Economic Valuation of Changes in the Amazon Forest Area

Economic Losses by Fires to Sustainable Timber Production




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Abstract

There is a gap in knowledge about the impacts of fire on different ecosystem services and goods. Assessing the economic impacts of fire is challenging because fire affects a wide array of potential ES markets and social values. This report describes EcoFire, which is a spatially-explicit model for valuing the economic losses attributable to fire in sustainable timber harvest operations in the Brazilian Amazon. To conduct this analysis, we have integrated a set of models that simulate the synergy between land-use change, fire spread, and logging. In particular, our study assesses the economic impact of fire on sustainable timber production. We find that interactions between fire and timber harvest indicate that fire could impact roughly 2% of the production areas that are projected to be harvested between 2012 and 2041, reducing returns by an average of US$ 39±2 $ha^{-1}year^{-1}$ in burned areas. These losses could reach up to US$ 183±30 $ha^{-1}year^{-1}$ in areas around timber milling centers hit by recurrent fires in southern and eastern Amazon. Our estimates consider the effects of 40 years of potential fire occurrence (2012 to 2041) on the economic losses of timber because the effects of fire can last more than a decade. Estimated economic losses are approximately US$ 689±184 million Net Present Value (NPV), representing a reduction of 4% in the total net revenues from sustainable timber in the region. Yet potential losses could be significantly larger, since only few burnt areas are eventually logged. If all burnt areas would have been logged in the near future, the potential losses could amount to US$ 7.6±2.4 billion. With these results, we show that fire can potentially deliver substantial economic losses to forestry in the Brazilian Amazon.

1. Introduction

"Fire is the great villain of loggers"
(Forest Engineer, Sinop – MT, August, 2015)

The literature on ecosystem services has been consistent in making clear to decision makers that Nature holds important economic values. In this respect, ecosystem disturbances, such as fire events, incur economic losses[1]. Fire, as a destructive force, can rapidly consume large amounts of biomass causing a series of negative impacts, such as greenhouse gas emissions, post-fire soil erosion, biodiversity loss, and air pollution. However, as a constructive force fire is also responsible for maintaining the health and perpetuity of certain fire-dependent ecosystems, such as the Cerrado—the South American savanna. Humid tropical forests are initially resistant to sporadic low intensity fires, but anthropogenic fires continue to be among the main causes of forest degradation [1-3]. In this context, the spatially explicit modeling of fire effects on ecosystem services, such as timber production, is an opportunity to quantify the economic impact of fire.

Assessing the economic impact of fire on sustainable timber harvest in the Brazilian Amazon is challenging because fire affects a wide array of ecosystem services' market and social values (section 2). In the Amazon, sustainable timber can provide returns to land owners (stumpage fee paid by loggers) of US$ 21±1.3 $ha^{-1}year^{-1}$, which makes it a potentially important alternative to agriculture [4-6]. However, two main factors affect the viability of sustainable timber harvest: illegal logging, which often adopts unsustainable practices [7, 8]; and fire, which diminishes the current and future value of timber harvest [1]. In the 1980s and 90s, illegal logging was prevalent in the Amazon due to the weak presence of the state [8]. However, since the middle of 2000's, there has been a substantial improvement in law enforcement. In 2005 alone, the environmental agencies have seized 202 thousand m^3 of roundwood harvested without proper authorization [5]. Even though this represents only a small share of ongoing illegal activities, it indicates increased forest governance in the region.

During 2015 the National Institute for Space Research (INPE) detected 236,000 hot pixels indicating fires, which is the second largest number since records began in 1998 [9]. While clear-cut deforestation rates have decreased steadily since 2004, the forest areas affected by fire have increased and even surpassed clearings in 2007 and 2010 (Figure 1.1). This paradox stems from the change in behavior of deforesters as well as in regional climate. Following the development of the digital version of PRODES (Program for Monitoring Deforestation in the Amazon), named DETER (the near real-time deforestation detection system) by INPE, the government was able to scale up its command and control actions in the Amazon [10]. As a response, landowners have changed their strategy and started to deforest in increasingly fragmented strategies using fire to gradually degrade the forest in hopes that these clearings

[1] 36,190 results found for (ecosystem services) and (economic value) while dis-services literature is marginal. (Science Direct, accessed 18 January 2016).

remain undetected by INPE's monitoring systems and law enforcers [11]. In addition to this new deforestation pattern, the spike in burned areas in 2005, 2007, and 2010 was due to large droughts in the region [12]. Despite the growing incidence of forest fires, studies that seek to inform policy-makers on the importance of fire mitigation policies remain scarce. Here we address this gap by providing an estimate of the economic impact of fire on timber production in the Brazilian Amazon as part of a comprehensive valuation platform developed by the research project "Economic Valuation of Changes in the Amazon Forest Area".

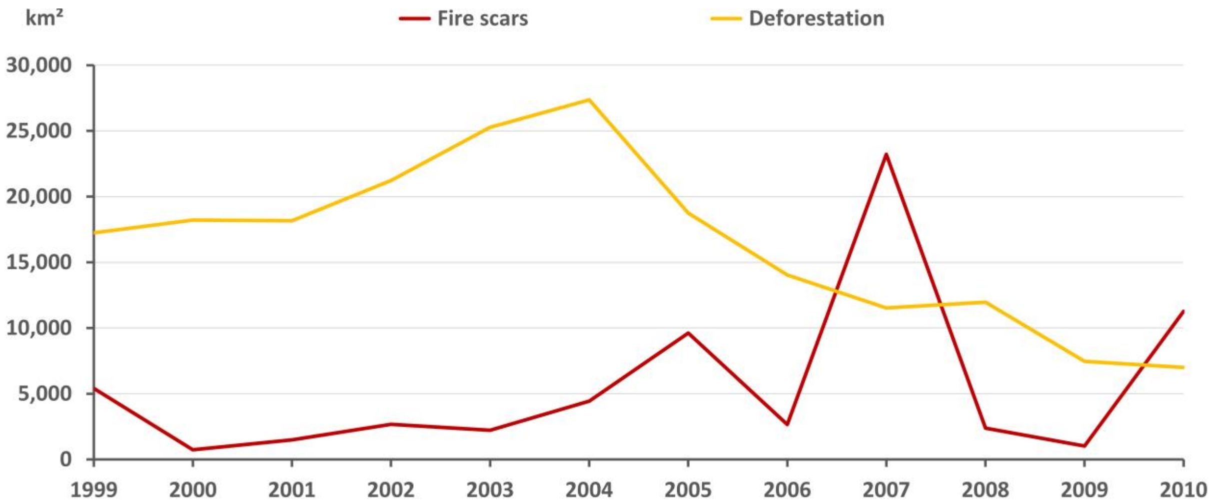

Figure 1.1 - Deforestation and forest affected by fire.

As part of the Amazon valuation platform, EcoFire is a spatially-explicit model that estimates potential losses by fire to sustainable timber profitability. Given the overall focus of the research project on the economic values of the Amazon rainforest, this study considers only timber production from native forests. This choice arises from the fact that most timber produced in the Amazon region comes from native forests [13]. It is important to note that sustainable logging of native forests provides an important economic incentive for harnessing development to conservation in the Amazon [6].

The next section provides a literature review on the ecological and socioeconomic aspects of fire in the Amazon, with specific attention paid to the few studies that provide estimates or formalize the economic impact of fire. The third section presents EcoFire's general framework and its integration with SimMadeira+ (the logging model), FISC-Amazon (the fire spread model), and OTIMIZAGRO (the land-use change model). That section also provides a detailed explanation on the parameters used to model losses to timber rents by fire. In the final section, we present and discuss the results of our study.

2. The impact of forest fires in the Amazon

For some time, studies have looked into the economic impact of forest fires in temperate regions [14-16]. Yet the study of forest fires in the tropics only emerged in the early 1980s following the growing concern about the consequences of the large-scale occupation of the Amazon [17]. Since then, a growing body of literature has illustrated the complex interaction between fire, climate, forest, and socioeconomic systems.

In order to unveil the impacts of forest fires it is important to map fire activity, but also to represent how fire interacts with climate, deforestation, and land use rents. More recently, various studies have pointed out complex local, regional, and global feedbacks influencing fire dynamics in the Amazon [18, 19] (Figure 2.1). In this respect, continued forest degradation and fragmentation by logging and deforestation can drastically alter the susceptibility of forests to fires [19, 20]. Several socioeconomic factors explain the prevalence of anthropogenic fires in the Amazon. Fire is used as a tool for reforming pasture, understory clearing, as part of the deforestation process, and slash-and-burn agriculture [18, 21, 22]. Logging also increases the risk of fires by opening the canopy, thereby reducing humidity, and increasing the availability of fuel loads on the forest floor [23, 24]. On the other hand, it has been shown that the presence of protected areas, local fire brigades, and prevention measures such as firebreaks, have been effective in reducing fire in the Amazon [20, 25, 26].

Regional climatic events have also played a substantial role in influencing the frequency and intensity of forest fires in the Amazon. The El Niño events of 1997, 1998, 2007, and 2010 caused a sharp increase in forest dryness. As a result, more than 20 thousand km^2 of forests burned [12, 23, 27]. Another burning spike has occurred in 2015/2016 due to the recurrence of El Niño [28]. In addition, climate change may exacerbate fire in the Amazon. Increase in the global temperature is likely to change rainfall patterns in the Amazon, causing more severe and frequent droughts, thereby increasing the susceptibility of forests to fire [19, 20, 29]. The occurrence of fires, in turn, releases greenhouse gases into the atmosphere contributing to global warming.

Many modeling efforts provide estimates of greenhouse gas emissions due to fires in the Amazon [19, 20, 22, 23]. Van der Werf et al. [30] estimate that in the Amazon rainforest fires alone were responsible for an average annual emission of 0.16 $GtCO_2e$ (Giga tons of Carbon Dioxide equivalent), which is approximately 37% of fire related global emissions between 1997 and 2009. Other studies point out that emissions from fires could increase substantially in the following decades, reaching 0.5±0.1 $GtCO_2e$ by 2050 [29]. In sum, the vicious cycle of forest fragmentation, illegal logging, global warming, and the expansion of cattle ranching degrades the forest and increases the chance of fire (Figure 2.1).

The impact of fire on tropical forests, however, varies considerably depending on its frequency, intensity, and the vegetation type [1, 23, 31]. Low intensity fire in the forest understory has little effect on larger trees (*i.e.* trees > 50 cm at breast high), but causes high mortality rates (around 95%) of smaller trunks. But, even the damage by low intensity fires continues to cause tree mortality in the following years. In contrast, high intensity fires even impact large trees, especially if recurrent [32]. Fire recurrence leads to long-term ecological changes, particularly in the transition ecosystem areas between the Amazon and the Cerrado biomes, and may transform forested areas into savannas by favoring invasion of grass and other fire-resistant species [33-36]. In turn, forest losses due to fire can also affect the regional climate by prolonging the dry season [37].

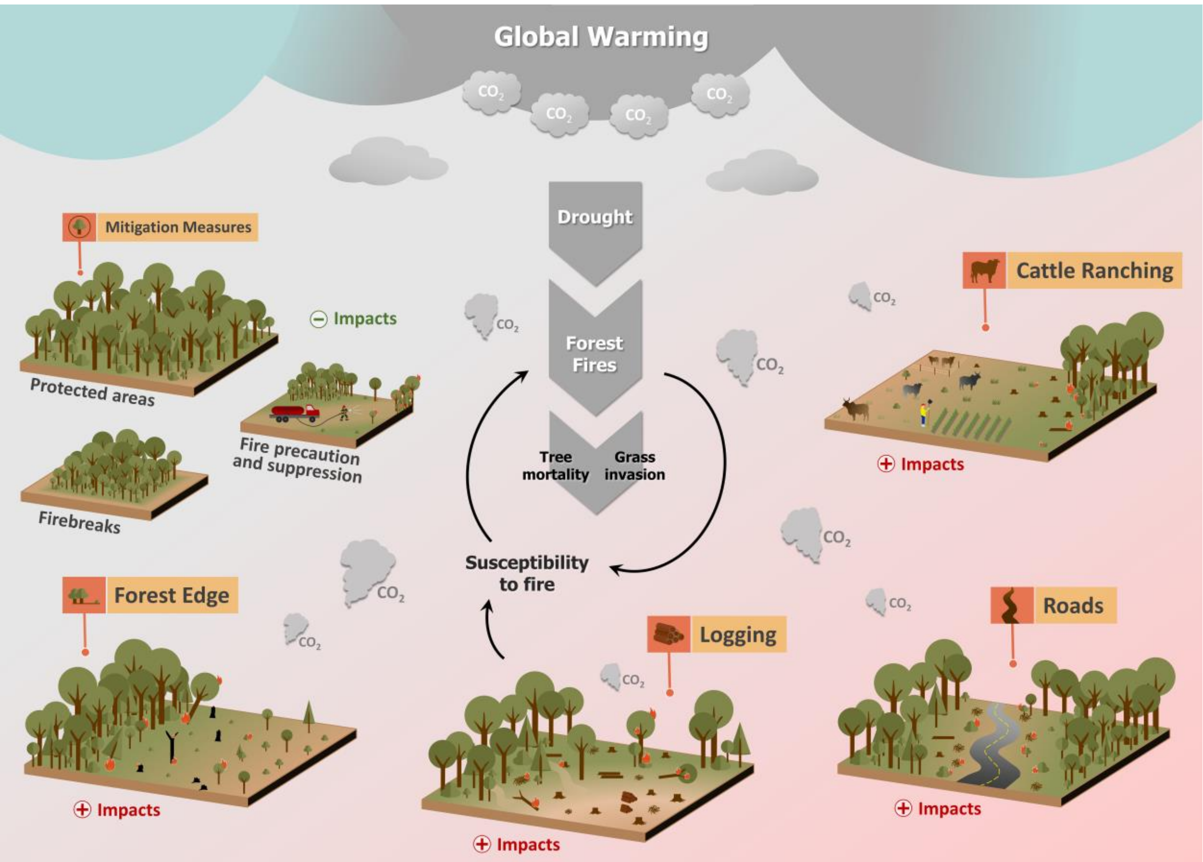

Figure 2.1 - Positive and negative feedbacks to forest fires in the Amazon.

