

ALINE SILVA DE OLIVEIRA

**ESTIMATIVAS DE PERDAS ECONÔMICAS E CUSTOS DE MANEJO DE
INCÊNDIOS FLORESTAIS NO CERRADO E NA AMAZÔNIA BRASILEIRA**

Tese apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Meteorologia Aplicada, para obtenção de título de *Doctor Scientiae*.

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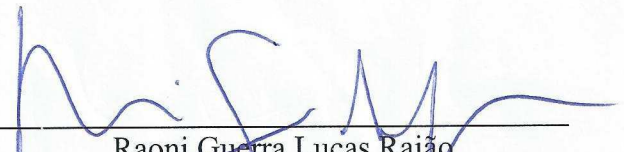
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*Dedico esse trabalho a Deus, aos meus pais
e aos meus verdadeiros amigos.*

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RESUMO

OLIVEIRA, Aline Silva de, D.Sc., Universidade Federal de Viçosa, agosto de 2018. **Estimativas de perdas econômicas e custos de manejo de incêndios florestais no Cerrado e na Amazônia brasileira.** Orientador: Britaldo Silveira Soares Filho. Coorientadores: Raoni Guerra Lucas Rajão e Marcos Heil Costa.

O fogo florestal estabelece uma função ecológica na produtividade de diversos ecossistemas. No entanto, os regimes de fogo estão sendo profundamente alterados para uma dinâmica de fogos recorrentes, cuja força destrutiva atraiu pesquisadores em todo mundo na busca de respostas para seus efeitos adversos. Embora o poder destrutivo do fogo seja reconhecido, seus impactos econômicos foram pouco estimados, assim como os investimentos realizados em práticas de manejo de incêndios florestais, particularmente em florestas tropicais. Através desse trabalho de pesquisa é possível identificar que a informação econômica sobre os custos (investimentos feitos em práticas de manejo do fogo) e os benefícios (perdas econômicas evitadas pela mitigação) da gama de políticas e programas de gestão de incêndios em todo mundo é insuficiente para tomadas de decisões na gestão de incêndios. Conseqüentemente, os recursos financeiros não são estrategicamente direcionados para tornar o manejo de fogo mais eficiente na redução de incêndios. Este trabalho, pretende contribuir para essa lacuna de conhecimento através da realização de uma estimativa das perdas econômicas na produção sustentável de madeira na Amazônia Brasileira e uma avaliação de custo-benefício das práticas de manejo de incêndios florestais nesse bioma e no bioma Cerrado. Os resultados foram gerados através de modelos espacialmente explícitos e demonstram que as perdas econômicas pelo fogo na produção sustentável de madeira podem chegar a US\$ 183 ± 30 ha/ano em áreas atingidas por incêndios recorrentes próximos a centros de moagem na Amazônia. Além disso, essas perdas podem chegar a US\$ 565 ha/ano em regiões de alto lucro agrícola em ambos os biomas. Apesar das altas perdas, os investimentos realizados na mitigação do fogo ainda são baixos, em média US\$ 3,7 ha/ano em terras públicas e US \$ 11,2 ha/ano em terras privadas. Em contrapartida, mesmo que a mitigação seja pouco adotada, os benefícios das práticas de manejo, quando são efetivas na redução do fogo evitam perdas econômicas, que são substancialmente maiores que os custos da mitigação. Em alguns locais de floresta com alto estoque de carbono e em áreas lucrativas de produção agrícola, os benefícios da

mitigação podem ser 25 vezes maiores que seus custos. Através desse trabalho é possível identificar que os programas de mitigação de incêndios no Brasil não atendem os pontos críticos de perdas econômicas na produção de madeira na Amazônia e devem ser melhor direcionados. Além disso, os benefícios públicos das práticas de manejo somente ocorrem no Cerrado, quando o combustível (o volume de biomassa disponível para queimar) é gerenciado adequadamente, e na Amazônia somente quando há uma ação conjunta entre práticas de supressão, políticas e programas de incentivo para prevenção de fogo. Da mesma forma, a prevenção do fogo gera benefícios privados significativos para produtores agrícolas envolvidos ativamente em programas de mitigação de incêndios.

ABSTRACT

OLIVEIRA, Aline Silva de, D.Sc., Universidade Federal de Viçosa, August, 2018. **Economic loss estimates and forest fire management costs in the Cerrado and Brazilian Amazon.** Adviser: Britaldo Silveira Soares Filho. Co-advisers: Raoni Guerra Lucas Rajão and Marcos Heil Costa.

The forest fire establishes an ecological function in the productivity of several ecosystems. However, fire regimes are being profoundly altered to a recurrent fire dynamic whose destructive force has drawn researchers around the world in search of answers to their adverse effects. Although the destructive power of fire is recognized, its economic impacts have been poorly estimated, as have investments in forest fire management practices, particularly in tropical forests. Through this research work it is possible to identify that economic information on costs (investments made in fire management practices) and the benefits (economic losses avoided by mitigation) of the range of fire management policies and programs worldwide is insufficient for decision making in fire management. Consequently, financial resources are not strategically directed to make fire management more efficient in reducing fire. This work intends to contribute to this knowledge gap through an estimate of the economic losses in the sustainable production of wood in the Brazilian Amazon and a cost-benefit assessment of forest fire management practices in this biome and the Cerrado biome. The results were generated through spatially explicit models and demonstrate that the economic losses by fire in sustainable wood production can reach US\$ 183 ± 30 ha/year in areas affected by recurrent fires near grinding centers in the Amazon. In addition, these losses can reach US\$ 565 ha/year in regions of high agricultural profit in both biomes. Despite high losses, investments in fire mitigation are still low, averaging US\$ 3.7 ha/year on public lands and US\$ 11.2 ha /year on private lands. On the other hand, even if mitigation is little adopted, the benefits of management practices, when they are effective in reducing fire avoid economic losses, which are substantially greater than mitigation costs. In some high-carbon forest sites and profitable areas of agricultural production, mitigation benefits can be 25 times greater than their costs. Through this work it is possible to identify that the fire mitigation programs in Brazil do not meet the critical points of economic losses in the production of wood in the Amazon and should be better targeted. In addition, the public benefits of management practices only occur

in the Cerrado, when the fuel (the volume of biomass available to burn) is properly managed, and in the Amazon only when there is a joint action between suppression practices, policies and incentive programs for fire prevention. Likewise, fire prevention generates significant private benefits for agricultural producers actively involved in fire mitigation programs.

INTRODUCTION

Since the early 1960s, there have been hundreds of attempts to account for the value of the world's ecosystem goods and services through a variety of techniques that are now well known and present in the literature (Costanza et al., 1997; Gerwing, 2002; Pagiola et al., 2004; Strand, 2017). However, despite some efforts to include the economic impacts of forest fires in this literature (Andersen et al., 2002; Mendonça et al., 2004; Nepstad et al., 2001) they are still undervalued, particularly in tropical forests. Fire affects a range of natural, social and economic processes in widely varied ways which makes the valuation exercise a major challenge for researchers (Mavsar et al., 2013). In addition, although the destructive power of fire is acknowledged worldwide, financial resources are not strategically directed to make forest fire management more efficient (Lankoande, 2005; Snider et al., 2006). In this way, the lack of economic information is creating a barrier for improving fire management in the world. This is because government budgets for fire impacts mitigation are increasingly limited and, therefore, there is an emergency need for better strategies for the allocation of economic resources (Mendes, 2010).

By developing spatially explicit models, this study seeks to contribute to fill this gap through two major objectives: 1. to estimate economic losses by fire on land uses in the Brazilian Amazon, and 2. to quantify the economic costs of forest fire management practices in the Amazon and Cerrado biomes. Two major chapters were developed to meet these goals. The first presents the economic losses for the sustainable production chain of timber in the Amazon, which were estimated through a set of models that simulate the synergy between logging and fire spread and intensity. The second chapter presents a cost-benefit analysis of forest fire management practices in both biomes. For this, the proposed methodology calculates the economic costs of the practices used by both public and private entities, in agricultural properties and federal conservation units, respectively. In addition, this study presents an estimate of economic losses caused by forest fires in these units, as well as on crop production (corn and soybeans) in agricultural properties.

For the development of this study, fieldwork campaigns were carried out in state of Mato Grosso, where the occurrence of fires is frequent and the activities under analysis (sustainable timber production and agriculture) are representative in the regional economy. Data were also collected from some of the most important

organizations working with forest fires management in Brazil, in this case the ICMBIO¹ and Aliança da Terra². In addition to the primary data collected, this study is also based on more accurate data derived from the literature. In both chapters, new spatial analysis methodologies were formulated based on heuristics derived from fieldwork (empirical parameters) for estimating economic losses by fire. Additionally, the cost-benefit analysis provided new insights into complex decision-making processes related to economic resource allocation between forest fire management practices in in the Amazon and Cerrado.

¹Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio/MMA, 2016)

²Aliança da Terra: Non-profit organization(TERRA, 2017)

CHAPTER 1 - ECONOMIC LOSSES TO SUSTAINABLE TIMBER PRODUCTION BY FIRE IN THE BRAZILIAN AMAZON³

ABSTRACT

Although still the largest expanse of tropical rainforests in the world, the Amazon is suffering a declining capacity to deliver ecosystem services, to which the widespread use of fire is one of the main contributing factors. Even if fires directly affect the timber sector, most current logging practices often tend to increase rather than mitigate the problem. We argue that in order to involve the timber sector in fire mitigation policies in the Amazon it is crucial to assess the economic impact of fire on the sector. This paper describes EcoFire, a spatially-explicit model for valuing the economic losses by fire to sustainable timber harvest operations in the Brazilian Amazon. To conduct this analysis, we have integrated a set of models that simulate the synergy between logging and fire spread and intensity. Our results show that fire affects roughly 2% of the timber production areas that would be harvested between 2012 and 2041. In burnt areas, fire causes losses on average of US\$ 39±2 ha/year (Equivalent Annual Annuity), which represents a loss of 0.8 % of expected rents. Yet losses can reach up to US\$ 183±30 ha/year in areas hit by recurrent fires that are near milling centres. The results indicate that some of the municipalities that are likely to accumulate most economic losses due to fire do not yet have local-level fire mitigation programmes. We therefore conclude that spatially-explicit valuations of the economic impact of fire can pinpoint priorities for better targeting fire action plans as well as for engaging local actors in integrated fire management practices.

Keywords: collective fire management, economic losses by fire, fire mitigation policies, spatially explicit modelling, timber species distribution

1.1 Introduction

Although still the largest expanse of tropical rainforests in the world, the Amazon is suffering a declining capacity to deliver ecosystem services such as climate regulation (Costanza *et al.* 1997, Baccini *et al.* 2017, Phillips and Brienen 2017). Moreover, some scholars have warned that “negative synergies between deforestation, climate change and widespread use of fire indicate a tipping point for the Amazon system to flip to non-forest ecosystems in eastern, southern and central Amazonia” (Morton *et al.* 2013, Lovejoy and Nobre 2018, p. 1). Forest fires are particularly detrimental at the deforestation frontier where forests are made vulnerable by logging activities, road construction and land occupation (Freifelder *et al.* 1998, Brando *et al.* 2012, Soares-Filho *et al.* 2012). In spite of increased governmental efforts to improve

³ Article accepted for publication (DOI: 10.1111/geoj.12276) in periodical *The Geographical Journal* in June of 2018 (<https://rgs-ibg.onlinelibrary.wiley.com/journal/14754959>).

forest conservation policies in the 2000s (Rajão and Vurdubakis 2013, Cunha *et al.* 2016), forest fire rates have remained high (INPE 2016). According to Moutinho *et al.* (2016), landowners have responded to these policies by changing deforestation strategies, such as deforestation in smaller patches and more frequent burning to induce gradual degradation, in the hope of remaining undetected by monitoring systems and law enforcement. Some scholars have tried to measure the economic losses of forest fires in the Amazon as a counterweight to the perceived economic benefits of land use change for individual landowners (Nepstad *et al.* 2001, Andersen *et al.* 2002, Gerwing 2002, Menton 2003, Mendonça *et al.* 2004, Strand 2017). However, these studies have not considered the spatial variability of these losses, which may be useful for public policy-making.

In this article we present EcoFire (Economic Cost of Fire), a spatially explicit model developed to estimate the economic losses in the forestry sector caused by forest fires between 2002 and 2041. More specifically, we simulate synergies between selective logging of native forests, fire spread and fire intensity by integrating EcoFire with FISC and SimMadeira, two models that simulate fire and timber rents (in the absence of fire) that have already been established in the scientific literature (Merry *et al.* 2009, Brando *et al.* 2012, 2014, Soares-Filho *et al.* 2012). In this respect, we aim not only to raise awareness of the costs of forest fires for the timber industry, as has been done in other studies (e.g. Andersen *et al.* 2002), but more importantly to identify regions where the losses are particularly high and, subsequently, to aid policy-makers in the formulation of fire mitigation policies. In addition, we aim to advance current methods and tools for mapping economic losses from ecosystems services in the Brazilian Amazon. The next section opens our argument with a discussion of the available literature on fire mitigation policies. Section 3 elaborates our research approach, in which we explain and discuss the integration of the FISC, SimMadeira and EcoFire models as well as our assumptions and primary data sources. In section 4, we present the results of our analysis, followed by a discussion on the implications for fire mitigation policies in the region.

1.1.1 The politics and economics of fire mitigation in the Brazilian Amazon

Historically, disincentive-based policies by the federal government have been the most common response to reduce fires in Brazil (Morello *et al.* 2017). According to

the Brazilian Forest Code (Brazilian Forest Code (Law 12651/12), the use of fire is generally prohibited and, if justified, requires a fire management plan as well as prior consent (i.e. licensing) from the state government (art. 38). In practice, however, most fires occur without formal licensing and use insufficient preventive measures and the few fines issued by the government are rarely paid (Rajão and Vurdubakis 2013). Consequently, these regulations are inefficient in reducing forest fires (Morello *et al.* 2017) and have led to calls for the reformulation of current mitigation policies (Cammelli 2013, Carmenta *et al.* 2013, Morello *et al.* 2017). Some existing fire prevention programmes led by governmental and non-governmental organizations with a stronger involvement of local communities have produced good results. These include the Register of Socio-environmental Commitment and Fire Brigade of the Land Alliance (Silvestrini *et al.* 2011), the "Green Flame" Project in Paragominas (Vilhena 2016) and the "Green Municipalities" in Pará (Guimarães *et al.* 2013). In contrast to the punitive character of state-level and federal disincentive-based policies, these local programmes invest most of their efforts in educational, preventive and integrated fire management practices associated with specific land uses, such as pasture and agriculture (Myers 2006). These programmes also tend to be more sensitive to the needs of small farmers who use fire as part of relatively sustainable slash-and-burn agriculture, while pressuring large farmers who use fire to deforest large tracts of land.

The successes of local fire mitigation programmes can be partially explained by their understanding of forest fires as a problem of collective action. While different economic actors collectively participate in regional land management processes (Tacconi *et al.* 2006, Cammelli 2013), land users often do not consider the broader effects of fire. Nepstad and Alencar (1999) argue that land users are so dependent on fire that it represents an inseparable component of management and expansion of agricultural frontiers. Furthermore, they often lack the willingness or knowledge to invest in fire control, which may have damaging consequences for adjacent economic activities. This is especially the case for large farmers who use fire as a way to reduce the cost of deforestation and pasture expansion (Nepstad and Alencar 1999, Cammelli 2013). In addition, forest fires also have damaging consequences for society, such as respiratory ailments and damage to livestock, pasture, crops, houses, and forestry resources (Mendonça *et al.* 2004). The main challenge, therefore, is to make such damaging consequences clear to both landowners and policy-makers in order to incentivize them to adopt more proactive action to reduce forest fires. According to

Zybach *et al.* (2009), for example, forest fire suppression costs can be 50 times lower than the total costs related to the damage that fire causes to society. For this purpose, some authors suggest that economic impact estimates could inform the establishment of preventive measures, such as agricultural credit schemes for rural production (Nepstad *et al.* 2001, Morello *et al.* 2017) or integrated fire management programmes (Myers 2006).

The non-integrated character of fire management practices is confirmed by scholars suggesting that, in spite of damaging consequences, the forestry sector contributes to increasing occurrences of forest fires. Furthermore, even sustainable practices have not been able to mitigate the problem. By augmenting fuel loads on the ground and opening forest understories, selective logging increases the vulnerability of forests to fire (Soares-Filho *et al.* 2012). Furthermore, roads built by loggers often provide access to land grabbers and cattle ranchers who use fire to clear lands (Freifelder *et al.* 1998, Brando *et al.* 2012). Since the use of fire has both costs and benefits, although borne differently by different actors, it is crucial to demonstrate the economic consequences of forest fires on the provision of forest products and services as key information to decision makers from both public and private sectors (Gerwing 2002, Menton 2003).

Some studies have already estimated the economic impact of forest fires on sustainable timber production. Andersen *et al.* (2002), for example, measured fire-induced forest cover loss in agricultural areas and the effects on the values of timber. The authors assumed that sustainable timber supply is worth US\$ 28 ha/year and that destructive fire entails a loss of 100% for a period of 50 years following the fire event (*ibid*: 178). Alternatively, Mendonça *et al.* (2004) integrated data from the literature to assess losses in agriculture, costs of respiratory illnesses, forest resource losses, and CO₂ emissions from forest fires. They calculated a total average yearly loss ranging between US\$ 90 million and US\$ 5 billion during the period 1996-1999 for the entire Brazilian Amazon. For these years, forest losses represent on average 0.5% of these total losses, equivalent to a value of US\$ 5 ha/year (Mendonça *et al.* 2004). Although these studies are an important starting point, there are some limitations. Both approaches have disregarded the way in which different fire intensities may have varying effects on different tree species and the quality of timber, instead treating the Amazon forest as a homogeneous ecosystem for which they calculate a single average marginal economic loss. According to Andersen *et al.* (2002), for example, it is

“obviously infeasible here to attach a different value to each of the several hundred million hectares of Amazon forest” (p. 170). Although such estimates provide valuable information, they are insufficient to guide policies aimed at reducing the impact of forest fires, since they do not consider the spatial variability of their occurrence, economic impact and ecological effects. By extension, they do not provide information about where preventive measures may be most cost-effective.

1.2 Methods

1.2.1 General Approach

In order to demonstrate the spatial variability of economic losses caused by fire in sustainable timber production, we have developed the spatially explicit model EcoFire (Economic Cost of Fire). In this paper, sustainable timber production refers to Reduced Impact Logging (RIL), which corresponds with the legal norms and practices (CONAMA 2009) for minimizing the ecological impacts in the areas of timber concessions (details in section 3.2). The Ecofire model processes and combines spatial data on the occurrence and intensity of forest fires, data on the impact variation on different tree species and economic data on timber production in the Amazon in order to estimate the economic losses. We simulated fire occurrence and intensity by using the FISC model (Fire Ignition, Spread and Carbon components) developed by Silvestrini *et al.* (2011) and Soares-Filho *et al.* (2012). In addition, we simulated timber production and rents by using the SimMadeira model developed by Merry *et al.* (2009). Both models were adapted in order to provide data for the entire Amazon region with a spatial resolution of 1km² and to facilitate integration with the EcoFire model (Figure 1), the details of which will be explained in the following sections. These new versions of the FISC and SimMadeira models that integrate with EcoFire were developed by Soares-Filho, Lima, *et al.* (2017) and Soares-Filho, Oliveira, *et al.* (2017) (available at <http://amazonas.info>). In order to establish the relationship between fire and timber, EcoFire consists of a set of heuristics (i.e. empirical parameters) that represent the economic impact of different fire intensities on different commercial tree species. For instance, low-intensity fires can reduce 5% of the selling price when they reach commercial timber coming from mature trees (Figure 1; see section 3.3 for details).

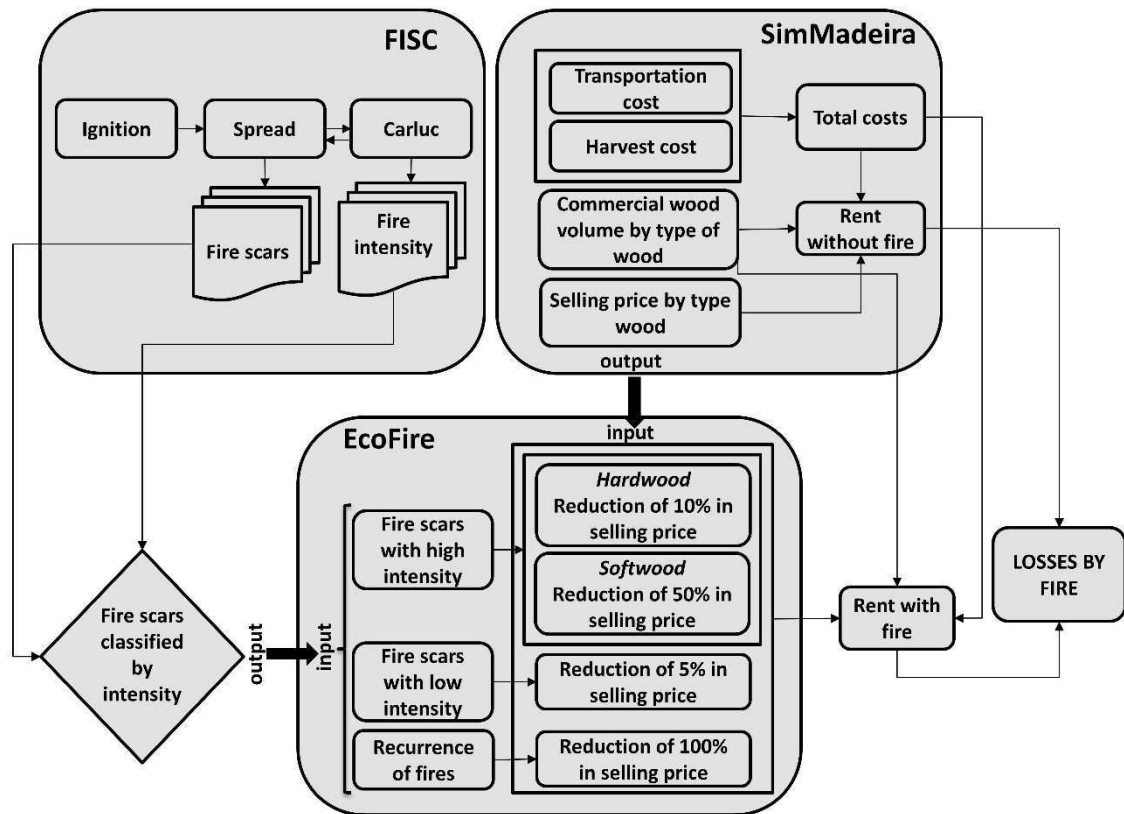


Figure 1 Integration of the models and heuristics derived from fieldwork used by EcoFire to calculate the economic losses to the sustainable timber production in the Amazon.

The annual net revenues (rents) and economic losses of sustainable timber are presented as the Equivalent Annual Annuity (EAA). Based on the Net Present Value (NPV), for which we used an interest rate of 5%, the EAA derives the annual uniform value of a project/activity that is evenly spread over its lifespan. The reference period of our analysis was chosen on the basis of current legislation in the state of Mato Grosso (Decree n° 2152/2014). This legislation states that a full production cycle of sustainable timber covers on average a 30-year period (art. 9-II). Choosing a starting year that facilitates the integration of the models used in our analysis, we therefore calculate the economic losses for the period 2012-2041. At the same time, the same legislation prohibits timber harvests in cases of fire recurrence (i.e. more than once) within a 10-year period (art. 25). In order to account for the possibility of an economic impact from fires in preceding years, we estimate fire occurrence for the period of 2002-2041. Correspondingly, EcoFire assumes a 10-year period as the maximum duration that fire entails timber losses, because this model takes into account that 90% of biomass losses could recover within this time interval as is estimated by the CARLUC component in the FISC model (Soares-Filho *et al.* 2012).

1.2.2 Localization of Forest Fires (FISC-Model)

FISC (Fire Ignition, Spread and Carbon components) is a process-based understory fire model developed for tropical forests (Silvestrini *et al.* 2011, Soares-Filho *et al.* 2012). Since the initial version was implemented for the Xingú region in state of Mato Grosso, we expanded the FISC model to simulate fire ignition and propagation processes in the entire Amazon biome. Furthermore, we expanded the spatial resolution from 10.2 ha (320 x 320m) to 25 ha (500 x 500m) in order to accommodate the larger area of analysis.

The ignition and fire spread components of FISC are interrelated in order to provide data on fire occurrence, namely the location of fire ignition and the subsequent spread of fire across the landscape that result in forest fire ‘scars’. The fire ignition component in FISC simulates hot pixels⁴ as a function of land use that are modulated by spatial determinants (e.g. distance to deforested land, roads and towns, and elevation), land-use restrictions (e.g. protected areas) and climatic seasonality represented by monthly data on Vapour Pressure Deficit (VPD) (Inputs - Table S1⁵). Following the fire ignition, the fire spread component employs a cellular automata model to simulate fire propagation as a function of distance to ignition sources, terrain features (e.g. declivity, obstacles, different land uses), fuel loads and wind direction (Inputs - Table S1). Furthermore, this component includes data on forest climatic conditions and availability of fuel loads (e.g. dry wood) from the CARLUC model (see below). Both components (ignition and spread) require probability maps for the simulations (e.g. climatic probability map). FISC uses, among other techniques, logistic regression to generate these maps and probability density functions (PDFs) which define where fires are likely to occur and spread. For the calibration of the fire ignition components we compared the monthly number of simulated and observed hot-pixels (NOAA 12, night - INPE 2016) between 2004 and 2010 (Figure S2). For the validation of fire spread data we compared burned area metrics, spatial distribution and scar size between the simulated and observed data of Morton *et al.* (2013) for the years 2002-2010 (Figures S3 and S4). For 2002-2010, the scars simulated from FISC present a difference of 18% (lower) in

⁴ Heat signals from fire as observable from satellite-based infrared sensors.

