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UNIVERSIDADE ESTADUAL PAULISTA
“JÚLIO DE MESQUITA FILHO”
INSTITUTO DE BIOCIÊNCIAS – RIO CLARO

PROGRAMA DE PÓS-GRADUAÇÃO EM
ECOLOGIA E BIODIVERSIDADE

THE EFFECT OF FOREST DEGRADATION ON ECOSYSTEM SERVICES RELATED TO FRUGIVORY AND INSECTIVORY PROMOTED BY BIRDS AND MAMMALS IN AMAZONIAN FORESTS

LIANA CHESINI ROSSI

Rio Claro – SP
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Tese apresentada ao Instituto de Biociências do Campus de Rio Claro, Universidade Estadual Paulista, como parte dos requisitos para obtenção do título de doutor em Ecologia e Biodiversidade.

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TÍTULO DA TESE: THE EFFECT OF FOREST DEGRADATION ON ECOSYSTEM SERVICES RELATED TO FRUGIVORY AND INSECTIVORY PROMOTED BY BIRDS AND MAMMALS IN AMAZONIAN FORESTS

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RESUMO

Efeito da degradação florestal sobre os serviços ecossistêmicos relacionados à frugivoria e insetivoria promovido pelas aves na Floresta Amazônica

Florestas tropicais estão enfrentando ameaças impulsionadas por múltiplas atividades antrópicas, como extração seletiva de madeira e fogo. Em toda a Amazônia, as florestas afetadas por essas atividades cobrem cerca de 1 milhão de km^2, correspondendo a 17% das florestas remanescentes da região. Dada sua grande extensão, as florestas modificadas pelo homem desempenham um papel importante na conservação das espécies e na prestação de serviços ecossistêmicos. No entanto, distúrbios causados pelo homem afetam negativamente a biodiversidade e os processos ecológicos. Além disso, os impactos destes distúrbios sobre processos ecológicos, como controle da herbivoria e da dispersão de sementes, ainda são pouco compreendidos. Esta tese visa preencher esta lacuna do conhecimento avaliando como os distúrbios causados pelo homem, em particular a extração seletiva de madeira e incêndios florestais afetam comunidades biológicas e processos ecossistêmicos relacionados à regeneração florestal. Em 17 transectos florestais no centro-leste da Amazônia brasileira, usei seis metodologias para registrar 192 espécies frugívoras e 4.670 interações de frugivoria. Além disso, em 30 transectos florestais eu medi a incidência de predação em 4.500 lagartas artificiais. O objetivo do primeiro capítulo foi mensurar os efeitos da extração seletiva de madeira e dos incêndios florestais sobre as comunidades de espécies frugívoras. Os resultados indicam que, florestas queimadas há mais de 15 anos apresentaram baixo número de frugívoros obrigatórios (i.e., ≤80% da dieta baseada em frutas) e de espécies de tamanho corporal grande, ao mesmo tempo que reduziram os valores de diversidade funcional. No segundo capítulo, avaliei os impactos da extração seletiva de madeira e dos incêndios florestais sobre as interações de frugivoria. Descobri que, florestas que queimaram a mais de 15 anos tiveram uma menor diversidade de espécies e interações. Apesar desses efeitos, não encontrei diferenças na estrutura das redes de frugivoria; todas as redes foram altamente modulares e especializadas. Também registrei elevados valores de diversidade beta, resultado da alta dissimilaridade de interação entre as classes florestais. Por fim, no terceiro capítulo, examinei os efeitos dos distúrbios antrópicos sobre a incidência de predação de artrópodes folívoros. Os resultados mostraram uma surpreendente resiliência do processo de controle de artrópodes folívoros à degradação florestal; alta incidência de predação em florestas queimadas durante o El Niño de 2015-16. A incidência de predação em artrópodes folívoros foi realizada principalmente por artrópodes predadores. No geral, esses resultados sugerem que, embora os incêndios florestais recentes não tenham impactado fortemente os processos ecológicos, em longo prazo, incêndios florestais podem levar a mudanças significativas em comunidades ecológicas, reduzindo a ocorrência de frugívoros especialistas e de grande porte, bem como levando à perda da diversidade funcional e de interações de frugivoria na Florestas Amazônica. Portanto, a perda e as mudanças na diversidade taxonômica e funcional devido aos incêndios florestais, somadas as previsões de aumento na frequência desses incêndios, levam à vulnerabilidade dos processos ecológicos, como a frugivoria e da insetivoria –fundamentais para a manutenção e recuperação florestal, com possíveis consequências negativas sobre os serviços ecossistêmicos promovidos pelas florestas tropicais.