Whereas the ecological consequences of forest fires are relatively well understood, only a few studies have tried to measure the economic impacts. Gerwing [38] shows that while fire in pristine areas damages only 3% of the commercial trees, losses may reach 46% in previously logged and heavily burned areas. Menton [39] provides evidence that an increase in forest fires due to illegal logging reduces household income from fruit harvest by 86%, in addition to a substantial decrease in game animals. Nepstad et al. [18] provide an estimate of the costs incurred on cattle ranching due to accidental fire in the Amazon rainforest. Based on interviews with ranchers, the authors found that even though medium scale ranchers (between 101 and 1,000 ha) invested approximately US$ 190 per year in firebreaks, they suffered economic losses from fire of between US$ 290 and 740 per property over a two year period.

Some studies have also attempted to estimate the economic losses due to fire and the related benefits from fire mitigation for the entire Brazilian Amazon. Mendonça et al. [21] integrated losses in agriculture, costs of respiratory illnesses, forest resource losses, and CO_2 emissions caused by fires between 1996 and 1999. They calculated a total average yearly loss of between US$ 90 million and US$ 5 billion for the entire region. The high level of uncertainty is explained by variation in carbon pricing (US$ 3.5 to 20 tCO_2e). The main economic loss is CO_2 emissions (98%) followed by agricultural losses (1%), with timber losses and respiratory illnesses accounting for the remaining 1%. It should be noted that the economic loss from the CO_2 emissions takes place at a global level due to climate change. Yet in a context in which individual nations have made the obligation to reduce emissions as part of the Paris Agreement, and could receive funds from emission reductions through mechanisms such as REDD+, an increase in emissions from fire could be translated in direct economic losses. The study also showed that in 1998, under the influence of El Niño, the economic losses from fire were about 13 times larger than the ones of normal years. Losses in timber production due to fire were estimated to be approximately US$ 5 per ha. By multiplying this value by the area affected by fire Mendonça et al. estimated that the economic losses for the entire Brazilian Amazon totaled US$ 1 and 13 million in 1995 and 1998, respectively [21, 40]. The authors point out that these estimates are conservative, since they underestimate the economic losses in primary forests that could be logged in the future. In any case, the study suggests that the economic impact of fire for the whole Amazon is likely to be small.

Two other studies have also estimated the value services provided by forests in reducing the probability (and thus the potential cost) of fire. Andersen et al. [41] estimated the average total economic value of one hectare of standing Amazon rainforest, distinguishing between the local private (*e.g.* timber supply), local public (*e.g*. tourism), and global benefits (*e.g*. carbon storage) from the forest. The authors estimated that fire protection provides a public benefit between US$ 67 and US$ 550 per hectare at discount rates of 12 and 2%, respectively. Andersen et al. considered the losses by fire in agricultural areas, and also the decrease in timber values in native forests. Due to the lack of more accurate data on the impact of fire on logging, the authors assumed that sustainable timber supply is worth US$ 28 ha/year and that fire entails a loss of 100% in this forest value for a period of 50 years.

Andersen et al.'s initial insight was further developed by Strand [42]. In a theoretical conceptualization of the interaction between deforestation, forest fires, forest dryness, and forest fragmentation, Strand formalizes the marginal value of rainforest losses due to fire. This work provides a basis for the establishment of forest fire mitigation as a separate value component in the calculation of the total economic value of the rainforest. The author defines the value of a plot of rainforest before and after a fire event. The model takes into account the feedback mechanisms related to forest fires by defining λ (the probability of fire in a given plot), as a function of both L (the amount of forest loss in a single plot as additional fragmentation increases fire risk) and D (the degree of forest dryness at the level of the biome). The value provided by the remaining forest is also a function of forest dryness (and thus of the amount of forest already cleared), given that the Amazon forest provides services and goods both within (*e.g.* timber and non-timber products) and outside its boundaries (*e.g.* rainfall for agriculture and hydropower). Dryness, in turn, is a function of *L*, because forest losses change hydrological regimes at a regional level. Forest fires and dryness appear recursively and act as "multipliers" in the calculation of the reduction of the economic value of the services and goods provided by the forest.

In the last three decades, a substantial body of literature on fire dynamics in the Brazilian Amazon has emerged. Yet, significant knowledge gaps remain, especially on the economics of fire. The empirical studies from Andersen et al. [41] and Mendonça et al. [21] provide important insights into economic losses by fire. However, there are also important limitations in these studies. First, these studies consider the effect of fire on timber production in a binary manner, whereby burned areas lose 100% their economic value. Yet, studies conducted in temperate forests, such as Marschall et al. [16], indicate that fires with different intensities reduce the selling value of round wood by a range of 1 to 100%, with economic losses under 20% in most instances. Second and more importantly, the current literature on tropical forests does not consider the spatial variability of the economic impact. As Andersen et al. [41] mention, their study "treats the Amazon forest as homogenous and calculates an average marginal value [as it was…] obviously infeasible here to attach a different value to each of the several hundred million hectares of Amazon forest" (Andersen et al. [41], pg. 170). While averages and overall estimates provide valuable information, they are insufficient to guide policies aimed at reducing the economic impact of fires. To account for this difficulty, Strand [42] calls for the development of empirical studies able to provide "geographically differentiated forest values across the biome".

In the next section, we advance the economics of forest fires in the Amazon presenting the design and results of EcoFire, a spatially explicit model for valuing fire losses to sustainable timber production.

3. EcoFire general approach

The EcoFire (Economic Cost of Fire) model is designed to estimate the fire-related economic losses to sustainable logging of native forests in the Amazon. Here sustainability is defined as the practice of Reduced Impact Logging, which is akin to the holistic concept of forest management and includes a significant component of planning to maximize efficiency while minimizing impacts. RIL represents the norms and practices adopted by the Brazilian government for timber concessions through rules of maximum harvest intensity, whereby timber production may not exceed 0.86 $m^3ha^{-1}year^{-1}$, adoption of forest management units, defined annual cutting areas, and protection against re-entry during the harvest cycle.

To develop the model we interviewed farmers, forests engineers, forest rangers, loggers, and sawmill owners in Sinop region in Mato Grosso (Supplementary Materials 5.2 and 5.3). This municipality was selected for fieldwork because Sinop is one of the main logging areas in the Amazon. Indeed, Sinop represents one of the biggest timber production centers, with an output of 155 thousand m^3 of timber in 2014, which generates an annual product value of some US$ 10 million [13]. Sinop also has a high incidence of fire events (Supplementary Material 5.2).

In order to develop EcoFire, we analyzed the role of fire in the sustainable timber production function. We examined the possibility of using biomass loss as a proxy for commercial volume loss. While this approach had the advantage of using a known parameter, it became clear during our fieldwork that the impact of fire on timber prices is not linearly related to biomass loss. Biomass losses occur mainly in smaller trees that do not have commercial value, and as such are not logged. According to forest engineers and timber producers, fire-related losses occur mainly when burnt portions of the logs have to be removed from the wood planks. Furthermore, most interviewees pointed out that high and low intensity fires influence the selling price of soft and hardwood timber in different ways. In much the same manner as in temperate forests [16], the economic loss is correlated with the intensity of the fire. However, conversely to temperate forests that contain only few timber species, our interviewees pointed out that the impact depends on the timber species distribution. In this respect, loggers and forest engineers use a non-technical typology to classify timber genus as either hardwood (roughly implying high density, high commercial value, and high resistance to fire) or softwood (roughly implying low density, low commercial value, and low resistance to fire). EcoFire responds to this reality by calculating the losses in the commercial value by different timber types (hard vs soft) and the effect of theses losses on net revenues in RIL in a spatially differentiated manner (Figure 3.1).

To estimate fire-related economic losses, spatially disaggregated input data used in Ecofire Include: expected net timber returns disaggregated by timber type; the annual occurrence of forest fires classified by intensity; and fire recurrence. The Equivalent Annual Annuity (EAA) for sustainable timber in the absence of fire comes from SimMadeira+, which is described in the report "Economic Valuation of Changes in the Amazon Forest Area: Value map for Timber". SimMadeira+ estimates the composition of commercial timber volume according to different wood types (soft and hardwood). EcoFire uses simulated burnt areas from FISC-Amazon, the region wide version of the FISC model (Fire Ignition, Spread, and Carbon Component) [20], which is in turn influenced by deforestation and hence forest fragmentation simulated using OTIMIZAGRO [43], a land-use change model. Here we estimate the economic impact of forest fires that occurred between 2002 and 2041 on a simulated 30-year timber harvest cycle. Our estimates consider that the losses of fire may last more than a decade (≈15 years). Ecofire model evaluates the economic impact of fire and deforestation in two ways: first, when an area is deforested CARLUC (see section 3.2) increases the probability of fire in neighbouring forests by modelling the decrease in humidity and the increase in the probability of anthropogenic sources of fire; secondly, the burning of a given area modifies the probability of future fires by changing the humidity and fuel parameters, whereby the former increases the probability of fire ignition and the later changes the probability of its spread and intensity. By calculating the difference between scenarios of net timber revenue *without fire* and *with fire* per ha throughout the Amazon we estimate the economic impact at regional and local, geographically disaggregated, scales. The following subsections provide an outline of SimMadeira+, FISC-Amazon, and OTIMIZAGRO that together with EcoFire form our valuation platform.

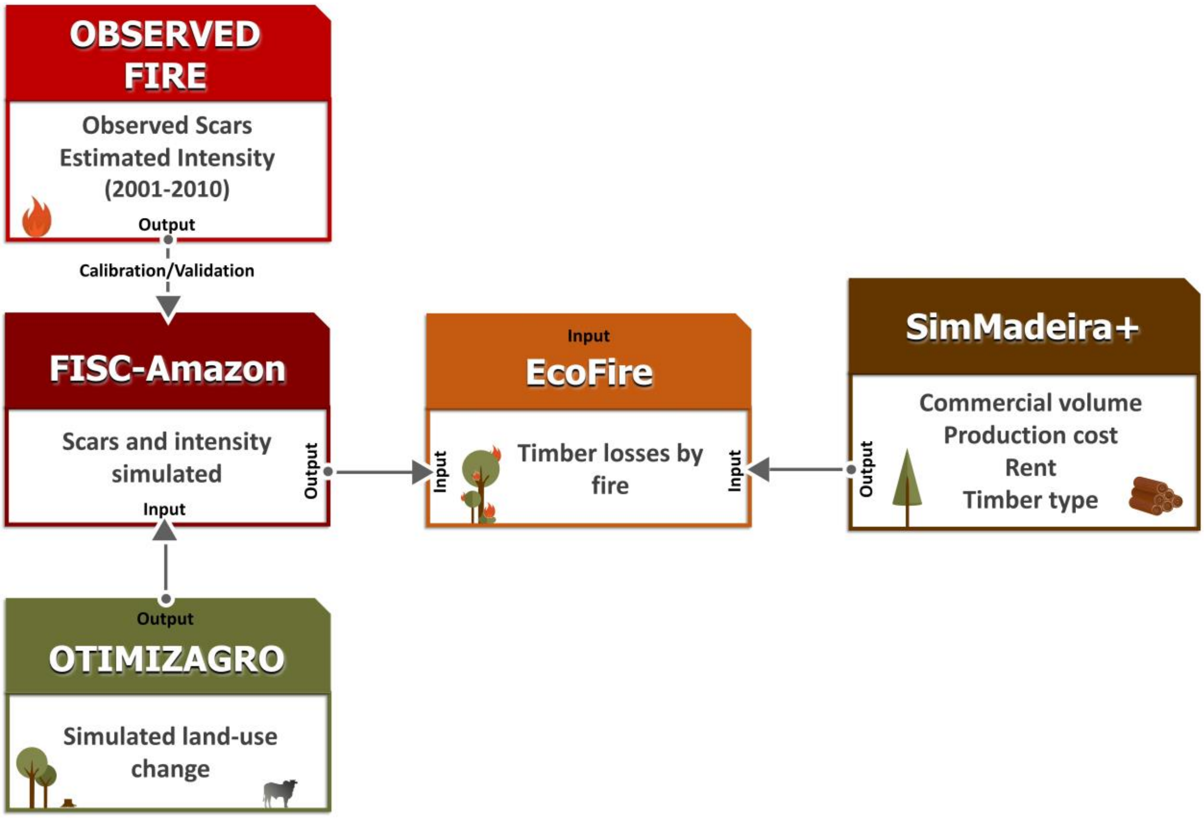

Figure 3.1 - EcoFire and its relation to OTIMIZAGRO, FISC-Amazon, and SimMadeira+.

3.1. OTIMIZAGRO

OTIMIZAGRO is a nationwide, spatially-explicit model that simulates land use, land-use change, forestry, deforestation, regrowth, and associated carbon emissions under various scenarios of agricultural land demand and deforestation policies for Brazil (Figure 3.2) [43]. OTIMIZAGRO simulates the production of nine annual crops (soy, sugarcane, corn, cotton, wheat, beans, rice, manioc, and tobacco), including single and double cropping, five perennial crops (Arabica coffee, Robusta coffee, oranges, bananas, and cocoa), and plantation forests. The model framework, developed using the Dinamica EGO platform [44], is structured in four spatial levels: (i) Brazil's biomes, (ii) IBGE micro-regions, (iii) Brazilian municipalities, and (iv) a raster grid of 25 ha spatial resolution. Concurrent allocation of crops at raster cell resolution is a function of crop aptitude and profitability, calculated using regional selling prices, as well as production and transportation costs [45, 46]. When the available land in a given micro-region (or other specified spatial unit) is insufficient to meet the specified land allocation, OTIMIZAGRO reallocates the distribution of remaining land demands to neighboring regions, creating a spillover effect. Future demand for crops and deforestation, and regrowth rates are exogenous to the model.