⁵ Tables and Figures denoted as Sx appear in on-line Supporting Information.

relation to average burnt areas in the map of Morton *et al.* (2013) (see details in Supporting Information; Figures S1 and S3).

FISC also contains a carbon and land use change component, the CARLUC model (Hirsch *et al.* 2004), for simulating fuel load dynamics, forest regrowth, and carbon emissions. The calibration of CARLUC was based on field observations in the Tapajós National Forest (see Brando *et al.* (2014) and Supporting Information for more details, Figure S5, S6 and Table S3). CARLUC simulates fire intensity dynamically, based on the amount of available fuel load and the fire spread and combustion heat (Byram 1959). As fire intensity has a direct impact on timber production (see section 3.3), we define thresholds of fire intensity from the work by Brando *et al.* (2014) which relates fire intensity with the tree mortality. In this way, we define forest fires of high intensity as being higher than 400 kW/m, when tree mortality in general exceeds 50%; fire events with values equal to or below this threshold are considered low intensity as they cause 10 to 20% tree mortality. For instance, during two drought years, 2005 and 2010, roughly 82% and 65% of fire scars simulated for those years, respectively, presented high intensity values, reaching more than 800 kW/m. FISC allows us to investigate, therefore, the changes in fire regime, such as fire frequency, extent, and interval, to simulate post-fire damage, e.g. burnt area, type of vegetation affected, and the recurrence of fire (Figure 2).

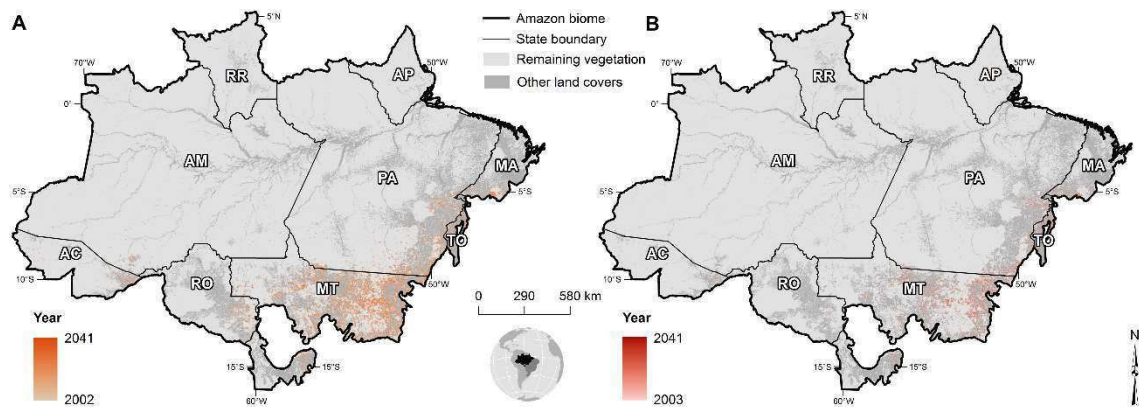


Figure 2 Fire occurrence (A) and recurrence (B) output from FISC-model.

The occurrences of fire simulated by FISC are closely related to the expansion of the agricultural frontier and the consequential forest fragmentation (Silvestrini *et al.* 2011, Soares-Filho *et al.* 2012). In order to take this into account, deforestation data for the years 2012 to 2015 were obtained from the Programme for the Estimation of

Deforestation in the Brazilian Amazon from the Brazilian Institute for Space Research (PRODES-INPE 2015). For the remaining years (2016-2041), we assumed a constant yearly deforestation rate of 5,000 km², which corresponds with the deforestation target of the National Climate Change Plan and the value detected by PRODES in 2012. As such, the recent increase in deforestation rates from 2013 and 2016 was disregarded, which renders our approach more conservative. This resulted in a spatially-explicit simulation of deforestation and fire scars in the Amazon between 2012 and 2041 (Figure S7).

1.2.3 Rents and timber production (SimMadeira-Model)

The SimMadeira model simulates the timber production of native forests in the Amazon (with a spatial resolution of 1 km²) based on Reduced Impact Logging (RIL). We understand RIL as a form of sustainable forest production, which refers to forms of harvest planning and logistics that maximize productive efficiency while minimizing the impacts on timber production. RIL reflects the norms and practices proposed by the Brazilian government for timber concessions. In this case, 1) timber production may not exceed 0.86 m³ ha/year, and involves adoption of forest management units; 2) annual harvest areas are defined; and 3) protection occurs against re-cutting during the harvest cycle (CONAMA 2009). SimMadeira calculates sustainable logging rents (parameters – Table S4) based on production costs (Table S5 and S6) and timber market prices (Table S7) in the Amazon (Merry *et al.* 2009). According to Brazilian resolution number 406/2009 (CONAMA 2009), timber harvest cannot occur in protected areas, and therefore SimMadeira does not envisage timber extraction in these areas.

For the development of EcoFire, SimMadeira was extended to provide robust geographically differentiated estimates of sustainable timber rents for 40 timber genera (each including one or more species) based on their ecological distribution (Table S7). These genera build on definitions and valuations developed by the Institute of Man and the Environment of Amazonia (IMAZON), which provide the most complete data source currently available (Pereira *et al.* 2010). We use data on the occurrence of tree species from online databases of species occurrences (CRIA - Specieslink (2015): <http://splink.cria.org.br> and Global Biodiversity Information Facility (GBIF 2015): <https://www.gbif.org/>) in order to model the distribution of these species based on their ecological niches (see section 2.1 of the Supporting Information for more detail).

The EcoFire model evaluates the economic losses for different types of timber affected by fires of different intensity. The SimMadeira model differentiates these genera of commercial timber on the basis of their densities and resistances, distinguishing between hardwood (i.e. high density, high commercial value, and high resistance to fire) and softwood (i.e. low density, low commercial value, and low resistance to fire). Although classifications already exist in the literature (Melo *et al.* 1990, Dias and Lahr 2004), they do not cover all genera/species listed by IMAZON. For this reason, four forest engineers independently classified each commercial timber genus/species from the IMAZON list as either hardwood or softwood. The list contains both genera, such as *Aspidospermasp* with many tree species that go under the common name of “Peroba”, and tree species such as *Mezilurusitauba* (Itaúba) that correspond to one genus. In this way, our classification draws on the market experience of these forest engineers in order to approach the impact of fires on timber production. Despite using a different approach, our classification based on forest engineer experience corresponds with 70% and 83% of comparable data presented by Dias and Lahr (2004) and (Nahuz *et al.* 2013), respectively. According to technical standards, high density timber has a value of 835 kg/m³ or higher, while low density timber has lower values.

The commercial timber volume for each tree species was based on volume data provided by Merry *et al.* (2009). Since these data are based on remote sensing biomass maps, these values only represent indirect measurements of commercial timber volumes, which is a common challenge in the available literature (Goetz *et al.* 2009, Baccini *et al.* 2012, Mitchard *et al.* 2014). In order to calculate the volume of each type of timber, we used our species distribution maps (see Figure S10) in order to locate the pixels representing each timber type, after which we allocated the commercial timber volumes of each pixel to the timber types therein present according to their relative abundance (Figure S11 and Figure S12). The relative abundance of tree species was calculated based on an Amazon-wide distribution of 4,962 tree species estimated by Steege *et al.* (2013).

We calculated the potential value of timber production by multiplying the timber volume estimates with its respective prices. The gross revenues of each timber genus were allocated to the softwood and hardwood categories (see above) in order to calculate timber losses accordingly in the EcoFire model (Figure S13). Roughly 14% of the harvested volume and 20% of the gross revenue stem from hardwood and the remainder from softwood timber types. The rent or stumpage value (i.e. residual value

for the landowner) from harvest timber was obtained by deducting all harvest costs from the gross revenue. The rent π_j for a cell j was calculated by SimMadeira as follows:

$$\pi_j = \sum_{\text{for each } g \text{ in } j} [(p_{jg} * V_{jg}) - ((TC_j + HC_j + PC_j) * (1 + I))] \quad (1)$$

Where p_j is the location-specific price of the timber type g in the cell j , V is the commercial volume of the timber type g , TC is the transportation cost of round wood from a specific cell j to the location of the nearest milling center, HC and PC are the harvest and processing costs, respectively, and I is a social discount rate (the model assumes an inflation-adjusted rate of 5%).

Transportation costs range from 0.05 to 2,564 US\$/m³/km (Table S6) depending on land-use types (e.g. deforested area, public forest without designation), road paving conditions (e.g. paved, unpaved, four-lane road) or waterway conditions (e.g. navigable waterway, limited navigability, navigability only in rainy season).

All costs remained unchanged in relation to the original version of SimMadeira, while rents were between 4.3% and 10% higher in the extended version due to a more refined representation of timber distribution and volumes (Merry *et al.* 2009). In the SimMadeira model, prices are taken as fixed throughout the entire harvest cycle due to difficulties to accurately forecast timber prices as well as other input prices that would also affect rents (e.g. fossil fuel prices affecting transportation costs), which also introduces some degree of uncertainty to our analysis. Moreover, timber prices are estimated as a weighted average value for a small sample of genus and species, since the available literature does not provide standardized data on variation in species, class, and density in different regions in the Amazon.

1.2.4 Economic Losses from destructive fire (EcoFire model and heuristics)

Both the data on fire occurrence from FISC and the data on timber revenues from SimMadeira were inserted in the EcoFire model, but our analysis of economic impacts required additional data on the relation between fire and timber production in order to complete input data. Since few studies provide such data in consideration of species variability, or differentiate types of forest fires (Andersen *et al.* 2002, Gerwing 2002, Menton 2003, Mendonça *et al.* 2004), our analysis obtained this data from questionnaires. We conducted 30 interviews with farmers, forest engineers, forest

rangers, loggers, and sawmill owners in the Sinop region in the state of Mato Grosso (see questionnaire in the Supporting Information and Table S9). This municipality was selected due to its high density of both logging activities and fire occurrence (Silvestrini *et al.* 2011, Morton *et al.* 2013, INPE 2016).

According to these questionnaires, there are three major drivers of fire-related economic losses in timber production: 1) fire intensity; 2) fire recurrence; and 3) the resilience to fire of individual timber species. These findings correspond with reports in the available literature on relation between fire and forest damage (Holdsworth and Uhl. 1998, Nepstad *et al.* 1999, Barlow *et al.* 2012, Brando *et al.* 2012, 2014). The majority of interviewees (75%) pointed out that low intensity fire reduces the average selling price of one m³ of soft and hardwood by around 5%. In the case of high intensity fires, most interviewees (83%) reported an average price reduction of 10% for hardwood, while price reductions for softwood reach up to 50% due to reduced tree resilience (Figure 1). Finally, respondents reported substantial economic losses to timber production regardless of fire intensity, which accounts for state legislation (i.e. Decree n° 2152 2014) that prohibits timber harvests in cases of fire recurrence (i.e. more than once) within a 10-year period. Extending this to the entire Amazon, we assume that the recurrence of fires entails a 100% loss of commercial value during this prohibitive period (Figure 1). Although the small number of respondents may pose limitations for generalization, the introduction of these ‘heuristics’ to our EcoFire model (Figure 1) introduces a novelty to existing literature on modelling the losses of fire.

In general, EcoFire estimates the economic losses in a number of consecutive steps. First, SimMadeira provides the EAA of sustainable timber production in the absence of fire for the period 2012-2041. In order to account for the uncertainties of the model, we considered bounds corresponding to $\pm 15\%$ variation in timber prices (see rents in the absence of fire in Figure S14 and S15). EcoFire then calculates the economic impact of fire on each pixel, taking into account the timing of fire events in relation to the harvest year and the set of heuristics related to fire damage (Figure 1). Since the economic impact varies according to the type of fire, we used the annual fire scar data from FISC classified by intensity for the period 2002-2041. The results, therefore, represent the economic impact of 40 years of fires in a full timber production cycle (see section 3.1). EcoFire calculates economic losses based on the commercial value of timber (Figure S13). In this way, economic losses by fire on timber net revenue (rents) by subtracting the costs from gross rents (commercial value) from the decreased

commercial values of timber caused by fire, considering that harvest costs remain the same. In cases where net rents are negative, we set the net rent to zero since those areas are not profitable. The model estimates effective losses (losses in simulated burnt areas that eventually would end up logged) and “potential values/losses” as if all burnt areas would be logged in the near future. In the same way that it is useful to consider the total amount of CO₂ that would be emitted if the Amazon were to be completely deforested, it is also relevant to consider the impact of fire on timber as if all those areas affected would be logged.

1.3 Results

Our spatially-explicit analysis indicates a substantial and growing decoupling between sustainable timber production and fire events in the Brazilian Amazon. While forest fires occur on 11.1 Mha of newly-burnt areas and 3.8 Mha on recurrent areas between 2012 and 2041, we estimate that only 693±168 thousand ha occur in productive areas (Figure S16). Conversely, these forest fires affected only 2% of the total cumulative area (i.e. 48±7 Mha) designated for sustainable timber production. We also observed a declining share of affected areas in the reference period. Even though the annual fire-affected area increases to 31±11 thousand hectares by 2024, the expansion of timber production grows at a faster rate in areas not prone to fire, hence, the percentage of the harvest area affected by fire reduces to 0.5% by the end of the period, in 2041 (Figure 3).

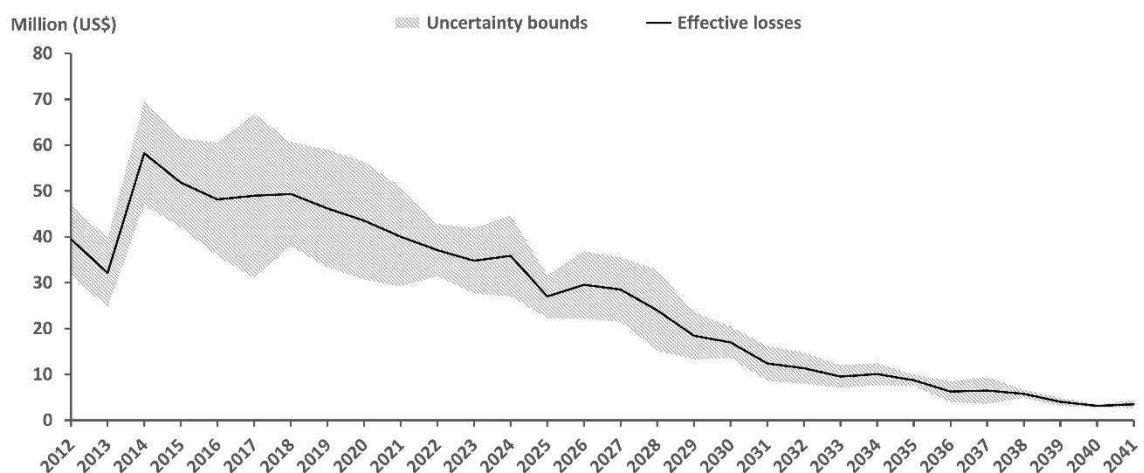


Figure 3 Annual economic losses by fire to sustainable timber production and uncertainty bounds (±15% of average timber prices).

Between 2012 and 2041, the total net revenue (rent) of sustainable timber production increases from 431±91 million in 2012 to US\$ 913±360 million in 2041, peaking at US\$ 1.04±0.3 billion in 2023 (Figure S15). Concurrently, the economic impact of forest fires peaks at US\$ 54±11 million (8%) in 2014 and steadily declines to US\$ 2.7±0.8 million (0.3%) by the end of the logging cycle (Figure 3). The gradual reduction of the impact of forest fires corresponds with the lower deforestation rates projected by FISC. Moreover, these observations indicate that most economic losses from forest fires occur before 2020, after which values decrease at an average rate of 10% per year. In the policy scenario considered, the decrease in the economic losses from fire reflect a migration of sustainable timber production away from the agricultural frontier, where forest fires are more likely due to high levels of fragmentation and dryness, towards more remote areas where valuable tree species are more abundant (Broadbent *et al.* 2008).

These impacts are not evenly distributed over the Amazon region. In the affected areas, the average economic losses induced by forest fire were estimated to be US\$ 39±2 ha/year, which represents a loss of 0.8% of the expected rent. We found that most forest fires concentrate near the agricultural frontier or major roads in the northwestern Mato Grosso, Eastern Pará, and south-central Maranhão states (Figure 4). Moreover, these regions may incur costs of up to US\$ 183±30 ha/year, especially in areas hit by recurrent fires near milling centres.

Although the aggregate economic losses may be very low (see previous paragraph), these observations indicate that the impact of forest fires at a local scale can be substantial. These results are slightly amplified when estimating the potential economic losses of forest fires (if all burnt areas would be logged in the near future). On average, the potential economic losses by forest fire for sustainable timber production were estimated at US\$ 726±193 million, with an NPV of US\$ 689±184 million, which are only 4% of the total net revenue (US\$ 1.52±0.2 billion) from a 30-year logging cycle in the absence of fire (Figure 5). By contrast, economic losses were absent in large expanses of the Northwestern Amazon, where there is a paucity of forest fires due to low agricultural activity and where high transportation costs (e.g. few roads) render sustainable forest production largely unprofitable.

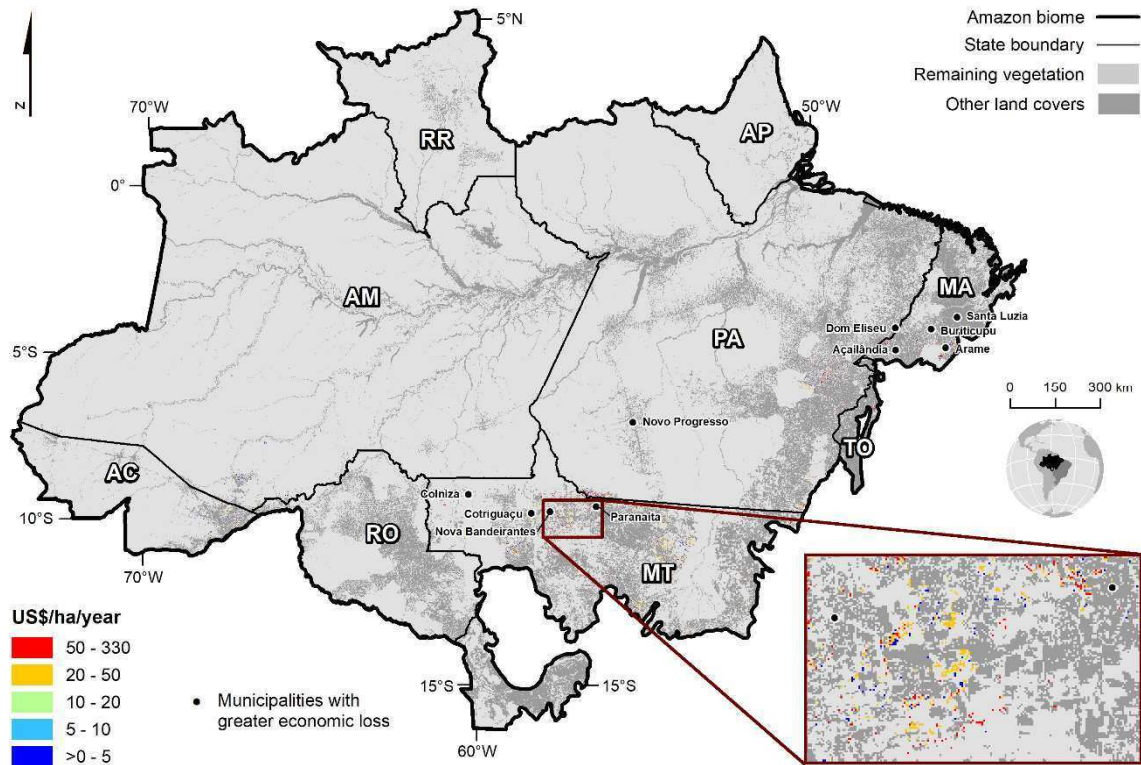


Figure 4 Economic losses by fire to sustainable timber production highlighting the region of Sinop.

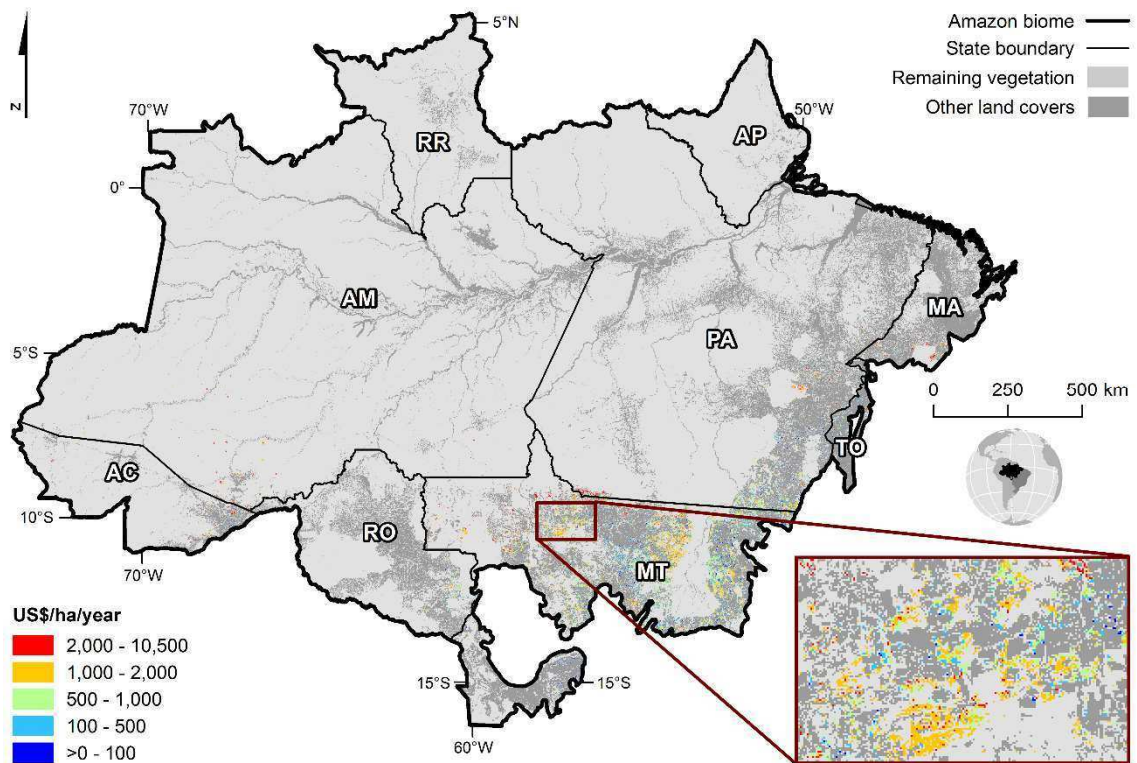


Figure 5 Potential economic losses (NPV) by fire to the sustainable timber production highlighting the region of Sinop.

1.4 Discussion and Conclusion

Our spatially explicit analysis of the economic impact from forest fires for sustainable timber production reveals higher economic losses than suggested by other scholars. Mendonça *et al.* (2004), for example, estimated the yearly total loss in timber production of US\$ 1-13 million, while our study indicates an annual average loss of US\$ 29±4 million. Moreover, Andersen *et al.* (2002) report that fire causes average losses to timber production of US\$ 28 ha/year, while we estimate a loss of US\$ 39±2 ha/year. The main difference between these estimates is to be found in diverging data sources and methodologies. For instance, our analysis includes fire scars where forest caught fire in forest understories, differentiates between different tree species and considers survival variation based on tree lifespan, which differs from these studies that measure the losses only by the mortality of trees at a constant rate for the whole forest. More importantly, our study has identified specific regions where economic losses are very high and drive up the average costs induced by forest fires. In these regions, the economic losses far exceed the relatively low shares of average net revenues (i.e. 4%) estimated for the entire Amazon region.

The most important factor that drives up economic losses from forest fires is the proximity of sustainable timber production to the agricultural frontier, where different economic practices (i.e. sustainable logging and agriculture) compete. Feeding these assumptions into our model (see section 3.2), we found that such damaging consequences are most likely to be concentrated in the northwestern Mato Grosso, Eastern Pará, and south-central Maranhão states. Moreover, economic losses tend to be highest in the first few years of the 30-year logging cycle, after which sustainable logging activities are likely to move away from the agricultural frontier.

These findings have important implications for decision-makers in both private and public sectors in terms of forest fire prevention. Firstly, preventive efforts could target the fire ‘hotspots’ identified by our analysis in order to reduce economic losses to sustainable timber production. With respect to fire mitigation programmes deployed in the Amazon (see section 2), we found little evidence that they target the fire ‘hotspots’ identified in our analysis. For instance, only two of the 10 most affected municipalities (Dom Eliseu, in the state of Pará and Paranaíta in Mato Grosso) are part of regional fire mitigation programmes. By contrast, we could not find local programmes in the municipalities of Arame, Buriticupu or Santa Luzia in Maranhão, and Colniza,

Cotriguaçu and Nova Bandeirantes in Mato Grosso, even though they are likely to experience the heaviest fire losses in the region (see Table S10, S11 and S12). In addition to spatial prioritization of fire prevention efforts, we also argue that such efforts must be quick to materialize in order to avoid most economic losses to sustainable timber production.