Palavras-chave: distúrbios antrópicos, funções ecológicas, florestas tropicais, interações ecológicas, incêndios florestais

ABSTRACT

The effect of forest degradation on ecosystem services related to frugivory and insectivory promoted by birds and mammals in Amazonian forests

Tropical forests are facing threats driven by multiple anthropogenic activities., such as selective logging and fires. Across Amazonia, forests affected by these activities cover c. 1 million km^2, corresponding to 17% of remaining forests in the region. Given its large extension, human-modified forests play an important role in species conservation and provision of ecosystem services. However, anthropogenic disturbances negatively affect biodiversity and ecological processes. Furthermore, the impacts of disturbances on ecological processes, such as herbivory control and seed dispersal, are still poorly understood. This thesis aims to fill these knowledge gaps by assessing how human-driven disturbances, in particular selective logging and forest fires, affect biological communities and ecosystems process related to forest regeneration, including insectivory and frugivory. Across 17 forest plots in central-eastern Brazilian Amazon, I combined six methodologies to record 192 frugivorous species; and 4,670 frugivory interactions. Additionally, across 30 plots, I measured predation incidence in 4,500 artificial caterpillars. My first Chapter aim was to measure the effects of selective logging and forest fires on frugivorous communities. The results indicate that forests burned more than 15 years in the past had a distinct frugivorous community composition in comparison to undisturbed forests, limiting the occurrence of obligate (≤80% diet based on fruits) and large-bodied frugivorous, while reduced the values of functional diversity. In the second Chapter, I assessed the impacts of selective logging and forest fires on frugivory interactions. I found that fires that occurred more than 15 years in the past reduced the number of species and unique interactions. Despite these effects, there were no impacts of neither selective logging or forest fires on the structure of frugivory networks - all networks were highly modular and specialized. I also recorded a high beta-diversity of interactions in all forests, resulted from the high interaction dissimilarity among forest classes. Finally, in the third Chapter, I measured the effects of selective logging and forest fires on predation incidence on folivorous arthropods. Results showed a surprising resilience of predation incidence, which were similar between control plots and those affected by selective logging and forest fires. Arthropods were the main predators of caterpillars. Overall, these findings suggest that although fires that occurred <15 years ago have not strongly impacted frugivory and insectivory, fires can lead to significant changes on ecological communities, loss specialist and large frugivorous species as well as diversity of frugivory interactions and functions in Amazonian forests. Therefore, loss and changes in taxonomic and functional diversity due to forest fires, added to predictions of increases in fires frequency, rise up the vulnerability of frugivory and insectivory functions, both fundamental for forest maintenance and recovery, with implication on the services provided by tropical forests.

Keywords: anthropogenic disturbances, ecological functions, tropical forests, ecological interactions, forest fires

À Amazônia, centro do mundo

Na floresta, a ecologia somos nós, os humanos. Mas não também, tanto quanto nós, os 'xapiri', os animais, as árvores, os rios, os peixes, o céu, a chuva, o vento e o sol! É tudo o que veio à existência na floresta, longe dos brancos; tudo o que ainda não tem cerca.

Davi Kopenawa

PREFACE

This thesis has been written as papers and each of the data Chapters will be or has already been submitted for publication in peer-reviewed journals. Although the Chapters are standalone pieces of work, they are connected, introduced and discussed in an integrated way. Overlap between the Chapters is reduced as each has its own aims, but there is some small overlap in the introduction, site descriptions and methodology sections. Variable formatting between Chapters is a result of target journals requirements.

Even though the study presented in this thesis is largely my own, including literature review, methods design, data collection, statistical analysis and write up, it is integrated within a larger project (Rede Amazônia Sustentável – RAS). A number of researchers have been involved over the lifetime of this work and have provided substantial improvement in its content. Dr. Marco Aurelio Pizo, my lead supervisor, has played a significant role helping to guide fieldwork design and the content of all of the presented Chapters, with regard to refining research questions, methodological design, data analysis and structuring and proof reading of draft manuscripts. Dr. Alexander Charles Lees and Dr. Jos Barlow, my co-supervisors, have played similar roles to Marco in all Chapters. Dr. Alexander Charles Lees was my supervisor during my internship at the Manchester Metropolitan University, with an important contribution in Chapter 3. Additionally, Erika Berenguer, Joice Ferreira and Filipe França have all engaged in valuable discussions of the research topics, guiding fieldwork design, advising on statistical approaches and reviewing the manuscripts from all Chapters. A number of other individuals have made contributions to the content of this thesis in the following ways. Co-authors, Dr. Carine Emer providing significant contributions data analysis and structuring and proof reading of a draft of the Chapter 2; Msc. Yan Gabriel Ramos that contributed in data collection and identification, as well as Msc. Paulo Tavares, contributing for map design on Chapters 2 and 3.