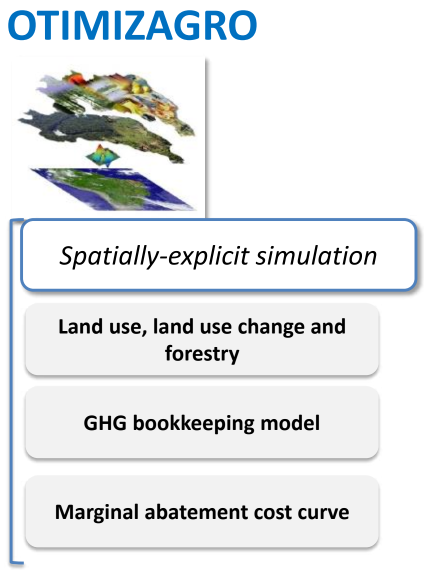

Figure 3.2 - OTIMIZAGRO framework.

The future land use map of agricultural expansion is based on projections for 2024 [47] extrapolated to 2041 by using historical trends between 1994 and 2013 [48]. Projected annual deforestation rates consist of 2009-2014 averages for the Amazon, Cerrado and Atlantic Forest, and 2008-2013 averages for the other biomes [49, 50, 51, 52]. The probability of deforestation is a function of spatial determinants, such as distances to roads and previously deforested areas [53]. OTIMIZAGRO is then used to spatially allocate future deforestation. The deforestation simulation component of OTIMIZAGRO is an adaptation of SimAmazonia [53] and OTIMZAGRO is the countrywide version of SimAmazonia [43].

3.2. FISC-Amazon

To our knowledge, FISC (Fire Ignition, Spread and Carbon components) is the only process-based understory fire model developed for tropical forests [55]. FISC is a spatially-explicit model that simulates fire ignition and propagation processes [20, 29]. Fire ignition is a function of land use, depicted by spatial determinants—such as distances to deforested land, roads and towns, elevation and land-use restrictions—and climatic seasonality represented by monthly VPD data (Vapor Pressure Deficit). Annual land-use and monthly climate probabilities maps are combined to produce a space-time model for fire ignition sources, which is calibrated and validated using hot pixel data. The fire spread component employs a cellular automata model to simulate fire propagation as a function of distance to ignition sources, terrain features, such as upslope direction, obstacles, different land uses, fuel loads and wind direction, plus climatic conditions inside the forest and biomass fuel loads produced by the CARLUC model [54]. CARLUC, nested in FISC, simulates fuel loads dynamics, forest regrowth, and carbon emissions.

We have expanded the FISC model to the Brazilian Amazon (FISC-Amazon). To calibrate and validate FISC-Amazon, we used 2001-2010 time-series maps of forest fire scars, which provide information on the spatial patterns of fires [12] (Figures 3.3, 3.4 and 3.5). Morton et al. [12] provide satellite-based measurements with a high spatial resolution and wide temporal span of the area affected by fire in the Amazon. The authors mapped understory forest fires in Amazonia using the Burn Damage and Recovery (BDR) algorithm, a time-series approach that distinguishes selective logging from fire-related canopy damages. The algorithm analyzes land-use images (normalized difference vegetation index) with spatial resolution of 250 meters provided by the Moderate-resolution Imaging Spectral Radiometer (MODIS) sensor. The algorithm generates a time series dataset with the location and extent of forest fires in the Amazon. We replicated the historical climate time series from the period 2012 to 2040 for a 30 year cycle taking into account the 10 years of fire records by Morton et al [12], which capture the current climate variability over the Amazon well and include two el Nino events, which is the main non-anthropogenic factor influencing the probability of fire.

We also incorporated new equations into the coupled CARLUC model to simulate fire intensity and tree mortality due to drought (see next section). Because deforestation increases the probability of fire ignition and spread, FISC-Amazon, which runs at 25 ha cell resolution, is coupled to OTIMIZAGRO to assess the effect of forest fragmentation on fire regimes (Figure 3.6).

FISC-Amazon allows us to investigate the changes in fire regime such as fire size (Figure S1), frequency, and interval, simulating post-fire damage—*e.g.,* burned area, type of vegetation affected, and cycles of recurrent fire (Figure 3.7). In addition, the coupling of FISC-Amazon to SimMadeira+ and EcoFire provides estimates on the economic impact of fire occurrence and recurrence over the life cycle of sustainable timber in the Amazon.

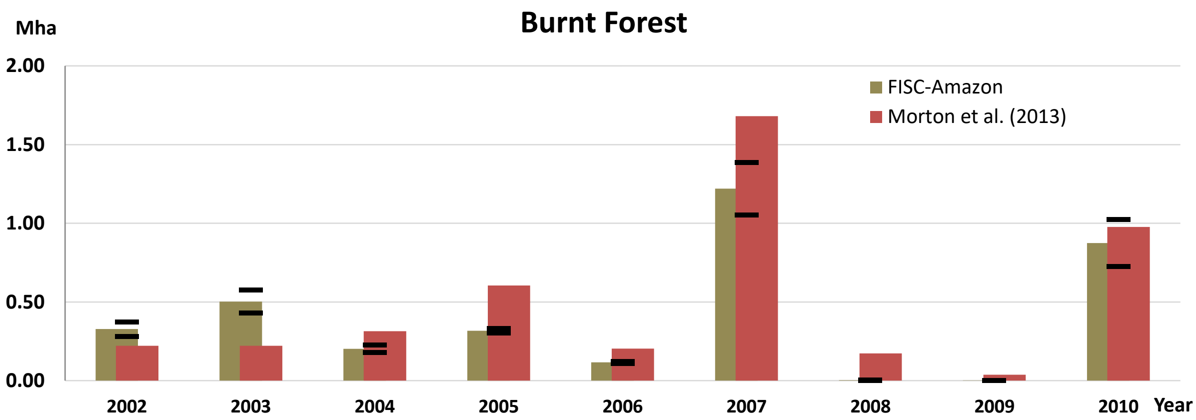

Figure 3.3 - Validation of simulated forest fire scars against observed ones. FISC-Amazon was calibrated using observed forest fire scars from 2002 and 2005 and validated by using data from the other years (horizontal bars define confidence interval).

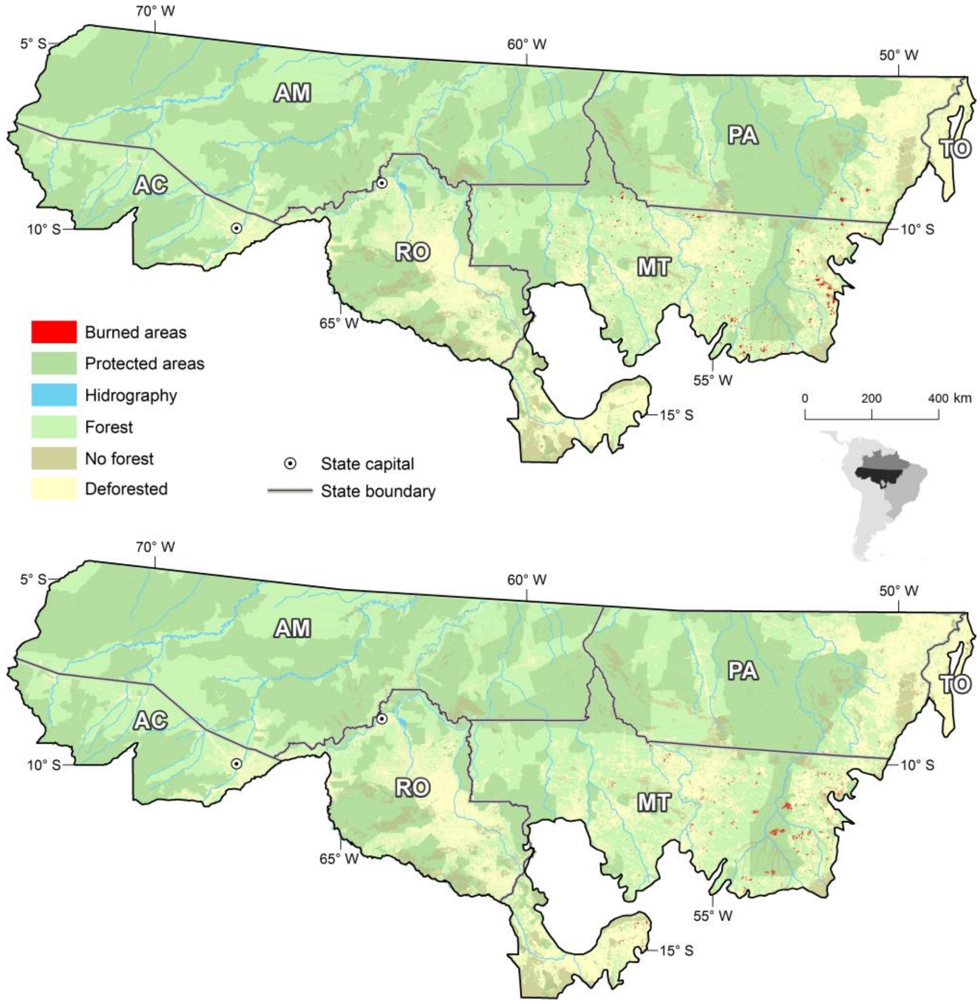

Figure 3.4 - Spatial pattern of simulated forest fire scars (lower) compared with observed one for 2002 (upper) in southern Amazon.

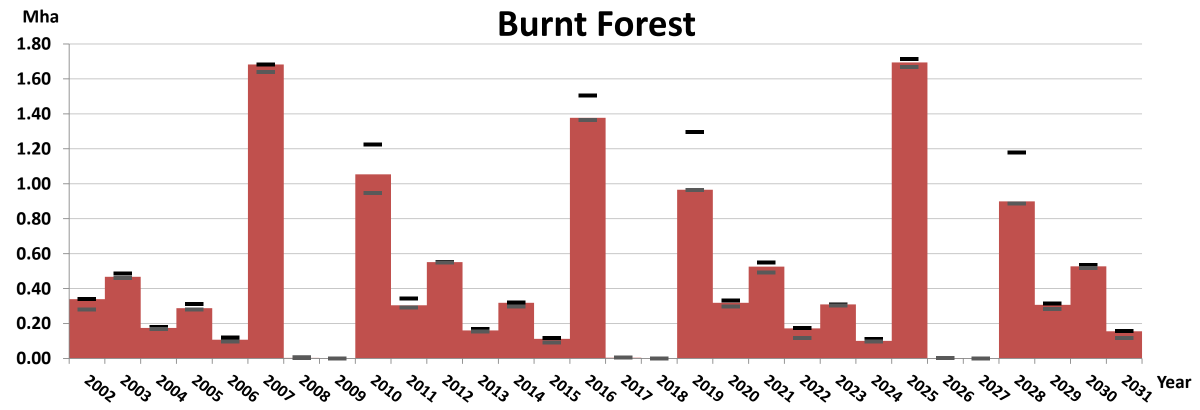

Figure 3.5 - Simulated forest fire scars from 2002 to 2031. Historical climate time-series from 2002 to 2010 was replicated throughout the period.

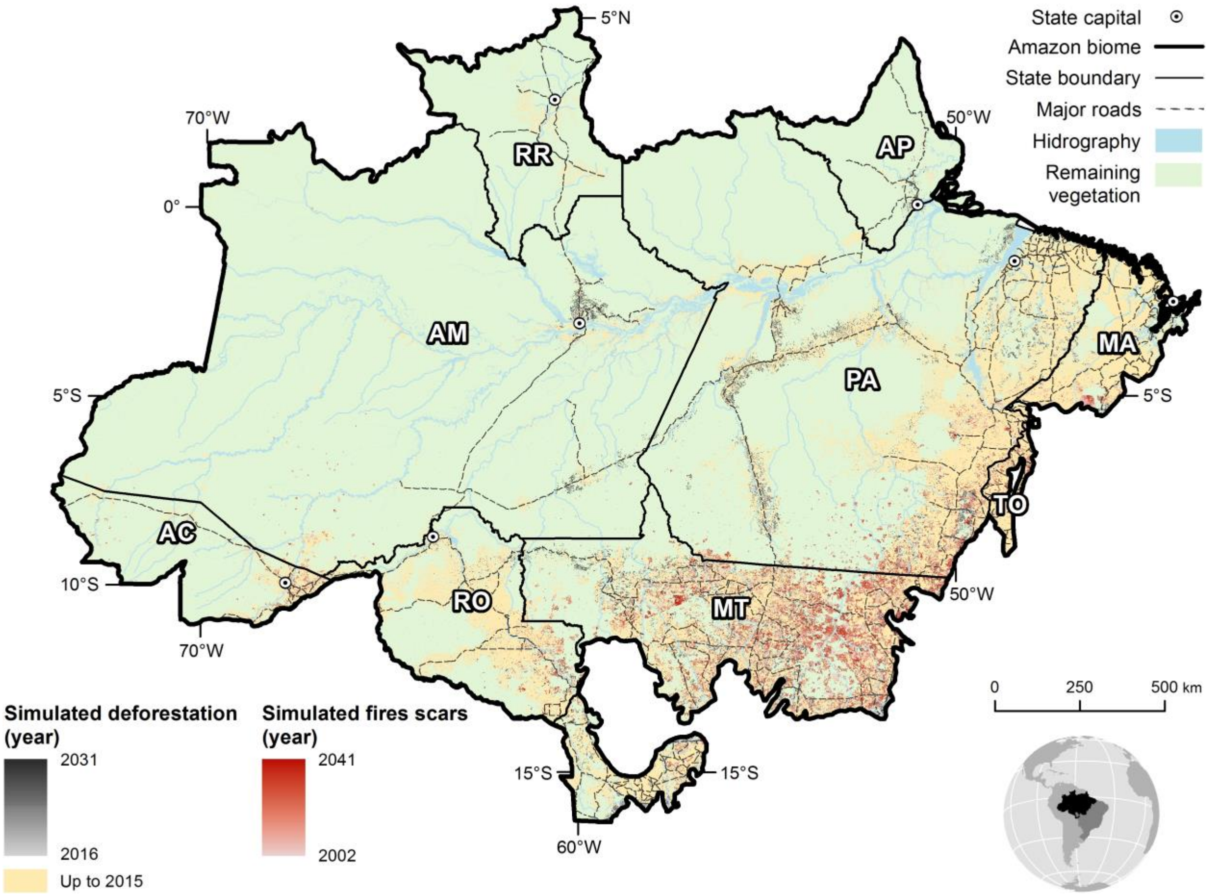

Figure 3.6 - Simulated forest fires and deforestation for the Brazilian Amazon.

