; desmatamento; expansão agrícola; secas severas.

[1] O presente capítulo foi publicado na Revista Land em 6 de dezembro de 2022: TAVARES, P. A.; FERREIRA, J.; SILVA, C. V. J.; BERENGUER, E.; BARLOW, J. Exploring the Role of Deforestation and Cropland Expansion in Driving a Fire-Transition in the Brazilian Amazon. **Land**, v. 11, n. 12, 2022. doi: doi.org/10.3390/land11122274.

Abstract: The Brazilian Amazonian Forest is undergoing significant changes in land use and land cover in the last few decades. This land-use transition, besides climate change, may be responsible for the fire regime transition in this territory. Therefore, we aimed at investigating how the fire-transition occurs over time in the Brazilian Amazonia Forest and identifying the key parameters that can help to predict this change. For this, we collected yearly data on fire occurrence, forest cover, deforestation rates, and cropland areas. We used a 0.45° spatial surface grid, and with these annual values, we produced: (i) generalised linear mixed models of fire occurrence against forest cover, using years and grids as random factors; (ii) annual linear models of fire occurrence against forest cover; (iii) linear models of the apex values against the years; and (iv) generalised linear models of these apex values against deforestation and cropland areas. We found that there is a fire-transition process in the Brazilian Amazon Forest since a quadratic model better predicted the fire occurrence behaviour. Moreover, the fire occurrence apex is transitioning to more forested landscapes, from 50.7% in 2003 to 55% in 2019 ($R^2 = 0.3$). The deforestation rates and the cropland expansion had important relationships with the fire-transition, the first is related to the fire occurrence in the landscape ($R^2 = 0.62$), while the second better predicts the transition to more forested areas ($R^2 = 0.38$). Thus, we found that the fire-transition in the Brazilian Amazon Forest is strongly related to the land-use transition stages in this region.

Keywords: fire-transition; deforestation; cropland expansion; severe droughts.

2.1 Introduction

Fire dynamics are changing across the world due to climate and land-use changes (Bowman *et al.*, 2020). Globally, there is a trend of increasing fire season length, due to favourable climate conditions for fire occurrence, such as an overall reduction in air humidity, an increase in surface temperature and the number of rainless days (Jolly *et al.*, 2015). Yet there has also been a reduction in burned areas between 1988 and 2015, which occurred mainly in regions with low and intermediate levels of tree cover, and was countered by an increase in fire occurrence in closed-canopy forests (Andela *et al.*, 2017). Understanding these fire dynamics is particularly important in fire-sensitive regions, such as humid tropical forests; fires have been historically rare or absent in these ecosystems (Pivello, 2011; Thonicke *et al.*, 2001), and in present day wildfires have a strong negative effect on biodiversity, climate regulation and human wellbeing (Barlow *et al.*, 2018; Bedia *et al.*, 2015; Cochrane; Barber, 2009; Kelly *et al.*, 2020).

In humid tropical forests, fires are closely related to land-use changes and the management of agricultural areas. Fire is a fundamental part of the deforestation process, and fire occurrence—as measured by satellites—is linked to the burning of felled trees following the conversion of forests to pasture or cropland (Morton *et al.*, 2008). As such, more fires tend to be detected in years with higher deforestation rates (Aragão *et al.*, 2018). Fires are also crucial for pasture management and subsistence agriculture (Barlow *et al.*, 2020). In the former, fire is used to periodically clear pastures of trees and weeds that decrease its carrying capacity. In the latter, fire is used for slash-and-burning as part of a farm-fallow cycle. Climate also influences fire occurrence—in the Brazilian Amazon, more fires are detected in years of extreme droughts, which are becoming more common (Anderson *et al.*, 2018; Erfanian; Wang; Fomenko, 2017; Wigneron *et al.*, 2020). Fires linked to droughts often occur in forests, when reductions in leaf litter humidity allow deforestation and agricultural fires to escape into surrounding forests (Barlow *et al.*, 2020; Brando *et al.*, 2020a; Cano-Crespo *et al.*, 2015). These forest fires are important as they are a major determinant of an Amazonian tipping point (Nobre *et al.*, 2016) and an important driver of biodiversity loss (Barlow *et al.*, 2012) and carbon emissions (Berenguer *et al.*, 2021; Silva *et al.*, 2020).

Although deforestation and agricultural expansion increase fire occurrence in humid tropical forest regions, it has been suggested that this is only temporary. Andela *et al.* (2017) propose a conceptual model in which fire follows a unimodal relationship during land-use transitions across the world. In the humid tropics, Andela *et al.* (2017) predict that fire extent increases in the initial phase of land clearance but then decreases as high capital activities, such as mechanised farming, replace low capital and extensive agriculture (Foley *et al.*, 2005). Such a transition is important as it could have an important influence on fire use, and the possibility of ignition events in agricultural land escaping into remaining forests. However, despite some evidence that fire occurrence increases when lands are being cleared, and that there is a reduction of total occurrence of fire across agricultural landscapes (Aragão; Shimabukuro, 2010), we still lack a detailed understanding of how the globally hypothesized fire transition is playing out in the Amazon and how any such transition is being modified by deforestation or changes in agricultural practices.

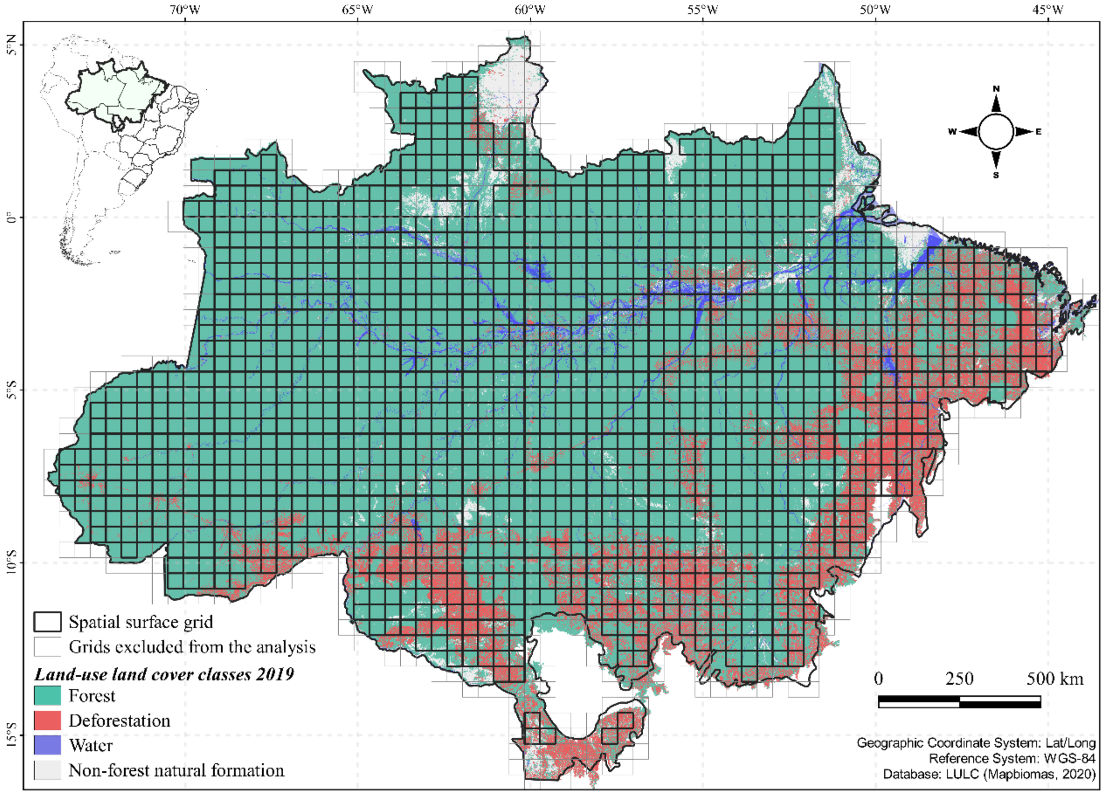
We address these knowledge gaps by exploring fire activity in the Brazilian Amazon from 2003 to 2019. We used active fire as our measure of fire prevalence at the landscape scale (0.45° by 0.45° grids) and examined it in relation to landscape-scale year-on-year datasets on forest cover, Land-use and Land Cover (LULC) and deforestation. We define a fire transition by the location of the apex of any relation between active fire and forest cover; and define fire prevalence as the height of the apex. Specifically, we ask: (1) is the Brazilian Amazon undergoing a fire-transition, and where is the transition point in relation to forest cover? (2) Has the transition point location and height changed over time? (3) Do annual changes in deforestation or expansion of cropland help predict the changes in the active fire and forest cover relationship peak values?

2.2 Materials and Methods

2.2.1 Study Area

The study area focuses on the Brazilian Amazon (Figure 4), a region with distinct climate characteristics and occupation histories. Annual deforestation rates varied substantially during the study period (i.e., 2003–2019). From a peak in 2004, deforestation rates reduced to their lowest level in 2012 and have gradually increased since then, with a severe spike in 2019 (Figure A2b) (INPE, 2022). A similar pattern occurs when considering deforestation from primary and secondary forests (Mapbiomas, 2021a), with the lowest level in 2012, but with a greater spike in 2016 (Figure A2a).

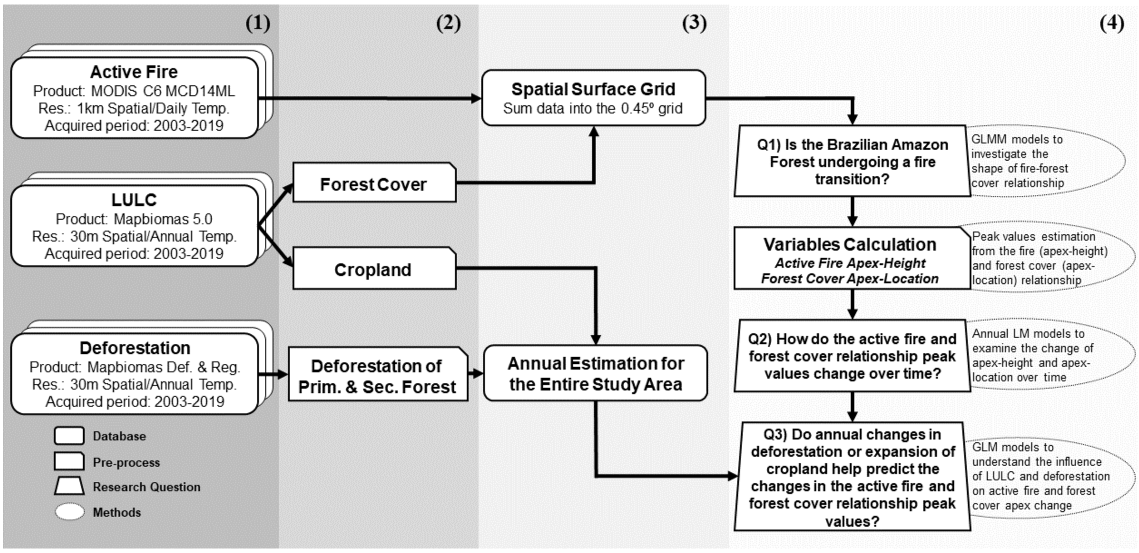
Figura 4 - Location of the base spatial surface grids used in our analysis.



2.2.2 Datasets

We focus our analyses on 2003 to 2019, a period in which the Brazilian Amazon experienced three severe droughts (i.e., 2005, 2010, and 2015–2016) and marked changes in deforestation rates (Appendix A). We set this time range by the availability of the active fire dataset (i.e., MODIS Terra and Aqua satellites data available since mid-2002). We created a 0.45° spatial surface grid, which we used as a base for all our spatial estimates. Subsequently, we removed grid cells with over 20% of savannas or mangroves coverage from the analysis (using 2003 as the base year from the Mapbiomas 5.0 dataset). We have excluded all savanna enclaves from the analyses as fire dynamics and fire outcomes are very different in these fire-dependent ecosystems (Barbosa; Fearnside, 2005). In addition, we excluded from the analyses grids that were on the edges of the biome, as they were not fully covered with LULC data (Figure 4). Thus, we investigated 1471 cells in our analysis, wherein we computed all acquired data for each of these cells. We summarise the datasets used, and the methods applied in Figure 5.

Figura 5 - Workflow of the used method, describing: (1) the three main datasets to analyse and interpret the active fire behaviour in relation to forest cover: (i) Active Fire occurrence (Giglio; Schroeder; Justice, 2016); (ii) LULC (Mapbiomas, 2020; Souza *et al.*, 2020); and (iii) Annual Deforestation (Mapbiomas, 2021a). (2) The land cover and deforestation metrics derived from these products. (3) The spatial surface grids metrics calculation used for statistical analyses. (4) The key questions.



2.2.2.1 Active Fire

We used data from MODIS Terra and Aqua satellites, which are produced from MODIS MCD14ML Collection 6, where active fires are detected at a 1 km spatial resolution. The MODIS MCD14ML Collection 6 improved the active fire detection in the Amazon by reducing false positives (Giglio; Schroeder; Justice, 2016). This dataset for the Amazon Forest may have low detection rates where canopy cover is particularly dense and is likely to underestimate understory fires. However, our hypotheses are mainly about changes in fire-use in open areas, and we repeat analysis removing dry years to account for the possible influence on forest fires. We collected these datasets in the Fire Information for Resource Management System (FIRMS) platform in a point-vector format. We first acquired data from 1 January 2003 to 31 December 2019 and then aggregated all active fires with confidence levels greater than 30% (nominal and high confidence fires as applied in Chen *et al.* (2013) and Armenteras *et al.* (2017)) within our 0.45° grid cells, counting the annual total for each cell.

2.2.2.2 Land Use and Land Cover

For this analysis, we used Mapbiomas' collection 5.0 data. The Mapbiomas product estimates forest formation areas, without distinguishing primary from secondary vegetation, so we considered both in our forest cover estimates. In addition, our main hypotheses were focussed on fire use in open lands, which further justifies grouping primary and secondary forests together. Thus, to estimate forest cover values, we calculated the percentage of each grid that is covered by the forest formation class. In addition, we estimated the cropland areas considering only the soybean crops as an intensive stage of land-use transition (Foley *et al.*, 2005) indicator in the rural areas of the Brazilian Amazon Forest. We considered using other agricultural classes as indicators of cropland areas, but these areas either not present in the landscape or inseparable from small-scale subsistence practices. However, Table B2 shows that there is no significant difference in the results when temporary crops were also considered. We used the Google Earth Engine platform to process the Mapbiomas dataset and calculate the forest cover percentage for each grid and we also estimated the cropland area per year for the entire study area in our analysis.

2.2.2.3 Deforestation

We collected the deforestation data from the Mapbiomas Deforestation and Regeneration dataset. This dataset considers 1988 as a base map to analyse the pixel-by-pixel trajectory of deforestation and regeneration up to 2019 (Mapbiomas, 2021b). We considered the total deforestation of primary and secondary forests, as both are potential sources of fire ignition (Aragão; Shimabukuro, 2010; Fearnside; Barbosa; Graça, 2007) and the LULC dataset also includes both categories in the forest formation class. To obtain yearly deforestation rates, we processed this dataset in the Google Earth Engine platform to sum the total deforested area within each grid cell. We then estimated yearly deforestation rates for the entire study area.

2.2.3 Data Analysis

We split the analyses into three stages of data processing: (1) To evaluate whether the Brazilian Amazon is undergoing a fire transition, we examined the shape of the relationship between active fires count and forest cover by comparing three Generalised

Linear Mixed Models (GLMM): (i) null, (ii) linear and (iii) quadratic. We produced the GLMMs using each grid cell and each year as random effects variables—a spatial and a temporal variable, respectively. Given the high number of zeros in the fire count dataset, we used a zero-inflation model and set the family as negative binomial, to reduce over-dispersion. We also estimated the R^2-marginal and R^2-conditional for the GLMM produced using the Nakagawa, Johnson e Schielzeth (2017) method as it can estimate these values for negative binomial models. To determine the best fit model, we tested and compared the Akaike Information Criterion (AIC) results. (2) Thereafter, to determine whether the transition point of the fire occurrence and forest cover relationship is transitioning over time, we produced yearly quadratic models to extract the vertices values. The use of a quadratic model implies that there is an apex at which we find a maximum number of active fires per year in each grid cell—hereafter, active fire apex-height, and there is also a maximum amount of forest cover for this to happen, the line of symmetry of the equation—hereafter, forest cover apex-location (in Figure 6 there is a visual representation of these variables). Thus, we extracted the apex-height and the apex-location for each year of the active fire and forest cover relationship. We then calculated how these parameters changed over time. The behaviour of the peaks in the active fire-forest cover relationship over time is important; not only is it a direct test of the hypotheses raised by Andela *et al.* (2017), it also allows us to verify in which landscapes (% of forest cover) the fire is more likely to happen. (3) Finally, to examine whether deforestation and cropland expansion can predict changes in the peak values from the active fire and forest cover relationship per year, we produced Generalised Linear Models (GLM) using active fire apex-height and forest cover apex-location as dependent variables, and as independent variables we used: (i) deforestation rates of primary and secondary forests; and (ii) cropland area estimation. In order to find the best-fitting model for active fire apex-height and forest cover apex-location, we used the dredge function analysis, where all possible models are considered, and compared their AIC results. In addition, we produced linear models with the dependent variables and their most significant independent variables. We conducted all statistical analyses in R v. 4.1.0 using glmmTMB (Brooks *et al.*, 2017), MuMIn (Bartón, 2020) and stats (R Core Team, 2021) packages.