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Articles in preparation

Rossi L.C., Emer, C., Lees A.C., Berenguer E., Barlow J., Ferreira J., França F.M., Ramos, Y.G., Tavares P., Pizo M.A. **Fruit-frugivore interactions mediated by fires and logging in the Amazonian forests**. To be submitted to *Ecology*.

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1. INTRODUCTION

1. INTRODUCTION

1.1 Tropical forests in a changing world

Tropical forests are important for the performance of numerous ecological and societal functions, such as carbon storage, biodiversity conservation, climate regulator, food and fuel provision, pest and disease control (BACCINI *et al.*, 2019; ERB *et al.*, 2018; MALHI, 2012). Despite this crucial importance, tropical forests face multiple threats driven by human activities and are especially vulnerable to economic and demographic pressures (MALHI *et al.*, 2014). The widespread degradation of forests can severely affect their biodiversity and associated ecosystem processes (BARLOW *et al.*, 2016; LAURANCE *et al.*, 2014; MARENGO *et al.*, 2018) and consequently the functions performed by these forests (CARDINALE *et al.*, 2012; EDWARDS *et al.*, 2014). For instance, Amazonian forests are vital as a climate controller, influencing rainfall patterns across the Americas (SPRACKLEN; GARCIA-CARRERAS, 2015).

The Amazon is the largest tropical forest in the world (6.5 million km^2), spread across nine countries in South America of which Brazil holds 4.1 million km^2 (IBGE, 2004). Amazonian forests are facing threats driven by multiple anthropogenic activities. The most pervasive threat is deforestation, which has increased 47% in the last three years (11,088 km^2) (SILVA JUNIOR *et al.*, 2021). Another threat is forest degradation, such as selective logging and fires (ASNER *et al.*, 2009; PIVELLO *et al.*, 2021), resulting in an increasing proportion of standing but degraded primary forests (e.g., currently, the area occupied by degraded forest surpasses deforested in the Brazilian Amazon; MATRICARDI *et al*., 2020).

The state of Pará is the second largest Brazilian states including Amazonian territory (see Figure 1.1a) (IBGE, 2022). Owing to current and historically high levels of forest degradation and deforestation, the state of Pará is characterized by a mosaic of land-uses including undisturbed and disturbed primary forests as well as regenerating secondary forests and a mosaic of different production systems (e.g., cattle ranching, large-scale soy bean and corn plantations, and small-scale manioc plantations; Figure 1.2). Therefore, Pará is a 'natural laboratory' with ideal conditions to study the effects of anthropogenic disturbances on forest ecosystems. This thesis focuses on Pará state, specifically the Santarém region of the central-eastern Brazilian Amazon (Figure 1.1b).