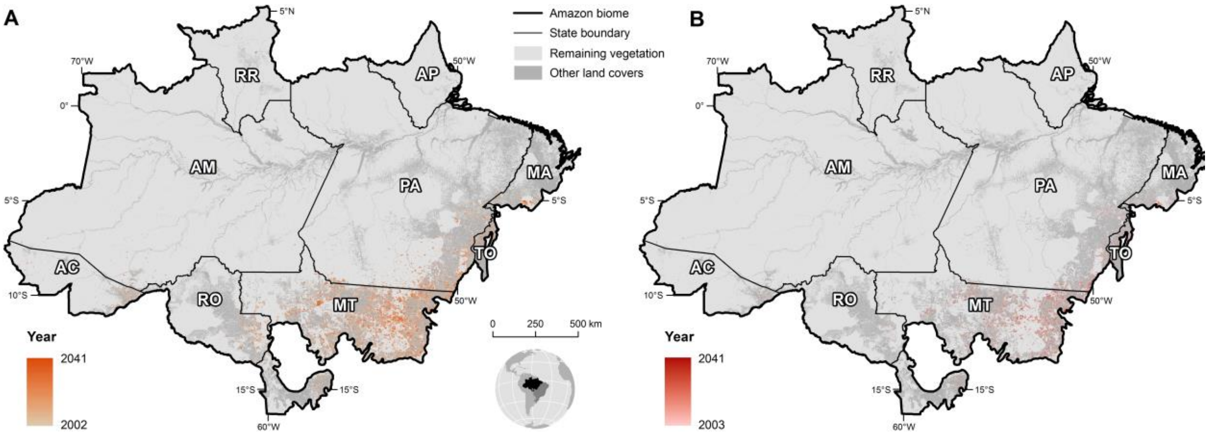

Figure 3.7 - Fire occurrence (A) and recurrence (B) output from FISC-Amazon.

3.3. SimMadeira+

SimMadeira+ calculates sustainable logging rents based on production costs and timber market prices (Figure 3.8). Because fire affects types of timber in a different manner, we redesigned timber distribution and pricing components of the previous version "SimMadeira" [6, 7]. SimMadeira+ now provides robust geographically differentiated estimates of sustainable timber rents for 40 timber types (classified as hard and soft woods) based on the ecological distribution of tree genera/species (Supplementary Material 5.4) (See report "Economic Valuation of Changes in the Amazon Forest Area: Value maps for Timber [56])". As a result, the gross revenues from harvesting individual timber genus are aggregated by soft and hardwood to allow EcoFire to calculate timber losses accordingly.

Since the definition of hard and softwood is related to local practices, a questionnaire with a list of the 40 most common commercial timber prepared by IMAZON [57] was developed (Supplementary Material 5.4). The list contains both genera, such as *Aspidosperma sp* with many tree species that go under the common name of "Peroba", or tree species such as *Mezilurus itauba* (Itaúba) that corresponds to one genus. A questionnaire was completed by four experienced forest engineers, who were asked to classify each commercial timber genus as either soft or hardwood based on its fire resistance characteristics (Supplementary Material 5.3).

The extent to which timber production leads to biodiversity loss has been a controversial topic, especially during the 1990s and early 2000s [58-61]. More recently, however, empirical studies conducted in areas under sustainable timber production in the Amazon have found that its impact on biodiversity to be minimal [62, 63]. In any case, it should be noticed that most areas in the Amazon are logged illegally and unsustainably, leading to forest degradation, increased fire risk, and subsequent clear-cut deforestation [64]. Nevertheless, in our study we only consider changes in the economic value of sustainable timber production (Figure 3.9).

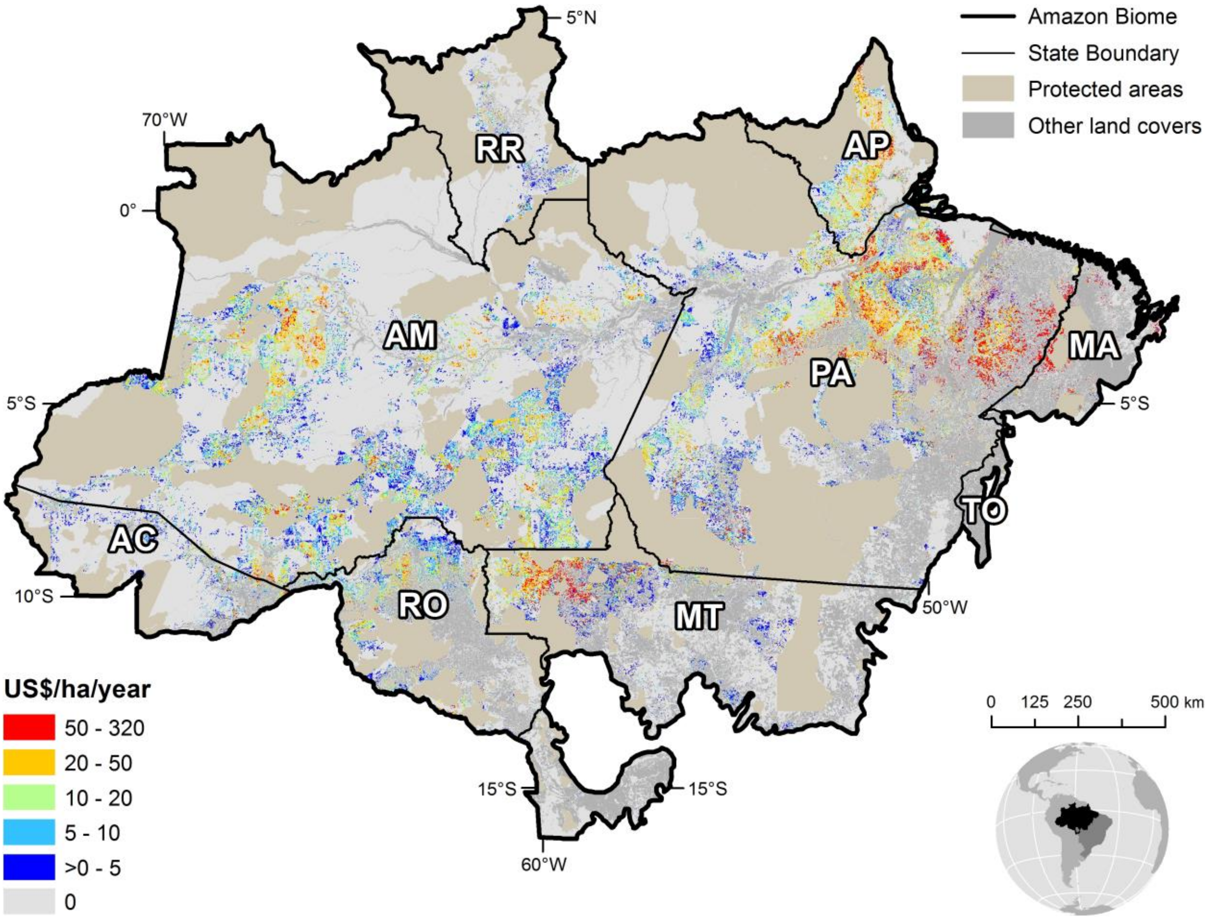

Figure 3.8 - Potential equivalent annual annuity (EAA) of sustainable logging rents.

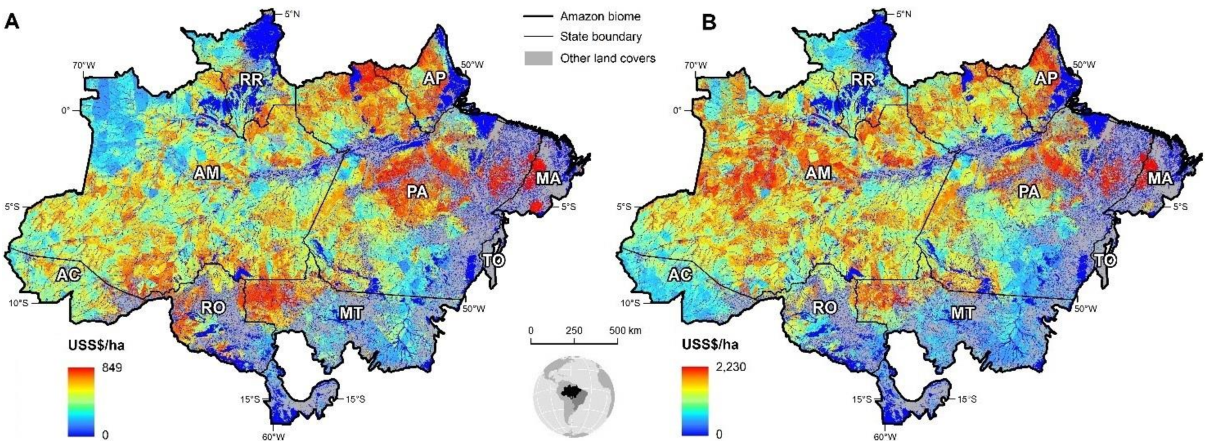

Figure 3.9 - Commercial values for hard (A) and softwoods (B).

3.4. Fire intensity

Fire intensity (FI), defined as the energy released per unit of fire line length ($kW \cdot m^{-1}$), determines the vegetation responses to fire events. Given that fire intensity and severity are highly correlated in tropical forests, a high value of FI indicates a high potential for fire-induced tree mortality and loss of live carbon stocks. FISC-Amazon models fire intensity using CARLUC, and CARLUC models fire intensity dynamically based on the amount of available fuel in the spread rate of fires. The definition of high and low fire intensity is taken from Brando et al. [65]. But, to model forest flammability, fire behavior, and fire impact for this simulation, we incorporated several new functions into CARLUC (Figure 3.10, Table 3.1), as follows:

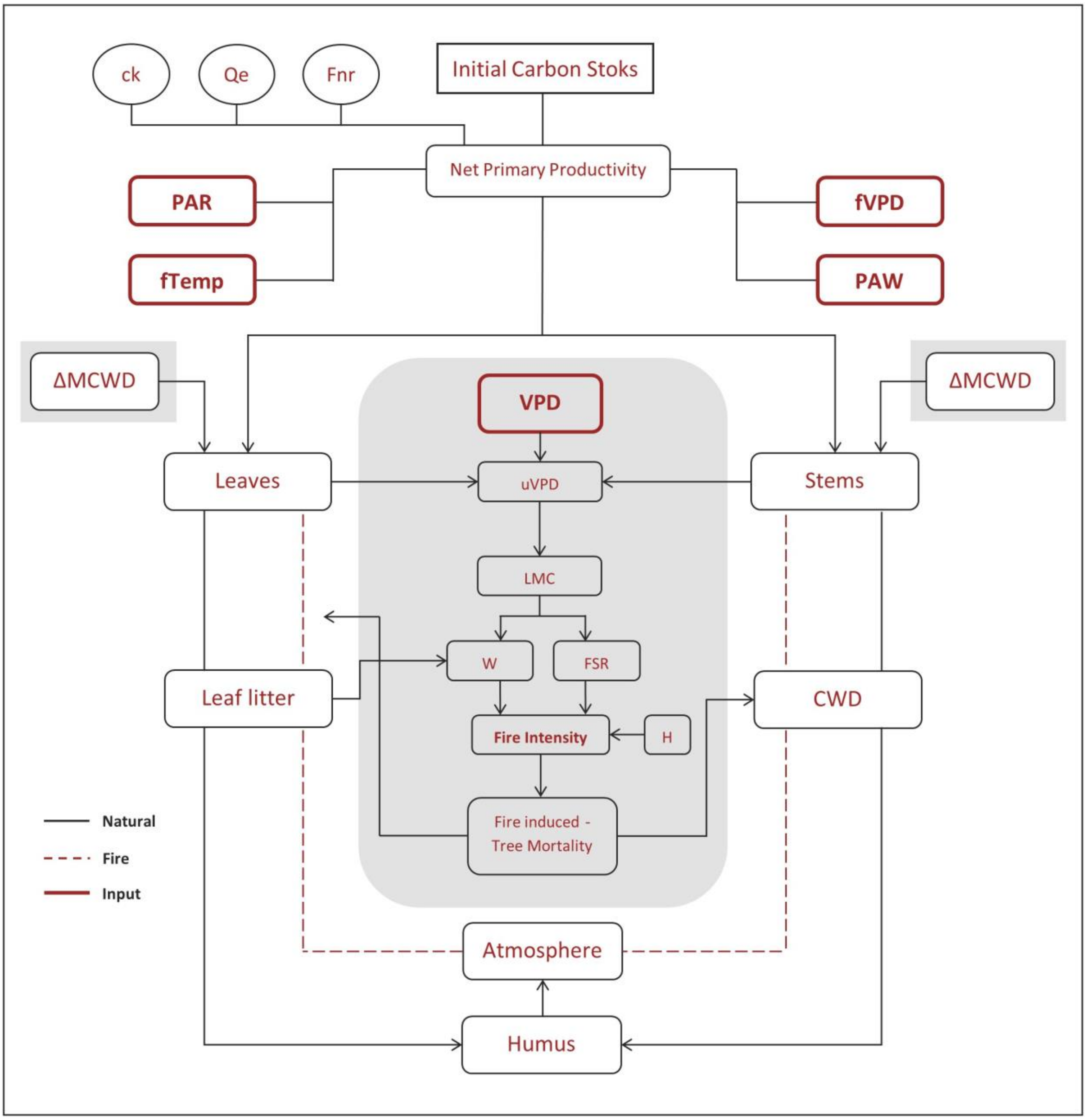

Figure 3.10 - CARLUCC diagram highlighting the fire intensity module.

Table 3.1 - Principal equations of CARLUC.