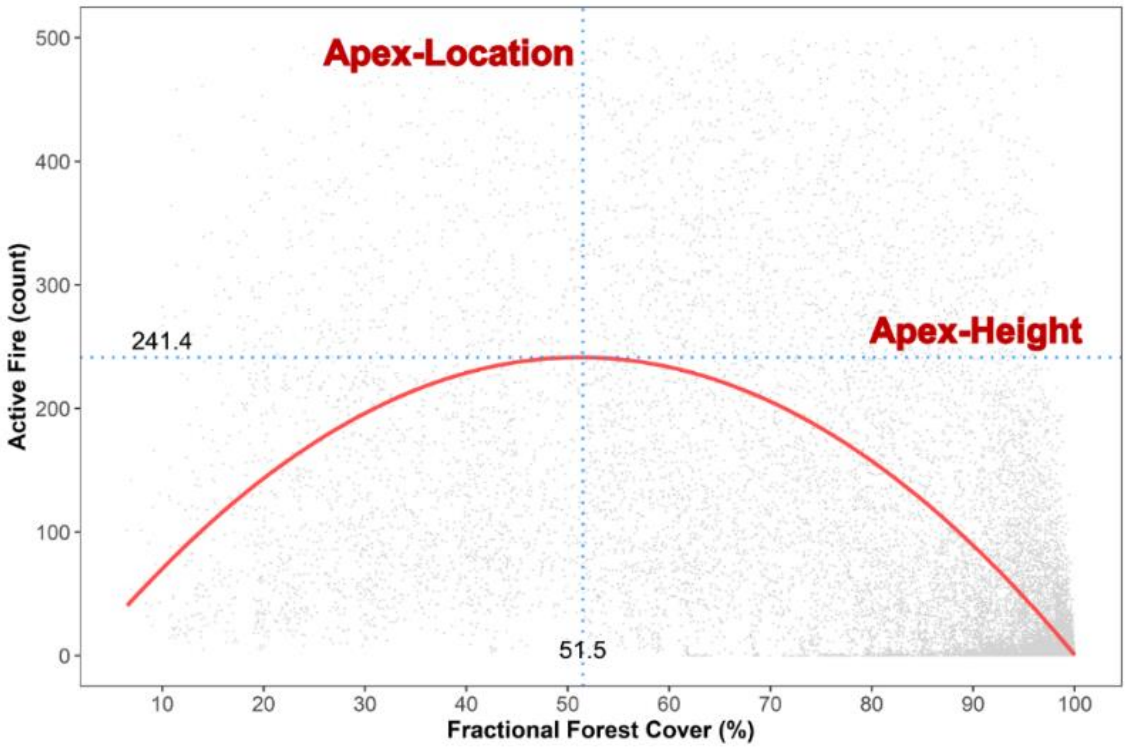
Our primary objective was to assess whether active fires are being affected by changes in land use, and not climate. We therefore analysed these changes considering two climate scenarios: (i) all years, and (ii) removing years with extreme droughts from the analyses, since in these years the number of active fires is higher than normal because of climate conditions—Appendix B, Table A3, and Figure A4. We also re-analysed the time series separating it into two distinct periods—from 2003 to 2011 and from 2012 to 2019—since the deforestation rates behaviour was very different in the Brazilian Amazon Forest during these two periods—Appendix C. Furthermore, in order to understand the relationship of the results with the anthropogenic dynamics in the region we review the socio-environmental implications of the fire-transition process for the Brazilian Amazon.

2.3 Results

2.3.1 Analysing an Amazon Fire-Transition

We found that the distribution between the active fire count and the forest cover per-centage, for each grid cell and year, was best described by a quadratic form (dAIC with null model = 767,315.8 and dAIC with linear model = 760.6). The quadratic model is shown in Figure 6. However, the proportion of active fire counts explained by the fixed term alone (percentage of forest cover) was low (R^2 marginal = 0.06), and the variance explained by the entire model was significantly higher (R^2 conditional = 0.59). The markedly higher explanatory power of the entire model suggests a strong influence of the random effects (years and grid cells).

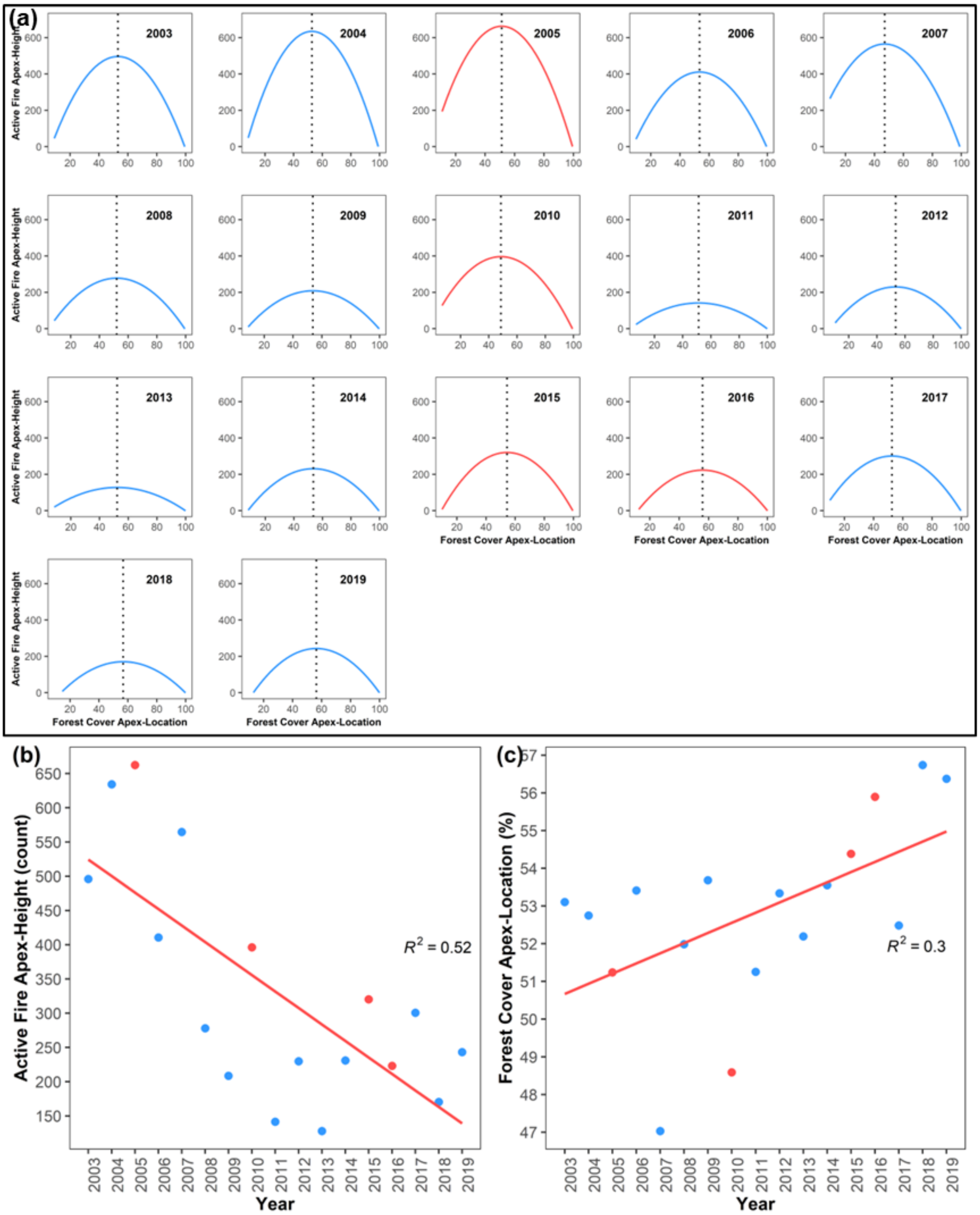
Figura 6 - The quadratic relationship between forest cover and active fire counts, as derived from the GLMM analysis. Active fire counts were highest (~241) in grids with 51.5% forest cover. Horizontal blue dotted line represents the active fire apex-height and vertical blue dotted line is the forest cover apex-location. Data points (0.45° grids) are represented in grey.



2.3.2 Key parameters Defining a Forest Cover-Fire Occurrence Relationship

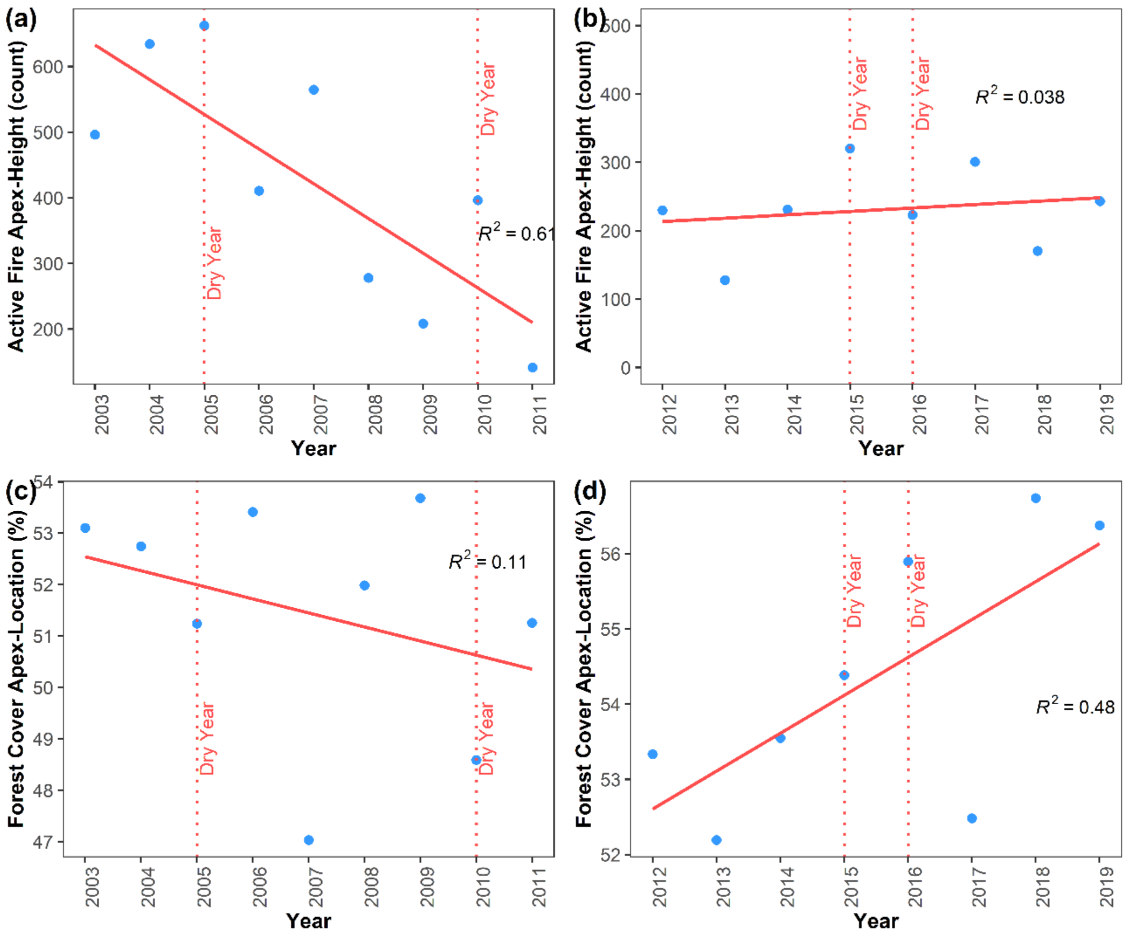
Both apex-height and apex-location of the forest cover-active fire relationships changed year to year (Figure 7a). The active fire apex-height registered varied from ~127 in 2013 to ~662 in 2005, while the forest cover apex-location varied from 47.03% in 2007 to 56.74% in 2018. This variation was predicted by time, as with active fire apex-height de-creasing from ~524 in 2003 to ~139 in 2019 ($R^2 = 0.52$), and the forest cover apex-location increasing from landscapes with 50.7% of forest cover in 2003 to landscapes with 55.0% of forest cover in 2019 ($R^2 = 0.3$) (Figure 7b, c).

Figura 7 - Active fire apex-height and forest cover apex-location behaviour during the analysed years. (a) Yearly quadratic models of active fire apex-height and forest cover apex-location relationship. The black dotted lines are the apex of the relationship. Normal climatic years are illustrated with blue plots, and severe dry years are with red plots. (b) Active fire apex-height value by year. The red dots are the severe dry years. (c) Forest Cover apex-location value by year. The red dots are the severe dry years.



When we investigated these relationships in two different periods (Figure 8): (i) during the 2003–2011 period, the active fire apex-height had an important decreasing trend ($R^2 = 0.61$) and the forest cover apex-location decreased but with a low significance value ($R^2 = 0.11$); ii) the opposite happened with the behaviour of these variables during the 2012–2019 period, in which the active fire apex-height slightly increased, with a low significance value ($R^2 = 0.038$), and the forest cover apex-location significantly increased ($R^2 = 0.48$). These results therefore indicate an important change in the fire transition during the two different periods, with the first period being most important in determining the de-crease in the apex-height, and the second period being more important for determining the increase in the apex-location.

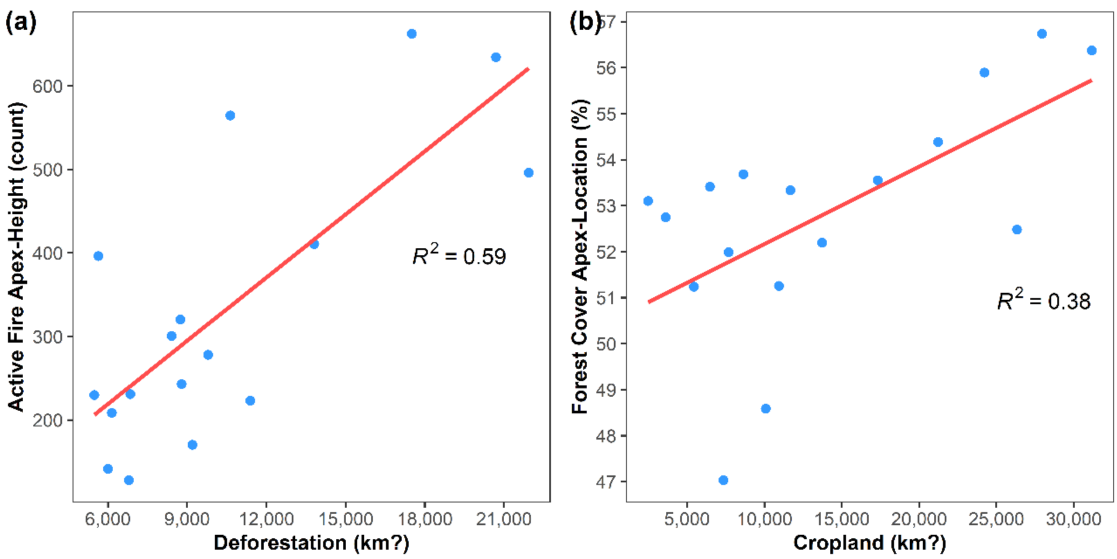
Figura 8 - Apex-height and apex-location behaviour in the two analysed periods. (a) Active fire apex-height from 2003 to 2011. (b) Active fire apex-height from 2012 to 2019. (c) Forest cover apex-location from 2003 to 2011. (d) Forest cover apex-location from 2012 to 2019.



2.3.3 The Influence of Deforestation Rates and Cropland Expansion on the Forest Cover-Fire Occurrence Relationship

The dredge analyses (Table B1) showed that two models are more plausible (dAIC < 2) for both active fire apex-height and forest cover apex-location. In these models, we found: (i) the deforestation rates in all best-ranked models for the active fire apex-height (R^2 = 0.59 and p-value = 0.0003 in the bivariate analyses—Figure 9a), and (ii) the cropland area is in all best-ranked models for forest cover apex-location (R^2 = 0.38 and p-value = 0.009 in the bivariate—Figure 9b). The strength of these relationships improved when we removed the severe dry years from the analyses (lower AIC values—Table B3), and we found better results in the active fire apex-height by deforestation rates model (R^2 = 0.67—Figure A4c). In addition, when we investigated these significant relationships in two different periods (Figure A6), we found that there is a strong relationship between the active fire apex-height and the deforestation rates during the 2003 to 2011 period (R^2 = 0.57 and p-value = 0.02) and an important relationship between forest cover apex-location and cropland area in the 2012 to 2019 period (R^2 = 0.38 and p-value = 0.05). In summary, the key variables are important to describe the active fire apex-height and forest cover apex-location, and the behaviour of each one is better predicted in different periods.

Figura 9 - Linear models of the significant variables used to describe active fire apex-height and forest cover apex-location. (a) Active fire apex-height by annual deforestation. (b) Forest cover apex-location by cropland area.



2.4 Discussion

2.4.1 Fire-Transition Patterns in Brazilian Amazon

Our analyses indicated that fire occurrence in Amazonia follows a quadratic relationship with forest cover and spatiotemporal variables. This relationship is not static over time: between 2003–2019, the active fire apex-height decreased while the forest cover apex-location increased. The deforestation rates and the cropland expansion predicted mainly the apex of these relationships within the landscape. Our results show that the reduction in the deforestation rates is crucial to the reduction of fire occurrence, reflecting the fact that many of the detected fires are those detected during the land clearing process. Furthermore, we highlight that the fire occurrence apex is transitioning to more forested landscapes which may be vulnerable to increased deforestation. We also show that the expansion of mechanised agriculture practices is resulting in the peak of fire occurrence shifting towards regions with higher levels of forest cover. Thus, our results broadly support the model of Andela *et al.* (2017). We found that the fire-transition in the Brazilian Amazonian Forest is related to the stage of land-use transition, increasing during the deforestation process, and further reducing when more advanced agricultural practices are implemented.

The amount of variance explained was higher when we removed the years with severe droughts from the analyses (Table A3 and Figures A4c and A4d). This is plausible since in these years, the amount of deforestation capture by Mapbiomas (Figure A2a) and the amount of active fire occurrence (Figure A1b) significantly increased, compared to previous years. For instance, Aragão *et al.* (2018) found a 36% increase in fire incidence during the 2015 drought event, and in that year the largest ever ratio between fire and deforestation was registered. On the other hand, the global analysis by Andela *et al.* (2017) indicated that climate is relevant only for the intra-annual fire occurrence behaviour. In the Amazonian forest, intra-annual analyses have indicated that fire occurs mainly during the dry season and there is also a spatial variance in this fire regime (Armenteras *et al.*, 2017; Schroeder *et al.*, 2009). These results, in accordance with the scientific literature, indicate that variation in climate has an important role in the fire-transition relationships.

2.4.2 Spatiotemporal Changes in Fire Occurrence

Our findings suggest that the two key variables responsible for the spatiotemporal variation in the fire-transition process in the Brazilian Amazonian Forest were the annual rates of deforestation and cropland expansion. In addition, our results have shown that in the first analysed period—from 2003 to 2011—higher rates of deforestation led to greater active fire apex-heights, while in the second period—from 2012 to 2019—there is a clearer relationship between the expansion of the cropland areas and the forest cover apex-location. These differences can be explained by changes in the Brazilian Amazon during these periods, as deforestation rates significantly decreased during the first period and constantly increased in the second period (Fearnside, 2015); while there was a constant expansion of the cropland areas.