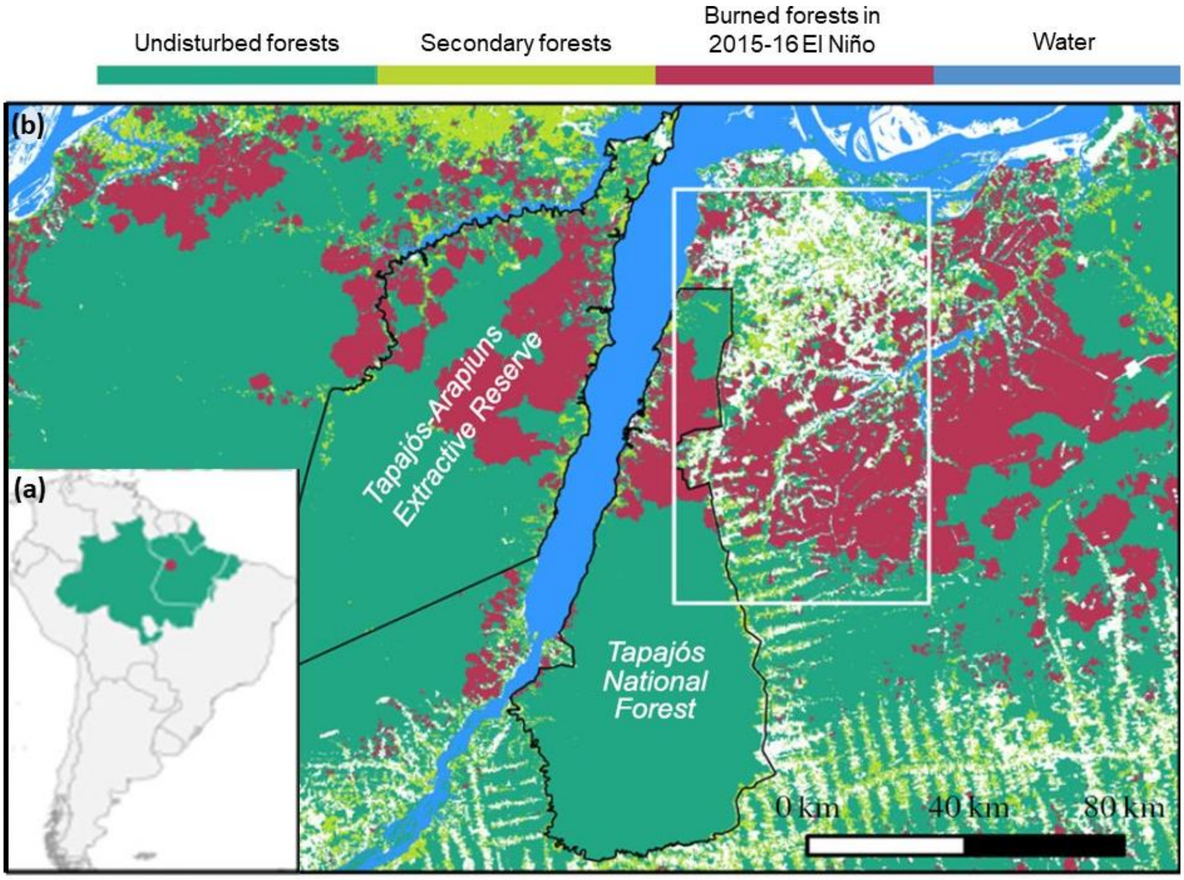

Figure 1.1 - Map of the study area in the Brazilian Amazon. (a) Location of Santarém within the Brazilian state of Pará; and (b) Santarém region. The white square corresponds to the study area. Map adapted from Withey *et al.* (2018).