Variable	Name	Unit	Unit name	Equation
uVPD	Inner Vapor Pressure Deficit	Kpa	Kilo Pascal	0.140494 - 0.006 * Cstem * 10 - 0.594074 * sqrt(Cleaf * 10 + 0.5) + 1.505 * sqrt(VPD + 0.5)
LMC	Litter Moisture Content	Kpa	Kilo Pascal	80 * exp(-0.9 * Ivpd)
ROS	Rate of Spread	m/min	Meter per Minute	0.043 + 0.83 * exp(-0.107 * lmc)
Fuel	Fuel Load	Kg/m²	Kilogram per square meter	((Cleaf + Cstem) * 20 / 350) * Cllstruc
W	Weight of Dry Fuel	Kg/m²	Kilogram per square meter	Fuel , LMC/me < 0.18 (1.2 -0.62 * LMC/me) * Fuel, 0.18 ≤ LMC/me ≤ 0.73 (2.45 – 2.45 LMC/me) * Fuel , LMC/me > 0.73
FI	Fire Intensity	kW/m	Kilo Watts per meter	W * ROS * 18700 * 0.16
Mort	Mortality	Kg/m²	Kilogram per square meter	1 / (1 + exp(2.45 - 0.002373 * FI)

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

1) Drought-induced loss of carbon stocks (AGB, above-ground biomass), expressed as biomass loss, associated changes in fuel loads.
2) Moisture as a function of the maximum climatological water deficit (MCWD) [66].
3) Litter moisture content (LMC, %), estimated from vapor pressure deficit; fire spread rate (FSR, $m \cdot min^{-1}$), estimated from LMC.
4) Fire fuel consumption (W, $kg \cdot m^{-2}$), estimated from LMC and fuel load mass.
5) Fire line intensity (FI, $kW \cdot m^{-1}$), estimated from FSR and W
6) Fire-induced biomass losses, derived from FI from field measurements.

The equation used to calculate forest flammability follows Byram`s fire intensity concept [67]:

$$\mathrm{FI} = \mathrm{W} * \mathrm{FSR} * \mathrm{H} * 0.16 \qquad \text{eq. (1)}$$

Combustion heat (H) is assumed constant at 18.700 kJ/kg [68, 69]. The surface fuel consumption (W) calculated as the proportion of each dead fuel class consumed by fire decreases as a function of its moisture content relative to its moisture of extinction [70, 71] (m_e) so that:

$$\boldsymbol{W} = \begin{Bmatrix} 1.0, \frac{\boldsymbol{LMC}}{\boldsymbol{me}} \leq 0.18 \\ 1.2 - 0.62\frac{\boldsymbol{LMC}}{\boldsymbol{me}}, \mathbf{0.18} \leq \frac{\boldsymbol{LMC}}{\boldsymbol{me}} \leq 0.73 \\ \mathbf{2.45} - \mathbf{2.45}\frac{\boldsymbol{LMC}}{\boldsymbol{me}}, \frac{\boldsymbol{LMC}}{\boldsymbol{me}} > \mathbf{0.73} \end{Bmatrix} * \text{1-h fuel} \qquad \text{eq. (2)}$$

The FSR, derived from field measures, is as folows:

$$\text{FSR} = 0.043 + 0.838\, \text{e}^{-107(\text{LMC})} \qquad \text{eq. (3)}$$

As fire intensity has a direct impact on timber production, it is important to define thresholds of fire severity to calculate the appropriate losses. In order to do so, we used CARLUC to compute fire intensity to evaluate its impact on tree mortality. Above ground biomass mortalities up to 20% are considered as low to moderate fire events [55]. Based on this observation we set 400 kW/m as a threshold for fire intensity using a correlation of fire intensity and mortality (Figure 3.11), so that:

$$\textbf{Mortality} = \mathbf{1/(1 + exp(2.45 - 0.002373 * FI))} \qquad \text{eq. (4)}$$

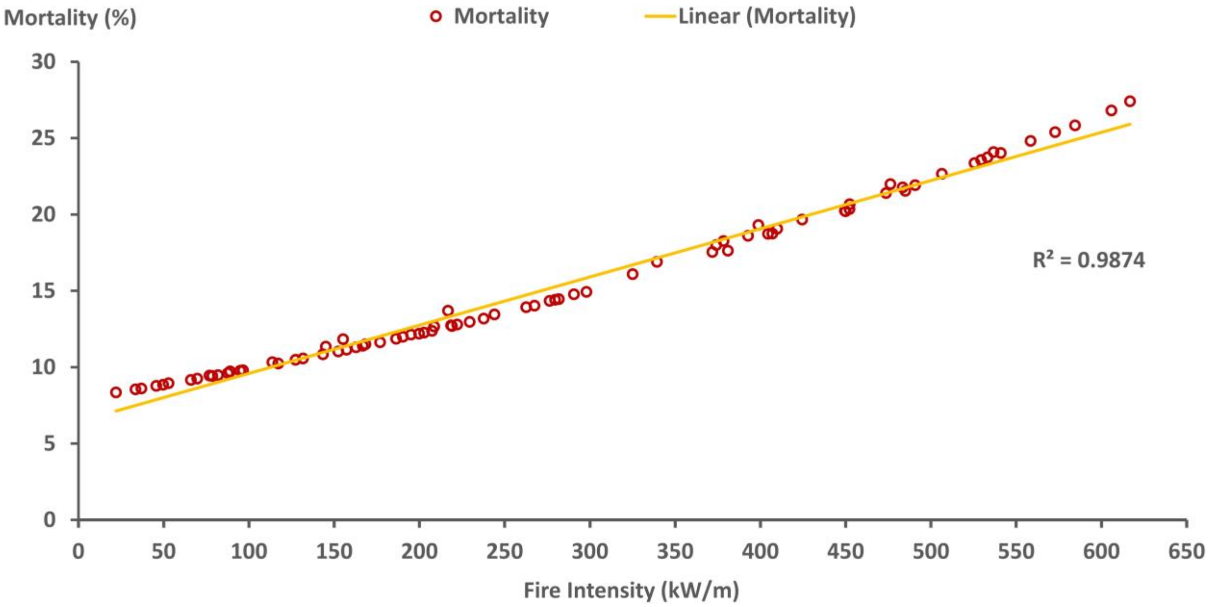

Figure 3.11 - Correlation between Fire Intensity and Mortality.

Figure 3.12 shows the Fire Intensity for two drought years, 2005 and 2010. Roughly, 82% and 65% of fire scars in 2005 and 2010 are classified as high intensity fires, respectively (Figure 3.13). Areas with lower humidity (*e.g.,* the transition between Cerrado and Amazon biomes) or with high levels of regional deforestation are more likely to have high intensity fires.

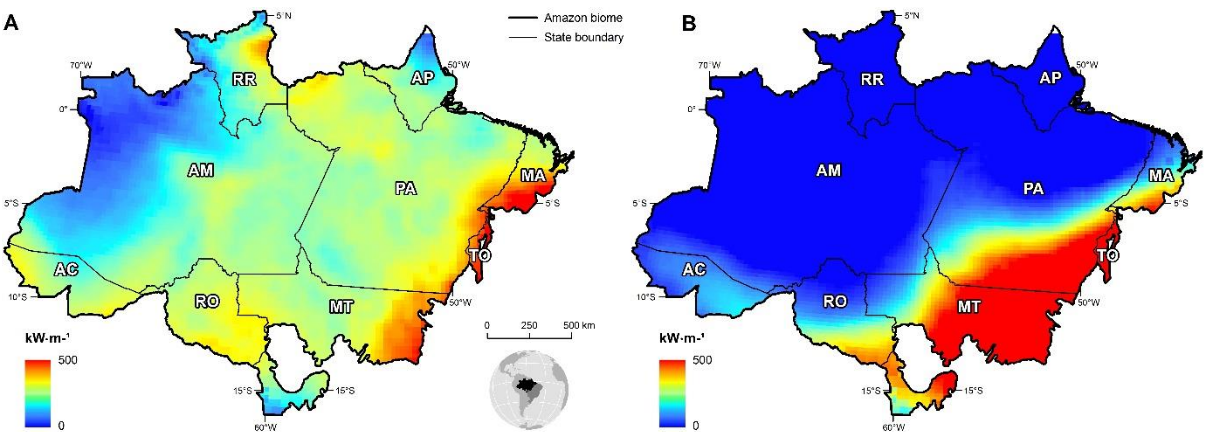

Figure 3.12 - Spatial distribution of fire intensities 2005 (A) and 2010 (B).

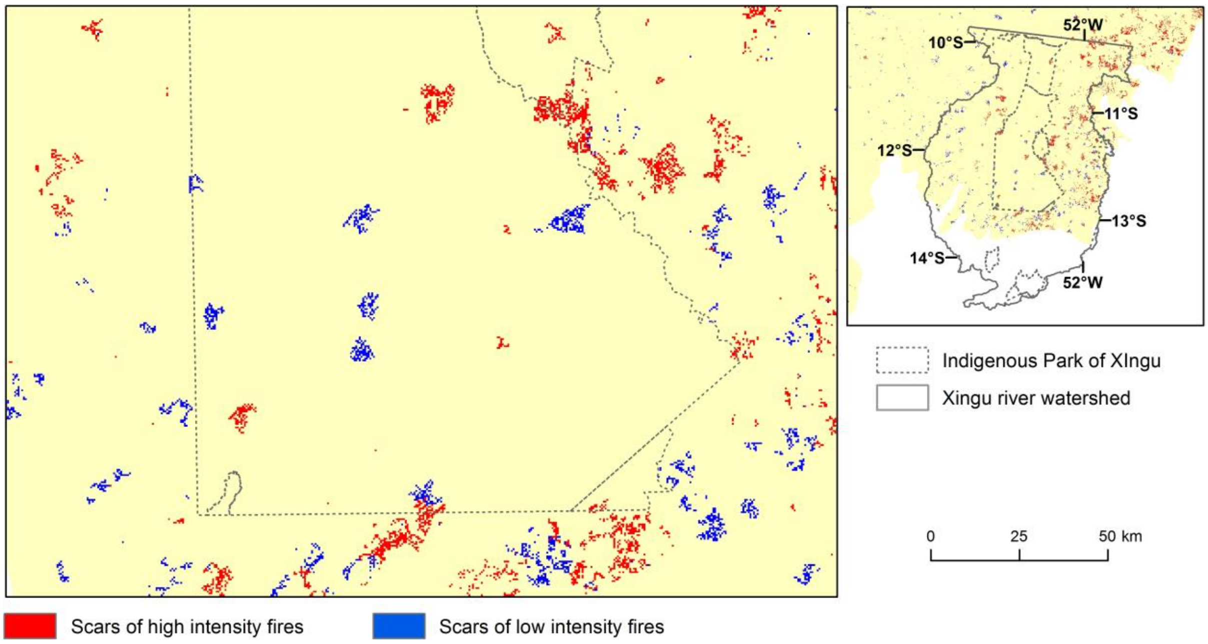

Figure 3.13 - Fire scars of high and low intensity.

3.5. Economic losses by fire to sustainable timber production

EcoFire combines fire and timber exploitation data to calculate losses to rents of sustainable timber production. The model deals with both effective losses (losses in simulated burned areas that eventually end up being logged) and potential losses as if all burned areas would be logged in the near future. Similarly to other value items in other reports of this project we estimate "potential values/losses". In the same way that is useful to consider the total amount of CO_2 that would be emitted if the Amazon were to be completely deforested, it is also relevant to consider the impact of fire in timber regardless of the fact that all those areas affected would be logged. EcoFire uses simulated fire scars from FISC-Amazon and rents from SimMadeira+, differentiated by hard and softwood, as input data.

EcoFire calculates economic losses based on a set of heuristics derived from fieldwork interviews in Sinop region, Mato Grosso state (Figure 3.14 & S2, Supplementary Material 5.3). According to informants, three major factors drive fire-related economic losses in timber production: 1) fire intensity (see section 3.4); 2) fire recurrence; and 3) individual timber species resistance to fire (Table S3 in the Supplementary Material). In particular, most informants pointed out that low intensity fire reduces the average selling price of the m^3 of soft and hardwood by around 5%. They clarified that these small reductions are explained mostly by the fact that low intensity fires burn mainly leaf litter and, in some cases, tree bark. Hence, most low intensity fires do not cause direct damage to commercial timber. Yet the informants reported that the mere presence of fire and the lack of detailed information about the actual fire intensity cause a small price reduction. By contrast, for high intensity fires, the reduction in price can be more substantial. The informants reported that in the case of hardwood the reduction in price reaches 10%. On the other hand, losses are much more substantial in softwood since this type of timber undergoes damage beyond the outer bark, resulting in a price reduction of approximately 50%.

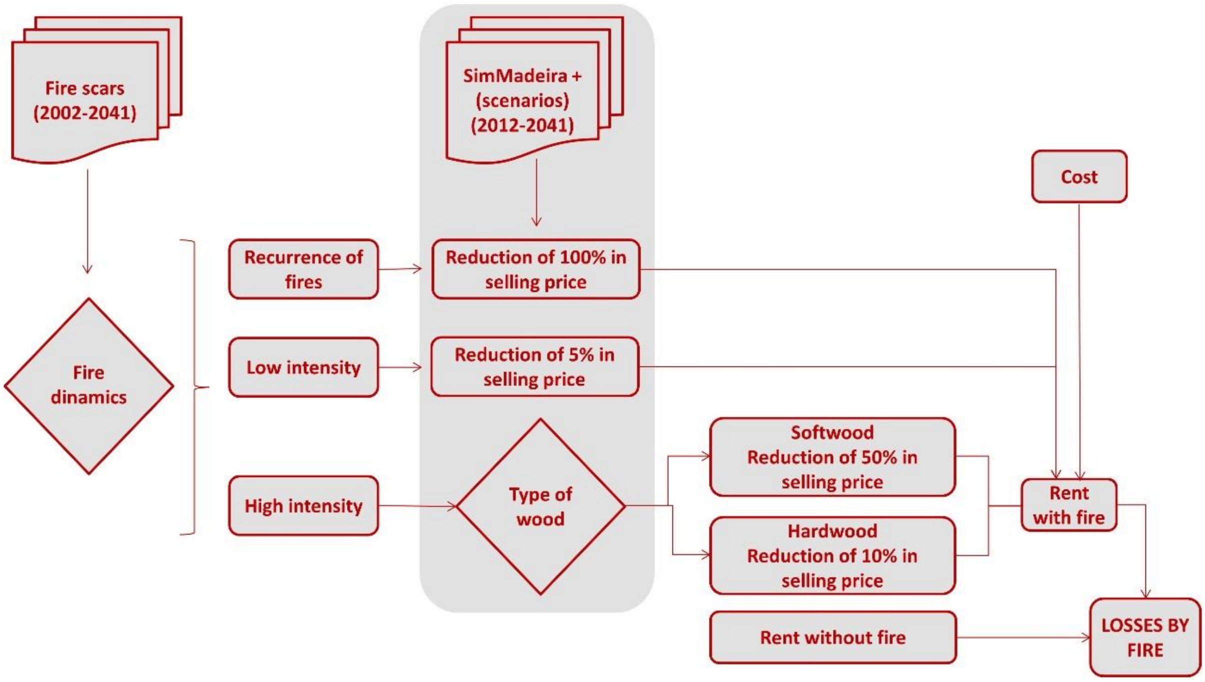

Figure 3.14 - Heuristics derived from fieldwork used by EcoFire to calculate the economic losses to the sustainable timber production in the Amazon.