The use of fire is expected during the initial phases of land-use transition (deforestation) since fire is a cheap tool to clear felled vegetation when converting forests to agriculture (Foley *et al.*, 2005). The deforestation phase is then followed by consolidation, which often starts with pastures, which may later on be converted into croplands as part of the intensification process (Gibbs *et al.*, 2007; Morton *et al.*, 2008) — although some deforested areas are converted straight to cropland (Morton *et al.*, 2008). Fire is a key tool during the initial stages of the clearance process. For instance, Aragão and Shimabukuro (2010) found that most of the reported fires occurred in recently deforested areas, indicating that new frontiers of deforestation may increase fire occurrence in the Brazilian Amazon Forest. Morton *et al.* (2008) showed that the cropland expansion trend is linked with the increase in the average size of deforested areas and with the frequency of fire usage for deforestation.

2.4.3 Socio-Environmental Implications of the Fire-Transition Relationship with Land-Use Variables in the Brazilian Amazon

The fire-transition behaviour and its relationships with deforestation and cropland expansion are key to understanding mechanisms and developing more effective environmental policies. Although agricultural intensification and mechanisation appear to be a solution to fire, this is overly simplistic as they have many important problems associated with them. First, much of the environmental harm associated with deforestation and fire may occur in the initial phase of these relationships, meaning any potential benefits of mechanisation for fire reduction occur when the remaining forests have already been fragmented and degraded. Second, an increase in incentives for cropland expansion may lead to more deforestation (Gibbs *et al.*, 2007; Morton *et al.*, 2008). Third, high capital activities are responsible for conflicts between land rights of the local populations and the agribusiness sector, since these socioeconomic dynamics only indulge business-as-usual development, excluding people from its process (Toledo *et al.*, 2017; Sauer, 2018). In the Brazilian Amazon, these disputes over territory during the land-use transition are commonly violent (Sauer, 2018), causing irreparable social and cultural losses to local communities including the depletion of key ecosystem services provided by the forest (Foley *et al.*, 2007), which compromises the ways of living of local communities (Steward, 2007). Moreover, mechanised agriculture is a high-capital intervention that is not affordable for most of the small-scale farmers, who have less access to financial subsidies, besides depending on a supply chain infrastructure to deliver high-income agricultural production limited to peri-urban or easily accessible areas (Garrett *et al.*, 2017). Finally, cropland expansion invariably involves increased use of agrochemicals, which result in a substantial amount of environmental pollutants entering the soil and being destined to groundwater water and surface water supplies (Schiesari; Grillitsch, 2011) and social conflicts due to the depletion of natural resources (Damiani *et al.,* 2020). Thus, this land-use transition is unfeasible for sustainable land management.

Taken together, these social and environmental impacts show that intensification should not be seen as a solution to Amazonia's fire problem. Rather, our results highlight the importance of ceasing further deforestation; forest loss is the biggest driver of changes in fire occurrence and marks the start of a transition to more intensive land uses. However, actions taken to reduce deforestation may not on their own be effective at preventing new forest fires, especially given the increases in temperature and reductions in dry season rainfall (Gatti *et al.*, 2021) and increasing levels of forest disturbance (Bullock *et al.*, 2020) that make forests more flammable (Barlow *et al.*, 2020; Holdsworth; Uhl, 1997). Tackling forest fires will require a broad range of measures, including greater participatory policy development (e.g., Carmenta *et al.*, (2013)), restoration (Barlow *et al.*, 2021), and much greater support for community firefighters and development of coherent fire monitoring and combat plans for protected areas (Spínola *et al.*, 2020).

2.5 Conclusions

Our study shows that the fire-transition process in the Brazilian Amazonian Forest is mainly related to anthropogenic changes in landscapes and that the fire occurrence apex is transitioning to more forested landscapes. We found deforestation rates as a key determinant of the apex of active fire occurrence, although cropland expansion (presumably in regions with low forest cover) has resulted in the apex of fire occurrence happening in areas with higher forest cover. This transition of the peak of active fire occurrence to areas with more forest cover appears to have accelerated in the last few years (2012–2019 analyses). So, although fire occurrence is lower in the more advanced phases of land-use transition, this fails to resolve fire occurrence at the frontier, where it is associated with deforestation and land speculation, and where it has the potential to affect large areas of previously undisturbed primary forests. Improving our understanding of the relationships underlying fire transition is important for the sustainable planning and management of the Amazon landscape.

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Data Availability Statement: The active fires data (MODIS MCD14ML Collection 6) is freely available in the Fire Information for Resource Management System (FIRMS) platform (https://firms.modaps.eosdis.nasa.gov/active_fire/ (accessed on 1 March 2021)). Both Mapbiomas data used in this paper are freely available on the Mapbiomas platform (https://brasil.mapbiomas.org/en/colecoes-mapbiomas-1?cama_set_language=en (accessed on 1 March 2021)). The deforestation and the precipitation data used in the appendices are freely available, respectively, on the PRODES/INPE platform (http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes (accessed on 1 January 2022)) and on the CHIRPS platform (https://www.chc.ucsb.edu/data/chirps (accessed on 1 January 2022)).
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Conflicts of Interest: The authors declare no conflict of interest.

3 THIRTY-YEAR ANALYSIS OF FOREST FIRES REVEALS TWO DOMINANT TRAJECTORIES IN THE BRAZILIAN AMAZON

Resumo: A transição do fogo nas paisagens da Amazônia é fortemente influenciada pelo desmatamento e pelas mudanças no uso da terra e na cobertura vegetal. No entanto, não é claro como essa transição do fogo se comporta em termos de incêndios florestais, que são áreas-chave para a manutenção da biodiversidade e dos estoques de carbono. Portanto, este artigo teve como objetivo investigar como ocorre a transição do fogo nas paisagens florestais da Amazônia brasileira e quais variáveis melhor explicam essa transição. Para isso, utilizou-se a Análise de Trajetórias Latentes (LTA, do inglês *Latent Trajectories Analyses*) para classificar as regiões da Amazônia com base em suas mudanças nos incêndios florestais ao longo do tempo e modelos lineares mistos generalizados para relacionar essas mudanças a fatores de paisagem e clima. O melhor modelo de LTA foi identificado com 29 classes, mas em todos os modelos testados, duas classes se destacaram com o maior número de áreas. A primeira trajetória latente destacada (número de grades = 187) foi caracterizada por um histórico mais longo de desmatamento, que teve início antes ou durante a década de 1990, e foi chamada de classe "Consolidada". A segunda trajetória (número de áreas = 110) foi chamada de "Transição", pois foi caracterizada por um histórico de ocupação da terra mais recente, começando na década de 1990 e atingindo o pico na década de 2000. Para as duas principais trajetórias latentes, a cobertura florestal e o desmatamento foram os principais preditores de incêndios florestais, seguidos pelo déficit hídrico. A agricultura mecanizada não foi significativa para nenhuma das duas trajetórias, o que significa que a expansão dessas áreas não protegerá a floresta remanescente nas paisagens amazônicas. Em ambas as trajetórias, foi identificado um aumento nas áreas de floresta queimada a partir de 2015, principalmente. Portanto, é essencial desenvolver políticas públicas que fortaleçam a cobertura florestal, como a restauração florestal, e reduzam o desmatamento nesta região.

Palavras-chave: análise de trajetórias latentes; transição do fogo; desmatamento; expansão agrícola; secas severas.

Abstract: The transition of fire in Amazonian landscapes is strongly influenced by deforestation and changes in land use and land cover. However, it is not clear how the transition of fire behaves in terms of forest fires, which are key areas for biodiversity maintenance and carbon stocks. Thus, this article aimed to investigate how the fire transition occurs in the forest landscapes of the Brazilian Amazon and which variables best explain this transition. To do so, we used Latent Trajectory Analysis (LTA) to classify Amazonia's regions by their changes in forest fires over time and generalized linear mixed models to link these changes to landscape and climate factors. The best LTA model was identified with 29 classes, but in all tested models, two classes stood out with the highest number of grids. The first highlighted latent trajectory (number of grids = 187) was characterized by a longer history of deforestation starting before or during the 1990s, and we called this class "Consolidated". The second trajectory (number of grids = 110) was called "Transition" as it was characterized by a more recent land occupation history starting in the 1990s and peaking in the 2000s. For the two main latent trajectories, forest cover and deforestation were the main predictors of forest fires, followed by water deficit. Mechanized agriculture was not significant for either of the two trajectories, meaning that the expansion of these areas will not protect the remaining forest in the Amazon landscapes. In both trajectories, an increase in burned forest areas was identified from 2015 onwards, primarily. Therefore, it is essential to develop public policies that reinforce forest cover, such as forest restoration, and reduce deforestation in this region.

Keywords: latent trajectory analyses, fire-transition; deforestation; cropland expansion; severe droughts.

3.1 Introduction

Forest fires are a growing threat around the world (Andela *et al.*, 2017; Boer; Resco de Dios; Bradstock, 2020; Kelly *et al.*, 2020; Van Wees *et al.*, 2021). Increasing trends in forest fires across the globe are strongly associated with climate and land-use change (Andela *et al.*, 2017; Bedia *et al.*, 2015; Bowman *et al.*, 2020; Foley *et al.*, 2005, 2007). This is particularly concerning for humid tropical ecosystems, since these areas did not evolve with fire and, therefore, have low resilience to it (Anderson *et al.*, 2018; Cano-Crespo *et al.*, 2023; Cochrane, 2003). This is the case for Amazonia, where forest fires are a major driver of forest degradation (Lapola *et al.*, 2023), due to high levels of tree mortality and biodiversity loss (Barlow *et al.*, 2018; Berenguer *et al.*, 2014, 2021; Lapola *et al.*, 2023).

Brazil holds 60% of the Amazon biome and most of the areas affected by forest fires within the biome. For instance, between 1992 and 2014, approximately 340,000 km² were degraded, of which around 35,000 km² were affected by forest fires (Matricardi *et al.*, 2020). Fire occurrence in the region is strongly associated with spatial variation in the timing of the dry season (Alencar *et al.*, 2011; Armenteras *et al.*, 2017; Carvalho *et al.*, 2021; Schroeder *et al.*, 2009). During abnormally dry years, forest fires tend to spread deeper into the forest, causing greater losses of carbon stocks and biodiversity (Barlow *et al.*, 2016; Berenguer *et al.*, 2014, 2021; Lapola *et al.*, 2023; Silva *et al.*, 2018, 2020; Withey *et al.*, 2018).

In 2020, the estimate of burned areas in the Amazon was the biggest since 2010 (Silva Junior *et al.*, 2021; Silveira *et al.*, 2022), and fire is a growing threat even in protected areas and indigenous territories (Qin *et al.*, 2023). Moreover, mega-fire events (i.e. which are commonly defined in literature as fire events that affect areas larger than 10,000 ha (Linley *et al.*, 2022)) can be explained by inter-annual variation in dry season intensity, being much more likely to occur during severe drought events (Anderson *et al.*, 2018; Brando *et al.*, 2020a, 2020b; Withey *et al.*, 2018). Anthropogenic activities are strongly associated with the occurrence of fires, which tend to be more frequent during the initial stages of land-use transition when higher deforestation rates are typically observed (Aragão; Shimabukuro, 2010; Silvestrini *et al.*, 2011; Van Marle *et al.*, 2017). As human occupation of the landscape increases, the occurrence of fires tends to decrease (Andela *et al.*, 2017; Aragão; Shimabukuro, 2010; Foley *et al.*, 2005; Morton *et al.*, 2008; Tavares *et al.*, 2022). Therefore, the understanding that forest fires vary according to changes in land use and spatiotemporal dynamics of climate suggests that distinct dynamics (trajectories) of forest fires may exist in the Amazon biome.

Despite these advances in the spatiotemporal determinants of fire in the Brazilian Amazon, there are some important uncertainties. Firstly, it is unclear whether different land-use dynamics in the Brazilian Amazon result in different trajectories of forest fires in this biome. Most previous studies have examined active fires, making it difficult to assign a fire event to a particular land-use class and limiting our understanding of how fire behaves in forested areas, where it causes the most ecological and social damage (Barlow *et al.*, 2020; Lapola *et al.*, 2023). Secondly, it is not clear to what extent landscape-level variables drive forest fire occurrence in the Amazon; understanding this is important to elucidate management guidelines to mitigate fire risk. And third, studies that analyse the biome as a whole may miss important spatial variation in forest fire trajectories, as the temporal trajectories of fire are likely to vary due to spatial differences in climate, land-use and occupation dynamics. While fire is an essential management tool in the Amazon biome, the growing trends of deforestation and the increasing frequency of severe drought events (Andela *et al.*, 2022; Anderson *et al.*, 2018; Aragão *et al.*, 2018) highlight the urgent need for effective public policies and future-oriented thinking to preserve this biome.

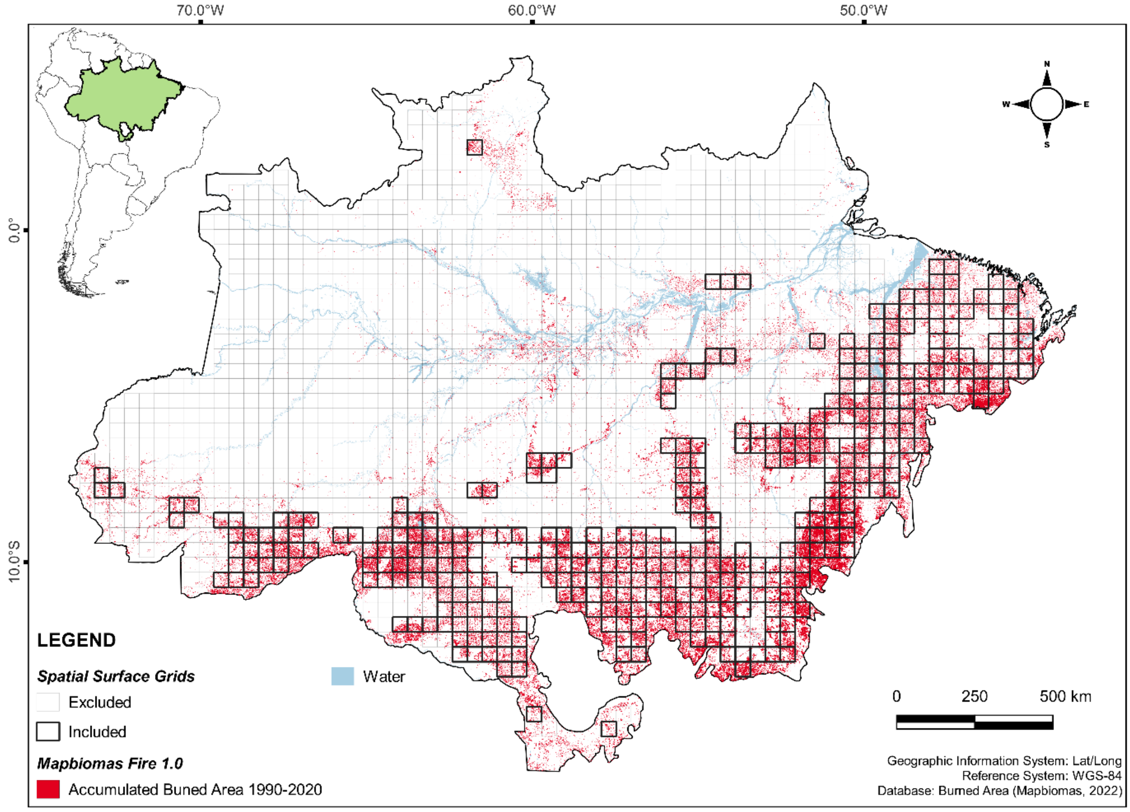
We addressed these knowledge gaps by using the recently developed long-term time series of burned area produced by Mapbiomas and used Latent Trajectory Analyses (LTA) to explore whether there are different fire trajectories across the Amazon, enabling us to examine the determinants of forest fires for each different trajectory. By analysing the percentage of remaining forest that burns in each year, we ask: (1) Are there different trajectories of forest fire extent in the Amazon? And, if so, (2) Can these different trajectories be predicted by landscape-level variables such as deforestation, forest cover, water balance, and the percentage of cropland? And (3) Did these drivers of forest fires change over time? We discuss results in relation to the policies needed to prevent fires.

3.2 Materials and Methods

3.2.1 Study Area

Our study focused on the Brazilian Amazon, specifically on landscapes dominated by forest formations according to the Mapbiomas project classification. To achieve this, we divided the Brazilian Amazon biome into 0.45º spatial grids, excluding grids that were partially outside the biome or had more than 20% coverage of savannas, grasslands, or mangroves. Additionally, we selected grids that corresponded to 90% of the forest fires in the biome during the analysed time series (see Figure 10). Our study analysed 30 years of forest fires in the Brazilian Amazon, starting from 1990. This period is particularly important in terms of forest fires, as the Brazilian Amazon underwent significant changes in its occupation trajectory, with public policies aimed at reducing deforestation in the early 21st century, and the occurrence of several periods of extreme drought.

Figura 10 - Location of the spatial surface grid used in our analysis and accumulated burned area from 1990 to 2020 in the Brazilian Amazon.



3.2.2 Database

3.2.2.1 Burned Area

We used Mapbiomas Fire Collection 1 to gather information on monthly fire scar maps from 1989 to 2020 across the Brazilian Amazon (Alencar *et al.*, 2022). To analyse the data, we used Google Earth Engine to calculate the total forest burned area per year and per grid cell. We considered the percentage of forest burned area within each grid per year. To consider the interannual variability of the fire burned area, we used a 3-year window, taking the average value of the previous, current, and subsequent year (Rosan *et al.*, 2022). With this 3-year window, it is possible to capture forest fires that spread over periods not delimited by the conventional calendar, i.e., crossing from one year to another. We focussed our analysis on the regions of the Amazon that have the greatest problem with fires over the past 30 years by restricting it to the grid cells that together represented 90% of the total forest burned area across the whole time series. This was also a statistical necessity, as our LTA could not converge with many zeros. The forest burned area data was used to classify the areas of interest and as the response variable in our models.