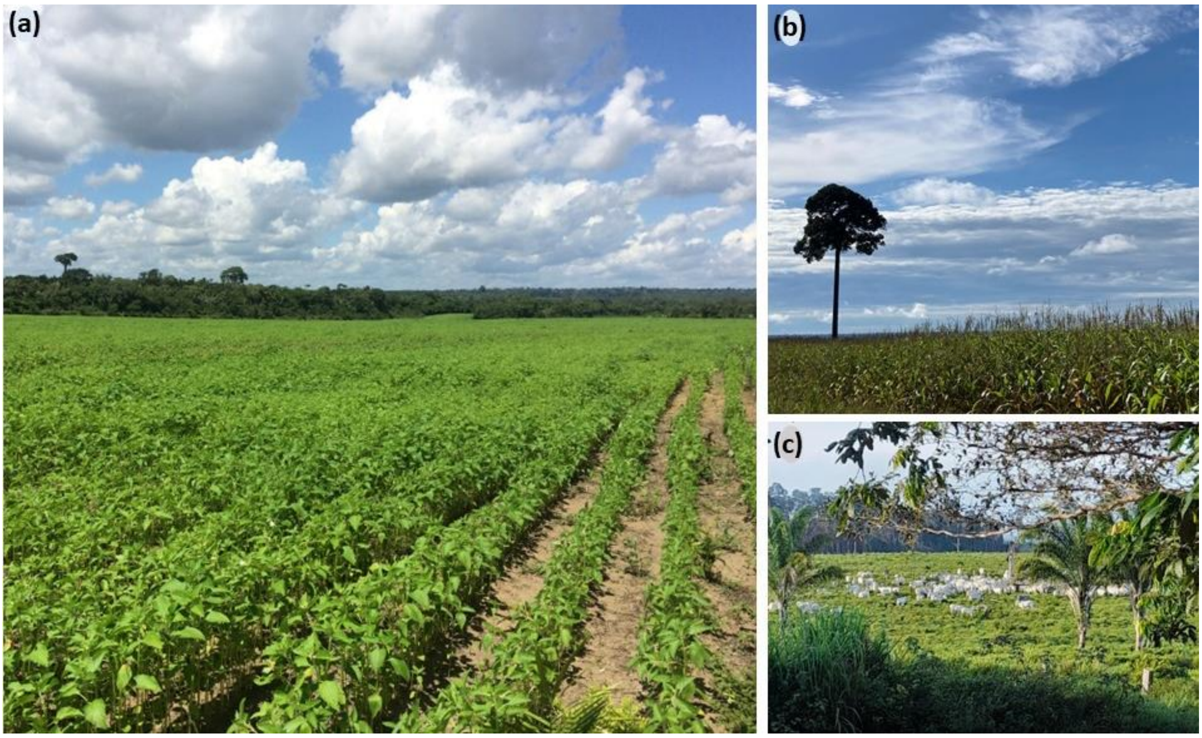

Figure 1.2 - Production systems in the Santarém region: (a) large-scale soybean and (b) corn plantations; (c) cattle ranching. First two photos were taken by L.C.R. and the last photo by Ester F. Oliveira.

The Santarém region is located 800 km west of Belém, the capital of Pará state (Figure 1a). Timber extraction increased substantially after the 1940s (LENTINI; VERÍSSIMO; PEREIRA, 2005) and reached the highest levels in the 1970s when the Brazilian government built a 3,467 km long road, connecting Santarém to Cuiabá, the capital of Mato Grosso state. Moreover, the combined the expansion of the city, the port and airport, the building of a hydroelectric dam and gold mining extraction led to a rapid increase in forest conversion rates (HOEFLE, 2013). Despite this, Santarém holds important areas of undisturbed forests, as well as a 5,491 km^2 national forest reserve, the Floresta Nacional do Tapajós (IBGE, 2022).

1.1.1 Forest degradation

1.1.1.1 Forest fires

Fire represents one of the greatest threats to tropical forests and its occurrence is directly linked to human activities (ANDERSON *et al.*, 2015; MALHI *et al.*, 2008; MARENGO *et al.*, 2018). For instance, Amazonian forests have recently been affected by the increase in frequency of extreme climatic events, and, consequently, the incidence of forest fires (BALCH *et al*., 2015; Figure 1.3). Intense climatic events such as the 2015-16 El Niño caused an intense and long period of drought leading to a 48% increase in the incidence of forest fires compared to the year before the El Niño event (BETTS *et al*., 2015; Figure 1.1b, 1.3).

Figure 1.3 - Fire dynamic in the Amazonian forests. (a) Understory fires; (b) forest post-fire; and (c) forest structure after three years of understory fires; First photo was taken by Erika Berenguer, second and third by L.C.R.

1.1.1.2 Selective logging

Another common human-driven disturbance in the tropics is selective logging. In Amazonian forests, logging operations tend to be selective, removing just a few valuable tree species from any given area. This practice is mainly conducted illegally and has already affected 20% of the remaining forests in the Brazilian Amazon (ASNER *et al.*; 2005; Figure 1.4).

1.1.1.3 Secondary forests

Human activities have resulted in an increasing number of secondary forests (HANSEN *et al.*, 2013). Secondary forests are forests that were totally deforested resulting in a distinct plant community composition and structure from primary forests. Commonly, secondary forests are found within degraded matrices with areas of agriculture and livestock (CHAZDON *et al.*, 2009; LAURANCE *et al.*, 2018). There are currently estimated to be 148,764 km^2 of secondary forests in the Amazon (JUNIOR *et al.*, 2020).

Figure 1.4 - Selective logging in Brazilian Amazon. (a) Transport of legal wood; (b) and (c) illegal extraction. Photos were taken by L.C.R.

1.2 Ecological Functions

Ecological functions are natural processes in the environment and support ecosystem functionality (SEKERCIOGLU; WENNY; WHELAN, 2016). Pollination, seed dispersal and biological control are examples of ecological functions. These processes involve fluxes of nutrients through food webs and the movement of propagules that keep ecosystems functioning (SRIVASTAVA *et al.*, 2012). Although numerous studies have described these process and their importance for the functioning of ecosystems (GARCÍA; MARTÍNEZ, 2012; MAAS *et al.*, 2016), they are still poorly understood, especially when they involve complex processes, such as the control of herbivorous insects performed by birds and bats – i.e., *top-down control* (VAN BAEL *et al.*, 2008; VIDAL *et al*., 2018). There are numerous driving factors in herbivore control, such plant allelopathy (biochemicals produced by plants to avoid herbivory) – i.e., *bottom-up control*, which can also influence predation rates (VIDAL *et al*., 2018).