The limitations of incentive-based and disincentive-based policies indicate that alternative approaches to fire prevention need to be considered. By exposing the potential economic losses, our study empowers the logging sector as an important ally of fire mitigation strategies (Nepstad *et al.* 2001, Mendonça *et al.* 2004). At the same time, however, the negative economic impacts of forest fires may include a myriad of other economic activities that also need to be included in integrated fire management programmes (Myers 2006). Unless a broader agreement is reached with rural producers, fire mitigation policies are unlikely to succeed (Tacconi *et al.* 2006, Cammelli 2013, Carmenta *et al.* 2013).

We recognize that our spatially-explicit analysis needs refinement in some respects in order to better reflect the complexity of estimating economic impacts. For instance, our assumptions were constrained by lacking parameters related to field experiments, scarce literature on the reaction of various tree species to different fire intensities damage and a lack of robust data on the occurrence of tree species in the Amazon. At the same time, however, our study merely scratches the surface of providing economic impact data on forest fires. We have assessed only one of 17 ecosystem services identified by Costanza *et al.* (1997), namely the provision of raw materials, and only one product within that category (i.e. timber), which suggest that the economic losses from forest fires may be much higher than estimated in our study. In this respect, our analysis denotes an important first step in advancing geographically differentiated impact assessments.

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CHAPTER 2 - THE COSTS AND BENEFITS OF PUBLIC AND PRIVATE FIRE MANAGEMENT IN THE BRAZILIAN AMAZON AND CERRADO BIOMES⁶

HIGHLIGHTS

- Fire suppression actions alone are not generating sufficient results to justify long-term investment in fire management in the Brazilian biomes;
- Although public investments in forest fire management practices are still low, their benefits by reducing fire can be very high, especially in the Amazon;
- Rural landowners avoid substantial economic losses in agricultural production when engaged in active fire prevention programs.

ABSTRACT

There is a noted lack of understanding if the investments directed to the forest fire management in Brazil are justifiable in their most diverse landscapes. Although direct firefighting by the suppression measures, may reduce the extent of the burn over the short-term, is easily quantified and is an obvious response to an immediate need, the benefits of preventive measures are yet to be accurately valued. In this study we conduct a cost-benefit analysis of fire management practices in the Brazilian Amazon and Cerrado, with a specific focus on the benefits of prevention and the differences between public and private fire management action. Our results show that the cost of fire management in public conservation units are on average US\$2.13 ha⁻¹ yr⁻¹ in the Amazon, and US\$5.3 ha⁻¹ yr⁻¹ in the Cerrado. These investments, however, avoid economic losses that can be as high as US\$27.5 ha⁻¹ yr⁻¹ in dense forest areas. On private lands, investment of US\$11.2 ha⁻¹ yr⁻¹ in fire management can avoid potential losses of US\$76 ha⁻¹ yr⁻¹ and may generate benefits of up to 25 times greater in lucrative agricultural production areas. The public benefits of management practices, however, occur in the Cerrado only when the fuel (the volume of biomass available to burn) is properly managed, and in the Amazon only when there is joint action between suppression practices, policies and incentive programs for prevention of fire. Likewise, we have identified that prevention generates significant private benefits for agricultural producers engaged in fire mitigation programs.

Keywords: Resource allocation, forest fire management, economic losses by fire, spatial cost-benefit analysis, Brazilian Amazon and Cerrado.

2.1 Introduction

Forest fires are widely recognized as a frontier driver of deforestation as well as a contributing factor to climate change (Lovejoy & Nobre, 2018; Soares-Filho et al., 2012). As the effects of climate change are already reflected in more frequent droughts and less precipitation, forest fires have become ever more unpredictable and their

⁶ This article will be submitted in periodical *Forest Policy and Economics* (<https://www.journals.elsevier.com/forest-policy-and-economics>) after the delivery of the final version of this thesis.

impacts are increasing in scope and severity (Bachmann & Allgöwer, 1998; Pacheco, Claro, & Oliveira, 2014). In this context, the increasing frequency and intensity of fire occurrences incurs costs for productive activities in the direct vicinity of agricultural fire use (Mendonça et al., 2004; Oliveira et al., 2018) and poses significant challenges to fire management practices (Mendes, 2010; Thompson & Calkin, 2011). Consequently, the onslaught of forest fires in recent years has spurred attention from many researchers (Martell, 2015; Rollins, et al., 2017). A common response to these trends has been to increase governmental budgets for fire combat activities (Mendes 2010; Topik, 2015). In the United States, for example, budgetary spending on fire suppression was driven upwards from about US\$ 600 million in 1995 to nearly US\$ 3 billion in 2014 (Topik, 2015). Other scholars have advocated a more balanced combination of fire prevention activities, active combat campaigns, and improved agricultural practices for promoting forest fire reduction, particularly in regions of intense land use change (Nepstad et al., 2001). Despite the commonsensical nature of these claims, there have been few analyses that adequately address the cost-effectiveness of diverging fire management policies and programs (Gebert et al., 2008; Mendes, 2010; Minas et al., 2012). Moreover, analyses that do quantify the economic costs of forest fire management practices are often focused on Northern countries (Lankoande, 2005; Topik, 2015; Zybach et al., 2009). These observations point to the need for such analyses in tropical regions, particularly Brazil, where deforestation rates have been highest and where forest fire are a significant driver.

In this research paper, we aim to contribute to this knowledge gap by conducting a cost-benefit evaluation of forest fire management practices in the Brazilian Amazon and Cerrado biomes. Our analysis quantifies the economic costs of fire management practices in both private and public lands between 2012 and 2016 and assess their impacts in terms of avoided economic losses. Our spatially explicit results identify locations where fire management practices are most cost-effective and sheds light on the diverging impacts of prevention and suppression activities. Such analysis helps rural landowners as well as policy-makers to make better decisions on strategies for preventive and combative fire management practices. Moreover, our research contributes to the improvement of forest fire management of two large biodiversity hotspots in tropical regions (Myers et al., 2000) and provides new insights into complex decision-making processes related to resource allocation between the fire management practices.

2.1.1 The economics of forest fire management and the misunderstood benefits of fire prevention

Brazilian biomes are experiencing higher frequencies of fire occurrence (INPE, 2016) that, combined with the effects of climate change and agricultural expansion, pushes ecosystems towards often dramatic changes (Lovejoy & Nobre, 2018). For instance, the Cerrado biome is losing the capacity to maintain biogeochemical cycles and the dispersion of organisms (Hirota et al., 2010), while the Amazon's climate regulation functions are also diminishing (Morton et al., 2013). Moreover, uncontrolled forest fires incur costs for alternative production activities in their vicinity, although appreciation by rural landowners still requires societal transformation (Mendonça et al., 2004; Nepstad et al., 2001; Oliveira et al., 2018). Despite their destructive effects, the use of fire is beneficial for rural landowners as it is a low-cost approach to agricultural and livestock expansion (Cammelli, 2013; Carmenta, et al., 2013; Nepstad & Alencar, 1999). In addition, landowners are often unaware of the economic damages from uncontrolled fire events that escape rural properties into neighboring private or public lands (Nepstad et al., 2001). As forest fires in tropical regions are still poorly understood (Tacconi et al., 2006), the probability that forest fires continue to be a substantial problem remains high.

The increasing fire occurrences in Brazil is illustrative of similar trends in other countries and has gained substantial attention from scholars in recent years. In particular, many studies have observed that budgetary spending tended to prioritize firefighting efforts (Mavsar et al., 2013; Mendes, 2010; Teague et al., 2010). In the United States, for example, annual fire combat costs have risen to more than a billion dollars in the past 15 years (NIFC, 2017) and budgetary spending on firefighting by the national forest service are expected to increase by another 67% in the next 10 years (Topik, 2015). Moreover, researchers have made contributions to support these efforts of fire suppression, such as improvements in forecasting techniques (Martell, 2015; Pacheco et al., 2014; Plucinski, 2013; Rachaniotis & Pappis, 2006; Rollins et al., 2017). Similarly, resource allocation in Brazil tends to prioritize emergencies (Mendes, 2010), such as the PrevFogo firefighting program in indigenous lands (IBAMA, 2017), and few efforts have actively promoted preventive approaches to forest fire management (Carmenta et al., 2013). These observations indicate a general emphasis on unplanned and responsive forest fire management practices.

Many scholars challenge this emphasis on suppressing rather than preventing forest fires. Studies have argued that fire suppression has not structurally led to reductions in damages caused by fire (Gebert et al., 2008; Zybach et al., 2009) and in some cases even increases the likelihood of fires in the near future through the accumulation of flammable material (Mavsar et al., 2013). Instead, scholars argue that the efficiency of forest fire management will depend on the development of more preventive practices (Gebert et al., 2008; Mendes, 2010). For instance, Lankoandé (2005) and Snider et al. (2006) demonstrate that the costs of firefighting activities in the United States far outweigh those of preventive activities, arguing that shifting the emphasis of forest fire management practices to the latter could save up to US\$ 240/ha. In the Brazilian Amazon, the benefits of preventive action could reach up to US\$ 550 ha⁻¹yr⁻¹ based on valuation of ecosystem services like carbon storage, tourism, or wood supply (Andersen, et al., 2002). Despite these benefits, Amazonian land users still only invest about US\$ 0.35 ha⁻¹yr⁻¹ in preventive activities (Nepstad et al., 2001).

Some initiatives have contributed to the promotion of preventive forest fire management in Brazil. Notable examples are the "Green Municipalities" project in the state of Pará (Guimarães et al., 2013) and the "Green Flame" project in Paragominas (Vilhena, 2016), but two initiatives deserve particular attention due to their comprehensiveness. The first initiative involves the Earth Alliance's independent fire brigade, which directly supports private landowners registered in the "Producing Right" platform⁷ to design and execute fire management plans with a focus on prevention and improve agricultural practices to reduce the use of fire (Mendonça et al., 2004; Oliveira et al., 2018). The main challenge of this initiative is to convince rural landowners that investing in preventive activities can bring much greater benefits as economic losses are avoided. The second initiative involves the fire suppression and prevention activities of the Chico Mendes Institute for Biodiversity Conservation (ICMBIO), which exclusively manages federal conservation units. Rather than focusing on combative measures alone, this initiative has made significant advances promoting integrated fire management. According to Myers (2006), integrated fire management entails mitigation strategies that reconcile social, political and environmental interests and which vary considerably for each type of landscape. For example, in environmental terms, unlike the Amazon, the landscapes of the Cerrado contain vegetation adapted to fire that

⁷<http://www.aliancadaterra.org>

allows for fuel management through prescribed burning, albeit in many cases under considerable uncertainty (Pivello, 2017).

Together with alternative programs like PrevFogo, the ICMBIO and the Aliança da Terra represent important advancements for forest fire management practices in Brazil. However, to date, no study has evaluated the cost-effectiveness of these initiatives to promote preventive activities. This implies that both rural landowners and policy-makers must decide on how to reduce the economic damages from forest fires. More information is needed on, for example, the different costs and benefits of both preventive and combative initiatives, the differences of forest fire management on private and public lands and the regions in which this management has been most successful. This research paper aims to answer these questions for the Brazilian Amazon and Cerrado biomes.

2.2 Methods

2.2.1 General Approach

This study analyzes the costs and benefits of fire management practices in the Brazilian Amazon and Cerradobiomes. We understand costs as the investments made in fire management practices and benefits as the avoided economic losses from forest fires. In addition, we distinguish between fire management practices on public lands, represented by ICMBIO's fire suppression and prevention activities within federal conservation units (CUs), and Earth Alliance's fire suppression and prevention program on private rural properties. For our analysis of the effectiveness of ICMBIO, we used a stepwise methodology (Figure 6) starting with a spatial evaluation of the evolution of fire occurrences both in the interior and the buffer zone (up to 10 km) of each CU (local analysis). Subsequently, we used the findings in the first step to conduct a comparative evaluation between CUs (with similar landscape) within each federal state (regional analysis), distinguishing between the presence (CU_p) or absence (CU_a) of fire mitigation practices (details in section 3.2). For our analysis of the effectiveness of the Earth Alliance, we compared fire occurrence probabilities on agricultural properties before and after their registry in the platform (details in section 3.3).

We build on semi-structured interviews with ICMBIO and Earth Alliance teams in order to acquire information about annual economic costs incurred between 2012 and

2016. Subsequently, these costs were categorized into prevention and suppression activities (section 3.4). The estimation of economic losses demanded a differentiated approach. For agricultural properties, we developed a spatially explicit model that establishes a relationship between fire occurrence and crop production (corn and soybean). This model follows two consecutive steps: 1) calculating net revenues (rents) from crop production and, 2) applying a set of heuristics (i.e. empirical parameters from fieldwork) that represent the economic impact of fires in these rents over the years. For federal conservation units, we calculated the avoided costs of committed CO₂ emissions by considering the potential economic losses of carbon stored in areas affected by fires. Both the annual net rents and economic losses for crop production are presented as Net Present Values (NPVs) at an interest rate of 6%. In the absence of market data for valuing ecosystem services in conservation units, we focused only on evaluating losses to carbon stocks. Similarly, agricultural properties incur economic losses from infrastructure as well as other diversified crops, but fieldwork data suggested that such damage rarely occurs and therefore the effort would increase methodological complexity without adding to the relevance of the data (details in section 3.5).

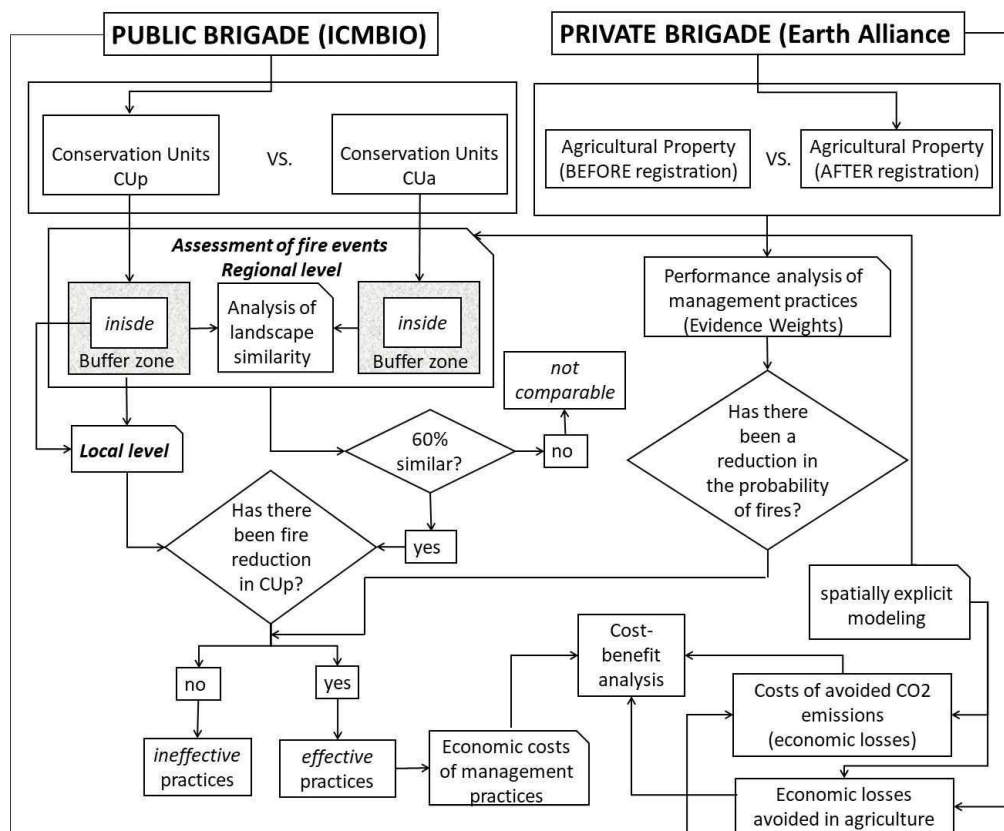


Figure 6 General Approach Flowchart

2.2.2 Forest fires in Federal Conservation Units

We evaluated whether there was a reduction in the occurrence of forest fires in federal conservation units as proxy of the effectiveness of ICMBIO management practices. First, we conducted the local analysis for determining fire occurrences both in the interior and in their buffer zones of CUs to monitor the influences of changes caused by land uses. Subsequently, we conducted the regional analysis that compares fire occurrences between CUs within each federal state (regional analysis), distinguishing between the presence (CUp) or absence (CUa) of fire mitigation practices. Our analyses cover both sustainable use (CUSu) and integral protection (CUip) Brazilian categories of conservation units (MMA/SBF, 2011). As 98% of CUp units in the Cerrado biome entail the CUip category, we restrict our analysis for this biome to those units. The regional analysis allows us to assess the influence of different degrees of landscape disturbance on fire events and the efficiency of mitigation policies and programs other than ICMBIO practices. Our assessments covered 133 conservation units in the Amazon (10% CUp) and 76 conservation units in the *Cerrado* (26% CUp) (Table S1⁸ and Figure S1).

Fire occurrence is described by the presence of hot pixels⁹ and burnt areas captured by MODIS-MCD45A1 sensor of the AQUA-afternoon satellite (INPE, 2016). We consider fire occurrences in buffer zones to indicate a direct threat to their interior (Nepstad et al., 2006). We also assume that conservation units of similar landscapes suffer the same degree of fire threat. Thus, to perform the regional comparison of fire occurrence between CUp and CUa, we consider a minimum threshold of 60% of landscape similarity between them, both in the interior and the buffer zone. To find this threshold, we calculate the areas of main land use (MapBiomas, 2016), using the following equation:

$$Z = \sum_{m=1}^{m=n} \left\{ \text{mean} \left[1 - \frac{X(m)}{Y(m)} \right] \right\} \quad \text{Eq.1}$$

Where, the summation determines the types of use:

⁸Tables and Figures denoted as Sx appear in on-line Supporting Information.

⁹Heat signals from fire as observable from satellite-based infrared sensors.

$$X(m) = \frac{\text{types of use (m)}}{\text{total area of the use with mitigation}}$$

$$Y(m) = \frac{\text{types of use (m)}}{\text{total area of the use without mitigation}}$$

The value of Z is the average of the similarity ratio between the land uses and the areas of the units and (m) the types of uses. The calculation is performed for each year to obtain the overall mean between the values of Z and the similarity for the study period. To evaluate the occurrence of fire over the years, we calculated the density of hot pixels (number of cells) and the size of burnt areas (ha) in the internal area (ha) of the units and in the buffer zone. We also evaluated the relation between land uses and the occurrence of fires in the buffer zone to identify the degree of influence of changes caused by factors extrinsic to the units (Ramos et al., 2016). If fire reduction is detected in the conservation units mitigated over the years, we consider that there was a percentage of effectiveness of the management practices of ICMBIO.

2.2.3 Forest fires in Rural Agricultural Properties

Earth Alliance's Social-Environmental Platform is an ongoing program that has already engaged more than 1,000 Brazilian rural properties in fire prevention and the adoption of better agricultural practices (Figure S2). We evaluate the performance of the Earth Alliance Platform to find out if its properties have been successful in reducing the likelihood of fire occurrences. We use a Bayesian algorithm that creates Weights of Evidence (Bonham-Carter, 1994) that represent measures of probability of occurrence of a phenomenon through empirical relations between spatial variables and changes in geographic space. The fire related performance of the Platform is defined by hot pixels and burned areas in the proprieties (INPE, 2016). We calculate the likelihood of fire at the pixel level by estimating the transition from an initial state (without fire) i to a final state j (with fire), given the presence of explanatory variables (B, C, D, ... N); in this case, the properties registered in the program, according to the following formula:

$$P\{i \rightarrow j | B \cap C \cap D \dots \cap N\} = \frac{e^{\sum W_N^+}}{1 + e^{\sum W_N^+}} \quad \text{Eq.2}$$

where the sum of the weight coefficients for the categorized value intervals of the N variables is represented by $\sum W_N^+$.

Most properties have been in the Earth Alliance Platform over a period of 12 years (2006 to 2016), therefore fire management performance can be evaluated by comparing the "before" (previous state, without technical guidelines of fire management) and "after" (later state, with technical orientations) of each property. Regions in which properties had lower probabilities of the occurrence of fire demonstrate successful performance of the Earth Alliance's prevention program.

2.2.4 The costs of fire management practices

To calculate the costs of firefighting we collected economic data with the ICMBIO technical team in Brasília and with the Earth Alliance team in Goiânia over a 3-year period (Table 1). Both institutions hire year-round teams. At ICMBIO, however, the fire teams only work in the dry season (August to December), while the Earth Alliance fire brigade works all year long in both prevention and suppression actions. Table 1 shows the average annual costs between 2012 and 2016 for both institutions (referring to the sum of the costs for the two biomes).

Unfortunately, not all data is available for ICMBIO. For this institution we consider fuel management by prescribed burning as a preventive practice that also involves Integrated Fire Management (MIF) training and the opening of firebreaks. For units that do not have preventive measures, the total costs refer exclusively to suppression actions, as is the case of the Amazon units. We observed that an average of 20% of costs are applicable to preventive or MIF actions, while 80% are for direct combat activities (suppression) in units that count with both management actions, as is the case of the Cerrado units.

Table 1 Economic costs of forest fire management practices from 2012 to 2016

INPUTS(average of the period)	ICMBIO (US\$)*	Earth Alliance (US\$)*
Number of Firemen (total for the period)	4222	9
Annual Salary of Brigade Chief	5,261	34,245
Annual Salary of Firemen	3,913	17,122
Equipment for individual use	1,476,228	10,234
Equipment for collective use	uninformed	1,077
Travel expenses	1,706,646	35,700
Food expenses	835,827	4,326
Equipment maintenance ¹	uninformed	452,83
Vehicle maintenance	uninformed	12,272
Aircraft expenses	991,522	not applicable
Administrative costs	uninformed	6,403
Communication costs	uninformed	9,315
Training costs	Included in travel and food expenses	18,483
Costs with firebreaks ²	32,975	uninformed
Total (annual average)	8,289,296	265,266

¹annual cost of amortization over the useful life of the electronic equipment of collective use; cost per km (we used the value of US\$ 37.8/km, according to information declared in fieldwork) *US\$ 1.0 = R\$\$ 2.66 (average change between 2012 to 2016).

Total costs were divided between the prevention and suppression. Preventive costs include firebreaks, but aircraft investments were considered only for suppression activities that were largely spent on high intensity fires (see ICMBIO classification). Our calculations were performed by region, per year and per conservation unit, in an absolute manner and relative to the area of the units without prevention (1) and with prevention (2), as follows:

$$\pi t \leftrightarrow \pi s = \sum_{i=1}^n [(b * rb + ch) + (b * pi)] + i]$$

$$\pi t = \sum_{i=1}^n [(b * rb + ch) + (b * pi)] + p], \text{ and also}$$

$$\pi p = \sum_{i=1}^n 0.2 * \pi t + a$$

$$\pi s = \sum_{i=1}^n 0.8 * \pi t + v$$

Where πt (total cost); πp (total cost of the prevention); πs (total cost of the suppression); b - number of wildland firefighters; rb - gross rents of wildland firefighters; ch - gross rents of the brigade chief; pi - cost with individual equipment per wildland firefighters; i - total cost with other expenses (including aircraft rental); p - total cost of other expenses (without firebreaks and aircraft rental); a - cost with firebreaks; v - cost with aircraft rental.

In the case of Earth Alliance, we calculated the performance of the Registry in the program in both Biomes and for all participating States. However, economic data was only available for the state of Mato Grosso. As 52% of the registered agricultural properties and 97 % of fire brigade activity occurred in this State (Figure S2), it clearly is the most representative location of the actions of the Earth Alliance (Figure 5B). In addition to training costs, prevention costs represent only 17% of total costs (Table 1), because the number of suppression activities was 5 times higher than the number of prevention actions in the period. We also show the absolute costs and relative to the extent of the areas affected by the fires fought in the year.

2.2.5 Economic losses from fires

Here we estimate the economic losses in the production function of the corn and soybean production chains. Due to lack of information in the literature, we interviewed farmers to establish empirical parameters that relate fire and crops. In 2016, 62 rural landowners from the northeastern region of Mato Grosso state were interviewed (see questionnaire in supporting information). Considering the large number of agricultural properties, we chose this region because of the high incidence of fires. Of the farmers interviewed, 73% produce soybeans and second-crop maize. The economic data for these crops are well known and allow producers to understand the potential fire damage. For this reason, our definition of empirical parameters (heuristics) is limited to these crops.

Our results suggest that because corn is very flammable, it has a greater susceptibility to fire. Indeed, when the fire hits the corn crop all production is lost. We therefore assume losses of 100% for corn in the case of fire events. Since maize straws are used as fertilizer for soybean production, farmers claim that each hectare of burnt corn causes a reduction in the productivity. Due to the poorer soil the producers

lose an average of 10 bags of soybeans and 12 bags of corn per hectare and per year, for the following two years. As a result, the economic losses are derived from the deduction of the rents from the hectares of corn burned in the year of occurrence of the fire and the productivity of soybeans and corn that are lost in subsequent years. These amounts were subtracted from gross revenue, together with operating costs for final net revenue accounting. In order to apply the heuristic, 7 years of fire occurrence (2010-2016) was considered for estimating economic losses in crop production between 2012 and 2016. We do not consider the loss after 2016 fire events due to lack of data for estimating net income (rents).