3.2.2.2 Deforestation

We used Mapbiomas Deforestation and Regeneration dataset to compute deforestation areas in each grid cell of our study area. This dataset provides a comprehensive analysis of land-use and land-cover changes by tracking the trajectory of each pixel cell since 1988. To quantify deforestation, we calculated the loss of both primary and secondary forest (Aragão; Shimabukuro, 2010; Fearnside; Barbosa; Graça, 2007). We used Google Earth Engine to process the Mapbiomas data within our study area and calculated a 2-year accumulated deforestation for each grid cell. This timeframe is important as it encompasses the period when fires are commonly used for land clearing, especially during the dry season, which can increase the risk of fire spread (Staal *et al.*, 2020). We then used the 2-year accumulated deforestation estimates as independent variables in our models to predict forest burn areas in the Brazilian Amazon Forest.

3.2.2.3 Land Use and Land Cover

We used the Mapbiomas Collection 6.0 Land Use and Land Cover (LULC) dataset for our analysis. This dataset, generated through machine learning algorithms and Landsat imagery, provides accurate (92.41% for forest classes and 87.73% for farming classes) images of LULC from 1985 to 2020 (Souza *et al.*, 2020). In our analysis, we focused on the following LULC classes: (i) Forest Formation, including both primary and secondary forests, (ii) Soybean as a marker of mechanised agriculture, and (iii) Pasture, Mosaic of Agriculture and Pasture, and Other Temporary Crops, as a representation of all other agricultural practices. We determined forest cover by calculating the total forested area within each grid cell of the landscape. The fraction of mechanised agriculture was calculated based on the percentage of soybean relative to all agricultural practices. These calculations were performed on the study area using Google Earth Engine and then summarised per grid cell. Finally, forest cover and mechanised agriculture fraction were used as independent variables to predict forest burn area in each grid cell and each year.

3.2.2.4 Monthly Precipitation

We calculated Maximum Cumulative Water Deficit (MCWD) in the Brazilian Amazon using the Climate Hazards group Infrared Precipitation with Stations (CHIRPS) monthly dataset. The CHIRPS dataset is based on 0.05º satellite imagery and in situ data and provides daily gridded rainfall time series starting from 1981 (Funk *et al.*, 2015). For the Brazilian Amazon, CHIRPS data explain 73% of what is found by the in-situ station data (Anderson *et al.*, 2018). We calculated the MCWD from 1990 to 2019 using a script made available by (Campanharo; Silva Junior, 2019). The MCWD measures the maximum cumulative water deficit for each year by calculating the monthly water deficit (WD) value and considering the maximum accumulated value (Aragão *et al.*, 2007; Silva Junior *et al.*, 2019). The calculation of WD was performed by considering any precipitation (P) value smaller than the mean Evapotranspiration (E) of the Amazonian forests (~100mm.month-1) as WD. This calculation was performed on a pixel-by-pixel basis for each month (n) using Equation 1. The cumulative WD was calculated based on the rule applied in Equation 1.

$$\text{If } WD_{n-1}(i,j) - E(i,j) + P_n(i,j) < 0;$$
$$\text{then } WD_n(i,j) = WD_{n-1}(i,j) - E(i,j) + P_n(i,j);$$
$$\text{else } WD_n(i,j) = 0$$

We then re-sampled and re-projected the MCWD dataset to our grid cell to obtain the pixel-based MCWD value per year in our study area. This value was used as one of the independent variables of our models to predict forest burned area.

3.2.3 Data Analyses

In an effort to determine whether there are different forest burn trajectories in the Brazilian Amazon, we employed Latent Trajectory Analyses (LTA) to understand the variability of forest fire extent over time and per grid cell. The LTA model simplifies heterogeneous groups into homogeneous patterns, or classes, within a given dataset (Lennon *et al.*, 2018). To classify our latent trajectories, we used the forest burned fraction as a response variable, years as random effects, and each grid cell as a subject, applying the *hlme* function in the *lcmm* package in R (Proust-Lima *et al.*, 2022; Proust-Lima; Philipps; Liquet, 2017). To determine the optimal number of latent classes, we tested various LTA models and selected the one with the best Akaike Information Criterion (AIC) value (Van de Schoot *et al.*, 2017). Ultimately, all models resulted in two major classes (i.e., differentiated by grids with distinct occupation history, either older or more recent), which we used for further analysis.

To understand the relationship between forest burned area in the Brazilian Amazon and landscape-level variables, we generated Generalized Linear Mixed Models (GLMMs) for each of the two main classes identified in the LTA model. As independent variables, we used: (i) 2-year accumulated deforestation, (ii) annual forest cover, (iii) annual fraction of mechanised agriculture, and (iv) MCWD for each grid cell. We treated years and grids as random variables in our models and used the beta family to predict our results, as it best fits fractions derived from continuous datasets (Douma; Weedon, 2019).

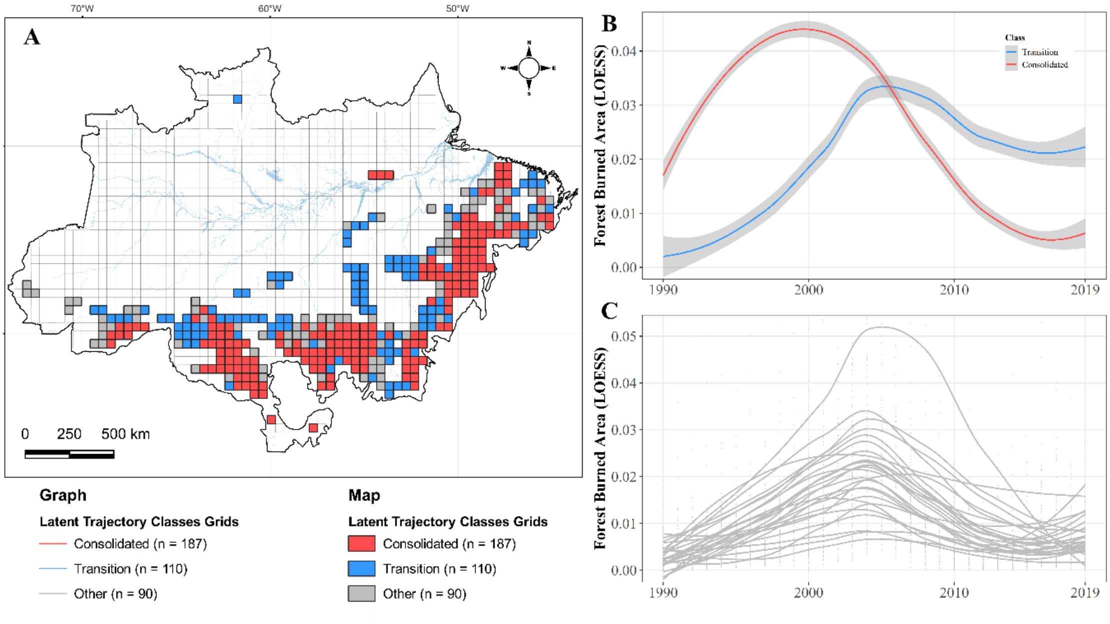
To assess whether the drivers of forest fires changed over time, we generated GLMMs for three distinct time periods, during which the LTA classes had different shapes: (i) 1990-1999, (ii) 2000-2009, and (iii) 2010-2019. For each time period and LTA class, we produced GLMMs, evaluated the models through dredge analyses, selected the best-fitting models, and estimated marginal and conditional R^2.

3.3 Results

3.3.1 Two major classes stand out for forest fires extent in the Brazilian Amazon

Our analysis revealed that the majority of forest fires occur in the so-called arc of deforestation in the Brazilian Amazon (Figure 11a). Furthermore, we observed an expansion of forest fires areas towards the newly affected areas in the arc of deforestation. To identify the best model, we tested a total of 30 latent classes. The optimal solution was obtained with 29 classes (dAIC = 6.15, to the second-best LTA – Appendix B, Table B1). However, all models highlighted only two major latent classes (Figure 11b) and the other classes accounted few grid cells (the total number of grids was 90, distributed among the remaining 27 classes, Figure 11c) Hereafter, we define these latent classes as either consolidated areas (with mean forest cover in 2019 of 41.6%) or transition areas (with mean forest cover in 2019 of 64.6%). According to our analysis, the consolidated areas displayed a significant amount of burned areas during the early period of the time series, with a peak in the early 2000s, followed by an overall decrease. In contrast, the transitioning areas exhibited low burned areas during the early period of the time series, with a peak value occurring in the later 2000s, and a slower decrease thereafter. Notably, both main classes detected showed an increase in burned areas after 2016.

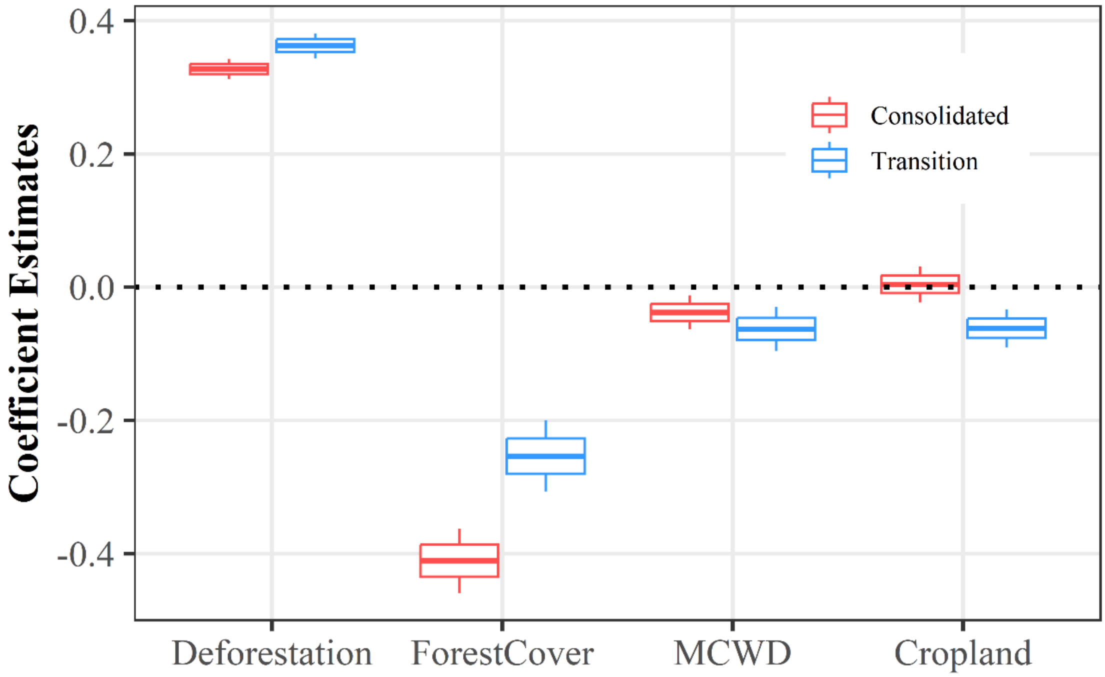
Figura 11 - Latent trajectories of burned area in the Brazilian Amazon Forest found in our analysis. (a) Forest burned area trajectories of the Consolidated and Transition class found in our study. (b) Forest burned area trajectories of the 27 remain classes, not further analysed in our study. (c) Spatial distribution map of the latent trajectories classes found in our study.



3.3.2 The key role of deforestation and forest cover in understanding the burned area dynamics

Over the whole time series, our analysis demonstrated the significance of all response variables in predicting forest burned areas in the Brazilian Amazon, as they were all included in the best-ranked models (Appendix B, Tables B2 and B3) for both consolidated (Conditional r-squared = 0.74; Marginal r-squared = 0.2) and transition areas (Conditional r-squared = 0.68; Marginal r-squared = 0.23). We found that forest cover is the most important variable to predict forest burned areas in consolidated grids, followed by recent deforestation, which is the most important for transitioning grids (Figure 12). In both areas, these are followed by MCWD. Cropland had a much smaller effect and was only slightly significant in the transition class.

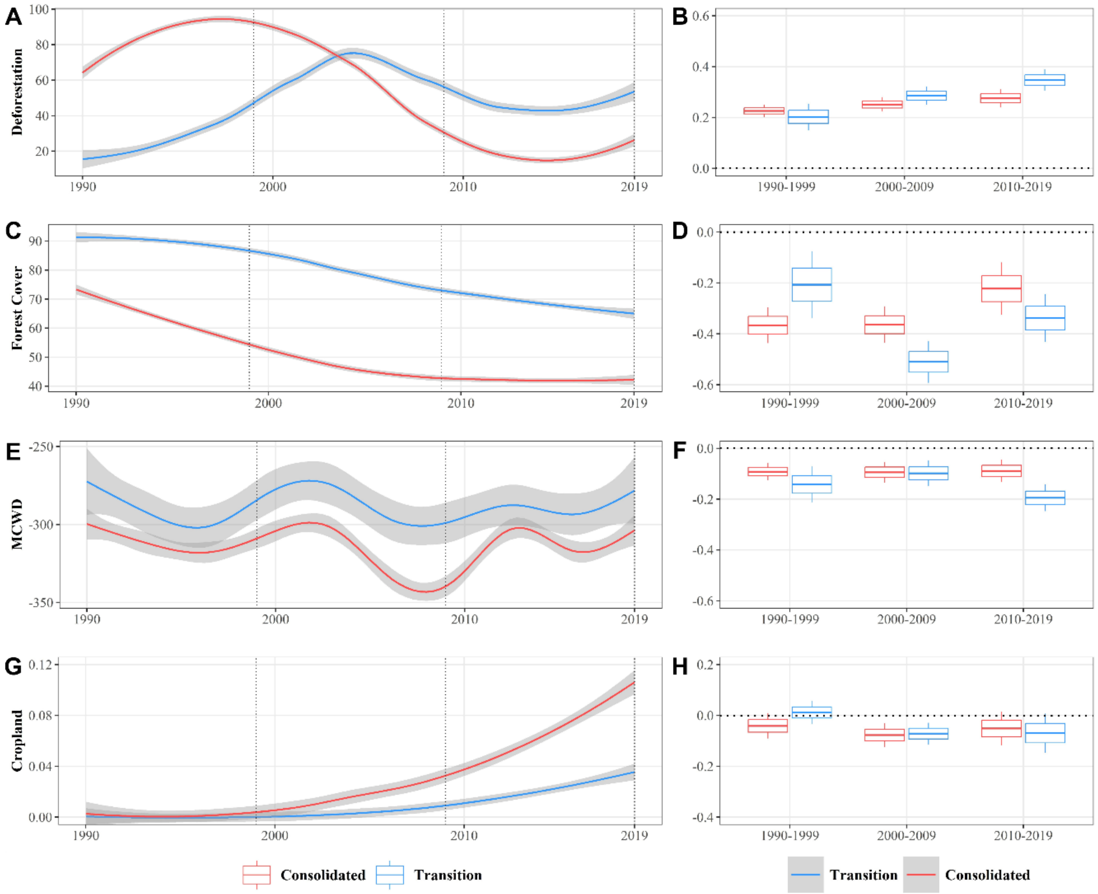
Figura 12 - Coefficient estimates of the Models for Consolidated (boxplots in red) and Transition (boxplots in blue) latent trajectories analysed.



3.3.3 The importance of response variables changes over time

Our analysis revealed notable differences when we examined three distinct time periods, i.e. 1990-1999, 2000-2009, and 2010-2019 (Figure 13). During 1990-1999, forest cover was found to be more significant for the consolidated class, while the transition class showed a greater dependence on forest cover, deforestation, and MCWD. Cropland did not have any significant overall effect during this period. Between 2000 and 2009, forest cover continued as the most significant factor, particularly for the transition class, where it had the highest coefficient value. Deforestation was the second in rank, followed by MCWD for both classes. This was the only period where cropland was significant for both analysed classes. In the most recent period, 2010-2019, both classes showed a similar trajectory and shared similar predictors. During this period, in transition areas, the MCWD importance was the highest in the entire historical series. In addition, the coefficient value of MCWD for the consolidated class appeared to be consistent throughout all analysed periods (Figure 13f). It is important to note that the importance of deforestation increased period after period for both classes, being more noticeable for the transition class.

Figura 13 - Time series distribution of the response variables (LOESS) and coefficient estimates of a-b) deforestation, c-d) forest cover, e-f) MCWD, g-h) cropland in each time period. Elements in red represent the consolidated class and elements in blue represent the transition class.



3.4 Discussion

3.4.1 Trajectories of forest fire are mainly explained by occupation history and change over time

Our study revealed two dominant fire trajectories in the Brazilian Amazon over the past three decades. These trajectories can be differentiated based on their shape and spatial distribution. The first trajectory peaked in the 1990s and was concentrated along the biome's border, while the second trajectory peaked in the 2000s and was more prevalent in more interior parts of the arc of deforestation. These findings align with previous research (Andela *et al.*, 2017; Aragão; Shimabukuro, 2010; Tavares *et al.*, 2022) proposing that fire peak values occur in the early stages of land-use transition for tropical biomes, although it is important to note that these previous studies looked at active fires across all land uses rather than forest fires per se.

Our results highlight that forest cover is the main driver to reduce forest fires and deforestation is the main drive causing them. These are key findings for policy, as they highlight the inherent risk of forest fires in highly deforested landscapes and supports studies suggesting that fire and deforestation could act together to bring about large-scale degradation and forest dieback (Cochrane; Barber, 2009; Malhi *et al.*, 2009; Nobre *et al.*, 2016). The implications of this are simple: they emphasise the urgent necessity to prevent further deforestation and maintaining forest cover, whether through the preservation of forest remnants or the expansion of forested areas. These recommendations have been made before (e.g., Barlow *et al.*, 2018; Morello *et al.*, 2017a; Mataveli *et al.*, 2022), and support Brazil's renewed commitments to combat deforestation as described in the Brazilian Action Plan for Preventing and Control of Deforestation in Amazonia (PPCDAm) phase V (Brasil, 2023) and some regional commitments to reforest at regional scale such as the Pará State Plan Amazonia Now (PEAA, (Pará, 2020).