Birds and mammals play key functional roles in many ecosystems, performing numerous ecological functions (LACHER *et al.*, 2019; MAAS *et al.*, 2016; SEKERCIOGLU; WENNY; WHELAN, 2016; SEKERCIOGLU, 2006; STOTZ *et al.*, 1996). Because of the great taxonomic diversity of most ecosystems around the world, animals are able to perform several functions, important for ecosystem dynamics, such as seed dispersal, pollination and herbivory control (WHELAN; WENNY; MARQUIS, 2008). Changes in animal communities (e.g., richness and composition) affect ecological function and consequently alter forest maintenance and regeneration (SEKERCIOGLU; DAILY; EHRLICH, 2004). In the last few decades, many studies have indicated the importance of the contribution of animals to ecosystem processes (see SEKERCIOGLU *et al*., 2016), in particular, on seed dispersal (CARLO; MORALES, 2015; CARREIRA *et al.*, 2020; DARIO, 2014; STEVENSON *et al.*, 2015) and on the control of herbivorous insects (MAAS *et al.*, 2016; ROELS; PORTER; LINDELL, 2018). Both have received special attention, as they influence plant reproduction capacity and, consequently, forest dynamics (HARRISON *et al.*, 2013; ROELS; PORTER; LINDELL, 2018; VIDAL *et al.*, 2014).

1.2.1 Ecological function in a changing world

Primary forests are irreplaceable in terms of their role in providing resources and maintaining biodiversity, especially for more specialist species, commonly more sensitive to human-driven disturbances (GIBSON *et al.*, 2011; LAURANCE *et al.*, 2018). However, degraded forests, such as secondary and burned forests represent a large part of the existing forests (MALHI *et al.*, 2014; MATRICARDI *et al.*, 2020; NEEFF *et al.*, 2006), thus playing an important role in species conservation (BARLOW *et al.*, 2016, 2007; CHAZDON *et al.*, 2009; MOURA *et al.*, 2013; NUNES *et al.*, 2022). Forest fires can directly impact animal communities by increasing mortality rates during the fire and smoke passage or indirectly by decreasing the availability of resources (BARLOW; PERES, 2004a, b). For instance, by increasing plant mortality (BERENGUER *et al.*, 2021), burned forests have an open canopy that lead to an increases in sunlight reaching the understory and, consequently leads to decreases in humidity, ultimately leading to changes in plant community composition (BARLOW *et al.*, 2003; HAWES *et al.*, 2020; PHILLIPS *et al.*, 2009; Figure 1.3). This may reduce the availability of fruits for frugivorous animals and in turn, resource availability - acting as a filter for some species, especially those with specific requirements as frugivores (PIGOT *et al.*, 2020).

Furthermore, the synergic effects of human-driven disturbances, such as hunting is na important driver of the decline of large animal abundance and cause of local extinctions, resulting in widespread losses of tropical biodiversity (LEWIS; EDWARDS; GALBRAITH, 2015; OSURI *et al.*, 2020). Hunting is a common practice in tropical forests and can strongly reduce the abundance and richness of several bird and mammal species, especially large-bodied species (SCABIN; PERES, 2021). In over-hunted tropical forests, the abundances of birds and mammals can decline by 50% and 80%, respectively (BENÍTEZ-LÓPEZ *et al.*, 2017). The defaunation induced by hunting can limit the long-term ecological functions promoted by animals (BOMFIM *et al.*, 2018; HARRISON *et al.*, 2013). Although strong and pervasive, the effects of hunting are hard to detect through remote-sensing analysis, being much less well quantified than other human-driven disturbances (PERES; BARLOW; LAURANCE, 2006). Moreover, the effects of hunting on community processes are commonly exacerbated by synergistic factors, such as logging and fires (BRODIE *et al.*, 2015; PERES; BARLOW; HAUGAASEN, 2003).