In order to estimate the fire impact on crop returns we developed a spatially explicit model. Input data of the occurrence of fires, areas of production and net incomes from agriculture were required. For fire data, we used annual burnt areas from the MODIS-MCD45A1 sensor (INPE, 2016). As most of the properties registered in the Earth Alliance are corn and soybean producers, including those we interviewed in field-work, we consider these properties as the producing areas. From the modeling of spatial surfaces of economic variables such as prices, productivity and costs (Table S2), we apply a distribution function based on moving averages to estimate the net incomes of these crops for all Brazil (details in Soares-Filho et al., (2016) and in supporting information). In this manner we are able to estimate the economic losses that would be caused if the fire events had not been avoided by the effective management practices in the period. Our estimates were restricted to the state of Mato Grosso so that we could compare the results with the economic costs of Earth Alliance.

The economic loss of federal conservation units represents the avoided costs of committed CO₂ emissions. We use the carbon stock map of Baccini et al., (2012) which estimates the total above ground carbon - an average equal to 117.7 (\pm 8.4) MgC/ha for tropical forests, with 95% confidence (maximum equal to 415 MgC/ha for Amazon and 370 MgC/ha for the Cerrado). Our reference price of carbon came from Guadalupe et al., (2018) and is set at US\$ 5 per ton of CO₂.

2.3 Results

2.3.1 Federal conservation units and management practices of ICMBIO

Our regional analysis found no reduction in fire occurrences within the CUs in either biome, with the notable exception of the State of Pará (Figure 7A). It is possible that the extreme drought event provoked by El Niño in the year 2015, which increased fires by 33% (Figure S3), is a related factor. A second explanatory factor is a high incidence of fires in the buffer zones, where the number of occurrences in buffer zones were 75% and 35% higher in relation to the fires in the interior of CUs of type IP (CUip) in the Amazon and Cerrado biome, respectively. In the Amazon, deforestation does not play a predominant role in explaining the fires in buffer zones, since it is related to only with 37% of occurrences (Figure S3). By contrast, deforestation in buffer zones of CUs of type SU (CUsu), accounted for an average of 61% of fire occurrences, which is 42% higher than fires in the interior (Figures 7A e S4). In the Cerrado, land uses explain only 21.6% of the fires occurring in buffer zones, deforestation explains 4.6%, pasture 5%, and agriculture 12% (Figure S4). In this biome natural fires can easily happen, where lightning has already led to 85% and 44% of burned areas in the Emas National Park and Serra da Canastra, respectively (Ramos et al., 2016).

Our findings provide some evidence for effective fire management practices by ICMBIO. In Pará, where fire occurrences were most abundant, we found a 24% reduction of burnt areas as well as a 40% reduction of hot spots between the CU_p (less occurrences) and CU_a (Figure 7A). To make this comparison (between CU_p and CU_a), overall, we found that conservation units of the state have similar landscapes in 62±0.4% of the cases, with forest cover predominating in CU_p and CU_a. Locally, CU_s in the Amazon also did not present fire reduction, with the exception of an 18% reduction of burnt areas between 2014 and 2016 in the *Campos Amazônicos* National Park (Figure 7D). In the same period, we found similar results in large conservation units in the Cerrado, although the reduction of burnt areas occurred in only three of the 26 units mitigated by the management practices of ICMBIO. For instance, there was a 10% reduction of fire occurrences in the *Serra Geral de Tocantins* Ecological Station even though prescribed burning activities have increased by 54% (figure 7C). In the *Chapada das Mesas* National Park, we identified a reduction of 23% between 2013 and 2016

(figure 7D). The *Serra do Cipó* National Park had the largest average reduction (41%) of burnt areas (figure 7D). The figure S1 demonstrates the spatial location of these federal conservation units.

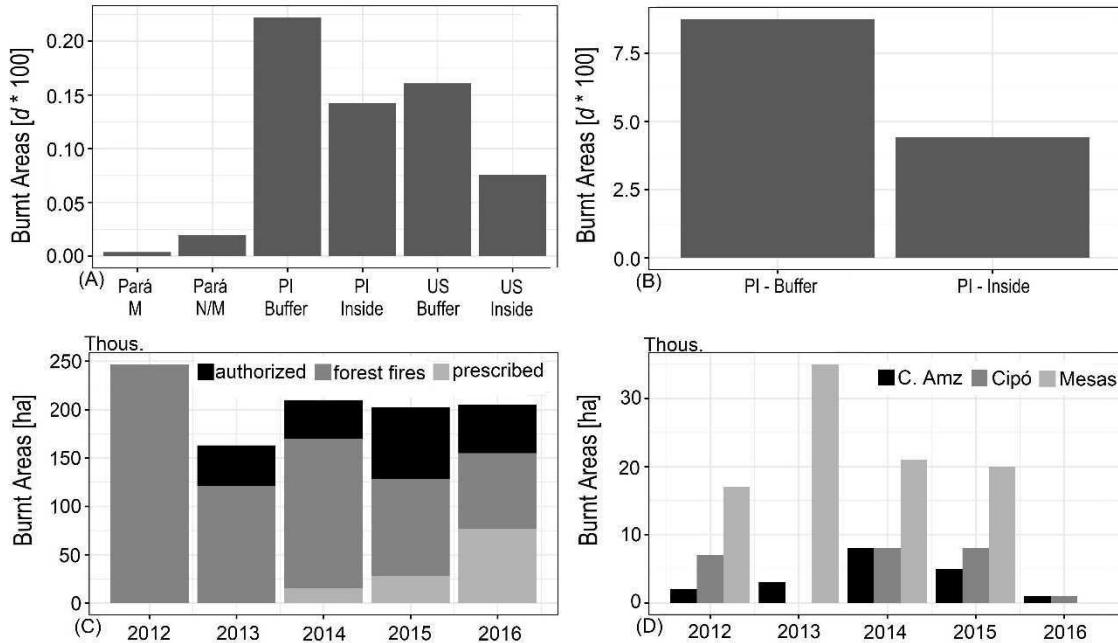


Figure 7 Annual average of burnt areas in the Amazon, in the state of Pará (A) and Cerrado (B) biomes, as well as annual values of burnt areas in the Ecological Station of *Serra Geral de Tocantins* (C) and National Parks: *Chapada das Mesas*, *Serra do Cipó* and *Campos Amazônicos* (D) – (“d” is density of fire occurrence – details in section 3.2).

In the Amazon, the average economic cost of fire suppression was US\$2.7 million per year, equivalent to US\$0.5 ha⁻¹yr⁻¹ (Figures 8A and 8B). In the state of Pará, management practices were effective in reducing 24% of burnt areas in the mitigated units, which generated a public benefit of US\$4.6 ha⁻¹yr⁻¹ (Figure 2A). As the economic costs of the state's management practices were US\$382 thousand per year, equivalent to US\$0.14 ha⁻¹yr⁻¹ (Figures 8A and 8B), these benefits were 32 times higher than the costs. The average costs of the *Campos Amazônicos* National Park were US\$216 thousand per year or US\$0.22 ha⁻¹ yr⁻¹(Figure 7C). Consisting of 85% of forest, the benefits of management investments to reduce 18% of areas burned in this unit (from 2014 to 2016) were particularly large in areas with a high carbon stock (Figure 7D), where avoided costs for CO₂ emissions attained US\$27.5 ha⁻¹ yr⁻¹.

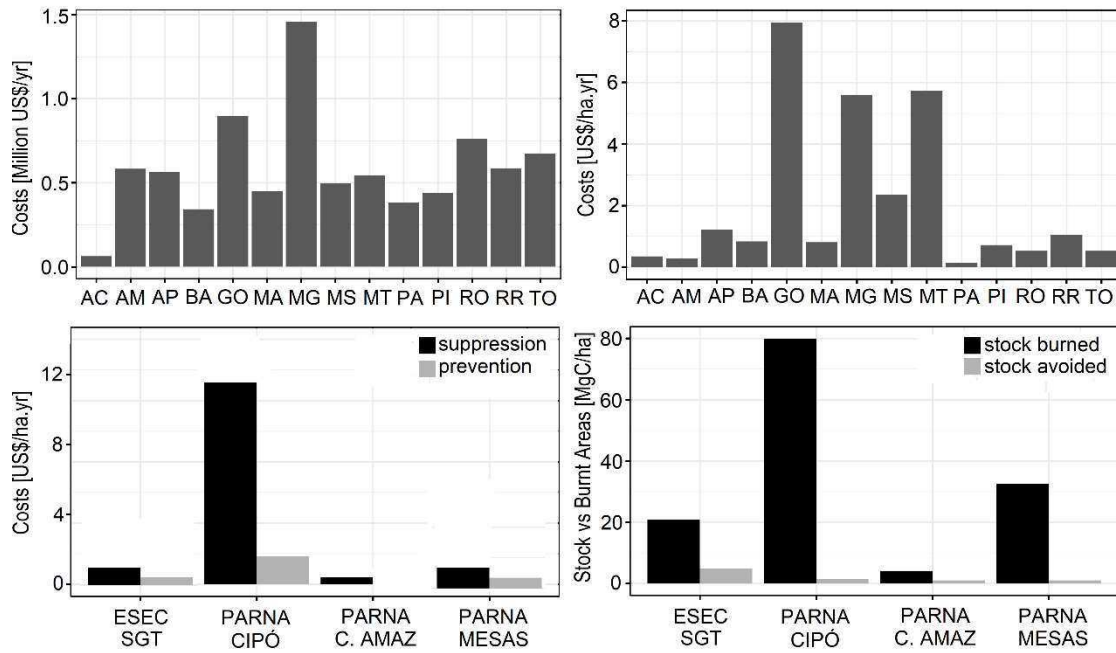


Figure 8 Annual average of the absolute and relative economic costs of management practices of the ICMBIO by state (A and B), relative costs per conservation unit with effective management (C) and carbon stock burned and avoided by mitigation (D).

For the *Cerrado* units, the costs of prevention averaged US\$529 thousand per year and the average costs of suppression were US\$4.8 million, equivalent to US\$0.27 ha⁻¹ yr⁻¹ and US\$5.1 ha⁻¹ yr⁻¹, respectively (Figures 8A e 8B). The prevention costs are much lower, because in addition to the few actions, the prescribed burning is performed in only 7 out of 26 mitigated units of the *Cerrado* (Table S1). The cost-benefit ratio was greatest for the *Serra Geral de Tocantins* Ecological Station. Average investments of US\$0.12 ha⁻¹ yr⁻¹ for prevention and US\$0.45 ha⁻¹ yr⁻¹ for suppression (Figure 8C) prompted a 10% reduction in burnt areas (lots of burning and little carbon stock) that engendered an average benefit US\$7.8 ha⁻¹ yr⁻¹. The *Chapadas das Mesas* National Park had investments of US\$0.28 ha⁻¹ yr⁻¹ for prevention and US\$1.2 ha⁻¹ yr⁻¹ for suppression, while benefits amounted to US\$20.2 ha⁻¹ yr⁻¹ (Figure 8C). The *Serra do Cipó* National Park had the lowest cost-benefit ratio of management practices. The average investments were US\$2.9 ha⁻¹ yr⁻¹ for prevention and US\$11.2 ha⁻¹ yr⁻¹ for suppression, the benefits of which were 1.6 times greater than investments and amounted to US\$23.1 ha⁻¹ yr⁻¹ (Figure 8C).

2.3.2 Agricultural properties and management practices of the Earth Alliance

With the exception of the state of Bahia (BA), our findings indicate excellent performance of Earth Alliance's fire brigade in both the Amazon and Cerrado biomes (Table 2). The probability of fire events has reduced by more than 60% in most regions that reduced the number of burnt areas by 29%. Amazingly, Tocantins, Pará and Minas Gerais reduced by more than 100% the probability of fire occurrence. The Amazon also showed a high probability of reduction, which was on average 26% higher in relation to the Cerrado (Table 2). Even in areas with high susceptibility to fire occurrence, such as the state of Mato Grosso, rural landowners have been able to reduce forest fires by 16% after joining the Earth Alliance initiative.

Table 2 Performance of the properties of the Earth Alliance - Weights of Evidence.

States ¹	Accumulated area (ha) (2006 - 2016)	Accumulated number of hot pixels (2006 - 2016)		Accumulated burnt areas (ha) (2006 - 2016)		Evidence ⁴ Weights (average) (2006 - 2016)		Probability reduction (%)	Burnt area reduction (%)
	Properties registered (million)	Properties registered (thousand)				W			
		Before	After	Before	After	Before	After		
RO	0.015	0	0	0	0	0	0	0	0
RR	0.004	0	0	0	0	0	0	0	0
PA	0.470	0.004	0.001	0.008	0.007	-0.22	-0.60	173	18
TO*	0.085	0.005	0.001	0.291	0.204	-0.14	-0.34	143	30
BA	0.295	0.002	0.002	1.202	1.426	-0.03	-0.01	0	0
PI	0.029	0.000	0.000	0.145	0.092	-0.09	-0.16	78	36
MA*	0.025	0.002	0.001	0.389	0.223	0.06	0.02	67	43
MT*	2.683	0.037	0.024	1.493	1.254	0.05	0.02	60	16
MS	0.194	0.000	0.000	0.140	0.092	-0.22	-0.4	82	34
GO	0.229	0.002	0.001	0.509	0.329	0.09	0.01	89	35
MG	0.138	0.002	0.001	0.106	0.055	-0.09	-0.24	167	48
AMZ ²	1.697	0.041	0.025	1.501	1.261	-0.05	-0.22	122	16
CRD ³	2.504	0.048	0.055	4.276	3.674	-0.04	-0.13	90	14

¹we only analyzed the states that have properties registered within the area of the biomes; ²AMZ: Amazon; ³CRD: Cerrado; *states that have territories in both biomes; ⁴ weights of evidence regarding the occurrence of burnt areas.

In the state of Mato Grosso, where the Earth Alliance’s platform registered most rural landowners, we identified that forest fires affected 10% of the total accumulated area (2.6 million hectares) of the agricultural properties. Average returns on these properties for corn and soybeans, are US\$181ha⁻¹yr⁻¹ and US\$922ha⁻¹yr⁻¹, respectively, which is 10% and 51% higher than the Brazilian average (Figures 9A and 9B). Economic loss from fire damage could reach up to US\$565 ha⁻¹yr⁻¹ in regions of high agricultural profits (Figure 9C). Due to the reduction of burnt areas (Table 2) from prevention and suppression actions of Earth Alliance, we estimate that economic losses of US\$76 ha⁻¹yr⁻¹ were avoided in corn and soybean production in Mato Grosso (Figure 9D).

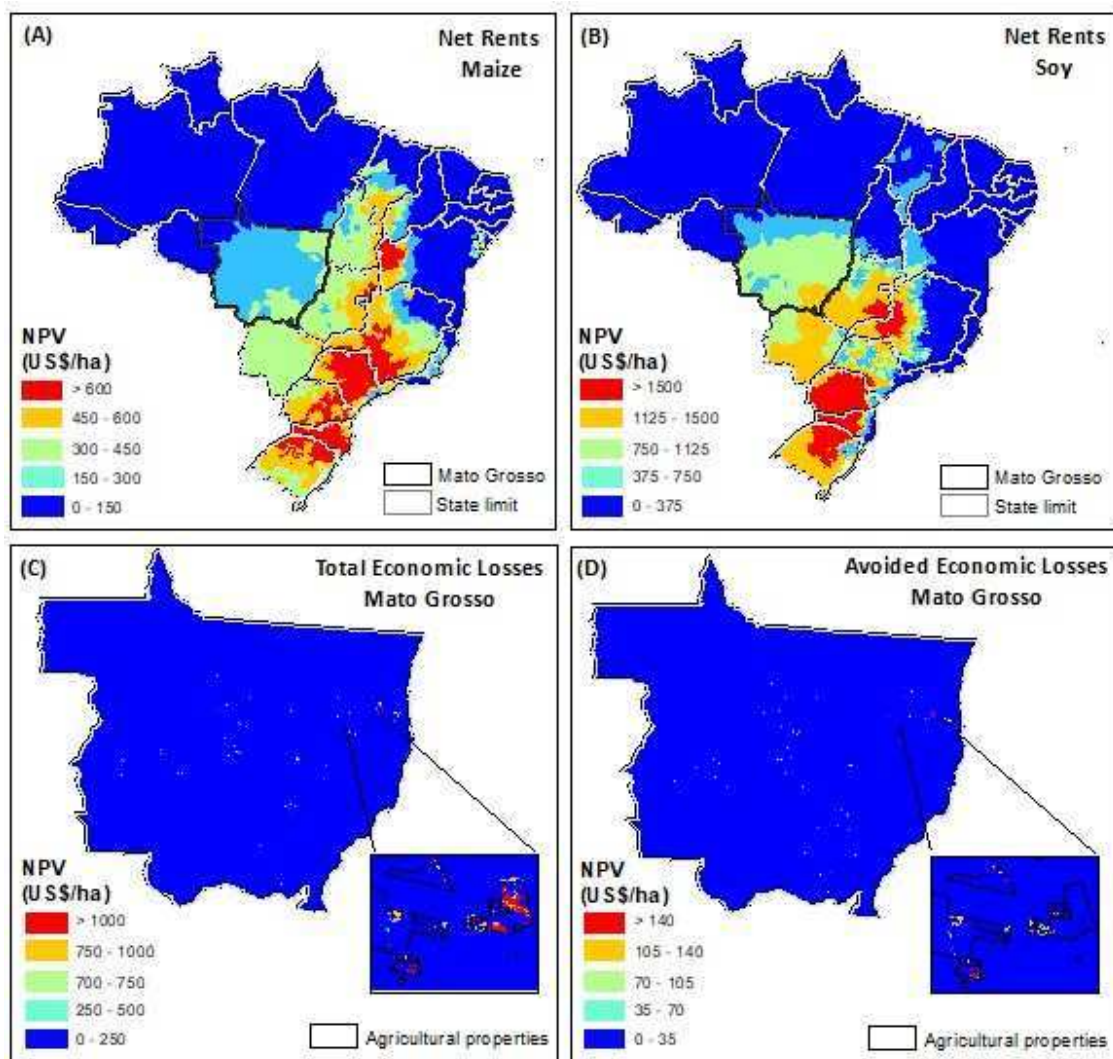


Figure 9 Net income from corn and soybean production in Brazil (A and B) and economic losses due to fire at Earth Alliance registered properties in the state of Mato Grosso (C and D).

The Earth Alliance invested on average of US\$ 44 thousand per year in prevention and US\$ 215 thousand in fire suppression (Figure 10A), the equivalent of US\$ 11.2 ha⁻¹ yr⁻¹ to manage on average 61 thousand hectares of areas affected by fire. In this case, the private benefit of the losses avoided by the management practices was on average 7% higher than the costs, reaching 25% for places of higher incidence of fires in the northeast of the state, where most of the management actions took place (Figure 10B).

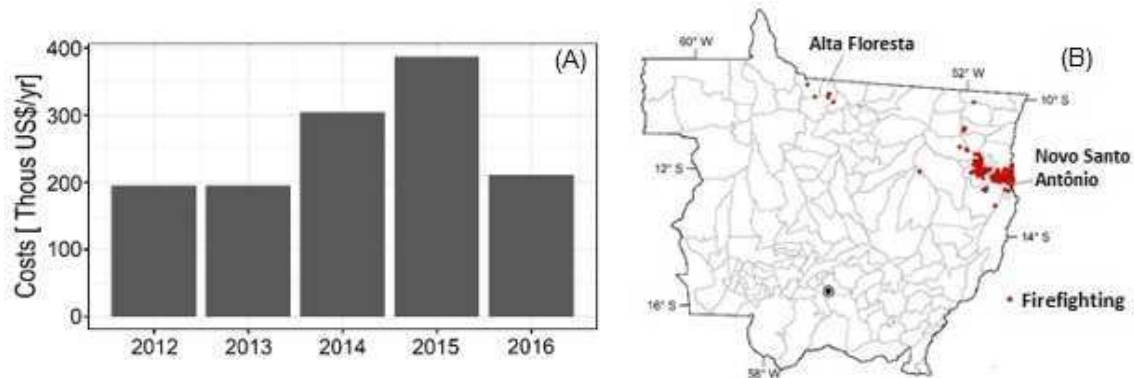


Figure 10 The annual economic costs of Earth Alliance management practices (A) and combat actions carried out by the Earth Alliance brigade in the northeast region of Mato Grosso (B).

2.4 Discussion and Conclusion

We note that fire management in Brazilian native forests operates in the same way as other countries, which commonly invest heavily in suppression activities (Mavsar et al., 2013). Indeed, our results suggest that although public investment in fire management by ICMBIO has increased or remained stable there have been no reductions in the extent of burnt areas in most federal conservation units. Thus, if the largest investments in fire suppression do not reduce these areas, the accumulation of flammable fuels coming from these actions will certainly increase the occurrence of fires in Brazilian biomes. In this respect, our results showed that only a combination of active fire prevention and suppression actions justify investments that have effective results in reducing fire. In the Cerrado, we noticed that reductions in fire occurrences started only in 2014, when fire prevention by the fuel management (MIF actions) began in some conservation units. The ESEC of *Serra Geral de Tocantins* is the main and best cost-benefit ratio due to such management practices. In the Amazon, where strong programs and fire prevention policies act in parallel with the suppression practices of

ICMBIO, we found a representative fire reduction in relation to areas not covered by mitigation. This occurs particularly in the state of Pará, where we identified that governmental fire mitigation programs have been in place since 2011, such as "Green Municipalities Project" (Guimarães et al., 2013) and the "Green Flame Project" (Vilhena, 2016).

Our cost-benefit analysis of ICMBIO management practices reveals investments similar to those suggested by other scholars. As estimated by Nepstad et al., (2001), the economic costs of these practices do not exceed US\$1 ha⁻¹yr⁻¹ in the Amazon and in the most fire-prone conservation units in the Cerrado. Although the investments were small, the public benefits of the economic losses avoided by the reduction of fires were high. The avoided costs of CO₂ emissions alone yielded a benefit of about 30 times higher than investments in dense forest areas. These findings correspond with studies on the economic impact of fire occurrences in non-tropical regions. Zybach et al., (2009), for instance, argue that the total economic losses from fire occurrences in boreal forests can be up to 50 times higher than the suppression costs invested. In contrast to Amazonian forests, the Cerrado still retains a large number of fire occurrences, suggesting that greater investments in management practices could yield significant gains in terms of public benefits.

We have identified that the probability of fire occurrences on agricultural properties decreases substantially when owners are informed about the benefits of including fire prevention practices in land management. For instance, the Earth Alliance was successful with the Socio-Environmental Platform, since the majority of the rural properties that participated in the program presented a reduction in the likelihood of fire occurrences, although this reduction was lower in the state of Mato Grosso, in relation to the other states. Mato Grosso is the state with the largest number of registered properties in Earth Alliance and the main challenge for the program. This state has the second highest rate of fire occurrences in Brazil (INPE, 2016), mainly coming from agricultural management and pasture cleaning. Consequently, our spatially explicit analysis, that measures the economic impact of fire on agriculture, has resulted in very high economic losses for the properties of this state. According to Nepstad et al., (2001) landowners are often reluctant to invest in mitigation practices to contain their management fires or to keep fires off their properties, because they believe that these investments do not pay for the damage caused by fire. However, we have identified that in the Northeast region of the Mato Grosso, where the Earth Alliance brigade operates, the private benefits coming

from fire reduction can be up to 25 times greater than investments in management practices.

Our valuation exercise is innovative. So far, our work has been the only one to present a method of to estimate economic losses caused by fire in agriculture of tropical regions. We identified that due to the greater ease of data acquisition, the studies present in the literature are limited to estimating economic losses to cattle ranchers, through the damages caused by fire in fences and pastures (Mendonça et al., 2004; Daniel Nepstad et al., 2001). On the other hand, due to the lack of other studies, our assumptions were limited to the parameters collected in the field work, which demands that our method be improved in a later agenda. Likewise, due to the great difficulty in assessing the genetic and biological patrimony of the forest, our study measures the fire impact in only one ecosystem service in conservation units. For this reason, our results do not escape the conservative measures currently found in the literature.

Although it needs some improvement, the results of our work contribute significantly to current Brazilian policy. In 2017, Brazil initiated the elaboration of a national policy to reduce the incidence and damages caused by the forest fires in the country (MMA, 2017). The federal government is willing to open interim measures to prevent and combat the high frequency of fires. We believe that the public benefits presented by our work will contribute to the decision on the definitive extension of the contracting period for ICMBIO brigades, which is already under discussion by the government and competent public bodies (ICMBIO/MMA, 2017). Another aspect would be to include private entities in cooperation regime and articulation with the national policy to the creation of new fire prevention programs in response to the private benefits coming from the Earth Alliance's program.

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FINAL CONSIDERATIONS

Forest fires are characterized by high levels of destruction of built, natural and human capital, imposing a great economic and environmental burden on societies of the tropics regions. In this context, in 2017, Brazil began drafting a national policy to reduce the incidence and damages caused by forest fires. This work, therefore, was developed at a very timely moment, bringing results with important implications for the formulation of this new policy, particularly regarding fire prevention. Likewise, new insights were presented for the adoption of more preventive practices in the private sector. Firstly, this study demonstrates that preventive efforts could target the fire ‘hotspots’ identified here in order to reduce economic losses to sustainable timber production in the short term. Secondly, it was also found that only through greater investments in preventive measures the occurrence of fires could be reduced and more public benefits could be obtained with protection of the Amazon and Cerrado biomes.