One key finding is the vital role that deforestation and forest cover have in determining forest fire occurrence. Although deforestation is recognized in the literature (Aragão; Shimabukuro, 2010; Barlow *et al.*, 2020; Cochrane, 2003; Morton *et al.*, 2008; Van Marle *et al.*, 2017) as the main drivers of fire occurrence in the Amazon, these studies tend to focus on all fires, including the fires that are used in the deforestation process itself. The implication of this tight link is that deforestation fires are an important driver of forest fires in the surrounding areas, such that their effect outweighs that of climate (MCWD) or land-use (Cropland). In the Brazilian Amazon, deforestation fires are frequently used for soil management in the vicinity of forested areas (Alencar *et al.*, 2022). This practice can lead to forest fires when the uncontrolled deforestation fires escape to the logged forests, particularly during dry years (Barlow *et al.*, 2020). Another important observation is that the two major forest fire trajectories (Figure 11a) are similar in shape to the changes in deforestation (Figure 13a). This suggests that the Mapbiomas fire product may be identifying deforestation fires as forest fires. This could be because some areas start the deforestation process by using fire, which is only officially registered as deforestation in later years. As a result, these events are aggregated as forest fires.

MCWD was also important in determining forest fire extent in both main trajectories, and across all the analysed time series, consistent with existing research on fire occurrence in the Brazilian Amazon (Alves *et al.*, 2017; Anderson *et al.*, 2018; Pontes-Lopes *et al.*, 2021; Staal *et al.*, 2020). Although our analysis did not allow us to fully understand why MCWD has a lower importance than forest cover or deforestation, however, a few considerations can be made based on this finding: ignition sources are more influential than dry conditions within the forest itself in driving forest fires in the Amazon (Brando *et al.*, 2020b; Ray; Nepstad; Moutinho, 2005); our study grids are primarily located within the arc of deforestation; and this area has the longer dry season length in the Brazilian Amazon (Berenguer *et al.*, 2020; Carvalho *et al.*, 2021). We also found that MCWD had the greatest impact during the 2010-2019 period for the transition class, a time when the Brazilian Amazon Forest experienced two intense drought events, one in 2010 and the other in 2015-2016, leading to mega fires (Aragão *et al.*, 2018; Withey *et al.*, 2018). Several factors likely contribute to this greater susceptibility, including greater deforestation in recent years and more recently degraded and fragmented forests (Hansen *et al.*, 2020; Matricardi *et al.*, 2020; Silva Junior *et al.*, 2018), harder-to-access areas, and fewer consolidated fire brigades (Spínola *et al.*, 2020).

Finally, our analysis showed a weak relationship between cropland expansion and fire occurrence in the Brazilian Amazon. While cropland expansion has been proposed to reduce the use of fire due to the greater use of technology in this land use (e.g., Andela *et al.*, 2017), our findings suggest that it may not effectively reduce forest fire occurrence at the landscape scale, as previously thought (Tavares *et al.*, 2022). In fact, we found that even though cropland expansion may reduce ignition sources, this is irrelevant if there are still ignition sources from deforestation, which remains a major contributor to fire occurrence in the Brazilian Amazon Forest. Thus, while cropland expansion has been seen as an important alternative for reducing fire and deforestation (Nepstad *et al.*, 2014), it alone will not be sufficient to protect forest remnants from fire.

3.4.2 Implications for public policies planning to control forest fires

A key outcome of our study is the importance of strengthening policies to reduce deforestation in order to reduce forest fires and maintaining forest cover across the biome. This will mean reversing the decline in effective environmental public policies that has occurred over the last six years (Amigo, 2020; Pelicice; Castello, 2021; Silva Junior *et al.*, 2021). Our results also show that controlling forest cover alone is not enough; the MCWD was also found to be a significant factor, highlighting the need to give special attention to areas that are most vulnerable to severe droughts and extreme climatological events. As a result, a thorough understanding of the relationship of climate and forest fires could be integrated into public policy planning. In addition, our results show that mechanisation and cropland expansion are not a viable solution; although cropland expansion may be about a fire transition in open lands, when agricultural fires are no longer needed (Andela *et al.*, 2017; Tavares *et al.*, 2022), it does not seem to be an effective measure for controlling forest fires.

In summary, our research has showed that in order to effectively reduce forest fires, public policies must prioritise both the reduction of deforestation and the promotion of landscape-level forest conservation and restoration efforts. Hence, these results give strong support to the re-development of PPCDAm by the Brazilian government, and a rapid transition towards zero deforestation (Moutinho; Guerra; Azevedo-Ramos, 2016), where forest areas are not cleared. These federal-level policies could be supported by regional policies aimed at reducing deforestation and forest fires, such as the aforementioned PEAA in the state of Pará. Moreover, public initiatives that strengthen the maintenance of forest cover must be reinforced and supported, such as creating and safeguarding protected areas and indigenous lands (Qin *et al.*, 2023; Villén-Pérez *et al.*, 2020). This will ensure the long-term health and biodiversity of the Amazon, as well as prevent forest fires to happen.

3.5 Conclusion

Our study has revealed two dominant trajectories of fire occurrence in the Brazilian Amazon, defined temporally and spatially, which separate areas with older and more recent occupation histories. Forest cover and deforestation emerged as the main predictors of forest fire occurrence, followed the water deficit indicator. Cropland areas were not important predictors of forest fires in any of the analysed scenarios, and it is evident that agricultural intensification has not acted to safeguard forest remnants. Hence, our results indicate that public policies aimed at reducing forest fires should focus on reducing deforestation, alongside preserving, and restoring forest cover. Given the recent surge in forest fires, it is vital to consider more direct and intensive measures to prevent fire from spreading into the forest, enabling sustainable local development, and safeguarding biodiversity and carbon stocks.

4 CONCLUSÃO GERAL

4.1 Resultados Chave: Impactos e Implicações

A presente pesquisa teve como objetivo geral investigar o processo de transição da ocorrência de fogo na Floresta Amazônica brasileira e identificou dois principais resultados. Primeiramente, foi possível verificar que a ocorrência de fogo na floresta segue uma relação unimodal com a antropização do território. Além disso, em relação às queimadas florestais, foi possível definir duas distintas trajetórias de transição desse tipo de fogo. Sobre esses resultados, destaca-se ainda:

i. O processo de transição da ocorrência de fogo na Floresta Amazônica brasileira segue uma relação quadrática com a cobertura florestal na região. O pico desse processo ocorre em paisagens em transição de altas taxas de desmatamento para expansão de agriculturas com maior grau de tecnologia, como as lavouras de soja, que não dependem de fogo no processo de plantio. O desmatamento foi a principal variável preditora para entender a ocorrência de fogo. Esse resultado é especialmente interessante, uma vez que é durante o processo de remoção da cobertura florestal que o fogo é geralmente introduzido nas paisagens de floresta na Amazônia.

ii. Em relação às queimadas florestais, foi possível identificar duas trajetórias distintas de ocorrência de fogo na Floresta Amazônica brasileira. A trajetória predominante (com 187 grades de 50km² cada) ocorreu em áreas com um processo de ocupação mais consolidado, com o pico de desmatamento ocorrendo no início da década de 2000. Já a segunda trajetória identificada (com 110 grades de 50km² cada) apresentou picos de desmatamento no final dos anos 2000. Em ambas as trajetórias, o desmatamento voltou a aumentar na segunda metade da década de 2010. O desmatamento e as alterações na cobertura florestal foram as principais variáveis preditoras dessas trajetórias, seguidas pela variável de déficit hídrico utilizada nesse estudo.

Esses resultados são particularmente importantes, uma vez que destacam os padrões de ocorrência de fogo que seguem os usos antrópicos do território. Em um primeiro momento, foi encontrado que a ocorrência de fogo na Floresta Amazônica brasileira diminui conforme as paisagens se tornam mais antropizadas, considerando todos os tipos de ocorrência de fogo. Entretanto, em um segundo momento, esse trabalho mostrou que essa redução não é suficiente para proteger as florestas das paisagens mais consolidadas. Portanto, pensar na preservação das florestas amazônicas, tanto para a conservação da biodiversidade quanto para o armazenamento de carbono, está intrinsecamente ligado à redução dos novos desmatamentos e à promoção de políticas públicas voltadas para a recuperação de áreas degradadas e restauração florestal sem o uso de fogo.

Os resultados encontrados nesta pesquisa podem ter implicações importantes ao pensar nas políticas públicas de desenvolvimento e conservação da Floresta Amazônica brasileira. No caso das queimadas florestais, é importante notar que medidas de ação imediata à ocorrência das queimadas serão menos eficazes do que medidas planejadas para prevenção a longo prazo. Dessa forma, os resultados deste estudo destacam duas principais ações de médio e longo prazo que terão impacto significativo na redução das queimadas e incêndios florestais, e que a manutenção do *"business as usual"* não garantirá a redução dessas ocorrências:

i. A redução do desmatamento é amplamente entendida na literatura científica como estando associada à ocorrência de fogo na Amazônia brasileira. Os dados e análises produzidos neste trabalho reforçam essa hipótese e mostram que o período em que o PPCDAm foi mais ativo na região coincidiu com uma redução na ocorrência de queimadas nesse território. Portanto, é importante enfatizar que as políticas públicas voltadas para a redução da ocorrência de fogo na Amazônia brasileira devem levar em consideração principalmente a redução gradual e o fim do desmatamento nesse território.

ii. Os resultados encontrados nesta pesquisa destacam que o aumento na cobertura florestal é importante para a redução da ocorrência de queimadas florestais. Portanto, investimentos tanto na manutenção das áreas florestais já existentes, com o fortalecimento e criação de unidades de conservação e terras indígenas, quanto na promoção de políticas públicas que incentivem a recuperação e restauração florestal são fundamentais no processo de redução das queimadas florestais na Amazônia brasileira.

iii. Embora a expansão das monoculturas, como a soja, possa reduzir a ocorrência de fogo na paisagem Amazônica, é importante ressaltar que esse método produtivo não contribui para a redução na ocorrência de fogo na floresta desse território. Assim, incentivar esse tipo de produção agrícola sem promover a redução do desmatamento e o fortalecimento das florestas na região não trará benefícios para os remanescentes florestais dos territórios. Pelo contrário, pode causar a perda de biodiversidade e dos estoques de carbono nas paisagens Amazônicas. Portanto, é fundamental adotar políticas públicas que incentivem práticas agrícolas sustentáveis que levem em conta a conservação da floresta.

Por fim, é importante ressaltar que a retomada das políticas federais para conservação da Floresta Amazônica brasileira terá um papel fundamental na redução da ocorrência de fogo nesse território. Os dados levantados e os resultados encontrados nesse estudo, assim como em diversas publicações científicas que lidam com a temática, mostram que, principalmente nos últimos seis anos, o aumento nas taxas de desmatamento causou também um aumento na ocorrência de fogo no território. Isso é válido para todos os tipos de fogo na paisagem e é uma situação chave para que muitos remanescentes florestais tenham se tornado mais degradados e cada vez mais vulneráveis ao fogo e às secas. Deste modo, para pensar o desenvolvimento sustentável na Região Amazônica, serão necessárias medidas abrangentes e união de esforços de todos os atores públicos, bem como a conscientização dos atores da iniciativa privada desse território. Assim, estudos como esse podem contribuir para aumentar o entendimento da dinâmica de fogo nas paisagens Amazônicas e quais variáveis poderão ser utilizadas como chave na construção dessas novas políticas públicas de preservação da Floresta Amazônica brasileira.

4.2 Prioridades para Pesquisas Futuras

Essa pesquisa adotou uma abordagem abrangente para a Amazônia brasileira como um todo. No entanto, é crucial considerar pontos prioritários para pesquisas futuras. Primeiramente, a inclusão de análises de sensibilidade é fundamental para compreender até que ponto os resultados desta Tese de Doutorado são aplicáveis à previsão da transição do fogo no bioma Amazônico brasileiro. Além disso, é relevante analisar como outras variáveis, como os aspectos climáticos mais robustos, por exemplo, a duração dos períodos de seca em diferentes regiões, podem influenciar a dinâmica da transição de fogo. A realização de análises mais aprofundadas, que levem em conta a sensibilidade dos resultados, pode ter um impacto significativo na identificação das variáveis-chave para compreender a transição do fogo na Amazônia Brasileira.

Por fim, é importante considerar a abordagem da transição de fogo em escalas mais locais e regionais. Os insights obtidos a partir desta análise podem servir como base para o desenvolvimento de políticas públicas mais sólidas destinadas à prevenção de incêndios em nível local.

4.3 Conclusões de Forma Integrada

Essa Tese mostrou como ocorre o processo de transição do regime de fogo na Amazônia brasileira. No capítulo 2, em análise considerando todos os tipos de focos de calor na paisagem, observou-se que o ponto máximo de ocorrência de fogo está migrando para áreas com maior cobertura florestal. Ademais, identificou-se também que as taxas de desmatamento e a expansão da soja são fatores determinantes para essa transição do regime de fogo nas paisagens Amazônicas.

No capítulo 3, foi possível destacar duas trajetórias dominantes de queimadas florestais na Amazônia brasileira, definidas temporal e espacialmente, que separam áreas com históricos de ocupação mais antigos e mais recentes. Para as áreas de incêndios florestais consideradas, o desmatamento e a cobertura florestal foram as duas principais variáveis preditoras do fogo. Além disso, a variável climática teve importância constante durante os anos analisados. Por fim, a expansão da soja não se mostrou relevante em ambas as classes.

A interação desses resultados com as suas principais implicações socioambientais e sobre políticas públicas foi explorada nessa Tese. De maneira geral, mostrou-se como a transição do regime de fogo e suas variáveis preditoras interagem causando impactos nas populações locais e nas suas formas de vida. Além disso, destacou-se como a literatura científica vêm contribuindo para entender como a floresta Amazônica está se adaptando a esses novos processos de interação antrópica na paisagem. Por fim, destacou-se que que as políticas públicas destinadas a reduzir os incêndios florestais devem concentrar-se na redução do desmatamento, juntamente com a preservação e restauração da cobertura florestal. Assim, é vital considerar medidas mais diretas e intensivas para prevenir a propagação do fogo nas florestas, possibilitando o desenvolvimento local sustentável e a preservação da biodiversidade e dos estoques de carbono.

REFERÊNCIAS

ALENCAR, A. *et al.* Temporal variability of forest fires in eastern Amazonia. **Ecological Applications**, v. 21, n. 7, p. 2397–2412, 2011. https://doi.org/10.1890/10-1168.1.

ALENCAR, A. A. C. *et al.* Long-term landsat-based monthly burned area dataset for the Brazilian biomes using deep learning. **Remote Sensing**, v. 14, n. 11, e2510, 2022. https://doi.org/10.3390/rs14112510.

ALVES, L. M. *et al.* Sensitivity of Amazon regional climate to deforestation. **American Journal of Climate Change**, v. 06, n. 01, p. 75–98, 2017. https://doi.org/10.4236/ajcc.2017.61005.

AMIGO, I. When will the Amazon hit a tipping point? **Nature**, v. 578, n. 7796, p. 505–507, 2020. https://doi.org/10.1038/d41586-020-00508-4.

ANDELA, N. *et al.* A human-driven decline in global burned area. **Science**, v. 356, n. 6345, p. 1356–1362, 2017. https://doi.org/10.1126/science.aal4108.

ANDELA, N. *et al.* Tracking and classifying Amazon fire events in near real time. **Sci. Adv**., v. 8, n. 30, eabd2713, 2022. https://doi.org/10.1126/sciadv.abd2713.

ANDERSON, L. O. *et al.* Vulnerability of Amazonian forests to repeated droughts. **Philosophical Transactions of the Royal Society B: Biological Sciences**, v. 373, n. 1760, e20170411, 2018. http://doi.org/10.1098/rstb.2017.0411.

ARAGÃO, L. E. O. C. *et al.* Spatial patterns and fire response of recent Amazonian droughts. **Geophysical Research Letters**, v. 34, n. 7, 2007. https://doi.org/10.1029/2006GL028946.

ARAGÃO, L. E. O. C. *et al.* 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. **Nature Communications**, v. 9, n. 1, p. 1–12, 2018. https://doi.org/10.1038/s41467-017-02771-y.

ARAGÃO, L. E. O. C.; SHIMABUKURO, Y. E. The incidence of fire in amazonian forests with implications for REDD. **Science**, v. 328, n. 5983, p. 1275–1278, 2010. https://doi.org/10.1126/science.1186925.

ARMENTERAS, D. *et al.* Changing patterns of fire occurrence in proximity to forest edges, roads and rivers between NW Amazonian countries. **Biogeosciences**, v. 14, n. 11, p. 2755–2765, 2017. https://doi.org/10.5194/bg-14-2755-2017.

BARBOSA, R. I.; FEARNSIDE, P. M. Fire frequency and area burned in the Roraima savannas of Brazilian Amazonia. **Forest Ecology and Management**, v. 204, n. 2–3, p. 371–384, 2005. https://doi.org/10.1016/j.foreco.2004.09.011.

BARLOW, J. *et al.* The critical importance of considering fire in REDD+ programs. **Biological Conservation**, v. 154, p. 1–8, 2012. https://doi.org/10.1016/j.biocon.2012.03.034.

BARLOW, J. *et al.* Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation. **Nature**, v. 535, n. 7610, p. 144–147, 2016. https://doi.org/10.1038/nature18326.

BARLOW, J. *et al.* The future of hyperdiverse tropical ecosystems. **Nature**, v. 559, n. 7715, p. 517–526, 2018. https://doi.org/10.1038/s41586-018-0301-1.

BARLOW, J. *et al.* Clarifying Amazonia's burning crisis. **Global Change Biology**, v. 26, n. 2, p. 319–321, 2020. https://doi.org/10.1111/gcb.14872.

BARLOW, J. *et al.* Restoration Priorities and Benefits within Landscapes and Catchments and Across the Amazon Basin. Em: **Amazon Assessment Report 2021**. Nova Iorque: United Nations Sustainable Development Solutions Network, 2021. p. 29.3-29.26.

BARTÓN, K. **MuMIn:** multi-model inference. R package version 1.43.17**.** 2020.

BEDIA, J. *et al.* Global patterns in the sensitivity of burned area to fire-weather: Implications for climate change. **Agricultural and Forest Meteorology**, v. 214–215, p. 369–379, 2015. https://doi.org/10.1016/j.agrformet.2015.09.002.

BERENGUER, E. *et al.* A large-scale field assessment of carbon stocks in human-modified tropical forests. **Global Change Biology**, v. 20, n. 12, p. 3713–3726, 2014. https://doi.org/10.1111/gcb.12627.

BERENGUER, E. *et al.* Improving the spatial-temporal analysis of Amazonian fires. **Global Change Biology**, p. 1–3, 2020. https://doi.org/10.1111/gcb.15425.