Nonetheless, fires and logging lead to replacement of specialist species with widespread generalist species (BURIVALOVA; ŞEKERCIOĞLU; KOH, 2014; MOURA *et al.*, 2013). Given that animals deliver important ecological functions, changes in species composition may result in changes in ecological processes (HAWES *et al.*, 2020; MIRANDA; IMPERATRIZ-FONSECA; GIANNINI, 2019). For instance, reduction in frugivores may lead to reduction in seed removal, which may impact forest resilience and plant establishment, both important process in tropical forests (MASON *et al.*, 2013; PETCHEY *et al.*, 2004; SEBASTIÁN-GONZÁLEZ *et al.*, 2017). Even though previous studies have examined animal responses to human-driven disturbances (BARLOW *et al.*, 2006; BREGMAN *et al.*, 2016; MOURA *et al.*, 2014), our understanding of the impacts of these disturbances on the ecological functions promoted by animal species is limited in Amazonian forests (GARDNER *et al.*, 2009). Thus, the extreme importance and vulnerability of ecological functions to forest degradation, combined with a lack of studies in the Amazon and the El Niño event, provide a unique opportunity to understand the effects of fire and other human-driven forest degradation on ecological functions related to important ecosystem processes to forest regeneration.

1.3 Objectives

The main objective of this study is to measure the effect of forest degradation on the ecological functions of frugivory and biological control of folivorous insects promoted by animals in the Amazon forests. To achieve this, three Chapters were prepared:

Chapter 1: *Responses of Amazonian frugivores to disturbance in human-modified tropical forests.* Here we evaluated the impact of selective logging and forest fires on the richness, composition, body mass and functional diversity of frugivorous animals.

Chapter 2: *Fruit-frugivore interactions mediated by forest fires in Amazonian forests* where we assessed the impacts of selective logging and forest fires on frugivory networks.

Chapter 3: *Predation on artificial caterpillars following understorey fires in human-modified Amazonian forests* where we evaluated the effect of human-driven forest degradation on predation rates of folivorous arthropods.

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5. CONCLUDING REMARKS

5.1 Key findings

This thesis explored the effects of multiple human-driven forest disturbances on ecological functions, providing significant advancement in our understanding of processes important for Amazonian forests resilience and conservation. These key findings are outlined below:

5.1.1 Responses of Amazonian frugivores to disturbance in human-modified tropical forests (Chapter 1)

In Chapter 1 we uncovered the impacts of forest fires on richness, composition, and functional diversity of frugivorous birds and mammals in variably-degraded Amazonian forests. Although the overall richness was not affected by human-driven disturbances, forest burned more than 18 years prior to the study had a lower number of obligate and large-bodied frugivores as well as lower functional diversity. In the long-term, fires can thus lead to changes in frugivore communities, limiting the occurrence of specialist and large body frugivores, while exerting negative effects on functional diversity with consequences for ecological functions almost 20 years after fire events.

5.1.2 Fruit-frugivore interactions in burned and logged Amazonian forests (Chapter 2)

In Chapter 2 I provided the first empirical study showing the impacts of long-term fires (≥18 years before the study) on frugivory interactions in Amazonian forests. Overall, these results suggest a degree of resilience in the network structure in logged and burned forest, historically-burned forests (i.e., forests burned ≥18 years and logged) had a lower number of species and unique interactions than undisturbed forests. These results also showed high beta-diversity for species and interaction in all forest classes, even in burned ones. This greater beta-diversity was explained by the high species and interaction turnover among forests demonstrating higher diversity of fruit-frugivore interaction. Notably, the distinct species and interaction composition in historically-burned forests are likely to play a more subtle role in determining the future of forest dynamics, even nearly two decades after fire events. Studies aimed at understanding the impacts of historic fires on frugivory interactions in Amazonian forests are fundamental given the increase in fire frequency in the Amazon region.

5.1.3 Predation on folivorous arthropods following forest degradation (Chapter 3)

In this Chapter, my co-authors and I used an experimental approach to show the effects of forest disturbance on the control of folivorous arthropods by vertebrates and arthropods. In addition, although we recorded high predation incidence in forests burned during the 2005-16 El Niño, folivore control was not greatly impacted by recent understorey fires. We found that the predation incidence on folivorous arthropods was similar in undisturbed, logged, burned and secondary forests. We also found that arthropod predators, especially ants, were the most common predator. These findings represent an important step for predicting the future of tropical forests, as herbivory control directly affects forest regeneration and hence resilience.