In the private sector, in fact, the association between fire prevention and suppression practices generates benefits. This study demonstrates that rural landowners involved in active fire mitigation programs were able to avoid substantial economic losses on their farms. Lastly, this study also indicates the need for a greater articulation between the public and private sectors for the protection of the forest. In this respect, the creation of new fire mitigation programs and action plans based on prevention in neighboring areas between public forests and rural properties is an important strategy to reduce the risk of fires in areas where the economic impacts are much greater. This work contributes to the science of fire by providing a set of new methods of spatial analysis. Although these methods require further improvement, it is expected that the analyzes developed here will indicate important steps for the progress of the assessments of forest fire impacts in tropical regions.

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SUPPORTING INFORMATION OF CHAPTER 01

1. THE FISC MODEL

1.1 IGNITION COMPONENT

The simulation component for fire ignition points is described by Silvestrini *et al.* (2011). Basically, the model estimates monthly maps of the probability of ignition as a function of climate that are calculated through monthly logistic regressions of the data on vapour pressure deficit - VPD (explanatory variable), with the dependent variable being the heat focus maps derived from the satellite NOAA - 12 night (Silvestrini *et al.* 2011). In addition, the ignition probability builds on anthropogenic probability maps that use a set of static spatial variables (Table S1) that are analyzed by using evidence weights based on a Bayesian algorithm commonly used in spatial analysis (Bonham-Carter 1994, Soares-Filho *et al.* 2012). These methods produce two distinct probability maps: climate risk and anthropogenic risk that the model merges by applying a weighted average (Silvestrini *et al.* 2011). The simulation mechanism for heat sources is based on stochastic selection of probabilities resulting from this mixed probability map. For this purpose, a probability density function (PDF) is used - see Silvestrini *et al.* (2011). In order to include an auto-regressive property in the model, the Moran index is used to regulate the mapping of probabilities for each simulated point (Bailey and Gatrell 1995).

Table S1 Input variables used in Ignition and Spread components. *Sources:* Various

Variable	Source	Period	Link
Land cover (ignition and spread)	PRODES (INPE)	2002-2016	http://www.obt.inpe.br/OBT/assuntos/ programas/amazonia/prodes
Protected areas (ignition)	Brazilian Forest Service - CNFP/SFB and Ministry of the Environment - MMA	2015	http://www.florestal.gov.br/cadastro- nacional-de-flores tas-publicas/62-informacoes- florestais/165-dados-por-es- tado-cnfp
Roads (ignition)	Ministry of Transport Brazil	2014	http://pnlt.imagem- govfed.opendata.arcgis.com/
Urban areas (ignition)	Brazilian Institute of Geography and Statistics - IBGE	2010	http://downloads.ibge.gov.br/download s_geociencias.htm
Terrain (ignition and spread)	SRTM - Brazilian Agricultural Research Company (EMBRAPA)	2000-2001	http://www.relevobr.cnpm.embrapa.br/ download/
Mechanized agriculture (ignition)	Federal University of Minas Gerais - CSR/UFMG	2012	www.csr.ufmg.br/maps
Vapor Pressure deficit (VPD) (ignition) uVPD (Inner VPD) (spread)	NCEP/NCAR - <u>Earth System</u> <u>Research Laboratory</u> (Physical Sciences <u>Division</u>) and University of East Anglia	1948-2015	Temperature: http://www.cru.uea.ac.uk/cru/data/hrg/ Humidity: https://www.esrl.noaa.gov/psd/data/gri dded/data.ncep.reanalysis2.pressure.ht ml uVPD: https://www.esrl.noaa.gov/psd/data/gri dded/data.ncep.reanalysis.html
Hydrography (spread)	National Water Agency - ANA	2010	http://hidroweb.ana.gov.br/HidroWeb. asp?TocItem=4100
Wind (spread)	LANDSAT - <u>Earth</u> <u>System Research</u> <u>Laboratory (Physical</u> <u>Sciences Division</u>	2000-2005	https://www.esrl.noaa.gov/psd/data/gri dded/data.ncep.reanalysis2.pressure.ht ml

Calibration of the ignition component is based on the monthly logistic regressions of the climatic data, on the PDF previously mentioned and on the adjustment parameters α , γ and θ (see Figure S1). In order to obtain the logistic regression coefficients, a sample twice as large as the monthly total number of hot pixels is extracted from the VPD data. A distribution was derived from the PDF as well as the blended probability map (climate + land use) of the year 2003, which showed the best fit for the data. For the parameters α , γ and θ , we start with the values used in Silvestrini *et al.*(2011), adjusting their values considering the results obtained in the expanded area of study (i.e. the entire Amazonbiome). The parameter α defines the integration ratio between the probability map of climatic risk and anthropogenic risk. In general, the anthropogenic risk results in greater spatial bias for the ignition points, while climatic risk is responsible for the seasonal variation and the interannual number of simulated occurrences. In order to select cells with simulated ignition points, the parameter γ defines thresholds (lower and upper) for the probabilities drawn using the PDF. The parameter θ , in turn, controls the number of simulated points and is directly impacted by the spatial resolution fixed for the study area. The finer the resolution, the more cells make up the probability maps, which increases the likelihood of cells becoming points of ignition(Silvestrini *et al.* 2011). The calibration was done by seeking a fit between the simulated and observed hotspots for 2003 (Figure S1). Likewise, the validation was done by comparing the monthly number of simulated and observed hot-pixels from 2004 to 2010. Although the model underestimates the total number of hot-pixels, the correlation between dispersions was sufficiently significant for the calibration. For the validation, the dry years (2005, 2007 and 2010) increase the scatter between the simulated and observed data, with 2009, 2008 and 2006 showing the best results (Figure S2).

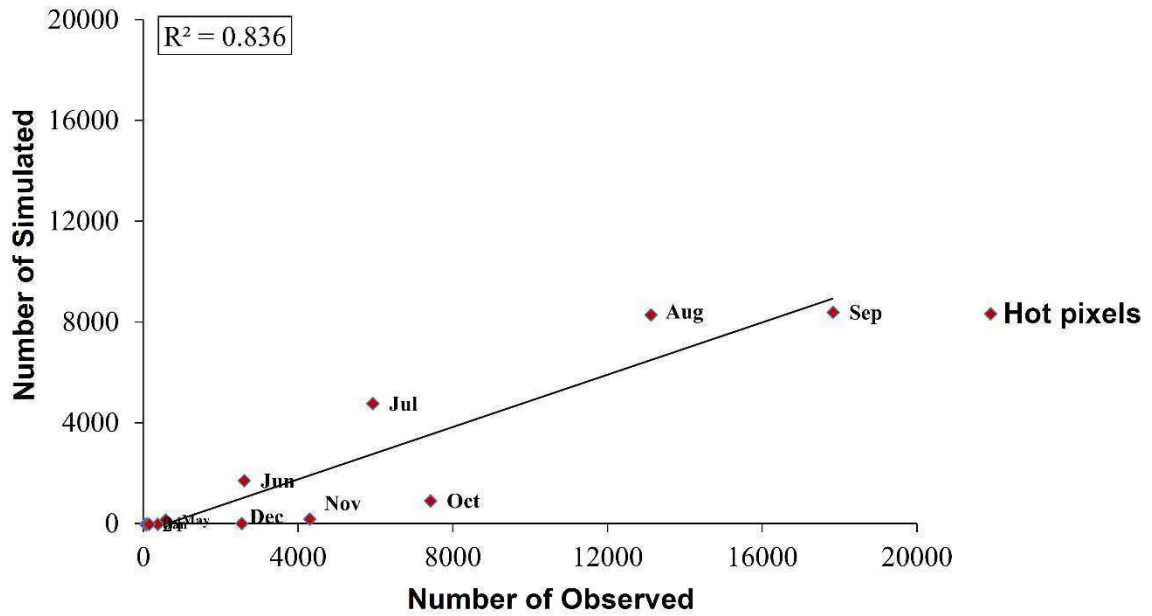


Figure S1 Calibration of the ignition component for the year 2003 indicating the fit between simulated and observed hot pixels. *Sources:* Data calculated by the authors using theFISC-model and observed hot-pixels from NOAA/12 (INPE 2016).

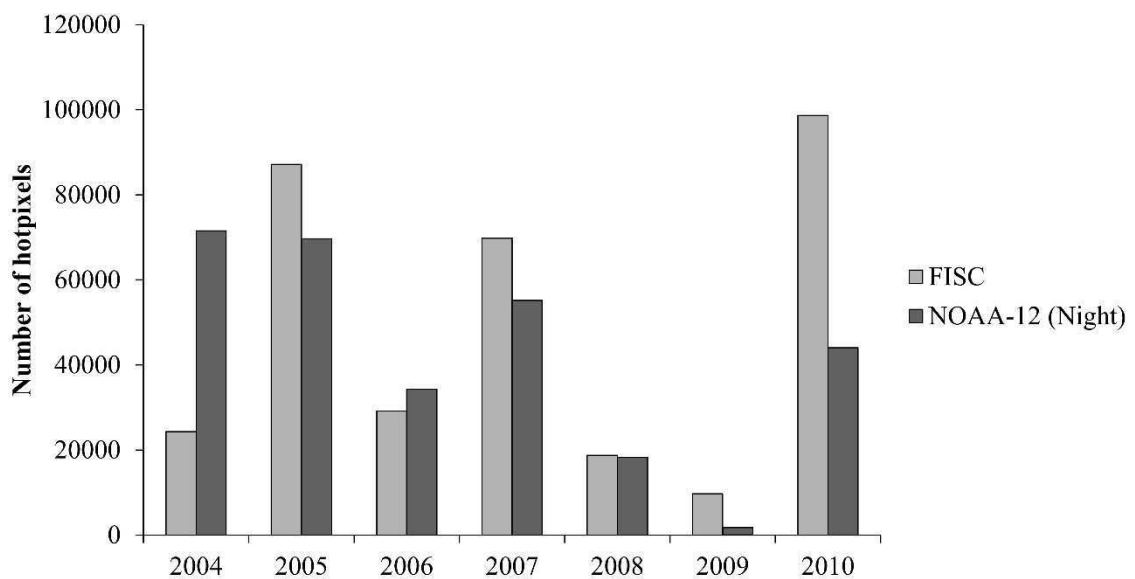


Figure S2 Validation of the ignition component from 2004 to 2010. *Sources:*Data calculated by the authors using theFISC-model (light gray) and observed hot-pixels from NOAA/12 - INPE 2016 (dark grey).

1.2 SPREAD COMPONENT

The development of the fire spread component as well as the interactions with the carbon component are both described in Soares-Filho *et al.*(2012). The techniques of calibration of the fire spread component were inherited from the model of Soares-Filho *et al.*(2012), but adaptations were necessary mainly due to substantial differences in the area of study and the spatial resolution between these studies. In the current study, the entire Amazon was treated at a resolution of 500m x 500m, whereas the previous study covers only the Amazon region of the basin Xingu river at 320 x 320m.

The probability of fire spreading for each portion of the study area results from the fusion of three main data groups, namely: a fuel map, a terrain map (e.g., slope, obstacles and different land uses) and microclimatic conditions (Inputs - Table S1). In addition, two more factors impact fire dynamics: the influence of wind and the neighborhood effect of fire fronts. The climatic probability is established as a function of the internal VPD gradient related to the microclimate of the forest interior (calculated by the CARLUC model). As a dependent variable, annual maps of observed understories fire scars are used for the Brazilian Amazon (Morton *et al.* 2013). In order to estimate the probability of fire spreading through by the terrain, we use weights-of-evidence techniques (i.e. Bayesian algorithm). For this purpose, static land use maps are used along with friction maps (i.e. cost maps that account for complications for fire spreading through the terrain, such as hydrography and slope maps). According to Soares-Filho *et al.*(2012) the cost map reflects the effort for the fire to propagate from the source of ignition. A linear transformation is applied to the cost map in order to obtain the spread probability based on the terrain. Fuel availability is the third probabilistic component for spreading (calculated by the CARLUC model). Similar to the ignition component, the fire spread component also uses a weighted average to merge the likelihood of the three previously described maps.

The simulation of fire spread involves a cellular automaton technique. This method allows the modelling of spatial dynamic systems that operate in discrete time, where the future state of the variable depends on its neighborhood. The FISC uses the previously estimated mixed map of the direction and intensity of the wind, and the ignition points of fire (simulated by the ignition component) in the vicinity of a cell. For each iteration of propagation (30 per month), the model checks all neighboring cells from an ignition source. Finding neighboring cells, the automaton updates its probability of fire by using intensity and direction of the wind.

The fire spread calibration consists of two main phases: finding optimal regression parameters in the climate data and defining the probability density function of the fire to spread. Since the time step of the current version of the FISC is monthly, the observed annual scars map the parameters for the most representative month in the simulation, which is September 2003. In order to obtain the regression parameters, we used data of internal VPD for the year 2003 (calculated from CARLUC) and observations of fire scars (Morton *et al.* 2013). The internal VPD is used as the explanatory variable, and the fire scars are the dependent variables. The probability density was calculated by extracting all the fire scoring points from the combined probability map of September 2003. Finally, the validation of this component is based on comparison of metrics for the burned area, the spatial distribution and the scar size, between the simulated results and the observed data of Morton *et al.* (2013) for the years 2002-2010 (Figure S3 and S4).

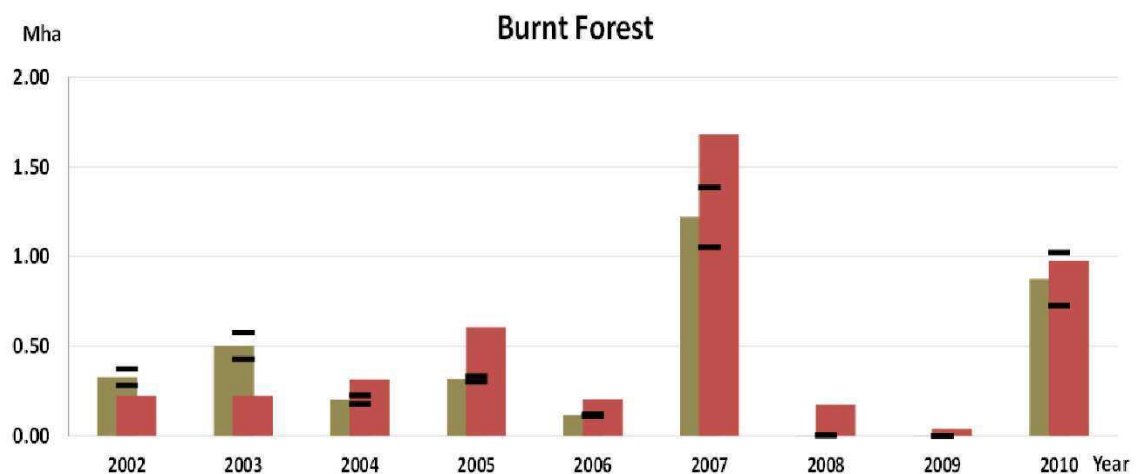


Figure S3 Validation of simulated forest fire scars against observed ones. FISC-model (green) was calibrated using observed forest fire scars from 2003 and 2005 (red) and validated by using data from 2002-2010 (horizontal bars define confidence interval). Sources: Data calculated by the authors using the FISC-model (green) and Morton *et al.* (2013) (red).

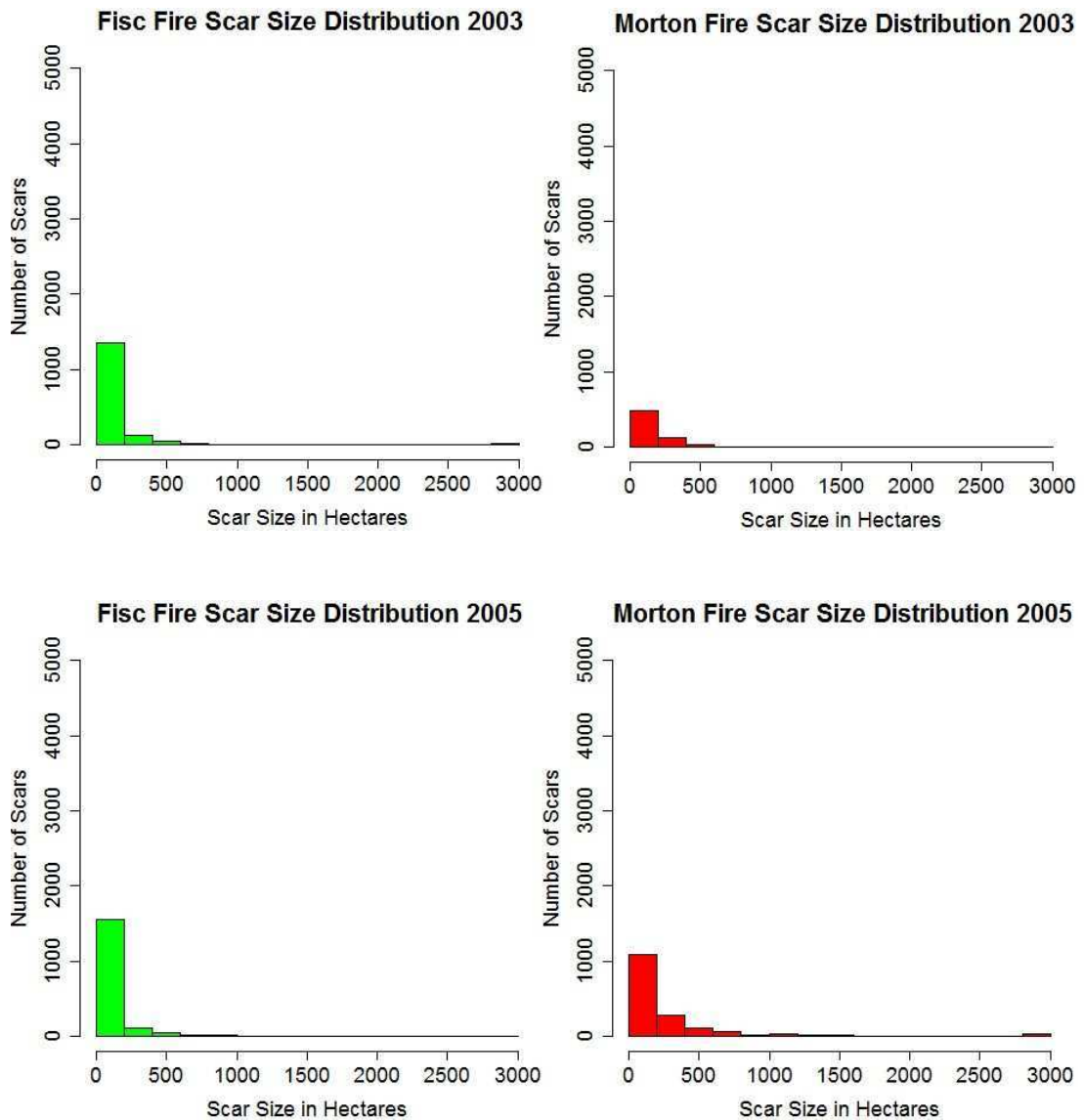


Figure S4 Size distributions of simulated (left in each pair, green) and observed (right, red) forest fire scars to a moist year (2003) and a year of extreme drought (2005). *Sources:*Data calculated by the authors using the FISC-model (left) and Morton *et al.* (2013) (right).

1.3 CARBON COMPONENT (CARLUC MODEL)

Briefly, CARLUC (Carbon and Land Use Change) is a process-based carbon cycle model that borrows its basic structure from the 3-PG model - a well-known dynamic model of vegetation of Landsberg and Waring (1997). CARLUC is coupled with FISC in order to provide microclimate conditions (for example, understory VPD) and the availability of fuel filler for fire, as well as to quantify carbon fluxes between the forest and the atmosphere. The model is parameterized and calibrated by using data

from a rain exclusion experiment in the Tapajós National Forest (Brando 2010, Brando et al. 2014). Model measurements of fuel loads, fire intensity and biomass turnover were compared and adjusted in a yearly basis with these observations from 2004 and 2007 (Figure S5).

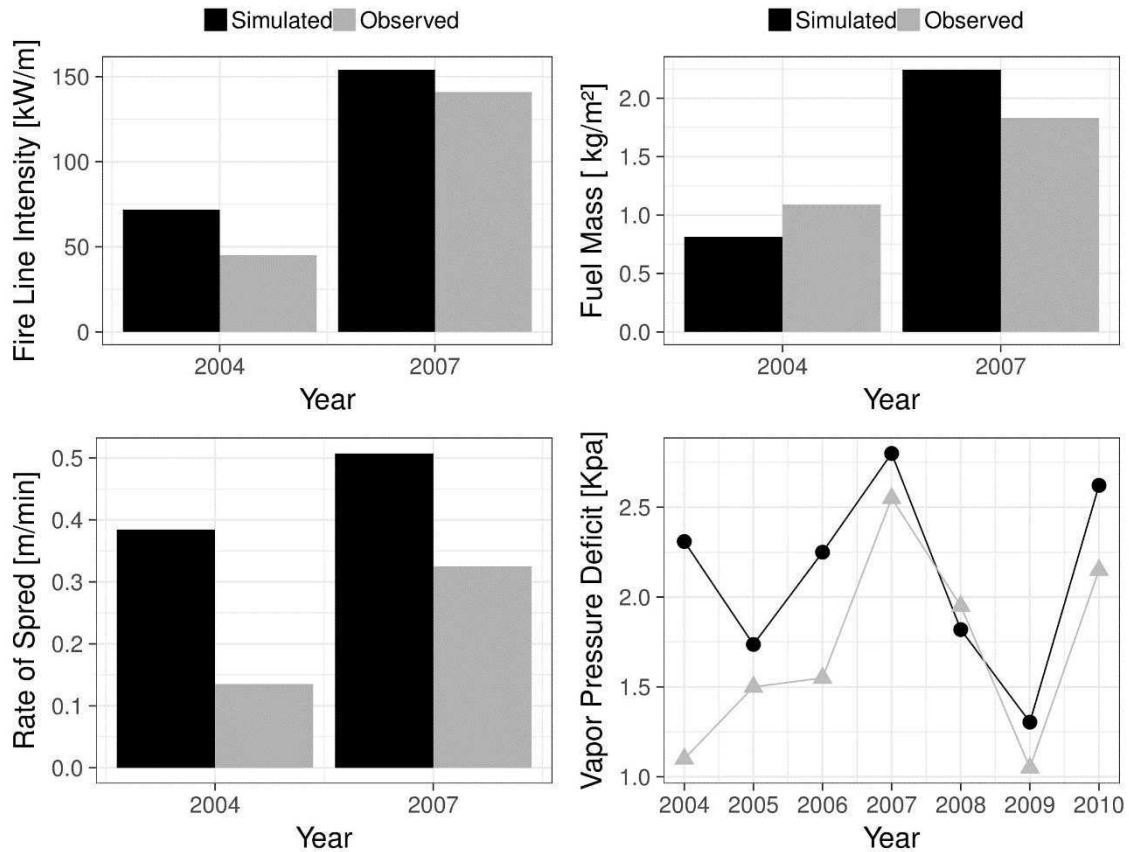


Figure S5 Calibration of CARLUC based on large-scale experiment. *Source:* (Brando et al. 2014)

CARLUC has a set of five climatic data inputs (Table S2): vapour pressure deficit (VPD), estimated from the temperature and humidity (NCEP/NCAR2 reanalysis data); active photosynthetic radiation (PAR), derived from the GOES-9 satellite product (Nepstad et al. 2004); water available for plants (PAW), estimated from the difference between soil field capacity and wilting point (Brando 2010); temperature (Temp), estimated from the NCEP/NCAR - Reanalysis2 (De Faria et al. 2017). The simulation of CARLUC is the outcome of the climate interacting with vegetation through a series of differential equations (Hirsch et al. 2004) that describe the flow of carbon within the forest. The model was designed to integrate process-based phenomena with empirical relationships derived from field experiments that allowed the inclusion of new equations in the model (Table S3), such as the equation that simulates the intensity of the fire

(Figure S6). The newest CARLUC updates are described in detail in De Faria et al. (2017).

Table S2 Climatic variables used in the CARLUC model. *Source:* Various

Variable	Source	Period	Link
PAW (Plant Available Water)	estimated from the difference between soil field capacity and wilting point	-	-
PAR (Photosynthetic active radiation)	GOES 9 Satellite <u>Earth System Research Laboratory</u> (<u>Physical Sciences Division</u>)	-	https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.pressure.html
Temperature	NCEP/NCAR - University of East Anglia	1948-2015	http://www.cru.uea.ac.uk/cru/data/hrg
Precipitation	TRMM/NASA	1948-2015	https://mirador.gsfc.nasa.gov/
Vapor Pressure deficit (VPD)	NCEP/NCAR - <u>Earth System Research Laboratory</u> (<u>Physical Sciences Division</u>) and University of East Anglia	1948-2015	Temperature: http://www.cru.uea.ac.uk/cru/data/hrg/ Humidity: https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.pressure.html

Table S3 Principal equations of CARLUC

Variable	Name	Unit	Unit name	Equation ¹
uVPD	Inner Vapor Pressure Deficit	Kpa	Kilo Pascal	$0.140494 - 0.006 * C_{stem} * 10 - 0.594074 * \sqrt{(C_{leaf} * 10 + 0.5) + 1.505 * \sqrt{VPD + 0.5}}$
LMC	Litter Moisture Content	Kpa	Kilo Pascal	$80 * \exp(-0.9 * I_{vpd})$
ROS	Rate of Spread	m/min	Meter per Minute	$0.043 + 0.83 * \exp(-0.107 * I_{mc})$
Fuel	Fuel Load	Kg/m ²	Kilogram per square meter	$((C_{leaf} + C_{stem}) * 20 / 350) * C_{llstruc}$
W	Weight of Dry Fuel	Kg/m ²	Kilogram per square meter	Fuel, LMC/me < 0.18 $(1.2 - 0.62 * LMC/me) * Fuel$, $0.18 \leq LMC/me \leq 0.73$ $(2.45 - 2.45 LMC/me) * Fuel$, LMC/me > 0.73
FI ²	Fire Intensity	kW/m	Kilo Watts per meter	$W * ROS * 18700 * 0.16$
Mort	Mortality	Kg/m ²	Kilogram per square meter	$1 / (1 + \exp(2.45 - 0.002373 * FI))$

¹Cstem: Carbon in stems. Cleaf: Carbon in leaves. Cllstruc: Carbon in structural leaf litter.