BERENGUER, E. *et al.* Tracking the impacts of El Niño drought and fire in human-modified Amazonian forests. **Proceedings of the National Academy of Sciences of the United States of America**, v. 118, n. 30, e2019377118, 2021. https://doi.org/10.1073/pnas.2019377118.

BOER, M. M.; RESCO DE DIOS, V.; BRADSTOCK, R. A. Unprecedented burn area of Australian mega forest fires. **Nature Climate Change**, v. 10, p. 171-172, 2020. https://doi.org/10.1038/s41558-020-0716-1.

BOWMAN, D. M. J. S. *et al.* Vegetation fires in the Anthropocene. **Nature Reviews Earth & Environment**, v. 1, n. 10, p. 500–515, 2020. https://doi.org/10.1038/s43017-020-0085-3.

BRANDO, P. *et al.* Amazon wildfires: Scenes from a foreseeable disaster. **Flora: Morphology, Distribution, Functional Ecology of Plants**, v. 268, p. 151609, 2020a. https://doi.org/10.1016/j.flora.2020.151609.

BRANDO, P. *et al.* The gathering firestorm in southern Amazonia. **Science Advances**, v. 6, n. 2, eaay1632, p. 1–10, 2020b. https://doi.org/10.1126/sciadv.aay1632.

BRASIL. **Reestablishes the Brazilian Action Plan for Preventing and Control of Deforestation in Amazonia (PPCDAm), Decree Nº 11,367**. 2023. Disponível em http://www.planalto.gov.br/ccivil_03/_ato2023-2026/2023/decreto/D11367.htm. Acessado em 28 de setembro de 2023.

BROOKS, M. *et al.* Modeling zero-inflated count data with glmmTMB. **bioRxiv**, p. 132753, 2017. https://doi.org/10.1101/132753.

BULLOCK, E. L. *et al.* Satellite-based estimates reveal widespread forest degradation in the Amazon. **Global Change Biology**, v. 26, n. 5, p. 2956–2969, 2020. https://doi.org/10.1111/gcb.15029.

CAMPANHARO, W. A.; SILVA JUNIOR, C. H. L. **Maximum cumulative Water Deficit - MCWD:** a R language script. 2019. Disponível em: https://zenodo.org/record/5034650. Acessado em 28 de setembro de 2023.

CANO-CRESPO, A. *et al.* Forest edge burning in the Brazilian Amazon promoted by escaping fires from managed pastures. **Journal of Geophysical Research: Biogeosciences**, v. 120, n. 10, p. 2095–2107, 2015. https://doi.org/10.1002/2015JG002914.

CANO-CRESPO, A. *et al.* Characterization of land cover-specific fire regimes in the Brazilian Amazon. **Regional Environmental Change**, v. 23, n. 1, 2023. https://doi.org/10.1007/s10113-022-02012-z.

CARMENTA, R. *et al.* Shifting Cultivation and Fire Policy: Insights from the Brazilian Amazon. **Human Ecology**, v. 41, n. 4, p. 603–614, 2013. https://doi.org/10.1007/s10745-013-9600-1.

CARVALHO, N. S. *et al.* Spatio-temporal variation in dry season determines the Amazonian fire calendar. **Environmental Research Letters**, v. 16, n. 12, p. 125009, 2021. https://doi.org/10.1088/1748-9326/ac3aa3.

CHEN, Y. *et al.* Long-term trends and interannual variability of forest, savanna and agricultural fires in South America. **Carbon Management**, v. 4, n. 6, p. 617–638, 2013. https://doi.org/10.4155/cmt.13.61.

COCHRANE, M. A. Fire science for rainforests. **Nature**, v. 421, p. 913-919, 2003. https://doi.org/10.1038/nature01437.

COCHRANE, M. A.; BARBER, C. P. Climate change, human land use and future fires in the Amazon. **Global Change Biology**, v. 15, n. 3, p. 601–612, 2009. https://doi.org/10.1111/j.1365-2486.2008.01786.x.

DAMIANI, S. *et al.* “All That’s Left is Bare Land and Sky”: Palm Oil Culture and Socioenvironmental Impacts on a Tembé Indigenous Territory in the Brazilian Amazon. **Ambiente e Sociedade**, v. 23, p. 1–25, 2020. https://doi.org/10.1590/1809-4422asoc20190049r2vu2020L6AO.

DOUMA, J. C.; WEEDON, J. T. Analysing continuous proportions in ecology and evolution: A practical introduction to beta and Dirichlet regression. **Methods in Ecology and Evolution,** v. 10, 2019. https://doi.org/10.1111/2041-210X.13234.

ERFANIAN, A.; WANG, G.; FOMENKO, L. Unprecedented drought over tropical South America in 2016: Significantly under-predicted by tropical SST. **Scientific Reports**, v. 7, n. 1, p. 22–24, 2017. https://doi.org/10.1038/s41598-017-05373-2.

FEARNSIDE, P. M. Deforestation soars in the Amazon. **Nature**, v. 521, p. 423, 2015. https://doi.org/10.1038/521423b.

FEARNSIDE, P. M.; BARBOSA, R. I.; GRAÇA, P. M. L. A. Burning of secondary forest in Amazonia: Biomass, burning efficiency and charcoal formation during land preparation for agriculture in Apiaú, Roraima, Brazil. **Forest Ecology and Management**, v. 242, n. 2–3, p. 678–687, 2007. https://doi.org/10.1016/j.foreco.2007.02.002.

FIRMS. **MODIS Collection 6.1 Active Fire Data**. 2022. Disponível em: https://firms.modaps.eosdis.nasa.gov/download/. Acessado em: 28 de setembro de 2023.

FOLEY, J. A. *et al.* Global consequences of land use. **Science**, v. 309, n. 5734, p. 570–574, 2005. https://doi.org/10.1126/science.1111772

FOLEY, J. A. *et al.* Amazonia revealed: Forest degradation and loss of ecosystem goods and services in the Amazon Basin. **Frontiers in Ecology and the Environment**, v. 5, n. 1, p. 25–32, 2007. https://doi.org/10.1890/1540-9295(2007)5[25:ARFDAL]2.0.CO;2.

FUNK, C. *et al.* The climate hazards infrared precipitation with stations - A new environmental record for monitoring extremes. **Scientific Data**, v. 2, 150066, p. 1–21, 2015. https://doi.org/10.1038/sdata.2015.66.

GARRETT, R. D. *et al.* Explaining the persistence of low income and environmentally degrading land uses in the Brazilian Amazon. **Ecology and Society**, v. 22, n. 3, 2017. https://doi.org/10.5751/ES-09364-220327.

GARRETT, R. D. *et al.* Forests and Sustainable Development in the Brazilian Amazon: History, Trends, and Future Prospects. **Annual Review of Environment and Resources**, v. 46, p. 625–652, 2021. https://doi.org/10.1146/annurev-environ-012220-010228.

GATTI, L. V. *et al.* Amazonia as a carbon source linked to deforestation and climate change. **Nature**, v. 595, 2021. https://doi.org/10.1038/s41586-021-03629-6.

GIBBS, H. K. *et al.* Monitoring and estimating tropical forest carbon stocks: Making REDD a reality. **Environmental Research Letters**, v. 2, n. 4, 045023, 2007. https://doi.org/10.1088/1748-9326/2/4/045023

GIGLIO, L.; SCHROEDER, W.; JUSTICE, C. O. The collection 6 MODIS active fire detection algorithm and fire products. **Remote Sensing of Environment**, v. 178, p. 31–41, 2016. https://doi.org/10.1016/j.rse.2016.02.054.

GOMES, V. H. F. *et al.* Amazonian tree species threatened by deforestation and climate change. **Nature Climate Change**, v. 9, n. 7, p. 547–553, 2019. https://doi.org/10.1038/s41558-019-0500-2.

HANSEN, M. C. *et al.* The fate of tropical forest fragments. **Sci. Adv**., v. 6, n. 11, eaax8574, 2020. https://doi.org/10.1126/sciadv.aax8574.

HOLDSWORTH, A. R.; UHL, C. Fire in Amazonian Selectively Logged Rain Forest and the Potential for Fire Reduction. **Ecological Applications**, v. 7, n. 2, p. 713-725, 1997. https://doi.org/10.2307/2269533.

INPE. **Monitoramento do Desmatamento da Floresta Amazônica Brasileira por Satélite - PRODES Amazônia**. 2022. Disponível em: http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes. Acessado em 28 de setembro de 2023.

JOLLY, W. M. *et al.* Climate-induced variations in global wildfire danger from 1979 to 2013. **Nature Communications**, v. 6, 7537, p. 1–11, 2015. https://doi.org/10.1038/ncomms8537.

KELLY, L. T. *et al.* Fire and biodiversity in the Anthropocene. **Science**, v. 370, n. 6519, eabb0355, 2020. https://doi.org/10.1126/science.abb0355.

LAPOLA, D. M. *et al.* The drivers and impacts of Amazon Forest degradation. **Science**, v. 379, n. 6630, eabp8622, 2023. https://doi.org/10.1126/science.abp8622.

LENNON, H. *et al.* Framework to construct and interpret latent class trajectory modelling. **BMJ Open**, v. 8, n. 7, e020683, 2018. https://doi.org/10.1136/bmjopen-2017-020683.

LINLEY, G. D. *et al.* What do you mean, 'megafire'? **Global Ecology and Biogeography**, v. 31, n. 10, p. 1906–1922, 2022. https://doi.org/10.1111/geb.13499.

MALHI, Y. *et al.* Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. **PNAS**, v. 106, n. 49, 2008. https://doi.org/10.1073/pnas.0804619106.

MAPBIOMAS. **Mapbiomas Collection 5.0**. 2020. Disponível em: http://mapbiomas.org/. Acessado em 28 de setembro de 2023.

MAPBIOMAS. **Mapbiomas Deforestation and Regeneration Toolkit**. 2021a.

MAPBIOMAS. **Deforestation Method**. 2021b. Disponível em: https://mapbiomas.org/en/deforestation-method. Acessado em 28 de setembro de 2023.

MATAVELI, G. *et al.* Science-based planning can support law enforcement actions to curb deforestation in the Brazilian Amazon. **Conservation Letters**, v. 15, n. 6, 2022. https://doi.org/10.1111/conl.12908.

MATRICARDI, E. A. T. *et al.* Long-term forest degradation surpasses deforestation in the Brazilian Amazon. **Science**, v. 369, n. 6509, p. 1378–1382, 2020. https://doi.org/10.1126/science.abb3021.

MAYLE, F. E.; POWER, M. J. Impact of a drier Early-Mid-Holocene climate upon Amazonian forests. **Philosophical Transactions of the Royal Society B: Biological Sciences**, v. 363, n. 1498, p. 1829–1838, 2008. https://doi.org/10.1098/rstb.2007.0019.

MELLO, N. G. R. DE; ARTAXO, P. Evolução do Plano de Ação para Prevenção e Controle do Desmatamento na Amazônia Legal. **Revista do Instituto de Estudos Brasileiros**, n. 66, p. 108, 2017. https://doi.org/10.11606/issn.2316-901X.v0i66p108-129.

MORELLO, T. F. *et al.* Fires in Brazilian Amazon: Why Does Policy Have a Limited Impact? **Ambiente & Sociedade**, v. 20, n. 4, p. 19–38, 2017b. https://doi.org/10.1590/1809-4422asoc0232r1v2042017.

MORELLO, T. F. *et al.* Policy instruments to control Amazon fires: A simulation approach. **Ecological Economics**, v. 138, p. 199–222, 2017a. https://doi.org/10.1016/j.ecolecon.2017.03.043.

MORTON, D. C. *et al.* Agricultural intensification increases deforestation fire activity in Amazonia. **Global Change Biology**, v. 14, n. 10, p. 2262–2275, 2008. https://doi.org/10.1111/j.1365-2486.2008.01652.x.

MOUTINHO, P.; GUERRA, R.; AZEVEDO-RAMOS, C. Achieving zero deforestation in the Brazilian Amazon: What is missing? **Elementa: Science of the Anthropocene**, v. 4, 2016. https://doi.org/10.12952/journal.elementa.000125.

NAKAGAWA, S.; JOHNSON, P. C. D.; SCHIELZETH, H. The coefficient of determination R2 and intra-class correlation coefficient from generalized linear mixed-effects models revisited and expanded. **Journal of the Royal Society Interface**, v. 14, n. 134, 2017. https://doi.org/10.1098/rsif.2017.0213.

NEPSTAD, D. *et al.* Amazon drought and its implications for forest flammability and tree growth: a basin-wide analysis. **Global Change Biology**, v. 10, n. 5, p. 704–717, 2004. https://doi.org/10.1111/j.1529-8817.2003.00772.x.

NEPSTAD, D. *et al.* Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. **Science**, v. 344, n. 6188, p. 1118–1123, 2014. https://doi.org/10.1126/science.1248525.

NEPSTAD, D. C. *et al.* Interactions among Amazon land use, forests and climate: Prospects for a near-term forest tipping point. **Philosophical Transactions of the Royal Society B: Biological Sciences**, v. 363, n. 1498, p. 1737–1746, 2008. https://doi.org/10.1098/rstb.2007.0036.

NOBRE, C. A. *et al.* Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. **Proceedings of the National Academy of Sciences**, v. 113, n. 39, p. 10759–10768, 2016. https://doi.org/10.1073/pnas.1605516113.

PAIVA, P. F. P. R. *et al.* Deforestation in protect areas in the Amazon: a threat to biodiversity. **Biodiversity and Conservation**, v. 29, n. 1, p. 19–38, 2020. https://doi.org/10.1007/s10531-019-01867-9.

PARÁ. **Establishes the Pará State Plan Amazonia Now (PEAA), Decree Nº 941**. 2020. Disponível em https://www.semas.pa.gov.br/legislacao/normas/view/192188. Acessado em 28 de setembro de 2023.

PELICICE, F. M.; CASTELLO, L. A political tsunami hits Amazon conservation. **Aquatic Conservation: Marine and Freshwater Ecosystems**, v. 31, n. 5, p. 1221–1229, 2021. https://doi.org/10.1002/aqc.3565.

PIVELLO, V. R. The use of fire in the cerrado and Amazonian rainforests of Brazil: Past and present. **Fire Ecology**, v. 7, n. 1, p. 24–39, 2011. https://doi.org/10.4996/fireecology.0701024.

PONTES-LOPES, A. *et al.* Drought-driven wildfire impacts on structure and dynamics in a wet Central Amazonian forest. **Proceedings of the Royal Society B: Biological Sciences**, v. 288, n. 1951, 2021. https://doi.org/10.1098/rspb.2021.0094.

PROUST-LIMA, C. *et al.* **lcmm: Extended Mixed Models Using Latent Classes and Latent Processes**. R package, 2022. Disponível em: https://cran.r-project.org/package=lcmm. Acessado em 9 de fevereiro de 2023.

PROUST-LIMA, C.; PHILIPPS, V.; LIQUET, B. Estimation of extended mixed models using latent classes and latent processes: The R package lcmm. **Journal of Statistical Software**, v. 78, 2017. https://doi.org/10.18637/jss.v078.i02.

QIN, Y. *et al.* Forest conservation in Indigenous territories and protected areas in the Brazilian Amazon. **Nature Sustainability**, v. 6, p. 295-305, 2023. https://doi.org/10.1038/s41893-022-01018-z.

R CORE TEAM. **R:** a language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing, 2021.

RAY, D.; NEPSTAD, D.; MOUTINHO, P. Micrometeorological and canopy controls of fire susceptibility in a forested Amazon landscape. **Ecological Applications**, v. 15, n. 5, p. 1664–1678, 2005. https://doi.org/10.1890/05-0404.

ROSAN, T. M. *et al.* Fragmentation-Driven Divergent Trends in Burned Area in Amazonia and Cerrado. **Frontiers in Forests and Global Change**, v. 5, e801408, 2022. https://doi.org/10.3389/ffgc.2022.801408.

SAUER, S. Soy expansion into the agricultural frontiers of the Brazilian Amazon: The agribusiness economy and its social and environmental conflicts. **Land Use Policy**, v. 79, p. 326–338, 2018. https://doi.org/10.1016/j.landusepol.2018.08.030.

SCHIESARI, L.; GRILLITSCH, B. Pesticides meet megadiversity in the expansion of biofuel crops. **Frontiers in Ecology and the Environment**, v. 9, n. 4, p. 215–221, 2011. https://doi.org/10.1890/090139.

SCHROEDER, W. *et al.* The spatial distribution and interannual variability of fire in Amazonia. **Geophysical Monograph Series**, v. 186, p. 43–60, 2009. https://doi.org/10.1029/2008GM000723.

SILVA, C. V. J. *et al.* Drought-induced Amazonian wildfires instigate a decadal-scale disruption of forest carbon dynamics. **Philosophical Transactions of the Royal Society B: Biological Sciences**, v. 373, n. 1760, 2018. https://doi.org/10.1098/rstb.2018.0043.

SILVA, C. V. J. *et al.* Estimating the multi-decadal carbon deficit of burned Amazonian forests. **Environmental Research Letters**, v. 15, n. 11, 2020. https://doi.org/10.1088/1748-9326/abb62c.

SILVA JUNIOR, C. H. L. *et al.* Deforestation-induced fragmentation increases forest fire occurrence in central Brazilian Amazonia. **Forests**, v. 9, n. 6, 2018. https://doi.org/10.3390/f9060305.

SILVA JUNIOR, C. H. L. *et al.* The Brazilian Amazon deforestation rate in 2020 is the greatest of the decade. **Nature Ecology and Evolution**, v. 5, n. 2, p. 144–145, 2021. https://doi.org/10.1038/s41559-020-01368-x.

SILVA JUNIOR, C. H. L. *et al.* Fire responses to the 2010 and 2015/2016 Amazonian droughts. **Frontiers in Earth Science**, v. 7, 2019. https://doi.org/10.3389/feart.2019.00097.

SILVEIRA, M. V. F. *et al.* Amazon fires in the 21st century: The year of 2020 in evidence. **Global Ecology and Biogeography**, v. 31, n. 10, p. 2026–2040, 2022. https://doi.org/10.1111/geb.13577.

SILVESTRINI, R. A. *et al.* Simulating fire regimes in the Amazon in response to climate change and deforestation. **Ecological Applications**, v. 21, n. 5, p. 1573–1590, 2011. https://doi.org/10.1890/10-0827.1.