Timber producers reported that the fire recurrence, regardless of intensity, leads to substantial economic losses. Indeed, the State-level environmental agency of Mato Grosso (SEMA-MT) does not authorize the timber harvest from areas that were affected by fire more than once in a period of 10 years (Mato Grosso State Decree n° 2152/2014 [72]). Based on the assumption that other environmental agencies adopt a similar policy, we estimate that the recurrence of fires entails a 100% loss.

In addition, forest engineers and literature report that both low and high intensity fires may hinder future forest yields by killing seeds and smaller trees [1, 73]. High intensity fires have been reported to cause the death of larger trees in the years following the blaze. Nonetheless, EcoFire considers fire damage to only fully-grown trees harvested from undisturbed forests. We assume that the maximum duration that fire affects timber losses is 15 years, taking into account that 90% of biomass losses could be recovered within this time interval as estimated by the CARLUC model.

We calculated the economic losses by fire over the simulated burnt areas between 2002 and 2041 (Figure 3.7), because timber harvest is forbidden from areas that were affected by fire more than once within a period of 10 years. SimMadeira+ first calculates the EAA of sustainable timber production in the absence of fire for the period 2012-2041 under the scenarios of current and inflated prices (Figure 3.8). EcoFire then calculates the economic impact of fire on each cell, taking into account the timing of fire events in relation to the harvest year. Since the economic impact varies according to the type of fire, we used the yearly fire intensity maps (Figure 3.12) to estimate the presence of high intensity fires. The result is a geographically differentiated estimate of the economic impact of 40 years of fires on a full timber production cycle.

Summarizing, ECOFIRE estimates economic losses of fires as follows:

1. Economic losses are calculated based on the commercial value of timber (gross rents). Gross rents without fire impact (A) are compared with the economic losses map (C). Net rent after fire (E) are compared with net rent from SimMadeira+ (map D) and decreases in net rent due to fire (map F). See Figure 3.15.
2. We calculated the map of net rent after fire (Map E) by subtracting the costs from gross rents (commercial volume) impacted by fire.
3. Wood has a commercial value that decreases when it burns. However, the harvest cost remains the same. Rents then decrease because wood value decreases with fire. In some cases when net rents are negative, we set the net rent to zero since those areas will not be logged.

While fire events and timber production take place widely across the landscape over the simulated time-period (11.1 Mha and 48±7 Mha, respectively; 3.8 Mha of fire recurrence over 40 years), the overlap between these two events is relatively rare (only ≈ 2% of productive areas are burnt). This is clear in the scarce distribution of timber production areas hit by fire across the region of Sinop (Figure 3.16). In the affected areas fire causes losses of US\$ 39±2 $ha^{-1}year^{-1}$ (Equivalent Annual Annuity), which is the average commercial value of timber logged in the production areas. But losses can reach up to US\$ 183±30 $ha^{-1}year^{-1}$ in areas hit by recurrent fires that are near milling centers. Different factors influence the interaction between fire and timber production. While some areas in the deforestation arc undergo smaller economic losses due to the scarcity of valuable timber, strict conservation units and indigenous lands experience no market-based economic impact due to the prohibition of timber harvest. Areas that undergo larger losses by fire are found near the agricultural frontier or major roads in the northwestern Mato Grosso, northern Rondônia, southeastern Acre, and eastern Pará. The relation between roads and larger economic losses is caused by the combination of lower transportation costs (and thus higher rents) and the presence of high intensity fires. Large areas with no, or very low, economic losses in Northwestern Amazonia are explained by transportation costs that make these areas unprofitable for timber harvest, as well as the paucity of fires in this region.

Analysis of the yearly influence of fire provides further insights into its relative impact on the economic value of timber production in the region (Figure 3.15). Between 2012 and 2041 timber production starts at an annual production of 10±0.23 million m^3 and goes up to 41±5 million m^3 over the last decade of the period. The total net revenue also increases from US\$ 431±91 million in 2012 to US\$ 1.04±0.3 billion in 2023, but then declines to US\$ 913±360 million by the end of the cycle in the absence of fire (Table S5). In this scenario harvest occurs on 500±30 thousand ha in 2012 and on 2.04±0.57 Mha by 2041, totaling 48±7 Mha over the

30-year cycle. Of this total, 693±168 thousand ha are affected by fire, (approximately 2 % of logged areas). Roughly, 30±6 thousand hectares are affected by fire in 2012, representing 6% of the total area. 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 towards area not prone to fire; hence, the percentage of the area affected by fire is reduced to 0.5% by the end of the period.

The total annual economic impact of fire is at its peak in 2014, reaching US$ 54±11 million (Figure 3.17). This value is deducted from timber commercial value, representing 8% of losses in the net rent, decreasing to US$ 2.7±0.8 million and affects 0.3% of the annual net revenue by the end of the logging cycle (Figure 3.15). The gradual reduction of the impact of fire is related to the expansion of timber production in areas that are more distant to the agricultural frontier and as such are less susceptible to fires. Over the 30-year logging cycle, economic losses by fire to the sustainable timber production amount to US$ 726±193 million or US$ 689±184 million in Net Present Value (NPV, 5% discount rate). These losses affect the commercial value of logged areas representing 4% of the total net revenue from a 30-year logging cycle in the absence of fire. Therefore, while fire has a relatively small economic impact at the level of the entire Brazilian Amazon, its impact at a local scale can be substantial. Furthermore, if all burnt areas would have been logged in the near future, the potential losses could amount to US$ 7.6±2.4 billion or US$ 7.2±2.3 billion NPV, considering concurrent fire and logging events (Figure 3.18).

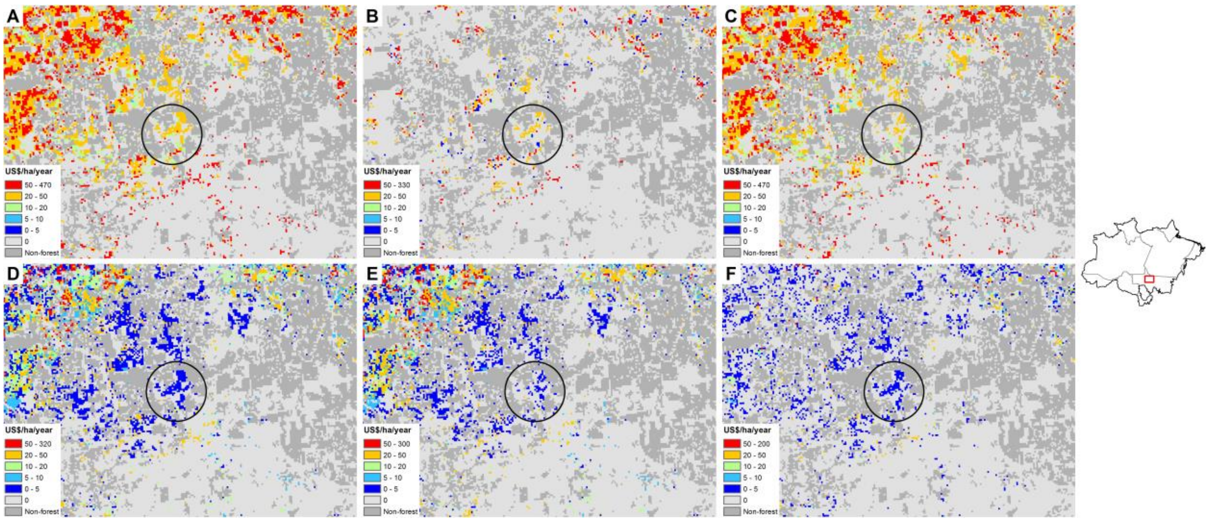

Figure 3.15. Gross rent (commercial value) without fire (A); Losses to gross rent in the areas affected by fire (B); Gross rent (commercial value - with fire (C); Net rent without fire (D); Net rent with fire (E); Decreases in net rent due to fire (F).

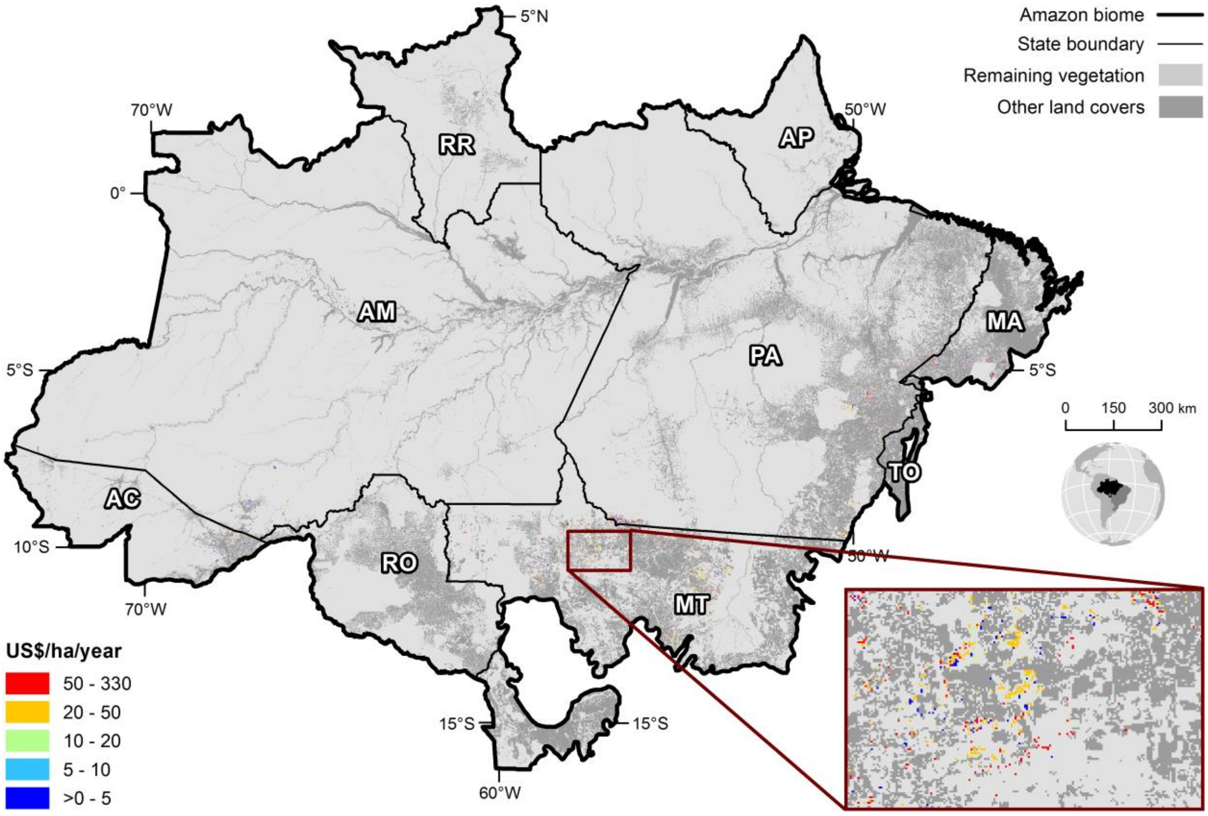

Figure 3.16 - Economic losses by fire to sustainable timber production highlighting the region of Sinop between 2012 and 2041.

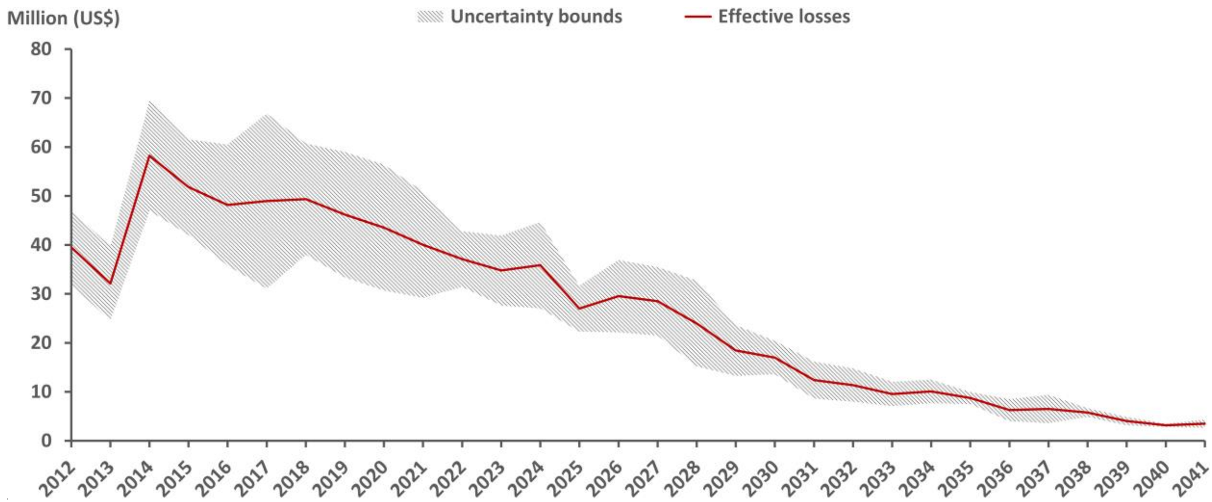

Figure 3.17 - Annual economic losses by fire to the sustainable timber production and uncertainty bounds (±15% of average timber prices).