²We use the fire intensity metrics provided by Brando *et al.* (2014) which uses kW/m as the unit for fire intensity. The paper of Brando *et al.* (2014) is based on (Alexander 1982) which in turn uses this same unit.

Source: CARLUC model - equations based on field experiments

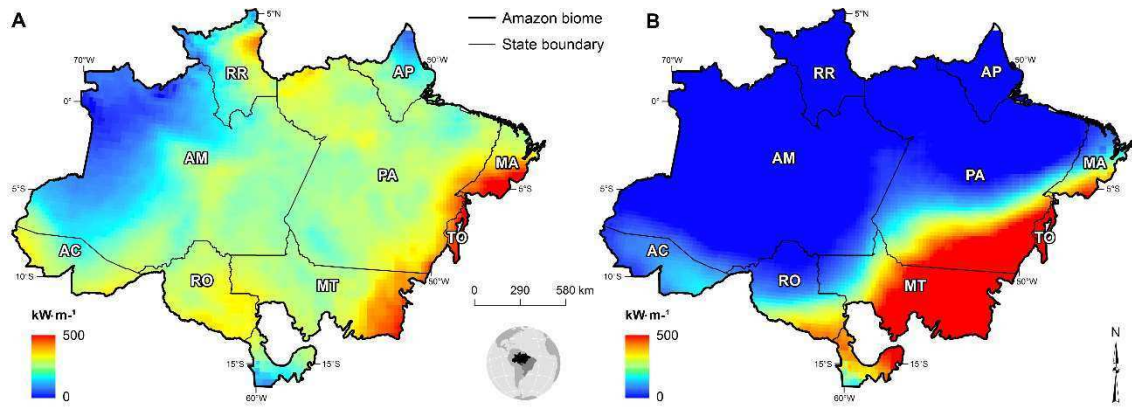


Figure S6 Spatial distribution of fire intensities 2005 (A) and 2010 (B). *Source:*Data calculated by the authors using the CARLUC model

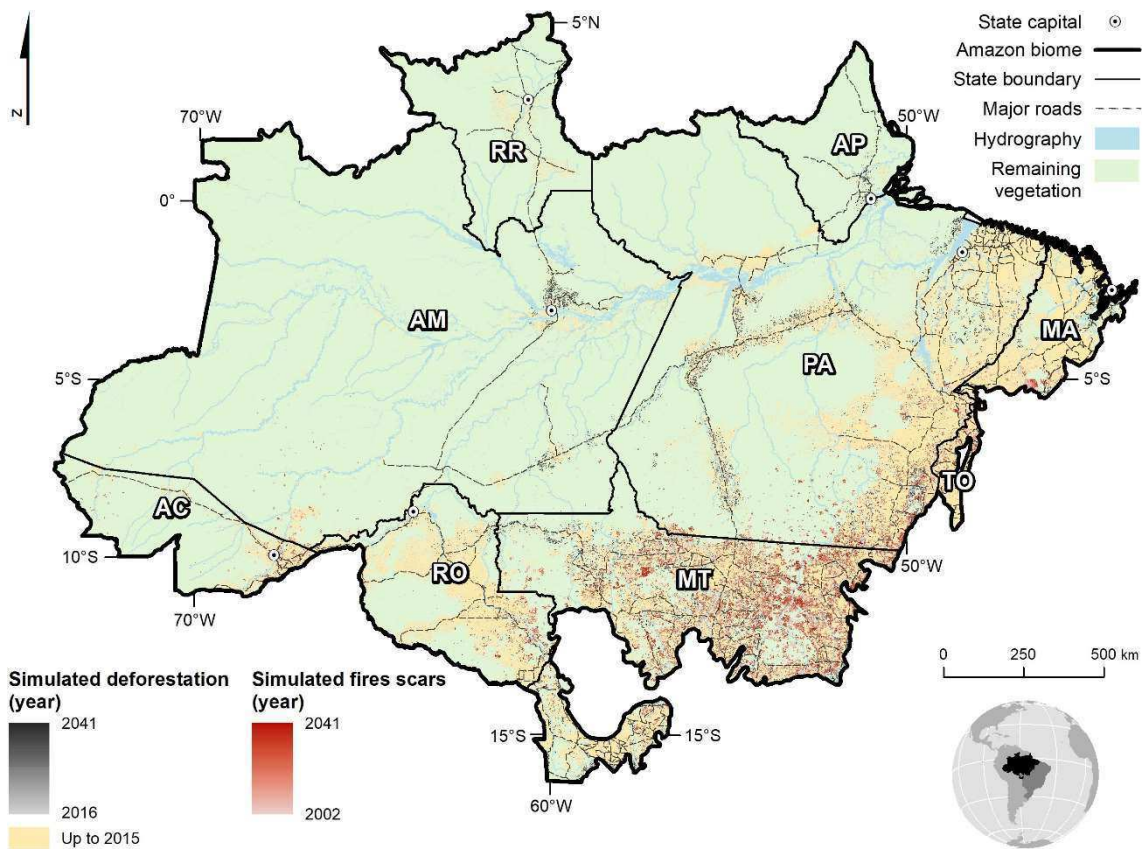


Figure S7 Simulated fires scars and deforestation for the Brazilian Amazon from 2012 to 2041. Deforestation rate from 2012 to 2015 is based on observed data from PRODES. *Sources:*Data calculated by the authors using theFISC-model and PRODES data (INPE 2015).

2. THE SIMMADEIRA MODEL

The original SimMadeira model developed by Merry *et al.* (2009) itself builds upon early simulation work of Stone (1998). Merry *et al.* (2009) have developed SimMadeira in Dinamica EGO freeware (Soares-Filho *et al.* 2013). In order to develop

the EcoFiremodel, SimMadeira was extended in order to provide robust geographically differentiated estimates of sustainable timber rents for 40 timber genera (each including one or more species) based on the ecological distribution of these commercial tree genera/species (see section 2.1). The model is set to run annually for a 30-year harvest cycle beginning with conditions as of 2012, our baseline year. Base maps cover the total area of the 9 Federal States of the Brazilian Amazon with a spatial resolution of 1 km², comprising a total area of around 516 Million hectares, of which 311 Million were considered forest area in 2012 according to PRODES/INPE. Table S4 summarizes parameter values used in the simulations and Tables S5 and S6 present the input data used in the model.

Table S4 Parameters of the SimMadeira model. *RIL = Reduced Impact Logging

Constant	Unit	Value
Initial year	-	2012
Number of simulated years	Year	30
Harvest cycle	Year	30
Initial capacity of newborn logging centers	m ³ year ⁻¹	50,000
Maximum logging intensity (RIL mode)	m ³ ha ⁻¹ year ⁻¹	0.86
Forest management unit (FMU) size (RIL mode)*	Ha	27,000
Annual production unit (APU) size (RIL mode)*	Ha	900
Temporal variation of round wood price	%year ⁻¹	0
Maximum potential increase in logging center Capacity	%year ⁻¹	20
Minimum distance to an emerging logging center	km	200
Maximum distance to an emerging logging center	km	500

Table S5 Input variables used in SimMadeira model. *1 US\$ = R\$ 2.36 (2015)

Variables	Description	Sources and Period	Link
Municipal centres	The municipalities are represented only by a cell that corresponds to the location of their centres	IBGE 2010	http://downloads.ibge.gov.br/downloads_geociencias.htm
Protected areas	Areas protected by type of protection	CNFP/SFB 2015	http://www.florestal.gov.br/cadastro-nacional-de-florestas-publicas/62-informacoes-florestais/165-dados-por-estado-cnfp-2015
Flonas and Flotas	Distribution of national and state forests areas	CNFP/SFB 2015	http://www.florestal.gov.br/cadastro-nacional-de-florestas-publicas/62-informacoes-florestais/165-dados-por-estado-cnfp-2015
Roads by type and conditions	Types of roads and their conditions (planned, deployed, paved, etc.).	PNLT/MT 2010	http://pnlt.imagem.govfed.opendata.arcgis.com/
Unpaved road	Unpaved road	CSR/UFGM 2014	www.csr.ufmg.br/maps
Waterways by conditions	Types of waterways and their conditions (navigable, inexpressive navigation, etc.).	PNLT/MT 2010	http://pnlt.imagem.govfed.opendata.arcgis.com/
Land use	Areas of forest, deforested areas and other types of cover	PRODES/INPE 2012	http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes
Hydrography	Hydrography	HydroSHEDS/WF 2005	https://www.worldwildlife.org/pages/hydrosheds
Commercial volume of timber (m ³ /ha)	Amount of commercial timber	Merry <i>et al.</i> (2009)	Merry, F., Soares-Filho, B., Nepstad, D., Amacher, G., and Rodrigues, H., 2009. Balancing Conservation and Economic Sustainability: The Future of the Amazon Timber Industry. <i>Environmental Management</i> , 44 (3), 395–407.
Settlements	Distribution and settlement area	INCRA	http://acervofundiario.incra.gov.br/geodownload/geodados.php
Quantity of timber produced [m ³ /year]	Amount of commercial timber produced	IBGE/ AMAZON 2009	IBGE: https://sidra.ibge.gov.br/home/ipp/brasil AMAZON: http://amazon.org.br/categorias/precos-de-produtos-da-floresta/
Operating cost [R\$/m ³]*	Amount paid for the extraction of wood in the forest until loading in transport vehicle	AMAZON 2009	http://amazon.org.br/categorias/precos-de-produtos-da-floresta/

Average price of timber [R\$/m ³]*	The average price of the timber value classes by genus and species	IMAZON 2010	http://imazon.org.br/categorias/pr-ecos-de-produtos-da-floresta/
Transport cost by type of terrain or path [R\$/m ³ /km]*	The values of transport cost reflect the effort of crossing a given environment. For the transport routes, values known in the literature are adopted, and for the other means (those that do not constitute roads, i.e: deforested area), larger values representing virtually a crossing barrier were adopted.	Soares-Filho <i>et al.</i> (2004) and Merry <i>et al.</i> (2009)	Soares-Filho, B., Alencar, A., Nepstad, D., Cerqueira, G., Vera Diaz, M. del C., Rivero, S., Solorzano, L., and Voll, E., 2004. Simulating the response of land-cover changes to road paving and governance along a major Amazon highway: the Santarem-Cuiaba corridor. <i>Global Change Biology</i> , 10 (5), 745–764. Merry, F., Soares-Filho, B., Nepstad, D., Amacher, G., and Rodrigues, H., 2009. Balancing Conservation and Economic Sustainability: The Future of the Amazon Timber Industry. <i>Environmental Management</i> , 44 (3), 395–407.

Table S6 Transportation costs used in SimMadeira model.

Category Name	Transportation cost (US\$ m ³ km ⁻¹)*
Sustainable use protected area	0.35
Public forest without designation	0.35
Strictly protected area	2,564 **
Military lands	2,564**
Indigenous lands	2,564**
Deforested area and Cerrado biome	0.30
Paved road	0.13
Unpaved road	0.21
Duplicate Road	0.08
Navigable waterway	0.05
Inexpressive navigability	0.43
Navigability only in rainy season	0.43

*1 US\$ = R\$ 2.36 (2015)

** High transportation costs represent the legal and economic barriers for crossing those areas.

Sources: Soares-Filho *et al.*(2004) and Merry *et al.* (2009)

2.1 TIMBER PRICES BY SIMMADEIRA MODEL

In the original logging model, 20%, 40%, and 60% of the volume is estimated as high, medium, and low value timber, and the respective roundwood price was calculated based on the mix of domestic and export percentages for prices at any given processing centre. These prices reflect the common mix of commercial timber species on logging frontiers.

In this simulation, we redesigned timber distribution and pricing components in SimMadeira, dividing commercial timber into softwood and hardwood based on a list of the 40 most common commercial timber identified originally by Institute of the Man and Environment of the Amazon - IMAZON (Pereira *et al.* 2010) - (Table S7). The species are classified as soft and hardwood according to fire response and are integral to the study detailing the interaction between logging and fire. Interviews with loggers were conducted in order to determine species descriptions. Note that these designations have nothing to do with coniferous vs broadleaf seeding that are used in temperate forestry. The list provided by IMAZON contains both genera such as *Aspidosperma* with many tree species that go under the common name of “Peroba” or tree species such as *Mezilaurus itauba* (Itaúba) that corresponds to one species.

Table S7 Tree genera/species and respective mean prices for roundwood Source: Pereira *et al.* (2010).

Name (in Portuguese)	Scientific name	Mean prices(US\$/m ³)				
		MatoGrosso	Pará	Rondônia	Mean	Category
<i>High Economic value tree species</i>		148	159	132	152	-
Ipê-amarelo	<i>Tabebuia serratifolia</i>	137	173	131	160	Hard
Ipê-roxo	<i>Tabebuia impetiginosa</i>	142	164	131	156	Hard
Cedro Vermelho	<i>Cedrela odorata</i>	137	137	156	140	Hard
Itaúba	<i>Mezilaurus itauba</i>	155	103	97	139	Hard
Freijó	<i>Cordia goeldiana</i>	126	120	140	125	Hard
<i>Medium economic value tree species</i>		101	102	74	94	-
Amescla	<i>Protium heptaphyllum</i>	73	74	60	70	Soft
Angelim-pedra	<i>Hymenolobium petraeum</i>	110	106	78	99	Hard
Angelim-vermelho	<i>Dinizia excelsa</i>	111	113	81	108	Soft
Breu	<i>Protium</i> sp.	68	89	62	73	Soft
Cambará	<i>Vochysia</i> sp.	86	117	64	79	Hard
Cedrinho	<i>Erismma uncinatum</i>	110	83	62	97	Hard
Cedromara	<i>Cedrela</i> sp.	84	105	65	73	Soft
Cerejeira	<i>Torresea acoreana</i>	113	-	94	97	Hard
Cumaru	<i>Dipteryx odorata</i>	115	111	87	105	Hard
Cupiúba	<i>Goupiaglabra</i>	98	96	68	90	Hard
Garapeira	<i>Apuleia molaris</i>	105	83	78	89	Hard
Goiabão	<i>Pouteria pachycarpa</i>	87	86	59	83	Soft
Jatobá	<i>Hymenaea courbaril</i>	101	100	77	95	Hard
Jequitibá	<i>Cariniana</i> sp.	144	84	71	81	Hard
Louro	<i>Ocotea</i> sp.	84	83	62	79	Soft
Maçaranduba	<i>Manilkara huberi</i>	90	114	83	107	Soft

Muiracatiara	<i>Astronium</i> sp.	81	100	76	92	Soft
Oiticica	<i>Clarisiaracemosa</i>	85	100	67	71	Soft
Pequiá	<i>Caryocarvillosum</i>	72	91	64	86	Soft
Peroba	<i>Aspidospermasp.</i>	116	156	82	108	Hard
Roxinho	<i>Peltogynesp.</i>	91	109	65	78	Soft
Sucupira	<i>Bowdichiasp.</i>	104	96	68	85	Hard
Tatajuba	<i>Bagassaguiensis</i>	72	99	64	92	Soft
Timborana	<i>Piptadeniasp.</i>	84	89	72	89	Soft
<i>Low economic value tree species</i>		77	73	61	69	-
Abiu	<i>Pouteriasp.</i>	84	83	64	78	Soft
Amapá	<i>Brosimumparinarioides</i>	134	71	51	71	Soft
Amesclão	<i>Trattinnickiaburseraefolia</i>	72	69	42	67	Soft
Angelim-amargoso	<i>Vataireopsis speciosa</i>	87	67	70	70	Soft
Angelim-saia	<i>Parkiapendula</i>	67	101	57	67	Soft
Caju	<i>Anacardium</i> sp.	55	64	56	62	Soft
Marupá	<i>Simaroubaamara</i> .	71	70	62	67	Soft
Copaíba	<i>Copaiferasp.</i>	72	72	56	67	Soft
Faveira	<i>Parkiasp.</i>	66	67	73	69	Soft
Mandioqueiro	<i>Qualeasp.</i>	78	84	42	83	Soft
Orelha-de-macaco	<i>Enterolobiumschomburgkii</i>	59	81	55	68	Soft
Paricá	<i>Schizolobiumamazonicum</i>	64	64	56	61	Soft
Sumaúma	<i>Ceibapentandra</i>	71	66	57	64	Soft
Tauari	<i>Couratarisp.</i>	78	83	61	72	Soft
Taxi	<i>Tachigalisp.</i>	78	73	58	72	Soft
Virola	<i>Virolasp.</i>	84	65	36	62	Soft

After classifying the commercial timber types as softwood and hardwood, the second step was to develop a tree-species distribution model for the Brazilian Amazon (Figure S7 and S8). This procedure relied on the database of tree species provided by Specieslink (<http://splink.cria.org.br>; CRIA - Specieslink 2015) and the Global Biodiversity Information Facility (<https://www.gbif.org/>; GBIF 2015). GBIF and CRIA list the geographical coordinates of 106,975 occurrences of tree species encompassing 40 timber types selected for this analysis. Even though this is one of the most comprehensive sources for the presence of tree species in the Amazon, this dataset has substantial sampling errors and a geographic bias that had to be corrected in order to obtain a reliable spatially explicit estimate.

For example, the geographic coordinates of single observations of tree species are sometimes inaccurate, some locations in the Amazon are more intensely sampled

than others, and the quality of data collection varies. Furthermore, many of the samples were taken in areas that had undergone years of illegal timber extraction, leading to the local disappearance of some hardwood species with higher commercial value. In order to reduce sampling bias, each tree species record was checked in relation to its geographical accuracy based on a georeferenced database of Brazilian municipalities. In the absence of actual coordinates, samples located at a municipality's seat were removed from the dataset. This was necessary due to the sensitivity of the spatial distribution model and the large area of some municipalities in the Amazon. Since the predictive ability of the model is affected by the sample size, we used only species with more than 15 occurrences (Figure S1). Together these restrictions eliminated 61% of the samples from the final dataset. Nevertheless, all commercial tree genus, as identified by IMAZON, 237 species (40,938 records), could still be found in the dataset.

To create the occurrence maps for each of the 40 timber types, the data from CRIA and GBIF were analyzed in relation to 19 predictive bioclimatic variables obtained from WordClim (2005) - (Table S8), plus elevation data for South America region. First, the bioclimatic and elevation data were preprocessed in order to avoid data collinearity. Then, a principal component analysis (PCA) identified that only the first four axes were statistically significant, representing 89.4% of the variance of the predictive variables. These variables were then transformed into raster maps and analyzed in relation to the tree species dataset using species distribution algorithms: Bioclim; Domain; Mahalanobis distance; Maxent, Garp; and SVM (Franklin 2010). Each algorithm generated a binary map of presence and absence for each tree species based on minimum value of suitability observed in the samples. The subsequent maps were then multiplied by the species suitability maps, so that within the area predicted as having species presence there would be variation of suitability values. This was done to estimate the spatial variation in the map of species abundance. The final distribution map of each species is therefore the result of a weighted average of these maps. In order to exclude maps with a low degree of confidence of the weighted average, only maps with area under curve (AUC) above 0.80 were adopted (Figure S7) - (AUC is a metric that indicates the relation between true and false positives).

Table S8 Bioclimatic Variables. *Source:* WordClim (2005)

COD	NAME
BIO 1	Annual Mean Temperature
BIO 2	Mean Diurnal Range (Mean of monthly (max temp - min temp))
BIO 3	Isothermality (BIO2/BIO7) (*100)
BIO 4	Temperature Seasonality (standard deviation *100)
BIO 5	Max Temperature of Warmest Month
BIO 6	Min Temperature of Coldest Month
BIO 7	Temperature Annual Range (BIO5-BIO6)
BIO 8	Mean Temperature of Wettest Quarter
BIO 9	Mean Temperature of Driest Quarter
BIO 10	Mean Temperature of Warmest Quarter
BIO 11	Mean Temperature of Coldest Quarter
BIO 12	Annual Precipitation
BIO 13	Precipitation of Wettest Month
BIO 14	Precipitation of Driest Month
BIO 15	Precipitation Seasonality (Coefficient of Variation)
BIO 16	Precipitation of Wettest Quarter
BIO 17	Precipitation of Driest Quarter
BIO 18	Precipitation of Warmest Quarter
BIO 19	Precipitation of Coldest Quarter

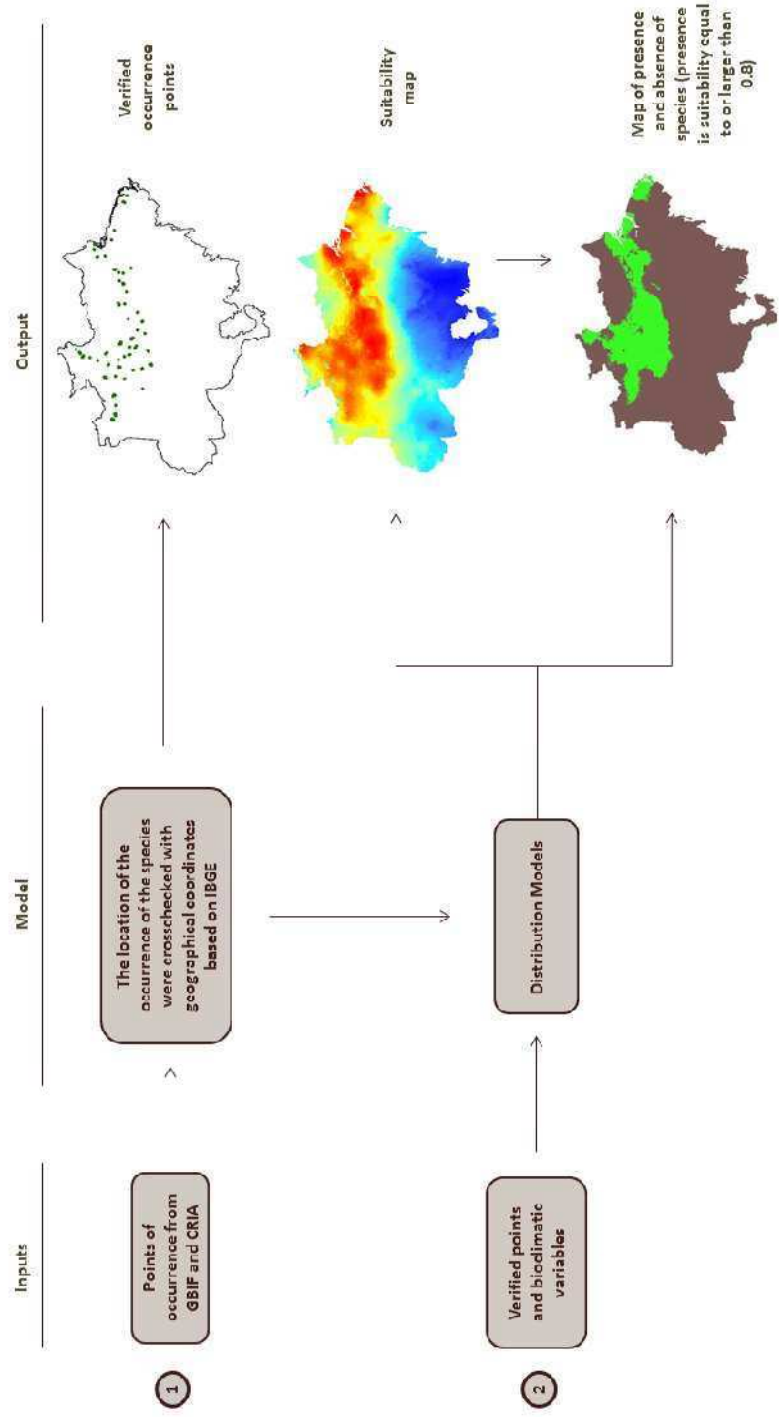


Figure S8Species distribution modeling. *Source:* Developed by the authors

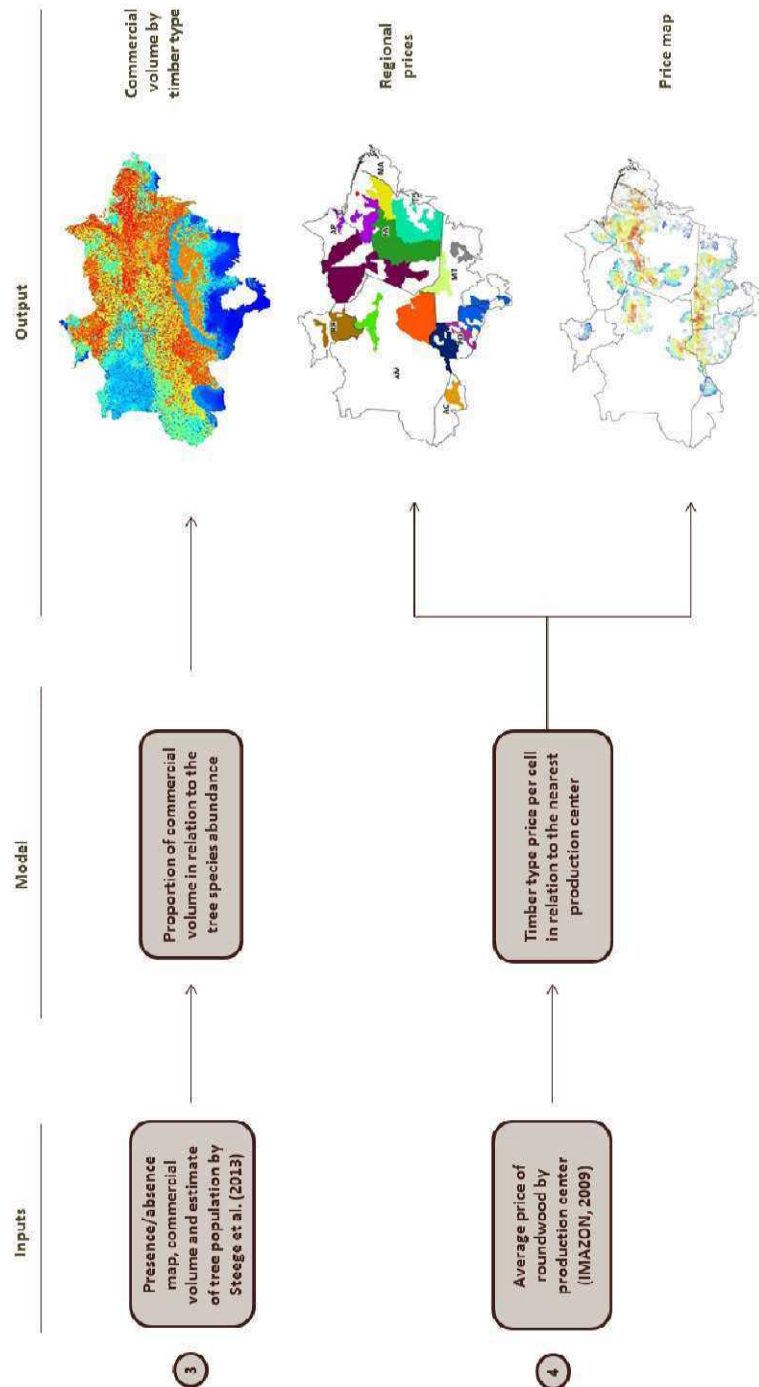


Figure S9 Steps in SimMadeira to calculate timber volume and prices. *Source:* Developed by the authors

In order to create a consensus between the models, a weighted average of the AUC value of the model results was generated per species. To obtain models of each timber type, we combined the models of each species corresponding to each timber type. The consensus models for the timber types were standardized by rescaling them to values between 0 and 1. This procedure generated a single map whose data points were deemed reliable, at a resolution of 1 km², for each of the 237 tree species. The tree

species and genera that correspond to the list of commercial timber type were combined to create a total of 40 maps; 27 of them corresponding to softwood and 13 to hardwood. These maps were again combined in order to create a map of the presence/absence of softwood and hardwood. Results show the number of softwood genera per location ranging between 7 and 27 types, while the number of hardwood genera ranges between 2 and 13(Figure S10).