SOUZA, C. M. *et al.* Reconstructing Three Decades of Land Use and Land Cover Changes in Brazilian Biomes with Landsat Archive and Earth Engine. **Remote Sensing**, v. 12, n. 17, p. 2735, 2020. https://doi.org/10.3390/rs12172735.

SPÍNOLA, J. N. *et al.* A shared perspective on managing Amazonian sustainable-use reserves in an era of megafires. **Journal of Applied Ecology**, v. 57, p. 2132–2138, 2020. https://doi.org/10.1111/1365-2664.13690.

STAAL, A. *et al.* Feedback between drought and deforestation in the Amazon. **Environmental Research Letters**, v. 15, n. 4, 2020. https://doi.org/10.1088/1748-9326/ab738e.

STEWARD, C. From colonization to “environmental soy”: A case study of environmental and socio-economic valuation in the Amazon soy frontier. **Agriculture and Human Values**, v. 24, n. 1, p. 107–122, 2007. https://doi.org/10.1007/s10460-006-9030-4.

TAVARES, P. A. *et al.* Exploring the Role of Deforestation and Cropland Expansion in Driving a Fire-Transition in the Brazilian Amazon. **Land**, v. 11, n. 12, 2022. https://doi.org/10.3390/land11122274.

THONICKE, K. *et al.* The role of fire disturbance for global vegetation dynamics: Coupling fire into a dynamic global vegetation model. **Global Ecology and Biogeography**, v. 10, n. 6, p. 661–677, 2001. https://doi.org/10.1046/j.1466-822X.2001.00175.x.

TOLEDO, P. M. de. *et al.* Development paradigms contributing to the transformation of the Brazilian Amazon: do people matter? **Current Opinion in Environmental Sustainability**, v. 26–27, p. 77–83, 2017. https://doi.org/10.1016/j.cosust.2017.01.009.

VAN DE SCHOOT, R. *et al.* The GRoLTS-Checklist: Guidelines for Reporting on Latent Trajectory Studies. **Structural Equation Modeling**, v. 24, n. 3, p. 451–467, 2017. https://doi.org/10.1080/10705511.2016.1247646.

VAN MARLE, M. J. E. *et al.* Fire and deforestation dynamics in Amazonia (1973-2014). **Global Biogeochemical Cycles**, v. 31, n. 1, p. 24–38, 2017. https://doi.org/10.1002/2016GB005445.

VAN WEES, D. *et al.* The role of fire in global forest loss dynamics. **Global Change Biology**, v. 27, n. 11, p. 2377–2391, 2021. https://doi.org/10.1111/gcb.15591.

VILLÉN-PÉREZ, S. *et al.* Brazilian Amazon gold: indigenous land rights under risk. **Elem Sci Anth**, v. 8, 2020. https://doi.org/10.1525/elementa.427.

WIGNERON, J.-P. *et al.* Tropical forests did not recover from the strong 2015–2016 El Niño event. **Science Advances**, v. 6, eaay4603, 2020. https://doi.org/10.1126/sciadv.aay4603.

WITHEY, K. *et al.* Quantifying immediate carbon emissions from El Niño-mediated wildfires in humid tropical forests. **Philosophical Transactions of the Royal Society B: Biological Sciences**, v. 373, n. 1760, 2018. https://doi.org/10.1098/rstb.2017.0312.

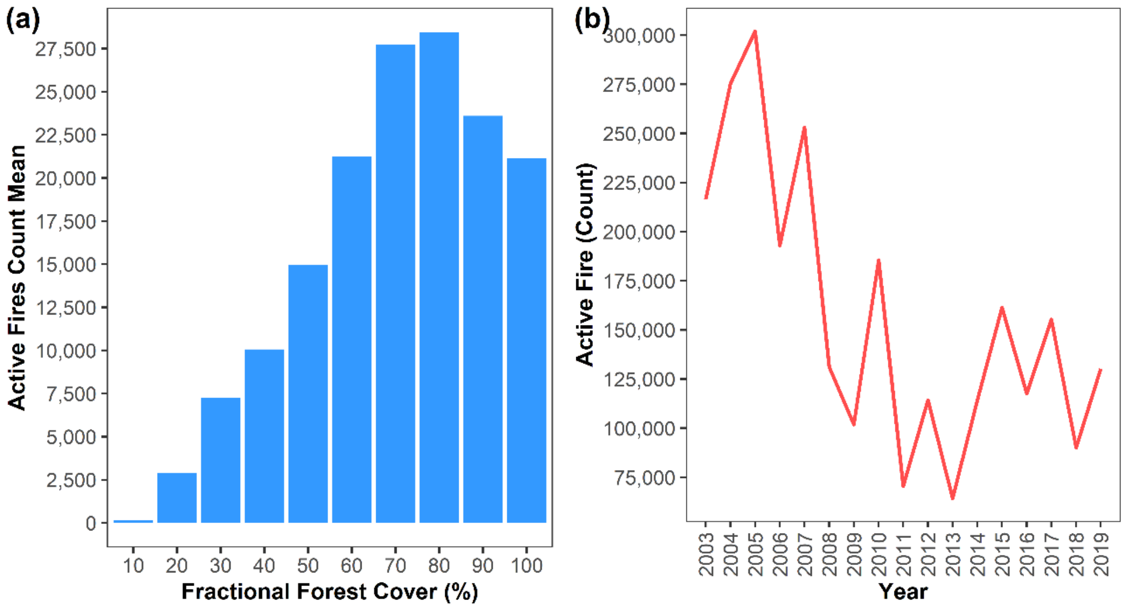
ZENG, N. *et al.* Causes and impacts of the 2005 Amazon drought. **Environmental Research Letters**, v. 3, n. 1, 2008. https://doi.org/10.1088/1748-9326/3/1/014002.

APÊNDICE A- EXPLORING THE ROLE OF DEFORESTATION AND CROPLAND EXPANSION IN DRIVING A FIRE-TRANSITION IN THE BRAZILIAN AMAZON

APÊNDICE A1

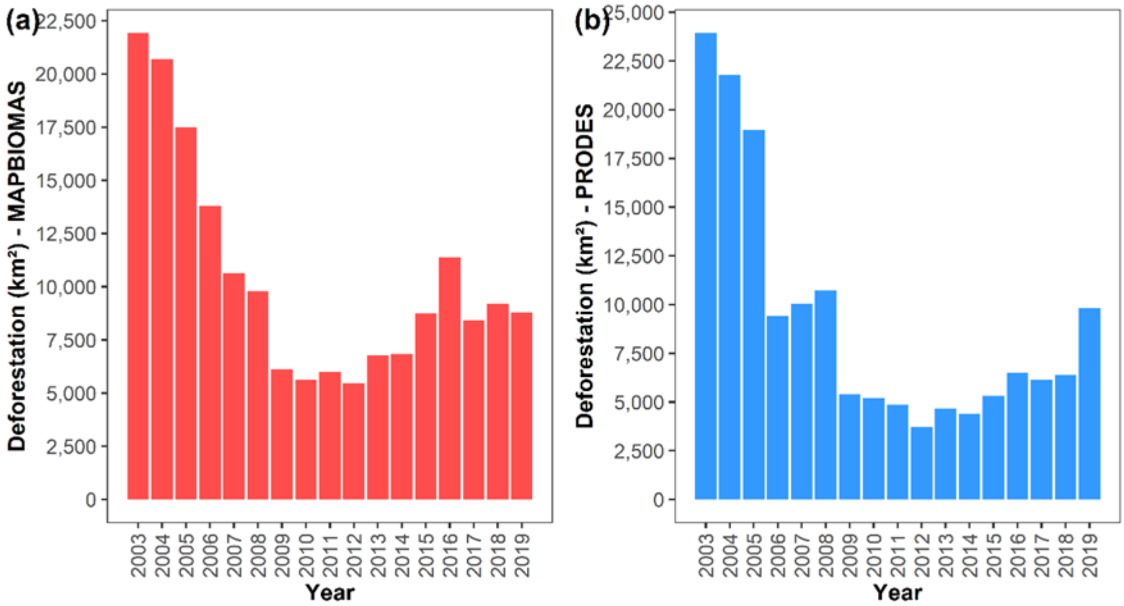
Most of the active fires occurs in grids with more than 50% of forest cover (Figure A1a), being the peak of hotpots occurrence in landscapes with 80% of forest cover. Over the analysed years, there was an important decrease in the active fires' occurrence (Figure A1b), from peaks of ~300,000 hotspots in the El Niño of 2005 to ~175,000 hotspots in the El Niño of 2015.

Figure A1 - Active fire behaviour plots: (a) Mean of active fires per year divided per fractional forest cover of each grid cell. (b) Active Fire per year.



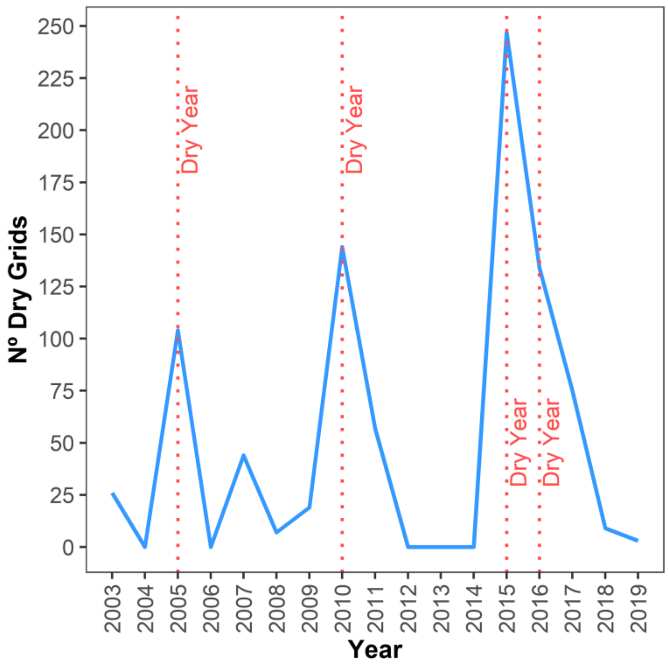
We used deforestation data for both primary and secondary forests from the Mapbiomas Deforestation and Regeneration database (Mapbiomas, 2021a)—Figure A2a. This Mapbiomas database is still new and being improved over time. Its method differs from PRODES/INPE (INPE, 2022) (Figure A2b)—which is the most conventional method to calculate deforestation in the Brazilian Amazon. The Mapbiomas Deforestation and Regeneration database computes deforestation from the first to the last day of the normal year and estimates the deforestation of secondary vegetation. Because of the differences in the deforestations rates patterns at the middle of the time series (decreasing in the first years and then increasing again), we conducted some investigations separating the analyses in two periods (2003–2011 and 2012–2019; Appendix C).

Figure A2 - Annual deforestation rates in the study area: (a) Mapbiomas Primary and Secondary Vegetation. (b) PRODES.



In order to determine the years impacted by severe droughts, we used the Climate Hazards group Infrared Precipitation with Stations (CHIRPS) (Funk *et al.*, 2015) monthly dataset to calculate the Maximum Cumulative Water Deficit (MCWD) (Aragão *et al.*, 2007; Campanharo; Silva Junior, 2019). We re-sampled the MCWD data to 0.45° and re-projected it to our grid to compute the pixel-based MCWD anomalies. We calculated these anomalies from the long-term mean from 1981 to 2019 (t) normalised by the standard deviation (σ) (Silva *et al.*, 2018). A reclassification was then applied and years with result values smaller than −1.96 were considered as anomalous. Lastly, the number of cells with MCWD anomalies for the entire study area per year was calculated (Figure A3). From these results, we considered 2005, 2010, 2015 and 2016 as dry years, and we made analyses where these years are not modelled to observe their implications in the analyses (Appendix B).

Figure A3 - Number of dry grid cells per year. The years that were considered as severe droughts are high-lighted in red.



APÊNDICE A2

In order to find the best-fitting model for predicting the active fire apex height and the forest cover apex-location, we produced a dredge analysis with the key variables (Table A1). For these models, we considered total deforestation rates of primary and secondary vegetation, and soybean areas as a marker of cropland area. In these analyses, all years were considered. The deforestation rate was the variable that better predicted the active fire apex-location, being in all the best ranked models; and cropland area was the variable most important for predicting the forest cover apex-location. However, both variables were found in the best-fitting models (dAIC < 2) for apex-height and apex-location.

Table A1 - Predicted models for the active fire apex-height and forest cover apex-location models. These analyses considered deforestation rates and cropland area as independent variables. The results are ranked by the AIC of each function.

Dependent Variable	Intercept	Cropland Area	Deforestation Area	Deforestation X Cropland	AICc	Delta	Weight
Active Fire Apex-Height 2003–2019	**68.1341**	**NA**	**0.0252**	**NA**	**214.2524**	**0.0000**	**0.5396**
	185.1137	**−0.0053**	**0.0210**	**NA**	**214.8702**	**0.6178**	**0.3962**
	227.6442	−0.0110	0.0176	0.0000	218.8215	4.5690	0.0549
	479.5580	−0.0106	NA	NA	222.6618	8.4093	0.0081
	331.6909	NA	NA	NA	226.4416	12.1892	0.0012
Forest Cover Apex-Location 2003–2019	**50.4838**	**0.0002**	**NA**	**NA**	**78.0671**	**0.0000**	**0.4685**
	47.9510	**0.0002**	**0.0002**	**NA**	**78.2357**	**0.1686**	**0.4306**
	47.7533	0.0002	0.0002	0.0000	82.3456	4.2785	0.0552
	52.8240	NA	NA	NA	83.1258	5.0587	0.0373
	52.7333	NA	0.0000	NA	86.1093	8.0423	0.0084

We also analysed the active fire apex-height and forest cover apex-location models, considering soybean and temporary crop as markers of cropland (mechanised production) areas (Table A2). We did not use these models because we could not confirm whether all temporary crops areas were mechanised. However, and for reference only, the results from the models were similar to the ones found when only the soybean areas were considered. Deforestation was the most repeated variable in the active fire apex-height models, and the cropland area was included in a greater number of forest cover apex-location models.

Table A2 - Predicted models for the active fire apex-height and forest cover apex-location models. These analyses considered deforestation rates and cropland area as independent variables. In these models, we considered soybean and temporary crops as cropland area. The results are ranked by the AIC of each function.

Dependent Variable	Intercept	Cropland Area	Deforestation Area	Deforestation X Cropland	AICc	Delta	Weight
Active Fire Apex-Height 2003–2019	**68.1341**	**NA**	**0.0252**	**NA**	**214.2524**	**0.0000**	**0.5024**
	217.5720	**−0.0051**	**0.0203**	**NA**	**214.7015**	**0.4490**	**0.4014**
	339.4363	−0.0152	0.0099	0.0000	217.8758	3.6234	0.0821
	531.5038	−0.0103	NA	NA	221.5704	7.3179	0.0129
	331.6909	NA	NA	NA	226.4416	12.1892	0.0011
Forest Cover Apex-Location 2003–2019	**46.5932**	**0.0002**	**0.0002**	**NA**	**77.1620**	**0.0000**	**0.5438**
	49.8425	**0.0002**	**NA**	**NA**	**78.0471**	**0.8851**	**0.3494**
	45.8719	0.0003	0.0003	0.0000	81.1776	4.0156	0.0730
	52.8240	NA	NA	NA	83.1258	5.9637	0.0276
	52.7333	NA	0.0000	NA	86.1093	8.9473	0.0062

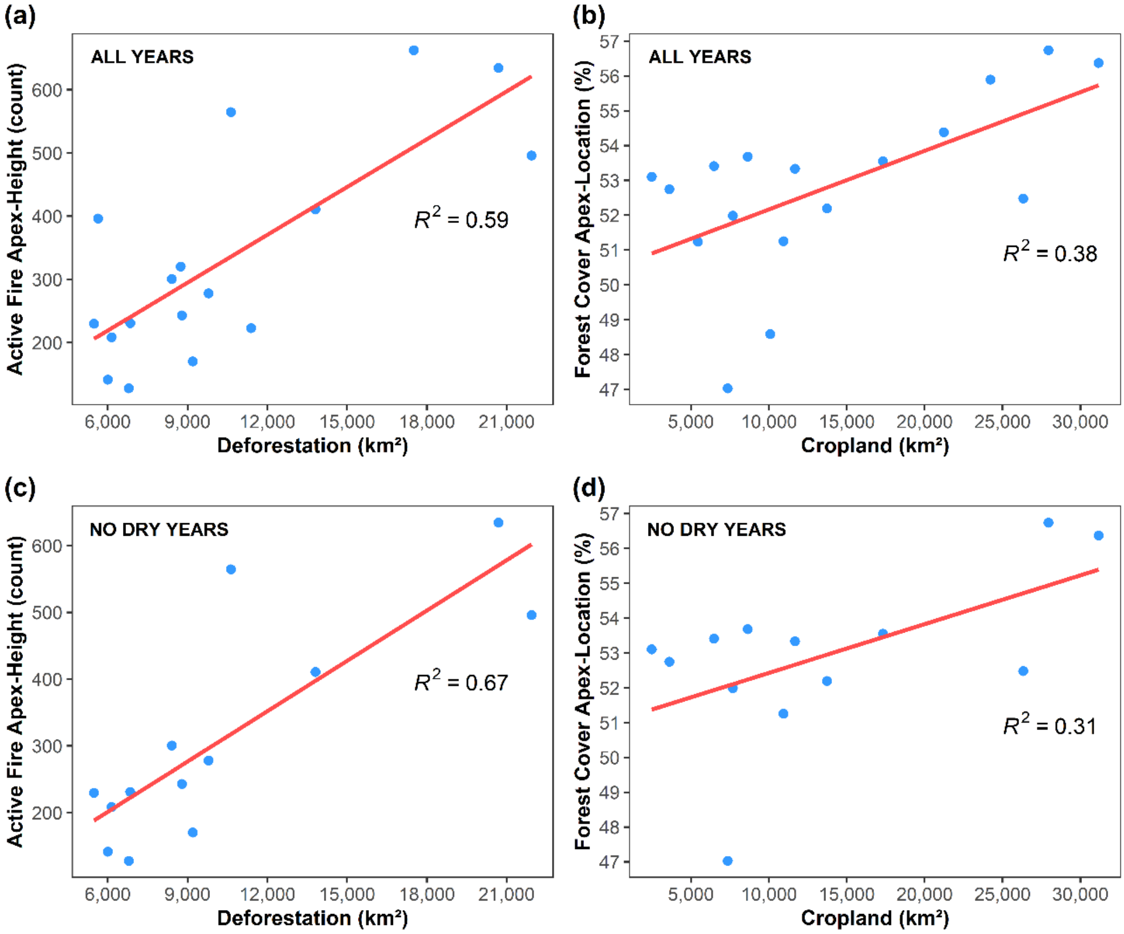
Additionally, we investigated the active fire apex-height and forest cover apex-location without considering dry years (2005, 2010, 2015 and 2016). We found these analyses relevant because in these years, the amount of active fire occurrence tends to be greater than in normal years, which might change the fire-transition patterns during the analysed period (Table A3). In these analyses, we also found the deforestation rates as the key variable for active fire apex-location and cropland area as the main predictor of forest cover apex-location. However, the results of the models performed slightly better without the dry years.