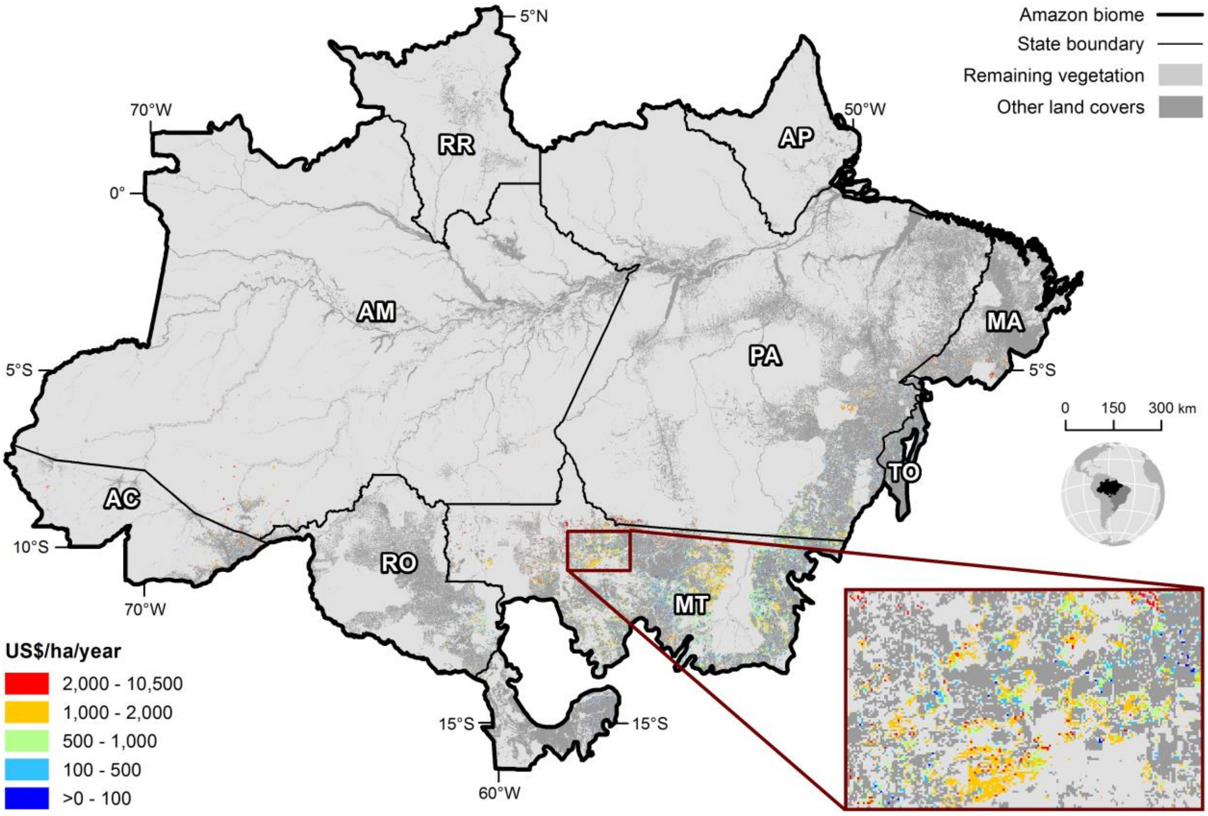

Figure 3.18 - Potential economic losses (NPV) by fire to the sustainable timber production.

4. Final Remarks

Quantifying the costs and benefits associated with changes in the Amazon forest ecosystem is a challenging task. Our study takes some steps forward by estimating the fire-related economic losses to sustainable timber production across the Brazilian Amazon. In doing so, we develop an innovative tool that addresses an important research gap in ecosystem service valuation.

Although the data sources and methodological procedures adopted by this study are different from former literature, the results are comparable. Mendonça et al. [21] estimate the yearly total loss in timber production by fire between US$ 1 and 13 million, a value in the same order as the annual average of US$ 29±4 million from our study. Similarly, Andersen et al. [41] report that fire entails losses to timber production of US$ 28 $ha^{-1}year^{-1}$ (EAA), on average, while we estimate a loss of US$ 39±2 $ha^{-1}year^{-1}$. These economic losses (US$ 689±184) represent a reduction of 4% in the total net revenues from sustainable timber in the region over a logging cycle of 30-years. Therefore, while fire causes a substantial impact at a local scale, it has a relatively small economic impact at the entire Brazilian Amazon. Yet potential losses could be significantly higher, since only few burnt areas are eventually logged. If all burnt areas were to have been logged in the near future, the potential losses could amount to the significant value of US$ 7.6±2.4 billion.

Furthermore, we found a strong correlation between forest fragmentation, dryness, the presence of roads, and the probability of high intensity fires. In the initial years of the simulation, fire losses are higher due to the proximity of the production areas to the agricultural frontier, and the related presence of higher levels of forest fragmentation and dryness. The relatively small percentage of timber production areas affected yearly by fires (≈ 2%) also confirms the information provided by timber producers that blazes are relatively rare in timber production areas away from main roads and forest edges.

EcoFire provides a basis for valuing the losses by fire in the provision of ecosystem services such as timber. The results of this study can be used as a source for gauging the costs as well as the benefits of fire avoidance strategies. These could involve, for example, command and control policies that extend fire bans in regions with high timber value that are prone to fire. Our results could also serve to foster economic mechanisms that seek to provide incentives for substituting fire practices in pasture management and slash and burn agriculture. Therefore, this study brings valuable inputs to policy-makers for the design and implementation of sustainable land management strategies across the Brazilian Amazon.

5. Supplementary Material

5.1. FISC-Amazon

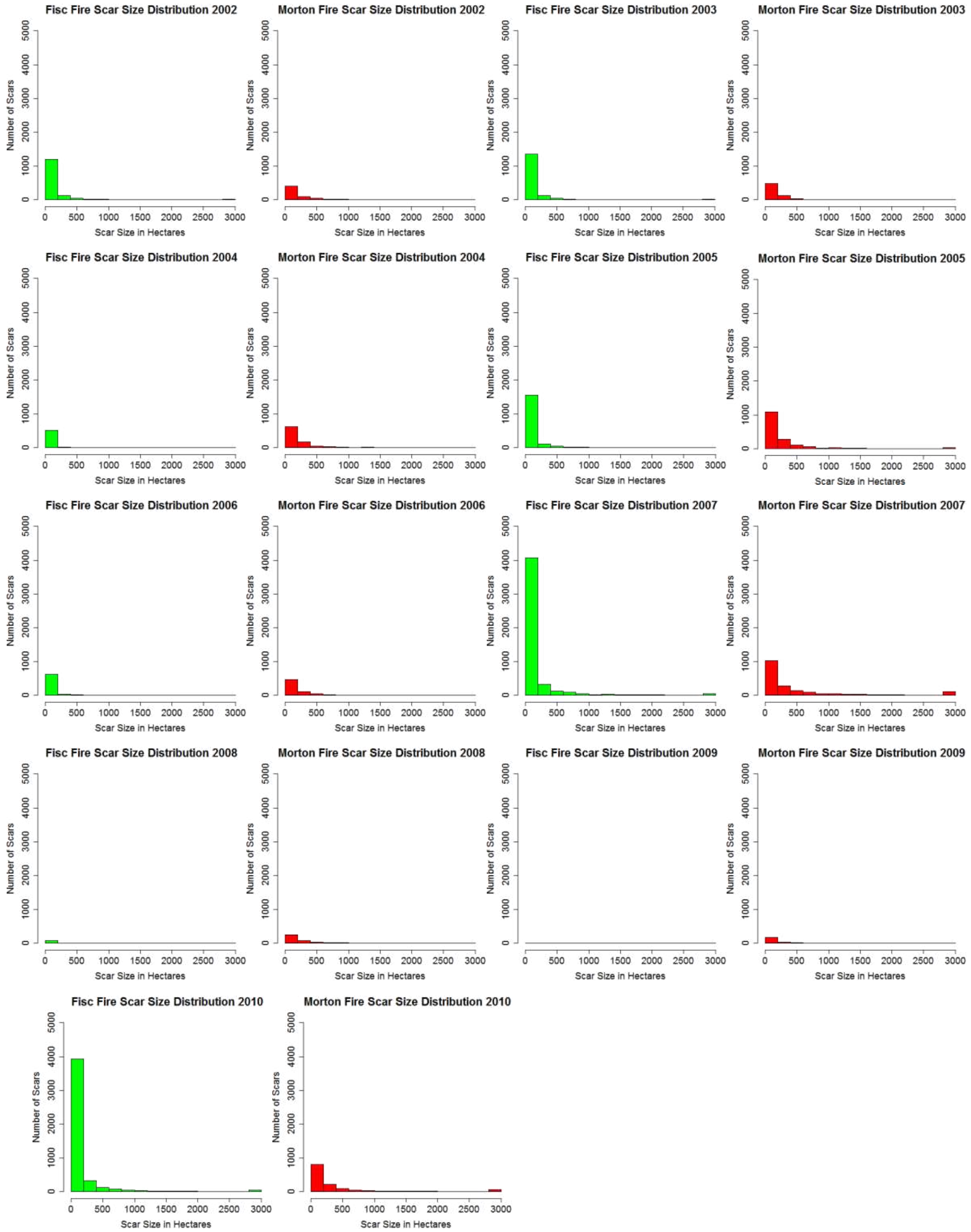

Figure S1 - Size distribution of simulated and observed forest fire scars.

5.2. Fieldwork in Sinop (MT)

The consolidated logging frontiers of the Amazon are the harvest areas that exist for more than 30 years and produce 60% of the timber in the biome (Figure S2). Located in the state of Para, Paragominas alone produced 300,000 m³ of logs in 2014, generating a gross product value of US$ 35 million [13]. The Sinop regional center comprises nearby municipalities including Marcelândia, Feliz Natal, Claudia, and Tabaporã.

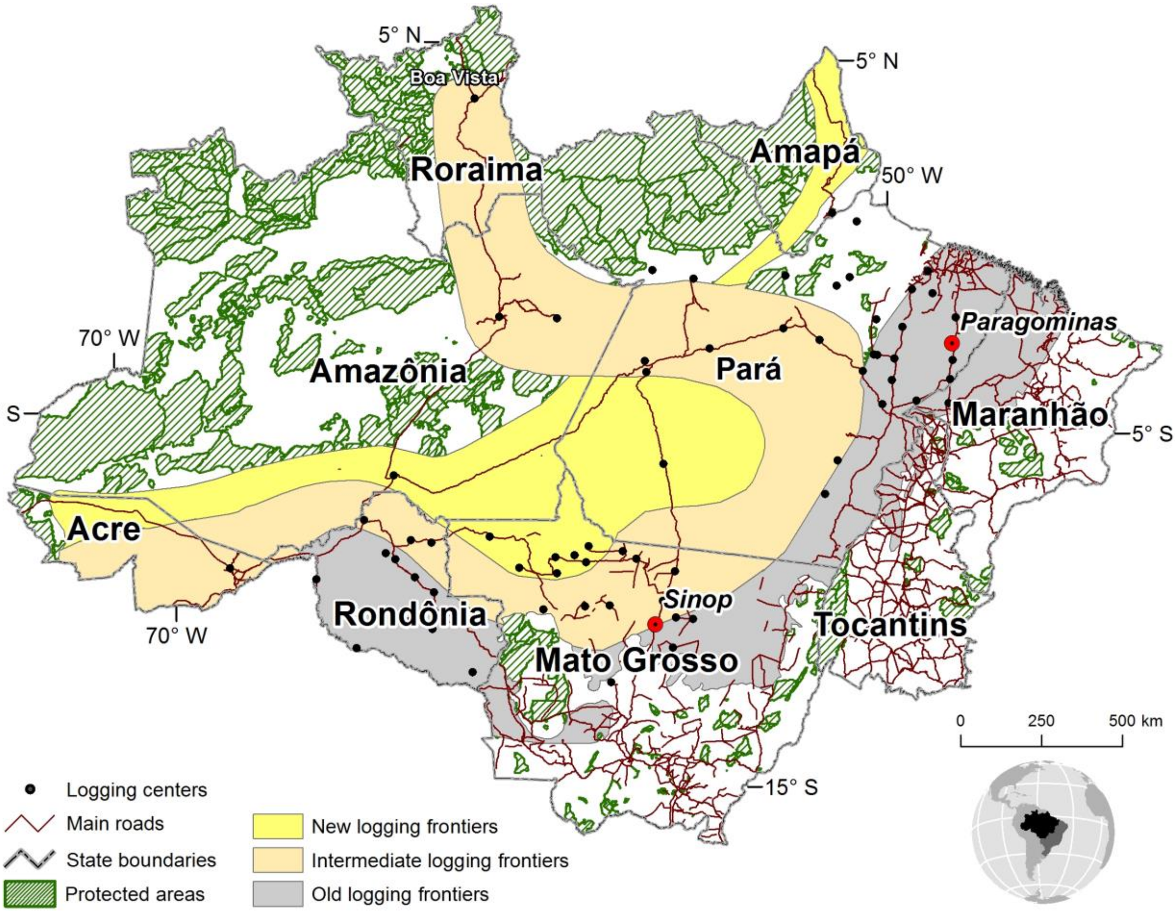

Figure S2 - Timber production centers and frontiers in the Amazon.

Due to its regional and national importance in the timber sector as well as the high incidence of fires, Sinop was selected for our data collection effort. The UFMG team conducted a 10-day fieldwork exercise in the region in August 2015. During this trip, 30 informants directly involved in the forest sector were interviewed (Table S1).

Table S1 - List of interviewees.

Type of informant	Municipality-Stakeholder
Forest Producers and Loggers	Altamir Souza (Produtor Florestal) Marcelo Kreibich (Vice- Presidente do SINDUSMAD) José Eduardo (Presidente do CIPEM) Gleisson Tagliari (Presidente do SINDUSMAD) Marcelo Cambará (Madeireiro) Luiz Fávero (Produtor Florestal) Antônio Balbinoti (Madeireiro) Flávio Berté (Diretor do SINDUSMAD) Diones Admad (Madereiro) Jaldes Langer (Produtor Florestal)
Forest Engineers	Angeli Katiucia Luciano Berti Patrícia Cleidi* Ivo Ramos Márcio Monteiro Renato Oliver Guilherme Costa* Marco Paula Giuliano Muniz Wanderley Batista* Cleber Michelan* Antonio Esquivel
Institutions	SEMA – Secretaria Estadual de Meio Ambiente IBAMA – Instituto Brasileiro de Meio Ambiente – Equipe PrevFogo Corpo de Bombeiros de Sinop-MT 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

*Forest engineers from Sinop who classified each tree genera as either soft or hardwood.