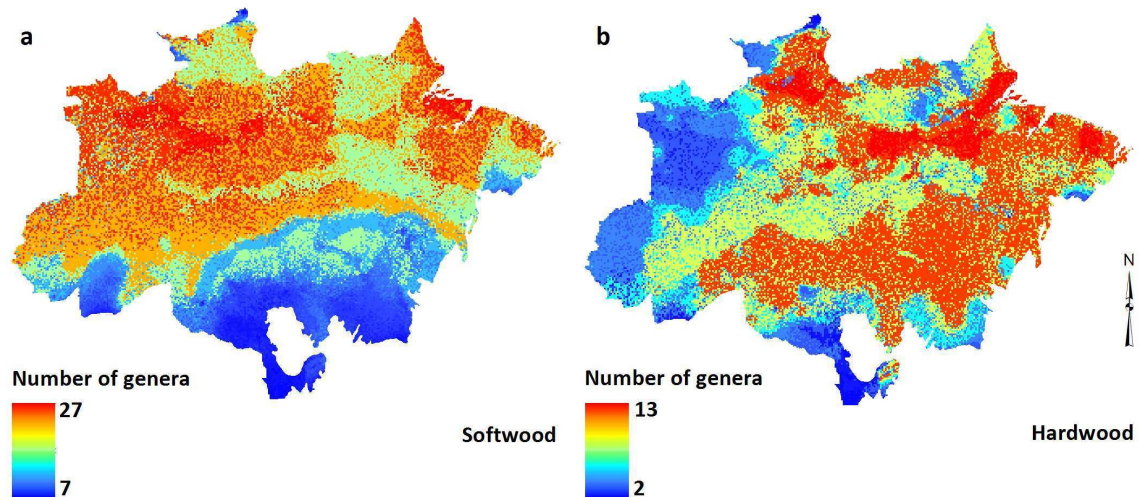


Figure S10 Number of tree genera of softwood (a) and hardwood (b) in 100ha cell locations

Source: Data calculated by the authors using “Species distribution modeling”

In a fourth step, we estimated the commercial volume for each timber type. We expanded on Merry *et al.* (2009) in order to differentiate the total commercial timber volume by timber type based on the genus distribution maps. In order to account for the relative abundance of tree species, we used the Amazon-wide distribution for the population of 4,962 species estimated by Steege *et al.* (2013) – Figure S10. The total commercial timber volume was divided among different tree genus found in each map cell based on the relative abundance of tree species in the Amazon (Figure S11).

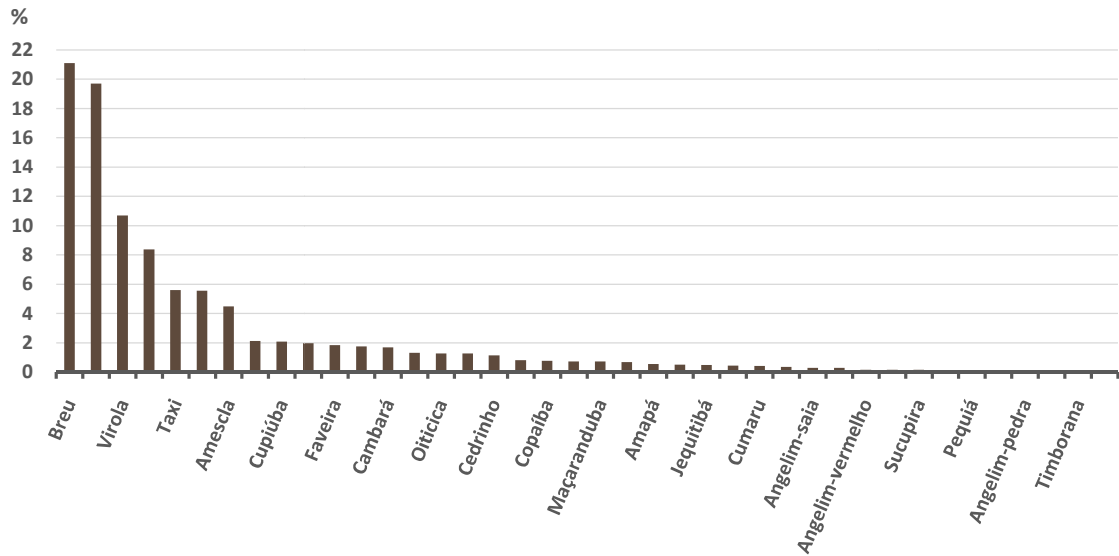


Figure S11 Share of commercial timber genus in relation to the total tree population in the Amazon. *Source: Steege et al. (2013)*

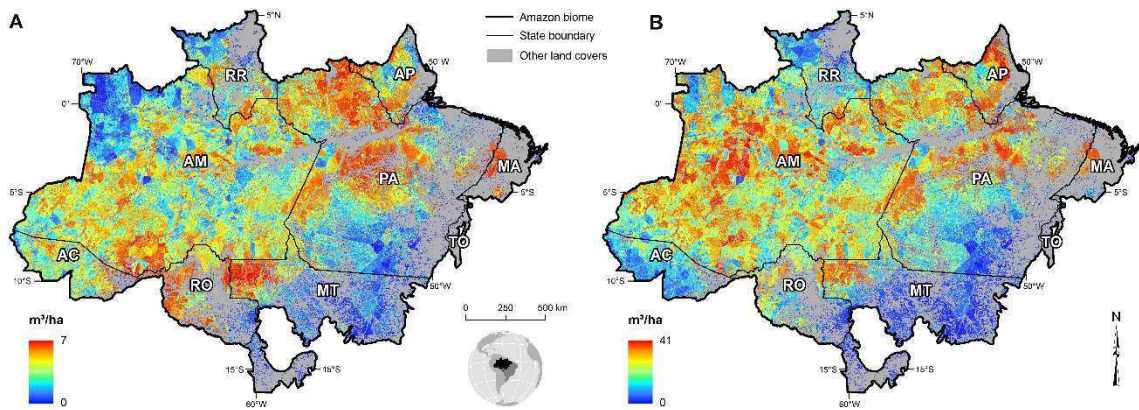


Figure S12 Commercial volumes for hard (A) and softwoods (B). *Source: Commercial volume data from Merry et al. (2009) and distribution of commercial volume by timber types calculated by the authors using the SimMadeira model.*

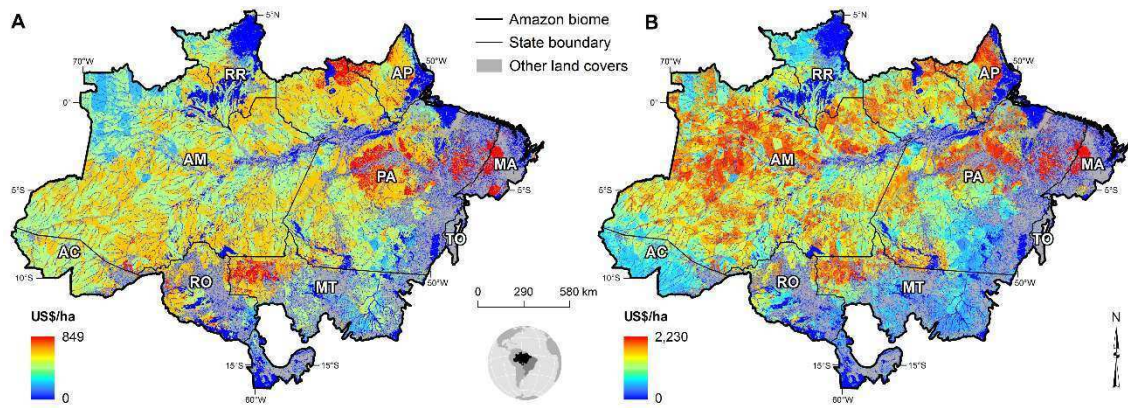


Figure S13 Commercial values for hard (A) and softwoods (B). *Source:* Data calculated by the authors using theSimMadeiramodel.

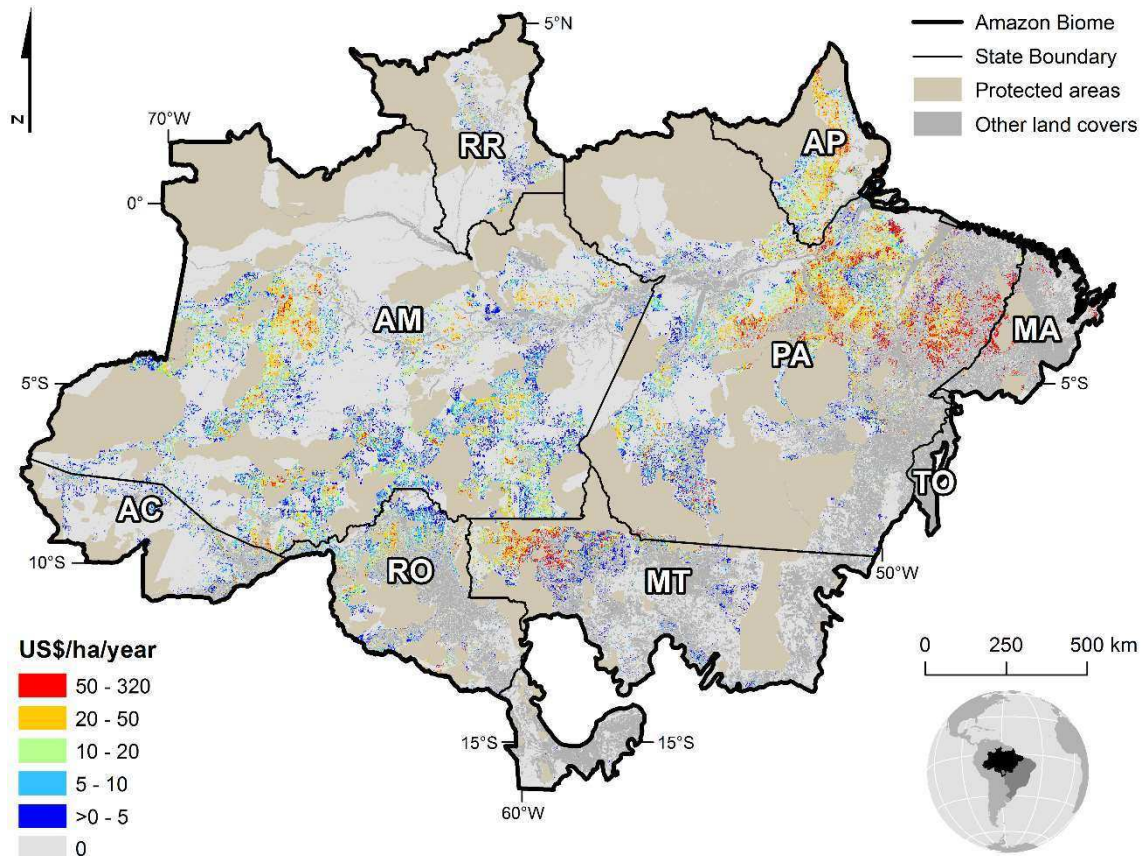


Figure S14 Potential equivalent annual annuity (EAA) of sustainable logging rents. *Source:* Data calculated by the authors using theSimMadeira model

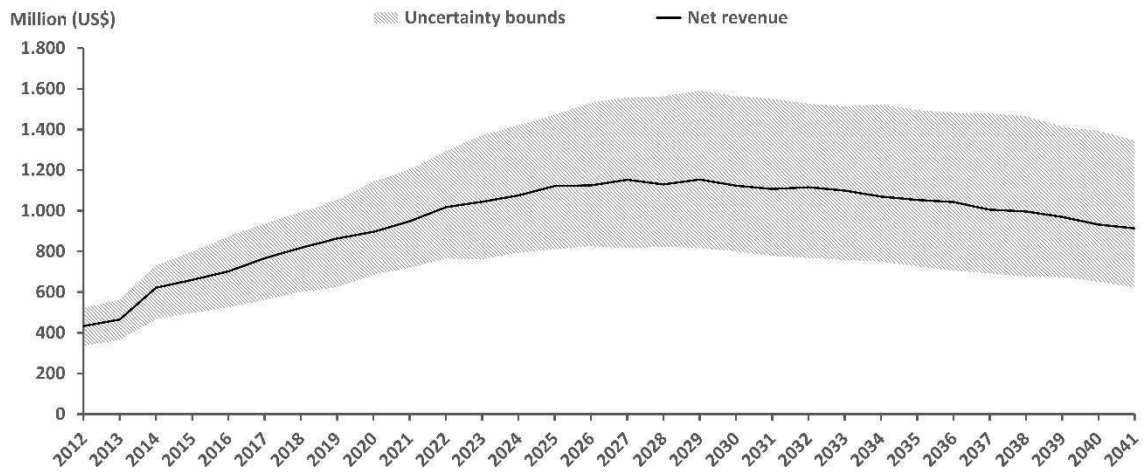


Figure S15 Total net revenue per year (uncertainty bounds correspond to $\pm 15\%$ variation in timber price). *Source:* Data calculated by the authors using the SimMadeira model

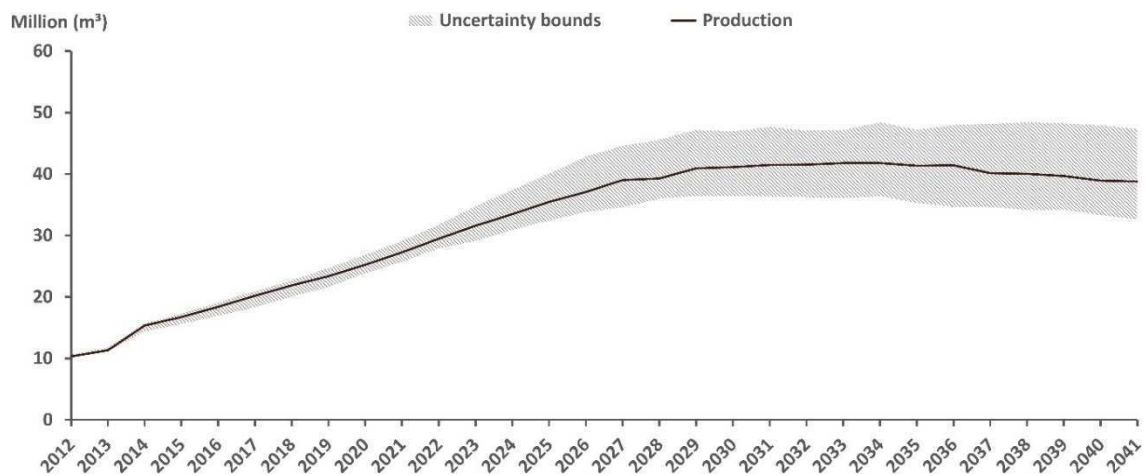


Figure S16 Timber production per year (uncertainty bounds correspond to $\pm 15\%$ variation in timber price). *Source:* Data calculated by the authors using the SimMadeira model

3. FIELDWORK IN SINOP-MT

Table S9 List of interviewees

Type of informant	Municipality-Stakeholder
17 Forest Producers and Loggers	producers in the Sinop region, some have more than 40 years of experience in timber production.
13 Forest Engineers*	engineers who carry out forest inventories in Sinop region, focused on legal timber production.
	SEMA – Secretaria Estadual de Meio Ambiente
	IBAMA – Instituto Brasileiro de Meio Ambiente – Equipe PrevFogo
	Corpo de Bombeiros de Sinop-MT
Institutions	UFMT – Universidade Federal de Mato Grosso
	EMBRAPA – Empresa Brasileira de Pesquisa Agropecuária
	SINDUSMAD – Sindicato dos Madeireiros
	CIPEM – Centro das Indústrias Produtoras e Exportadoras de Madeira do Estado do Mato Grosso

*Four forest engineers from Sinop who classified each tree genera as either soft or hardwood

4 QUESTIONNAIRE

RESEARCH

Damages caused by fire in the commercial wood: How much is financially lost when burns occur in forests with potential to timber production?

Questionnaire number: _____

1. Identification

Interviewee name:		Employ:	
Institution/ Company/ Property		Time experience in the area:	
Phone:		E-mail:	
Interviewer:		Date:	/ / 2015
Geographic coordinates:			

2. Presentation of the interviewer and Description of Research Objectives

We are researchers from the Federal University of Minas Gerais and we are conducting a survey, which aims to understand the economic losses that forest fires can cause the production of commercial timber in the Amazon.

3. Interview

1. Is Timber directed to which markets/products?

MARKETS/INDUSTRIES	10 – 20%	30 – 50%	60 – 90%	90 – 100%
Sawn wood				
Products benefit				
Laminates and Plywood				
Purposes Fuels (Coal/Firewood)				
Other (please specify):				

2. When fire occurs, to which markets/products is the wood destined?

MARKETS/INDUSTRIES	10 – 20%	30 – 50%	60 – 90%	90 – 100%
Sawn wood				
Products benefit				
Laminates and Plywood				
Purposes Fuels (Coal/Firewood)				
Other (please specify):				

3. What would be the cost to the producer for renting land destined to production of commercial timber? (Cost per hectare)

a) Cost in relation to distance from the timber industry (or city center):

VALUE	10 - 20%	20 - 40%	40 - 60%	60 - 80%
INCREASES				
DECREASES				
KEEPS	()			

PRODUCTS	>100,000/ha (or by	100,000- 500,000/ha	500,000- 1,000,000/ha	>1,000,000/ha (or by

	property) (US\$) or 10 to 20%	(or by property) (US\$) or 20 to 40%	(or by property) (US\$) or de 40 to 60%	property) (US\$) or 60 to 80%
Sawn wood				
Products benefit				
Laminates and Plywood				
Purposes Fuels (Coal/ Firewood)				
Other (please specify):				

4. Concerning markets/industries mentioned in the previous question, what is the approximated economical losses when fire occurs in a forest property associated to the production of commercial timber for each market/product?

5. What is the fire recurrence observed in recent years in properties that provide commercial timber?
 - a. every 6 months
 - b. annually
 - c. every 2 years
 - d. every 5 years
 - e. every 10 years
 - f. Other: _____

6. What are the main events of fire that have occurred in the region? Mention the date of occurrence, and the main consequences of these events.

7. How much forest per hectare with potential commercial timber production is burned annually on average?
 - a. 10-20% per hectare
 - b. 20 – 30% per hectare
 - c. 30 – 60% per hectare
 - d. > de 60% per hectare
 - e. Other: _____

8. What damages may occur to production, when fire reaches forest properties? *E.g.* property infrastructure (free response).

9. Over the damage mentioned in the previous question, what are the costs related to these damages, on average?

DAMAGE CAUSED BY FIRE	>100,000/ha (or by property) (US\$)	100,000-500,000/ha (or by property) (US\$)	500,000-1,000,000/ha (or by property) (US\$)	>1,000,000/ha (or by property) (US\$)
Mean Cost				

10. What are the main losses in the commercial timber production? Number 1 to 5.

Timber theft ()

Pests ()

Gale ()

Fire ()

Others: _____ ()

11. Concerning land costs after fire event, its value:

VALUE	10 - 20%	20 - 40%	40 - 60%	60 - 80%
INCREASES				
DECREASES				
KEEPS	()			

12. Is there any evaluation or control of the deaths of trees after fire events?

No ()

Yes () How many trees per hectare? _____ (free response). Are there spatial and tabular data of tree mortality, where can we get it?

13. Are there fire control measures on properties that produce commercial timber?

No ()

Yes ()

a. If so, what are these control measures? (Fire breaks, prescribed Fire)

b. If so, what are the costs linked to such measures, on average?

CONTROL MEASURES	>100,000/ha (or by property) (US\$)	100,000-500,000/ha (or by property) (US\$)	500,000-1,000,000/ha (or by property) (US\$)	>1,000,000/ha (or by property) (US\$)
Mean Cost				

14. Does the management of the properties that produce commercial timber make use of fire?

No ()

Yes () In which situations fire is used?

Prescribed fire	Daily	Monthly	Half yearly	Annually
Cleaning				
Pasture management				
Road opening				
Other (please specify):				

15. What is currently being done to control the fire in commercial timber production? What are the new fire control trends in the sector?

16. What are the future prospects for the timber sector concerning economy, trade and environment?

17. Are you a forestry producer?

No ()

Yes ()

If so, taking into account the losses and costs associated to fire, how much would you pay, yearly, per hectare of land to prevent fire risks on your property?