Table A3 - Predicted models for the active fire apex-height and forest cover apex-location models. These analyses considered deforestation rates and cropland area as independent variables. In these models, we removed the years with severe droughts (2005, 2010, 2015 and 2016). The results are ranked by the AIC of each function.

Dependent Variable	Intercept	Cropland Area	Deforestation Area	Deforestation X Cropland	AICc	Delta	Weight
Active Fire Apex-Height No Dry Years	**50.5988**	**NA**	**0.0251**	**NA**	**162.5920**	**0.0000**	**0.8178**
	118.6297	−0.0030	0.0225	NA	165.9493	3.3573	0.1526
	262.6756	−0.0258	0.0104	0.0000	169.8633	7.2713	0.0216
	435.2554	−0.0093	NA	NA	172.8497	10.2576	0.0048
	310.5030	NA	NA	NA	173.7141	11.1221	0.0031
Forest Cover Apex-Location No Dry Years	**51.0259**	**0.0001**	**NA**	**NA**	**61.9643**	**0.0000**	**0.5479**
	52.9153	**NA**	**NA**	**NA**	**63.4096**	**1.4453**	**0.2660**
	49.1293	0.0002	0.0001	NA	64.8540	2.8897	0.1292
	53.0844	NA	0.0000	NA	66.8583	4.8940	0.0474
	47.7071	0.0004	0.0003	0.0000	70.0586	8.0943	0.0096

Subsequently, we present the key variables results when compared with the active fire apex-height and forest cover apex-location when the severe dry years (2005, 2010, 2015 and 2016) are not considered in the analyses (Figure A4). In these analyses, the deforestation rates were more significant to describe the active fire apex-height without dry years in the analyses, and the cropland areas were slightly relevant to predict the forest cover apex-location when all years are considered. However, the differences between these models and the ones with all years were not significant.

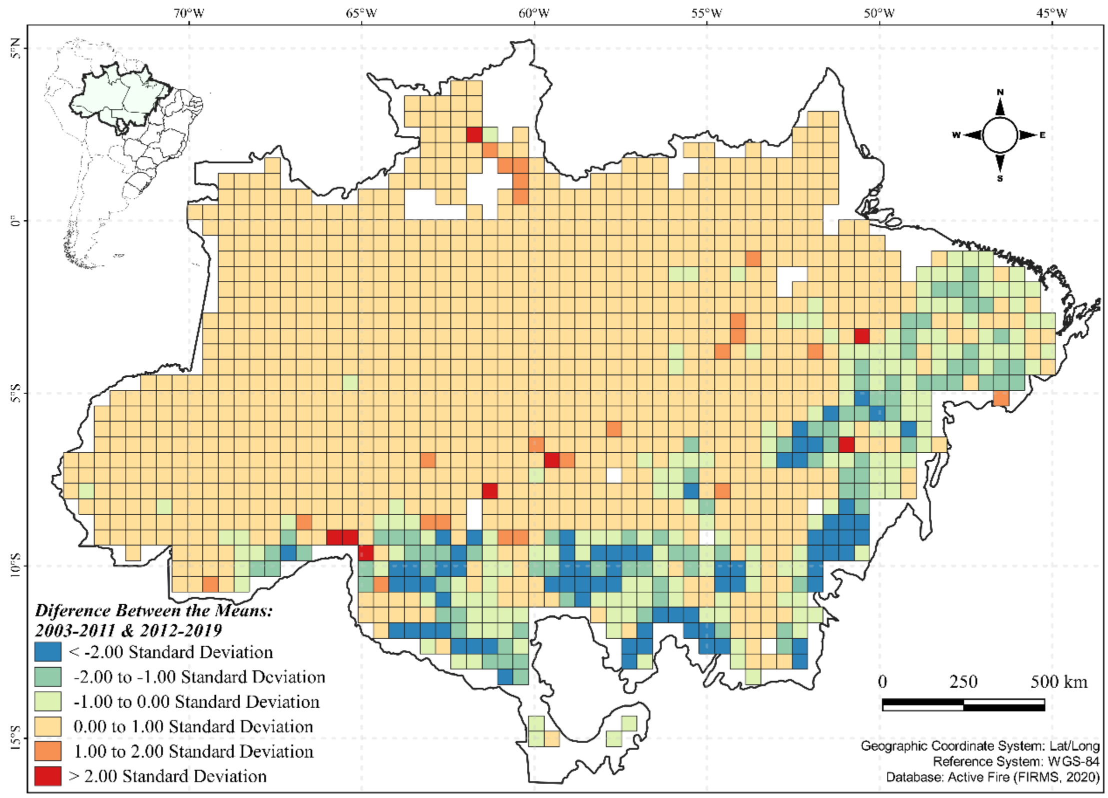
Figure A4 - Linear models of the significant variables used to describe active fire apex-height and forest cover apex-location. (a) Active fire apex-height by annual deforestation with all years. (b) Forest cover apex-location by cropland area over all years. (c) Active fire apex-height by annual deforestation without severe drought years. (d) Forest cover apex-location by cropland area without severe drought years.



APÊNDICE A3

We also analysed the active fire apex-height and forest cover apex-location in two different periods: (i) from 2003 to 2011, period in which the deforestation rates had a significant decrease due to governmental interventions in Amazon to reduce deforestation; and (ii) from 2012 to 2019, during which the deforestation rates first stabilised and then increased again. In addition, there were also differences in the fire behaviour when these two periods are compared. Figure A5 shows the fire behaviour in each grid cell, wherein most of the areas with the oldest occupancy history (northeast and south-southeast) had a reduction in fire occurrence, and the rest had a small increase. Moreover, there are more areas with a significant decrease in fire occurrence than there are areas with a significant increase in fire occurrence.

Figure A5 - Standard deviation difference between the fire occurrence in the two analysed periods. We made this calculation based on the mean of the second period (2012–2019) minus the mean of the first period (2003–2011).



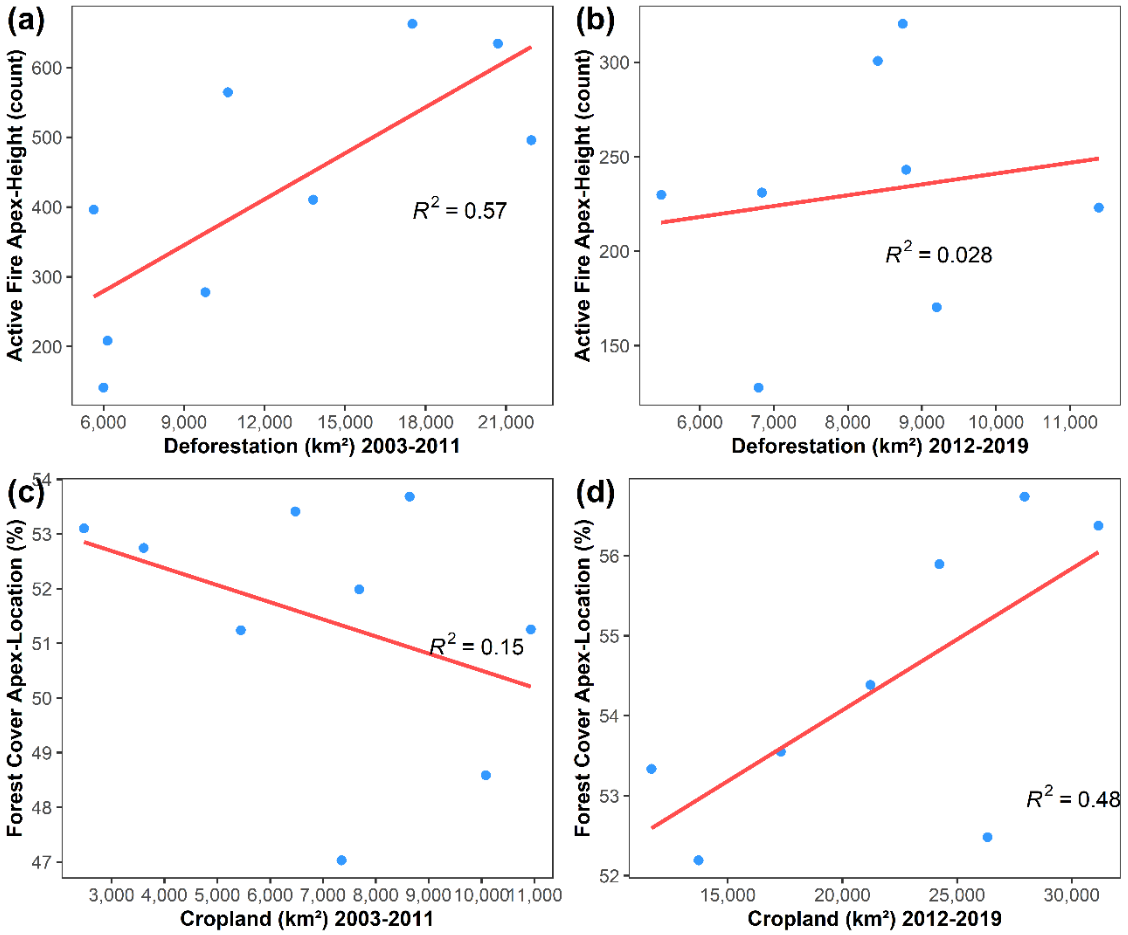
Additionally, we performed a dredge analysis of the active fire apex-height and forest cover apex-location for each period, to investigate whether deforestation rates or cropland areas can predict their behaviour (Table A4). Our results show that deforestation metrics are good for predicting the apex-height in the 2003–2011 period, while we found the cropland areas in the second best-fitting model for all dependent variables. The apex-location models for the 2012–2019 period had three models with similar AIC, and they also had the smallest AIC values when all analyses are considered.

Table A4 - Predicted models for the active fire apex-height and forest cover apex-location models for the two analyses periods: (i) 2003–2011 and (ii) 2012–2019. These analyses considered deforestation rates and cropland area as independent variables. The results are ranked by the AIC of each function.

Dependent Variable	Intercept	Cropland Area	Deforestation Area	Deforestation X Cropland	AICc	Delta	Weight
Active Fire Apex-Height 2003–2011	**147.816**	**NA**	**0.022**	**NA**	**121.706**	**0.000**	**0.523**
	753.998	**−0.048**	**NA**	**NA**	**122.615**	**0.908**	**0.332**
	421.384	NA	NA	NA	124.472	2.766	0.131
	7.281	0.011	0.027	NA	128.872	7.165	0.015
	175.291	-0.023	0.009	0.000	138.938	17.231	0.000
Active Fire Apex-Height 2012–2019	**230.786**	**NA**	**NA**	**NA**	**94.197**	**0.000**	**0.868**
	177.852	0.002	NA	NA	99.182	4.985	0.072
	183.840	NA	0.006	NA	99.572	5.375	0.059
	187.893	0.003	−0.002	NA	108.494	14.297	0.001
	−266.007	0.026	0.061	0.000	126.271	32.074	0.000
Forest Cover Apex-Location 2003–2011	**51.450**	**NA**	**NA**	**NA**	**45.261**	**0.000**	**0.735**
	53.629	−0.0003	NA	NA	48.610	3.348	0.138
	49.862	NA	0.0001	NA	48.836	3.575	0.123
	56.883	−0.0006	−0.0001	NA	55.746	10.485	0.004
	55.904	−0.0004	0.0000	0.0000	67.544	22.283	0.000
Forest Cover Apex-Location 2012–2019	**54.369**	**NA**	**NA**	**NA**	**37.193**	**0.000**	**0.398**
	50.529	**0.0002**	**NA**	**NA**	**37.494**	**0.302**	**0.343**
	49.036	**NA**	**0.0007**	**NA**	**38.094**	**0.901**	**0.254**
	49.194	0.0001	0.0003	NA	45.967	8.774	0.005
	65.328	−0.0007	−0.002	0.0000	61.432	24.239	0.000

We also investigated the individual relationship between the active fire apex-height and the forest cover apex-location per period with each of the key independent variables (Figure A6). Our results shows that the deforestation rates are key to understanding the active fire apex-height in the first period (2003–2011)—Figure A6a, while the increase in the cropland area is strongly related with the increase in the forest cover apex-location in the second period (2012–2019)—Figure A6d. Therefore, to reduce the amount of active fire occurrence per year the deforestation of new areas must be avoided, and investments in mechanized agriculture are not a guarantee that forests will be preserved in the near future, since the increase in its area is related to an increase in the forest cover apex-location investigated in our analyses.

Figure A6 - Linear models of the significant variables used to describe active fire apex-height and forest cover apex-location per analysed period. (a) Active fire height by annual deforestation from 2003 to 2011. (b) Active fire height by annual deforestation from 2012 to 2019. (c) Location of the active fire apex in relation to forest cover against cropland area from 2003 to 2011. (d) Location of the active fire apex in relation to forest cover against cropland area from 2012 to 2019.



APÊNDICE B - THIRTY-YEAR ANALYSIS OF FOREST FIRES REVEALS TWO DOMINANT TRAJECTORIES IN THE BRAZILIAN AMAZON

APÊNDICE B1

Table B1 - AIC of LTA models per nº of classes.

Nº of LTA classes	**AIC**	**Nº of LTA classes**	**AIC**	**Nº of LTA classes**	**AIC**
1	-44279.50	11	-44244.31	21	-44217.88
2	-44279.83	12	-44239.16	22	-44212.04
3	-44276.45	13	-44240.74	23	-44209.66
4	-44272.95	14	-44239.16	24	-44209.07
5	-44268.84	15	-44234.01	25	-44203.95
6	-44265.37	16	-44230.32	26	-44204.78
7	-44261.58	17	-44232.02	27	-44197.83
8	-44262.94	18	-44227.93	28	-44197.62
9	-44254.86	19	-44223.13	**29**	**-44191.47**
10	-44247.28	20	-44218.24	30	-44198.48

Table B2 - All years “Consolidated Class Model” (Conditional r-squared = 0.743; Marginal r-squared = 0.203). Dredge Analyses.

Intercept	**Cropland**	**Deforestation**	**Forest Cover**	**MCWD**	**AICc**	**delta**	**weight**
-4.09	**NA**	**0.328**	**-0.411**	**-0.038**	**-37530.7**	**0.0**	**0.69**
-4.09	**0.004**	**0.328**	**-0.410**	**-0.038**	**-37528.8**	**1.9**	**0.27**
-4.08	NA	0.328	-0.411	NA	-37524.3	6.4	0.03
-4.08	0.005	0.327	-0.411	NA	-37522.4	8.3	0.01
-4.08	NA	0.335	NA	-0.034	-37270.2	260.5	0.00
-4.08	0.017	0.334	NA	-0.034	-37269.7	261.0	0.00
-4.07	NA	0.335	NA	NA	-37265.7	265.0	0.00
-4.07	0.017	0.334	NA	NA	-37265.3	265.4	0.00
-4.05	0.030	NA	-0.426	-0.030	-36080.3	1450.4	0.00
-4.05	0.031	NA	-0.427	NA	-36078.0	1452.7	0.00
-4.05	NA	NA	-0.431	-0.030	-36077.5	1453.2	0.00
-4.05	NA	NA	-0.431	NA	-36075.1	1455.5	0.00
-4.03	0.045	NA	NA	-0.027	-35843.7	1687.0	0.00
-4.03	0.045	NA	NA	NA	-35842.5	1688.2	0.00
-4.03	NA	NA	NA	-0.027	-35835.4	1695.3	0.00
-4.03	NA	NA	NA	NA	-35834.0	1696.7	0.00

Table B3 - All years "Transition Class Model" - Conditional r-squared = 0.676; Marginal r-squared = 0.229. Dredge Analyses.

Intercept	Cropland	Deforestation	Forest Cover	MCWD	AICc	delta	weight
-4.510	**-0.062**	**0.363**	**-0.253**	**-0.063**	**-24529.7**	**0.0**	**1.0**
-4.509	-0.063	0.362	-0.245	NA	-24518.9	10.8	0.0
-4.507	NA	0.365	-0.256	-0.064	-24512.0	17.6	0.0
-4.506	NA	0.365	-0.248	NA	-24500.6	29.1	0.0
-4.511	-0.063	0.365	NA	-0.047	-24446.3	83.4	0.0
-4.511	-0.064	0.365	NA	NA	-24441.0	88.7	0.0
-4.508	NA	0.368	NA	-0.049	-24427.0	102.7	0.0
-4.508	NA	0.368	NA	NA	-24421.1	108.6	0.0
-4.404	-0.076	NA	-0.318	-0.072	-23393.3	1136.3	0.0
-4.403	-0.077	NA	-0.310	NA	-23384.0	1145.7	0.0
-4.402	NA	NA	-0.315	-0.075	-23372.9	1156.7	0.0
-4.401	NA	NA	-0.307	NA	-23362.9	1166.7	0.0
-4.408	-0.070	NA	NA	-0.054	-23299.1	1230.5	0.0
-4.407	-0.071	NA	NA	NA	-23294.7	1235.0	0.0
-4.406	NA	NA	NA	-0.057	-23280.3	1249.4	0.0
-4.405	NA	NA	NA	NA	-23275.2	1254.5	0.0

Table B4 - Pseudo marginal and conditional r-squared GLMM per class (consolidated or transitioning) and per period (1990-1999, 2000-2009, 2010-2019).

Consolidated			Transition		
Period	**Marginal r-squared**	**Conditional r-squared**	**Period**	**Marginal r-squared**	**Conditional r-squared**
1990-1999	0.368	0.791	1990-1999	0.105	0.696
2000-2009	0.259	0.707	2000-2009	0.453	0.796
2010-2019	0.124	0.670	2010-2019	0.363	0.695