With the assistance of a questionnaire (Supplementary Material 5.3), the interviewees provided information about the timber market as well as the production of sustainable management system including final product destination, production costs and investments, sales and marketing of wood, legislation, and individual perspectives for the timber sector. More importantly, they provided information about the consequences of fire on timber production specifying: a) eventual changes in burnt timber selling market; b) losses in usable timber from burnt logs; c) decreases in price in the m^3 of round wood due to fire; d) costs of preventive measures; and e) regional fire dynamics and prevention measures. Due to the small sampling size and consistency of the answers, the results reported below are based on the mode (*i.e.* most frequent answer) of each question.

Most informants declared that 80% of the timber produced in the regional center of Sinop is destined to the domestic market, specifically to the south and southeast regions of Brazil. The remaining 20% are for export, which underwent a high growth in 2015 due to the appreciation of the dollar. Earlier, lumber intended to the external market in Sinop was around 5%. In relation to the industry and timber processing, about 60% of the production are turned into planks in sawmills (Figure S3), 15% go to the plywood industry, 5% to the laminate industry, and 20% turned into products with more added value such as furniture and wooden decks. The interviewees provided data about the main costs associated to the system of sustainable management in Mato Grosso (Table S2).

Figure S3 - CSR team in a sawmill log yard in Sinop - MT.

Table S2 - Investment and costs of the Sustainable Management System.

Type of cost	Investiment (US$)*
Standing Forest Purchase (Cost Stampage)**	up to 30 to 64 US$/$m^3$
Gathering License Cost[1]	over US$ 4,200
Development of Sustainable Management Project Cost[2]	up to 76 to 106 US$/ha
Logging Cost	up to 21 to 30 US$/$m^3$
Cost of Forest Replacement[3]	over 420 US$/ha
Cost of round wood transportation (freight value)	- up to 13 to 25 US$/$m^3$ (distance of 150 km between the forest propriety to sawmill courtyard) - up to 30 to 51 US$/$m^3$ (distance of 350 km between the forest propriety to sawmill courtyard)

*Considering the conversion factor of 2014 (2.36).
**depending on the forest species, [1]depending on the commercial volume of the area, [2]depending on the size of the area that the forest engineer is responsible (traveling and payment staff), [3]depending on the timber volume explored.

According to the loggers and forest owners, transport costs can increase their total costs by up to 20%. Loggers often lose interest for the purchase of wood beyond 150 km of distance. Regarding selling prices, the value of round wood in Sinop sold in the sawmill log yard is around US$ 84/m³ to US$ 211/m³, and price varies according to timber species.

Other information collected was the price of the land with forest, which is valuable to the timber production. This value varies with the distance between the forest property and the commercial center closer to it. In general, at distances of approximately 400 km from the commercial center, forested land is around R$ 1,000 ha^{-1} (US$ 423 ha^{-1}). On the other hand, at distances < 100 km its value can reach up to R$ 10,000/ha (US$ 4,237 ha^{-1}).

Producers interviewed all claim to being victims of several accidental fires that occur in their properties. While these burns may not change the final destination of the wood, the fire impact is capable to reducing the commercial value, the quality of the wood, and the usable portion of round wood in the sawmills. This is reflected in EcoFire the reduction of the selling price of the timber (Table S3).

The potential economic losses attributable to fire and timber depend of three main factors: the intensity of the fire, the wood quality, and the recurrence of fires. The informants reported that burnt logs suffer losses from 5 to 100% of the selling price of timber per m^3 of round wood. Table S3 shows the parameters reported by forest owners that reflect the approximate economic losses and related to the potential impact of fire on trees of commercial value represented by the quality of the wood provided.

Table S3 - Declared parameters for economic losses involving timber and fire.

Fire type	**Selling price loss (%/M³) / Timber type**			
	Timber Use		Commercial Value	
	Hardwood	*Softwood*	*Hardwood*	*Softwood*
High intensity	20%	70%	10%	50%
Low intensity	15%	15%	5%	5%
Fire recurrence (10 years)	100%		100%	

* Wood of lower density, lower commercial value and less fire resistant.

Events of high intensity fire and wood density are key parameters to understand the relationship between fire and forest damage [1, 20, 23, 31]. Brando et al. [1] report, from two experiments performed in southern Amazon, that the tree mortality increases when high intensity fires reach trees of smaller diameter, height and wood density. Experiments performed in Eastern Amazon by IMAZON [57] also demonstrate that mortality is fifteen times larger in areas of high intensity fires and logging without proper forest management, when compared to fires of lower intensity in forests under sustainable management.

According to the forest engineers interviewed, fire usually brings future economic loss to landowners over the cycle of regeneration of the forest for timber production. Fire of higher intensity are able to damage the seed banks of the forest and kill the remaining trees that, in the future would be trees of ideal size for cutting. In this way, the usual forest regrowth cycle of 30 years is extended to 40 years or more depending on the intensity of the fire event on the property. Given the lack of reliable longitudinal data on the impact of fire on the seedbanks of commercial timber, this issue was not captured in the model. In addition, areas with consecutive impacts by fire cannot be harvested, which implies in a total economic loss (Mato Grosso Decree No. 2152/2014 [72]). This was included in the model by attributing a loss of 100% in the selling price of timber following the recurrence of fire in a 10 years period.

According to forest owners, fire is the second factor that causes more economic damage to the timber sector; the first being theft. The complex bureaucratic procedures required to obtain sustainable timber authorization also cause production delays, which can contribute to the decision to harvest timber illegally. Aggressive timber harvest approaches, often adopted in illegal logging practices, waste wood while jeopardizing environmental and economic sustainability.

Forest owners usually adopt some preventive actions against fire. These involve the construction of firebreaks, surveillance teams, signage, direct combat, and the use of equipment such as agricultural machinery and water tank trucks. Costs for adopting preventive measures of fire are relatively small and often limited to the construction of firebreaks on farms. Forest producers reported that they observed improvements in forest fire control practices in recent years. According to them, satellite fire monitoring and a stricter enforcement of environmental agencies have led to this result. Fines for unauthorized use of fire can cost on average US$ 22,000 ha^{-1} for burned areas.

In the case of the future prospects of the timber sector, the majority of respondents claim that the industry based on native logging is declining every year. The timber production currently tends to specialize in monocultures (*e.g. eucalyptus*) that have lower production costs. In the municipality of Sinop the number of sawmills has declined from 800 to 50. With the decrease in wood stocks near the commercial centers, transportation costs are rising considerably. Forest producers also reported that they do not have certainty on the approval of the forest management project, which increases risk. In addition, the logging technology is still low and the sector does not have any government incentives and credits for investments in new technologies. In relation to environmental protection, however, many owners claim to perform improvements in the management systems. Loggers are more aligned with the environmental laws. However, government officers deny that legal requirements are interfering with sustainable timber production.

5.3. 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	( )			

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/products?

PRODUCTS	>100,000/ha (or by property) (US$) or 10 to 20%	100,000-500,000/ha (or by property) (US$) or 20 to 40%	500,000-1,000,000/ha (or by property) (US$) or de 40 to 60%	>1,000,000/ha (or by property) (US$) or 60 to 80%
Sawn wood				
Products benefit				
Laminates and Plywood				
Purposes Fuels (Coal/ Firewood)				
Other (please specify):				

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?

5.4. Tree genera and mean prices

Table S4 - Tree genera/species and respective mean prices for roundwood.

Name (in Portuguese)	Scientific name	Mean prices (US$/m^3)				Category
		Mato Grosso	Pará	Rondônia	Mean	
High Economic value tree species		**148**	**159**	**132**	**152**	
Ipê-amarelo	*Tabebuia serratifolia*	137	173	131	160	Hard
Ipê-roxo	*Tabebuia impetiginosa*	142	164	131	156	Hard
Cedro Vermelho	*Cedrela odorata*	137	137	156	140	Hard
Itaúba	*Mezilaurus itauba*	155	103	97	139	Hard
Freijó	*Cordia goeldiana*	126	120	140	125	Hard
Medium economic value tree species		**101**	**102**	**74**	**94**	
Amescla	*Protium heptaphyllum*	73	74	60	70	Soft
Angelim-pedra	*Hymenolobium petraeum*	110	106	78	99	Hard
Angelim-vermelho	*Dinizia excelsa*	111	113	81	108	Soft
Breu	*Protium sp.*	68	89	62	73	Soft
Cambará	*Vochysia sp.*	86	117	64	79	Hard
Cedrinho	*Erisma uncinatum*	110	83	62	97	Hard
Cedromara	*Cedrela sp.*	84	105	65	73	Soft
Cerejeira	*Torresea acreana*	113	-	94	97	Hard
Cumaru	*Dipteryx odorata*	115	111	87	105	Hard
Cupiúba	*Goupia glabra*	98	96	68	90	Hard
Garapeira	*Apuleia molaris*	105	83	78	89	Hard
Goiabão	*Pouteria pachycarpa*	87	86	59	83	Soft
Jatobá	*Hymenaea courbaril*	101	100	77	95	Hard
Jequitibá	*Cariniana sp.*	144	84	71	81	Hard
Louro	*Ocotea sp.*	84	83	62	79	Soft
Maçaranduba	*Manilkara huberi*	90	114	83	107	Soft
Muiracatiara	*Astronium sp.*	81	100	76	92	Soft
Oiticica	*Clarisia racemosa*	85	100	67	71	Soft
Pequiá	*Caryocar villosum*	72	91	64	86	Soft
Peroba	*Aspidosperma sp.*	116	156	82	108	Hard
Roxinho	*Peltogyne sp.*	91	109	65	78	Soft
Sucupira	*Bowdichia sp.*	104	96	68	85	Hard
Tatajuba	*Bagassa guianensis*	72	99	64	92	Soft
Timborana	*Piptadenia sp.*	84	89	72	89	Soft
Low economic value tree species		**77**	**73**	**61**	**69**	
Abiu	*Pouteria sp.*	84	83	64	78	Soft
Amapá	*Brosimum parinarioides*	134	71	51	71	Soft
Amesclão	*Trattinnickia burseraefolia*	72	69	42	67	Soft
Angelim-amargoso	*Vataireopsis speciosa*	87	67	70	70	Soft
Angelim-saia	*Parkia pendula*	67	101	57	67	Soft
Caju	*Anacardium sp.*	55	64	56	62	Soft
Marupá	*Simarouba amara.*	71	70	62	67	Soft

Copaíba	*Copaifera sp.*	72	72	56	67	Soft
Faveira	*Parkia sp.*	66	67	73	69	Soft
Mandioqueiro	*Qualea sp.*	78	84	42	83	Soft
Orelha-de-macaco	*Enterolobium schomburgkii*	59	81	55	68	Soft
Paricá	*Schizolobium amazonicum*	64	64	56	61	Soft
Sumaúma	*Ceiba pentandra*	71	66	57	64	Soft
Tauari	*Couratari sp.*	78	83	61	72	Soft
Taxi	*Tachigali sp.*	78	73	58	72	Soft
Virola	*Virola sp.*	84	65	36	62	Soft

*US$ 1 = R$ 2.36.

Source: [57].

Table S5 - Total economic losses in rents from timber production for the Brazilian Amazon that would take place between 2012 and 2041.

Year	Explored area (million ha)	Burnt area with timber (thousand ha)	% of the explored area	SimMadeira+ rent without fire (billion US$)	SimMadeira+ rent with fire (billion US$)	Loss due to fire (million US$)	% of total rent loss
2012	0.50	30.6	6.1	0.43	0.39	36.0	8.3
2013	0.54	24.2	4.4	0.45	0.43	28.6	6.1
2014	0.76	48.0	6.2	0.62	0.56	54.7	8.8
2015	0.83	41.6	4.9	0.65	0.61	48.8	7.4
2016	0.91	40.9	4.4	0.70	0.65	47.2	6.7
2017	1.00	44.1	4.3	0.76	0.71	50.5	6.5
2018	1.08	42.1	3.8	0.81	0.76	48.1	5.8
2019	1.15	41.3	3.5	0.86	0.81	45.1	5.2
2020	1.25	37.1	2,9	0.89	0.85	37.5	4.1
2021	1.33	35.6	2.6	0.94	0.91	34.5	3.6
2022	1.45	39.0	2.7	1.01	0.98	33.2	3.2
2023	1.55	38.0	2.4	1.04	1.01	33.7	3.2
2024	1.65	31.4	1.9	1.07	1.05	25.2	2.3
2025	1.75	34.7	1.9	1.12	1.09	30.0	2.6
2026	1.84	29.7	1.6	1.12	1.09	24.8	2.2
2027	1.94	26.9	1.3	1.15	1.12	23.6	2.0
2028	1.97	26.9	1.3	1.12	1.07	22.2	1.9
2029	2.05	24.7	1.2	1.15	1.13	18.0	1.5
2030	2.06	20.2	0.9	1.12	1.11	11.5	1.0
2031	2.09	21.2	1.0	1.10	1.09	9.7	0.8
2032	2.09	24.4	1.1	1.11	1.10	11.1	1.0
2033	2.11	21.8	1.0	1.09	1.08	10.7	0.9
2034	2.12	15.0	0.7	1.06	1.06	6.2	0.5
2035	2.10	14.3	0.6	1.05	1.04	6.1	0.5
2036	2.12	14.9	0.7	1.04	1.03	6.1	0.5
2037	2.07	14.9	0.7	1.00	0.99	7.1	0.7
2038	2.07	14.4	0.6	0.99	0.99	4.8	0.4
2039	2.07	28.7	1.3	0.96	0.96	3.4	0.3
2040	2.04	28.7	1.4	0.93	0.92	3.5	0.3
2041	2.04	10.0	0.5	0.91	0.91	2.7	0.3

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