5.2 The future of the forest

Forest degradation rates in the Brazilian Amazon have remained high in recent decades, especially in the last few years, such that currently the extent of degraded forests is greater than that of the deforested forest area (MATRICARDI *et al.*, 2020; SILVA JUNIOR *et al.*, 2021). Fires are one of the major threats to the Amazonian forests, affecting biological communities and ecological process (BARLOW; PERES, 2004; HAWES; PERES, 2014; PIVELLO *et al.*, 2021; SLIK; VAN BALEN, 2006). Here we have shown the pervasive effects of forest fires on ecological communities. Based on our results, long-term fires can lead to changes in frugivore composition, as well as limiting the occurrence of specialist and large-bodied frugivores, while exerting a strong effect by reducing the functional diversity even more than 15 years after fire events. Nonetheless, fires had negative effects on frugivory interactions, reducing diversity and changing the fruit-frugivore interaction composition. Altogether, these findings indicate that neither interaction networks nor the folivores arthropods control were strongly affected by recent fire and selective logging, fires lead to long-term loss diversity of species and interactions which may lead to loss of important ecological function. Indeed, our results showed the loss of large body frugivores in forests burned in the past which may negatively affect dispersal of large seeds with important implications for forest resilience. Thus, with forest fires likely to become more ubiquitous, they are likely to play a more subtle role in determining future forest dynamics.

5.3 Future research priorities

This thesis has contributed in increasing our knowledge about how ecological functions, such as the control of folivorous arthropods and frugivory interactions potentially leading to seed dispersal, are affected by different human-driven forest disturbances, providing further insight into the maintenance of ecosystem processes in tropical forests. Human impacts on tropical forests are expected to continue to grow worldwide (ASNER *et al.*, 2009; BERENGUER *et al.*, 2021; JUNIOR *et al.*, 2020; PIVELLO *et al.*, 2021; SILVA JUNIOR *et al.*, 2021), and exacerbated by increasingly severe climate change predictions (GATTI *et al.*, 2021). As such my mains suggestion for future research directions are:

5.3.1 Long-term monitoring of biodiversity in disturbed forests

The results obtained in this thesis help fill a gap in the knowledge about the long-term responses of ecological function to human-driven forest disturbances. Long-term studies providing a broad understanding about impacts of forest fires and selective logging on tropical forests (MAGURRAN *et al.*, 2010). Research is greatly needed to assess how long forest fires effects will persist impacting frugivore communities and their interaction networks and whether these effects may become apparent on the structure of frugivory networks as well as on ecosystem functions, such as folivore control. Nevertheless, further research is needed to understand how ecological function will be shaped by re-occurring fires.

5.3.2 Usage of different survey methods for sampling

High quality biological surveys are essential to improve the knowledge base which is crucial to set conservation priorities and assessing management actions. Recently, the use of new technologies, such as camera traps and automatic recorders has expanded, improving survey efficiency, allowing a broader taxonomic spectrum to be surveyed, as well as providing insights on the magnitude of human impacts on biodiversity (METCALF *et al.*, 2022; RIVAS-ROMERO; SOTO-SHOENDER, 2015). Passive acoustic recorders and camera trap methods can increase the detection of frugivorous animals, while enhancing our understanding about ecological processes, such as frugivory interactions (ZHU *et al.*, 2021). For instance, camera traps provide a broad temporal sample of species and interaction detections, while detecting cryptic and nocturnal animals, rarely recorded by traditional survey methods (ZHU *et al.*, 2022).

5.3.3 Studies exploring the fruit-frugivore interactions

Animal-plant interactions, such as seed dispersal networks provide essential ecosystem services, fundamental to forest regeneration (CARLO; MORALES, 2015; ROGERS *et al.*, 2021). Despite the importance of frugivory interactions in the maintenance and resilience of tropical forests, our knowledge about these interactions and their responses to human-driven disturbances in the Amazonian forests is limited. This gap in the knowledge is especially alarming in the face of pervasive effects of forest fires which tend to worsen due to climate change (BALDIVIEZO; PASSOS; DE AZEVEDO, 2019; OLIVEIRA *et al.*, 2022). Therefore, there is a growing need for baseline data to understand the frugivory interactions in tropical forests, as well as to better understand further the consequences of human-driven disturbance on seed dispersal process.

5.3.4 Exploring the responses of functional diversity to human-driven disturbances with a phylogenetic perspective

Knowledge of ecological functions is fundamental; higher functional diversity increases the provisioning of ecosystem function via a variety of mechanisms (CARDINALE *et al.*, 2012; HOOPER *et al.*, 2012). Including a phylogenetic approach to functional diversity indexes can provide further insights into understanding how phylogenetic composition affects ecosystem functions along with taking into account the idiosyncratic responses of each community (SRIVASTAVA *et al.*, 2012). For instance, phylogenetic allows us to describe the more affected groups as well as the evolutionary history extinctions due to human-driven disturbances. Furthermore, high phylogenetic diversity is associated with high values of ecosystem functions, which may infer resilience to environmental changes (PRESCOTT *et al.*, 2016; SRIVASTAVA *et al.*, 2012).

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