5. OTHERS

Table S10 Municipalities with the greatest economic loss by fire. *Accumulated losses from 2012 to 2041. *Source:* Data calculated by the authors using theEcoFire model

Number	Municipalities	Federation unit	Economic loss (US\$)*	Mitigation program
1	Arame	MA	1,544,633	NO
2	Buriticupu	MA	1,542,357	NO
3	Santa Luzia	MA	1,521,936	NO
4	Açailândia	MA	1,487,928	NO
5	Dom Eliseu	PA	1,445,143	Green Municipalities Project
6	Colniza	MT	1,304,968	NO
7	Cotriguaçu	MT	1,268,867	NO
8	Nova Bandeirantes	MT	1,182,283	NO
9	Novo Progresso	MT	1,163,826	NO
10	Paranaíta	MT	1,161,564	Aliança da Terra
11	Apicás	MT	1,161,250	NO
12	Aripuaña	MT	1,153,149	NO
13	Novo Mundo	MT	1,152,169	NO
14	Jacareacanga	PA	1,147,367	NO
15	Altamira	PA	1,132,219	Green Municipalities Project
16	Guarantã do Norte	MT	1,123,747	NO
17	Alta Floresta	MT	1,120,915	Aliança da Terra
18	Bom Jesus da Selva	MA	999,427	NO
19	Marajá do Sena	MA	976,898	NO
20	Xinguara	PA	898,249	Green Municipalities Project

Table S11 Municipalities Participating in the “Green Municipalities Project”.
*Source:*Fundo Amazônia (2017)

Number	ID	Municipalities	Project Category
1	1500107	Abaetetuba	consolidated
2	1500131	Abel Figueiredo	consolidated
3	1500206	Acará	consolidated
4	1500347	Água Azul do Norte	consolidated
5	1500404	Alenquer	green municipalities
6	1500503	Almeirim	under pressure
7	1500602	Altamira	embargoed
8	1500800	Ananindeua	consolidated
9	1500859	Anapú	embargoed
10	1500909	Augusto Corrêa	consolidated
11	1500958	Aurora do Pará	consolidated
12	1501006	Aveiro	under pressure
13	1501204	Baião	consolidated
14	1501253	Bannach	consolidated
15	1501303	Barcarena	consolidated
16	1501402	Belém	consolidated
17	1501451	Belterra	forest
18	1501501	Benevides	consolidated
19	1501576	Bom Jesus do Tocantins	consolidated
20	1501600	Bonito	consolidated
21	1501709	Bragança	consolidated
22	1501725	Brasil Novo	green municipalities
23	1501758	Brejo Grande do Araguaia	consolidated
24	1501782	Breu Branco	consolidated
25	1502004	Cachoeira do Arari	consolidated
26	1501956	Cachoeira do Piriá	forest
27	1502152	Canãa dos Carajás	green municipalities
28	1502202	Capanema	consolidated
29	1502301	CapitãoPoço	consolidated
30	1502400	Castanhal	consolidated
31	1502509	Chaves	forest
32	1502707	Conceição do Araguaia	consolidated
33	1502756	Concórdia do Pará	consolidated
34	1502764	Cumarú do Norte	green municipalities
35	1502772	Curionópolis	consolidated
36	1502806	Curralinho	forest
37	1502855	Curuá	forest
38	1502905	Curuçá	consolidated
39	1502939	Dom Eliseu	green municipalities
40	1502954	Eldorado dos Carajás	consolidated
41	1503002	Faro	forest

42	1503044	Floresta do Araguaia	consolidated
43	1503093	Goianésia do Pará	consolidated
44	1503101	Gurupá	under pressure
45	1503200	Igarapé-açu	consolidated
46	1503309	Igarapé-miri	consolidated
47	1503457	Ipixuna do Pará	consolidated
48	1503507	Irituia	consolidated
49	1503606	Itaituba	under pressure
50	1503705	Itupiranga	embargoed
51	1503754	Jacareacanga	forest
52	1503804	Jacundá	consolidated
53	1503903	Juruti	green municipalities
54	1504059	Mãe do Rio	consolidated
55	1504109	MagalhãesBarata	consolidated
56	1504208	Marabá	embargoed
57	1504307	Maracanã	consolidated
58	1504422	Marituba	consolidated
59	1504455	Medicilândia	under pressure
60	1504505	Melgaço	forest
61	1504703	Moju	embargoed
62	1504752	Mojuí dos Campos	under pressure
63	1504802	Monte Alegre	under pressure
64	1504901	Muaná	Florestal
65	1504976	Nova Ipixuna	consolidated
66	1505031	Novo Progresso	embargoed
67	1505064	Novo Repartimento	embargoed
68	1505106	Óbidos	green municipalities
69	1505205	Oeiras do Pará	forest
70	1505304	Oriximiná	forest
71	1505403	Ourém	consolidated
72	1505437	Ourilândia do Norte	consolidated
73	1505486	Pacajá	embargoed
74	1505494	Palestina do Pará	consolidated
75	1505502	Paragominas	green municipalities
76	1505536	Parauapebas	consolidated
77	1505551	Pau d'arco	consolidated
78	1505601	Peixeboi	consolidated
79	1505635	Piçarra	consolidated
80	1505650	Placas	under pressure
81	1505700	Ponta de Pedras	forest
82	1505908	Porto de Moz	consolidated
83	1506005	Prainha	under pressure
84	1506104	Primavera	consolidated
85	1506138	Redenção	green municipalities
86	1506161	Rio Maria	consolidated
87	1506187	Rondon do Pará	embargoed

88	1506195	Rurópolis	under pressure
89	1506203	Salinópolis	forest
90	1506302	Salvaterra	forest
91	1506351	Santa Barbara do Pará	consolidated
92	1506500	Santa Izabel do Pará	consolidated
93	1506559	Santa Luzia do Pará	consolidated
94	1506583	Santa Maria das Barreiras	green municipalities
95	1506609	Santa Maria do Pará	consolidated
96	1506708	Santana do Araguaia	green municipalities
97	1506807	Santarém	green municipalities
98	1507102	São Caetano de Odivelas	consolidated
99	1507151	São Domingos do Araguaia	consolidated
100	1507201	São Domingos do Capim	consolidated
101	1507300	São Félix do Xingu	embargoed
102	1507458	São Geraldo do Araguaia	consolidated
103	1507474	São João de Pirabas	consolidated
104	1507607	São Miguel do Guamá	consolidated
105	1507706	São Sebastião da Boa Vista	forest
106	1507755	Sapucaia	consolidated
107	1507805	Senador José Porfírio	embargoed
108	1507904	Soure	consolidated
109	1507953	Tailândia	green municipalities
110	1507961	Terra Alta	consolidated
111	1507979	Terra Santa	forest
112	1508001	Tome-açu	consolidated
113	1508035	Tracuateua	consolidated
114	1508050	Trairão	under pressure
115	1508084	Tucumã	green municipalities
116	1508100	Tucuruí	consolidated
117	1508126	Ulianópolis	green municipalities
118	1508159	Uruará	under pressure

Table S12 Municipalities most attended by the fire brigade of the Aliança da Terra between 2010 to 2015. *Source:*Aliança da Terra (2017)

Municipalities	Federation unit
Novo Santo Antônio	MT
Bom Jesus do Araguaia	MT
São Felix do Araguaia	MT
Confresa	MT
RibeirãoCascalheira	MT
Serra Nova Dourada	MT
São Felix do Xingu	MT
Gaúcha do Norte	MT
Alto Boa Vista	MT
Paranaíta	MT
Alta Floresta	MT
Porto Alegre do Norte	MT

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SUPPORTING INFORMATION OF CHAPTER 02

Table SS1 Federal conservation units mitigated by the management of ICMBio

FEDERAL CONSERVATION UNITS	STATES	BIOME	YEAR
ESEC da Serra das Araras	MT	CERRADO	2001
ESEC da Terra do Meio	PA	AMAZON	2010
ESEC de Caracaraí	RR	AMAZON	2002
ESEC de Cuniã	RO/AM	AMAZON	2008
ESEC de Iquê	MT	CERRADO	2004
ESEC de Maracá	RR	AMAZON	2004
ESEC de Maracá-Jipioca	AP	AMAZON	2003
ESEC de Uruçuí-Una	PI	CERRADO	2001
ESEC Niquiá	RR	AMAZON	2010
ESEC Serra Geral do Tocantins*	BA/TO	CERRADO	2004
FLONA de Altamira	PA	AMAZON	2010
FLONA de Brasília	GO/DF	CERRADO	2001
FLONA de Roraima	AM/RR	AMAZON	2004
FLONA do Bom Futuro	RO	AMAZON	2010
FLONA do Iquiri	AM	AMAZON	2011
FLONA do Jamanxim	PA	AMAZON	2010
FLONA do Jamari	RO	AMAZON	2001
FLONA do Macauã	AC	AMAZON	2012
FLONA do Tapajós	PA	AMAZON	2002
PARNA Cavernas do Peruaçu	MG	CERRADO	2001
PARNA da Chapada das Mesas*	MA	CERRADO	2007
PARNA da Chapada dos Guimarães	MT	CERRADO	2001
PARNA da Chapada dos Veadeiros*	GO	CERRADO	2001
PARNA da Serra da Bodoquena	MS	CERRADO	2002
PARNA da Serra da Canastra*	MG	CERRADO	2001
PARNA da Serra das Confusões	PI	CERRADO	2001
PARNA da Serra do Cipó*	MG	CERRADO	2001
PARNA da Serra do Pardo	PA	AMAZON	2012
PARNA das Emas	MS/GO	CERRADO	2001
PARNA das Nascentes do Rio Parnaíba	MA/PI/BA	CERRADO	2003
PARNA das Sempre-Vivas*	MG	CERRADO	2006
PARNA de Brasília	DF	CERRADO	2001
PARNA de PacaásNovos	RO	AMAZON	2001

PARNA do Araguaia*	TO	CERRADO	2001
PARNA do Cabo Orange	AP	AMAZON	2003
PARNA do Jamanxim	PA	AMAZON	2010
PARNA do Viruá	RR	AMAZON	2004
PARNA dos Campos Amazônicos	RO/MT/AM	AMAZON	2011
PARNA Grande Sertão Veredas	BA/MG	CERRADO	2001
PARNA Mapinguari	AM/RO	AMAZON	2011
REBIO da Contagem	DF	CERRADO	2008
REBIO do Guaporé	RO	AMAZON	2004
REBIO do Gurupi	MA	AMAZON	2010
REBIO do Jaru	RO	AMAZON	2001
REBIO do Lago Piratuba	AP	AMAZON	2002
REVIS das Veredas do Oeste Baiano	BA	CERRADO	2012

*units that have prevention action

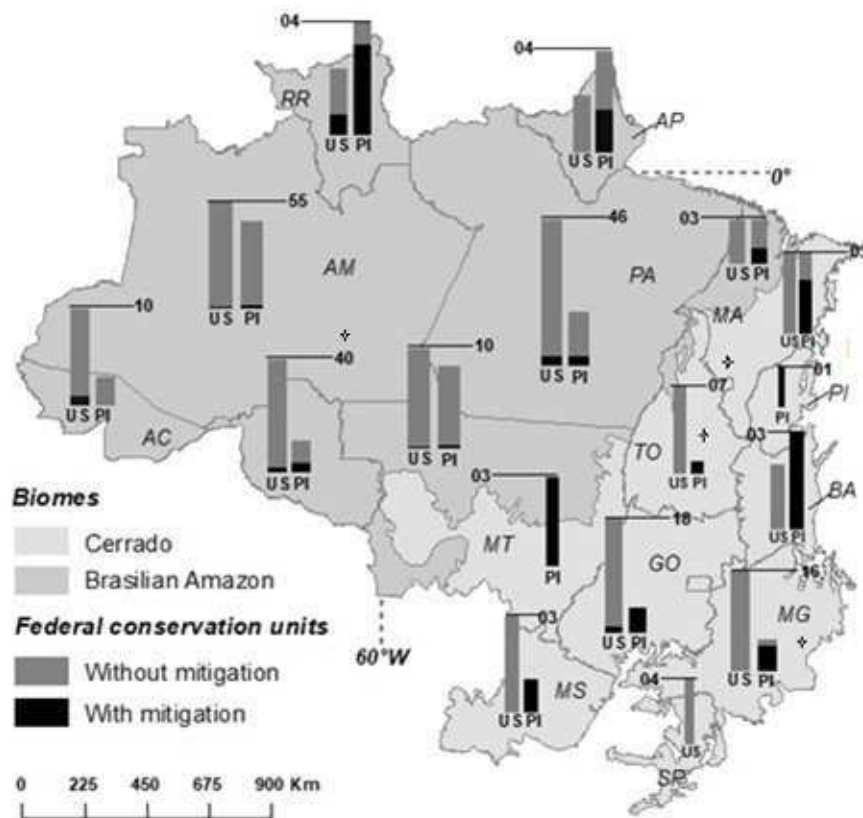


Figure SS1 Federal conservation units by state, category of protection and the presence of mitigation. The points marked in the states of Tocantins (TO), Maranhão (MA), Minas Gerais (MG) and Amazonas (AM) represent the *Ecological Station of Serra Geral de Tocantins* and *National Parks: Chapada das Mesas, Serra do Cipó and Campos Amazônicos*, respectively.

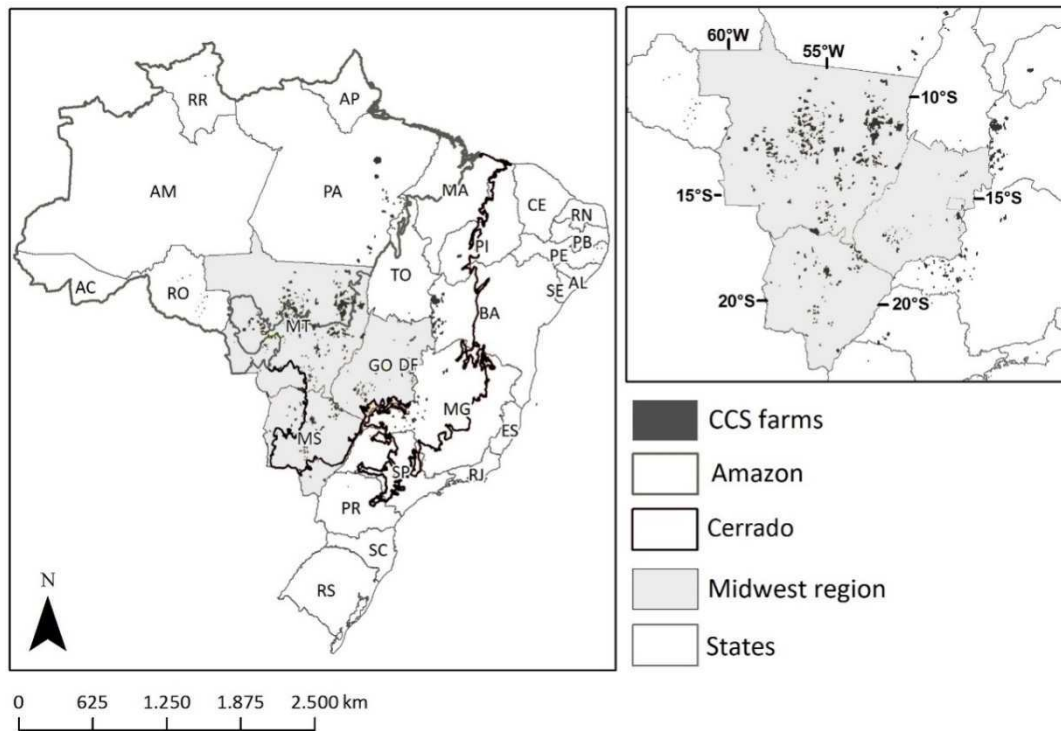


Figure SS2 Properties registered in Earth Alliance

Estimate of net rents from agricultural properties

To estimate the net income of crops, we first compile input data from several secondary sources (Table SS2). Then we apply a spatial distribution function, interpolating through moving averages, values of prices, production samples and costs creating continuous surfaces at municipal level. The production data were then associated with the sales price surface and operating costs to obtain estimates of potential profitability per crop. As the farmer interweaves the production of soybean (summer crop) and maize (winter crop), we consider the total net revenue as the sum of the income of the two crops, since our model results in total economic loss by fire. In order to compare net revenues over a time horizon, we performed an analysis of the net present value (NPV) for a period of 30 at an interest rate of 6%. The same was done for economic losses.

Table SS2 Variables used to estimate the net rents of maize and soybeans

Variable	Source	Period	Link
Yield (kilograms per hectare)	Brazilian Institute of Geography and Statistics IBGE	2012 - 2016	https://sidra.ibge.gov.br/pesquisa/pam/tabelas
Production value (R\$)*	Brazilian Institute of Geography and Statistics IBGE	2012 - 2016	https://sidra.ibge.gov.br/pesquisa/pam/tabelas
Total production (kilograms)	Brazilian Institute of Geography and Statistics IBGE	2012 - 2016	https://sidra.ibge.gov.br/pesquisa/pam/tabelas
Harvested area (hectares)	Brazilian Institute of Geography and Statistics IBGE	2012 - 2016	https://sidra.ibge.gov.br/pesquisa/pam/tabelas
Spatial distribution of states and municipalities	Brazilian Institute of Geography and Statistics IBGE	2011	http://downloads.ibge.gov.br/downloads_geociencias.htm
Production cost ¹ (R\$)*	National Supply Company CONAB Mato Grosso Institute of Agricultural Economics IMEA-MT Brazilian Agricultural Research Corporation EMBRAPA	2012 - 2016	https://www.conab.gov.br/info-agro/custos-de-producao http://www.imea.com.br/imea-site/ https://www.embrapa.br/
Sale prices (R\$/Saco de 60 kg)*	National Supply Company CONAB Agrolink	2012 - 2016	https://www.conab.gov.br/info-agro/precos https://www.agrolink.com.br/

*US\$ 1.0 = R\$ 2.65 (average change between 2012 to 2016); ¹expenditure incurred by the producer in the treatment of the crop, that is, the sum of direct expenses with indirect expenses related to the depreciation of the durable goods used in the activity, the depreciation of the capital invested in the orchard formation, social charges and remuneration to capital current (cost of interest).

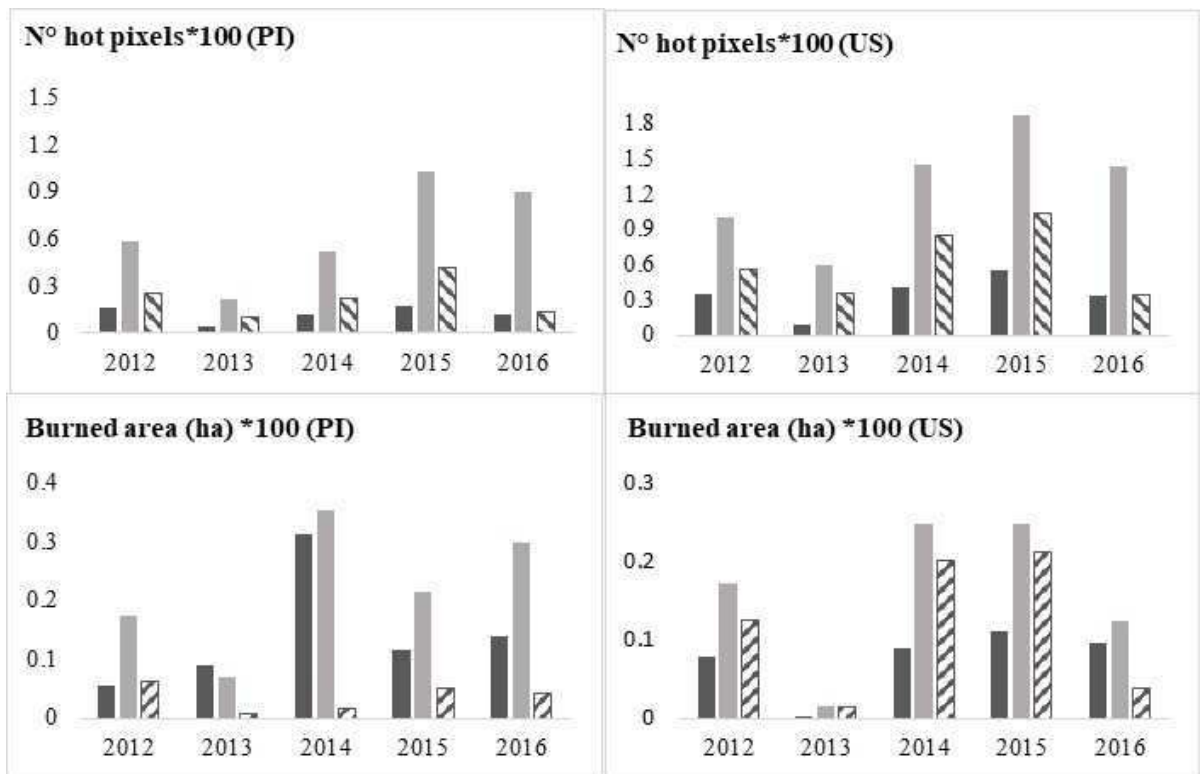


Figure SS3 Number of hot pixels and burnt areas inside the conservation units (dark gray), in the surroundings (light gray) and the relation between fire and deforestation (dashed) in the Amazon.

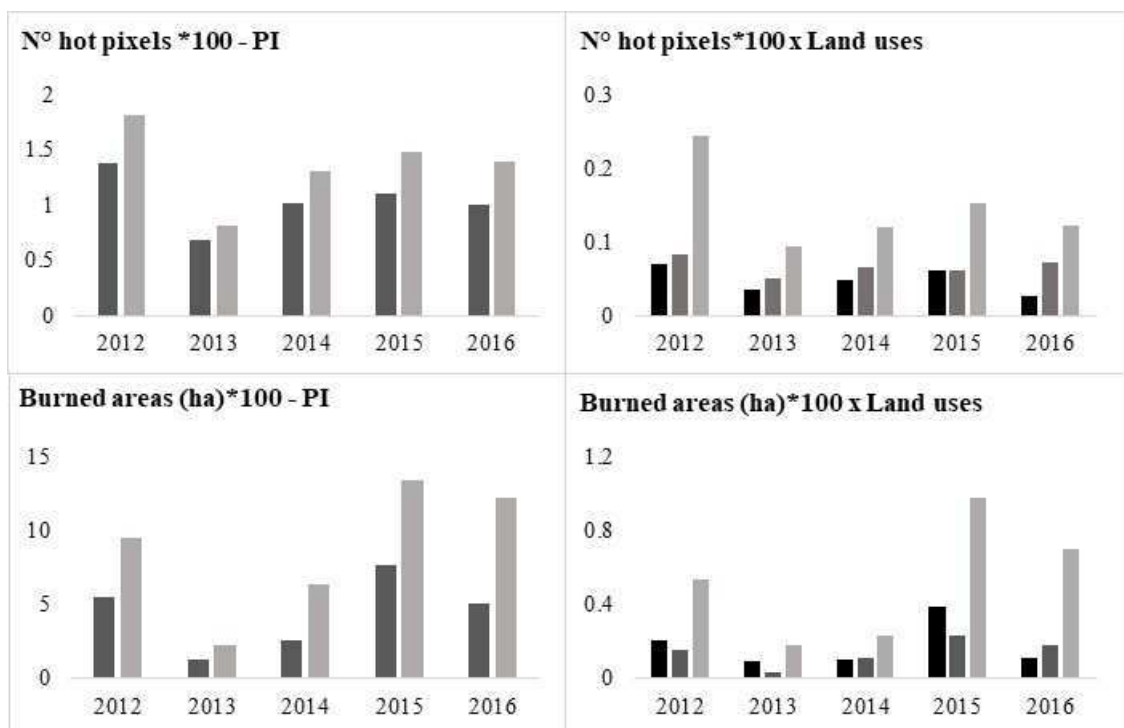


Figure SS4 Number of hot pixels and burnt areas in the conservation unit of integral protection in the Cerrado and the relation between occurrence of fires and uses of the surrounding land. For PI units (left graphs): hot pixels and burnt areas inside the units (dark gray) and hot pixels and burnt areas in buffer zone (light gray). For buffer zone of the PI units (right graphs): hot pixels and burnt areas versus

deforestation (black), hot pixels and burnt areas versus pasture (dark gray) and hot pixels and burnt areas versus agriculture (light gray).

QUESTIONNAIRE

1. Number of the Questionnaire:

2. PROPERTY IDENTIFICATION AND CHARACTERIZATION:

PROPERTY:		LOCATION / COORDINATES:	
TOTAL AREA:		PASTURE AREA:	
BIOMAS:	<i>Cerrado:</i>	<i>Amazônia:</i>	
PREDOMINANT PRODUCTION:			
PHYSICAL BARRIERS OF FORESTRY FIRE PREVENTION:			
FIREFIGHTING EQUIPMENT:			
FIREFIGHTING TRAINING:			
RURAL ENVIRONMENTAL REGISTRATION:			
ENVIRONMENTAL LICENSING (CONTROLLED FIRE):			
SITUATION OF THE LEGAL RESERVE:			
ENVIRONMENTAL HIGHLIGHTS:			
CARBON STOCKS:			

3. HISTORY OF BURNS:

4. BURNT AREAS:

5. INTERVIEW

1. Does the management of your property make use of fire?

No ___

Yes ___

In what situations is the fire used?

USE OF FIRE	Daily	Monthly	Semiannually	Yearly
Cleaning the land				
Grazing Management				
Road Opening				
Other (please specify):				

2. On average, how much of the area of your property is burned annually?

f. of 5 –10%

g. of 10 –15%

- h. of 15 – 20%
- i. of 20 – 30%
- j. > of 30%
- k. Other: _____

3. What is the recurrence of fires observed in recent years on your property? (Burned controlled or not)

- a. every 6 months
- b. annually
- c. every 2 years
- d. every 5 years
- e. every 10 years
- f. other: _____

4. When a fire occurs on your property, what is the approximate economic loss associated with your production?

Type of Production	% of production revenue lost due to fire / year
Crops	
Forest (Wood and Non-timber Products)	
Animals (deaths)	
Infrastructure of the property (fencing, equipment, real estate, etc.)	
Notifications and fines	
Other (please specify)	

5. Are there fire control measures on your property?

No ___

Yes ___

- c. If so, on average what would be the costs associated with these control measures?

Control measures	Construction of Firebreaks	Acquisition of Equipment	Training of personnel

Instruction: Producers should provide the total costs, and the interviewer should also specify the distribution of expenditures (e.g.: km of fireworks, cost per km).

Others: _____

6. In relation to the price of land after a fire event? The value:

VALUE	of 10-20%	of 20-40%	of 40-60%	of 60-80%
INCREASES				
DECREASES				
KEEPS:	()			

7. Are there alternatives that replace the use of fire? Which are?

- a. If so, on average what are the costs associated with these alternatives?

AVERAGE COST	
Alternative 01:	
Alternative 02:	
Alternative 03:	

Instruction: Producers should provide the total costs and the interviewer should also specify the distribution of expenditures (e.g. skilled labor, production technology).

8. What are the future prospects for the use of fire in Brazilian rural properties?
9. As a rural producer and given the losses and costs associated with fire, how much would you be willing to pay per year and per hectare of land to avoid the risk of fire on your property?*Instruction: The interviewer should remember the max / min and the procedure to increase / decrease the values at the time of asking the question.*
10. Suppose there is an environmental program that pays you to not use fire on your property, how much should the program pay you per year and per hectare?
Instruction: The interviewer should remember the max / min and the procedure to increase / decrease the values at the time of asking the question.