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# Fire risk perpetuates poverty and fire use among Amazonian smallholders

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ABSTRACT

Forest fires exacerbate carbon emissions, threaten biodiversity and cause welfare losses to local populations. Most fires accidentally ignite from mismanaged swidden and pasture fires. We provide evidence that fire risk in the Brazilian Amazon, the world's largest remaining tropical forest, perpetuates low yield and environmentally degrading agricultural activities. Using a combination of household interviews and remotely sensed data on fire occurrence in Eastern Amazon municipalities of Paragominas and Santarém, we show that smallholders in consolidated farm-forest frontier regions are locked into a vicious cycle that inhibits their adoption of fire-free practices. Households that invest in more capital-intensive fire-free agricultural technologies experience greater revenue losses from escaped fires than non-fire users. Changes in revenues are as sensitive to these fire impacts as they are to changes in physical capital investments. To overcome this fire-poverty trap, a "big push" of co-ordinated local incentives is needed. Policies mitigating fire risk may achieve a triple-win that reduces greenhouse gas emissions, forest degradation, and fosters inclusive economic development.

## 1. Introduction

Tropical forests are critical to planetary health and human well-being, yet disappearing faster than ever. Clearance and degradation of these forests areas for agriculture is often justified by their ability to generate foreign exchange and contribute to domestic food security and economic development (De Sartre and Taravella, 2009). Yet, a majority of the people residing in forest regions remain impoverished because they are locked into environmental degrading and low-income land uses (Garrett et al., 2017; Sunderlin et al., 2003). Nowhere is this challenge more apparent than the Brazilian Amazon, where millions of farmers engage in subsistence agriculture and extensive ranching for their livelihoods (Carmenta et al., 2013; Ioris, 2016).

Between 2004 and 2014, efforts aimed at ramping up environmental enforcement and harnessing market forces succeeded in reducing deforestation among soybean and beef producers in the Amazon (Gibbs et al., 2016; Gibbs et al., 2015; Nepstad et al., 2014). Yet, forest degradation continued to worsen through the increased occurrence of fires (Alencar et al., 2015) causing large carbon emissions, biodiversity and welfare losses to Amazonian people. Fires in the Brazilian Amazon release more $CO_2$ emissions than the whole Brazilian energy sector, reduce up to 40% of the potential carbon stock of standing forest, slow forest re-growth and have halved biodiversity (Anderson et al., 2015; Barlow et al., 2016; Barlow et al., 2012; Berenguer et al., 2014; Silva et al., 2018).

Although fire spread is mostly associated with droughts and forest degradation (Alencar et al., 2015; Nepstad et al., 2004; Schwartz et al., 2015), there are no natural ignition sources in the rainforest (Cochrane, 2003). All fires are anthropogenic and mainly related to agricultural activities (Cano-Crespo et al., 2015). Speculative arson fires in private lands are unlikely (i.e., when the forest is burned before being cleared), since many trees die while standing and no agricultural activity is possible (Nepstad et al., 1999). Such fires are more commonly used with the intent of illegally clearing and acquiring new land (e.g., from indigenous reserves) (Barlow et al., 2019). Instead, fire in private lands is primarily for agricultural purposes, helping farmers to clear vegetation, control pests, and fertilize soil. Fire use reduces the amount of physical capital and labour needed to achieve these ends, especially in the absence of mechanization.

Fire control mechanisms, such as clearing firebreaks around the area that is intended to be burnt, are the only major direct costs associated with fire use (Bowman et al., 2008). Yet, the indirect costs of

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uncontrolled fire use across the Amazon basin are substantial. Besides causing respiratory diseases (Diaz et al., 2002; Smith et al., 2014), fires can escape the intended area, burning crops, pastures, and farm structures (Bowman et al., 2008; de Mendonça et al., 2004). In the Eastern Amazon, Cammelli and Angelsen (2019) report that 43% of 576 smallholder households had experienced at least one accidental fire in the previous five years. In the Western Amazon state of Acre, Campanharo et al. (2019) estimate losses from fires between 2008 and 2012 at 9% of the local GDP. Within a 30-year period, roughly 15%-60% of tree plantations in the Amazon region of Brazil, Bolivia, Peru and Ecuador are expected to experience losses from fire (Pokorny et al., 2012; Simmons et al., 2002). Even farmers that spend time and resources to control their own fire on property can incur losses when they are exposed to fires started by their neighbours (Bowman et al., 2008; Cammelli et al., 2019; Nepstad et al., 2001). These conditions lead to a mismatch in costs and benefits that requires policy interventions. While a large array of actors benefit from reduced fires and forest degradation (Barlow et al., 2012), many of the costs and responsibilities for fire control are incurred by the farmers (Brazil, 2012), some of which have the highest dependency on fire.

Theoretically, exposure to fire risk from outside the property could dilute incentives to spend time preventing fire risk on one's own property or investing in farm improvements necessary to adopt fire-free techniques (Nepstad et al., 2001). Adoption of fire-free techniques is typically a complex matter (Pollini, 2009) related, among other things, to poverty and lack of financial capital access, cost and risk minimizing behaviour, the cultural role of fire, and exclusion from markets for inputs and outputs (Palm et al., 2005; Pollini, 2014). Combined with these factors, fire risk from neighbouring farms could contribute to a vicious cycle that traps farmers in low income land uses and degrades the environment. This "lock-in" may help explain why substantial ongoing efforts to tackle deforestation have not succeeded in reducing fire risk and forest degradation (Barlow et al., 2012; Cammelli and Angelsen, 2019; Morello et al., 2017). Nonetheless, these conjectures have not been tested empirically.

Here we explore how fire risk interacts with physical capital availability to influence the expected revenues associated with land use choices. We use agricultural production data from a cross sectional farm survey assembled by the Sustainable Amazon Network between 2010-2011 in the Eastern Amazon (Gardner et al., 2013), as well as remotely sensed data on fire occurrence (measured as fire hotspot count around each property derived from MODIS FIRMS collection 6). We focus on smallholders, as they have the greatest proportional dependency on fire of all property sizes, and include many of the poorest people in rural Amazonia. To assess these interactions we answer the following three questions: i) how does fire usage by smallholders relate to their physical capital availability? ii) how do fire risk externalities influence smallholder household revenue and does this impact differ between fire users and non-fire users?, and iii) how does the impact of fire risk on revenue compare to other constraints facing smallholders, such as labour, land, and physical capital (e.g. machinery, equipment)?

## 2. Theory and background

We build on a simplified household model of fire use and fire control choices inspired by Bowman et al. (2008), but also include endogenous fire risk formation, following Shafran (2008) (see SI for the full analytical model). We assume that smallholder households can produce from one or a combination of two alternative land use types: A) a fire intensive land use that gives a low, but sure revenue, even under exposure to fire, or B) a fire-free land use that *can* provide higher revenue due to high yields and/or high prices per yield, but is highly vulnerable to damages from fire exposure.

Land uses that fall into type A may include manioc production and extensive cattle ranching. Manioc production in a swidden system faces low risk of losses from fires because there is no fine fuel left on fields after the first burn (the main risks occur when the forests are in their fallow state, if the slashed vegetation burns when it is too green, or if associated capital assets such as houses for making toasted manioc flour (*farinha)* burn). Extensive pasture management (where cattle are left to graze continuous on large unmanaged parcels) has low risk of losses because there are little to no high value plants or infrastructure (only limited fencing). Both systems can generate moderate returns under more intensive management or processing, but typically are associated with low revenues (Garrett et al., 2017). Land use type B – activities that can theoretically generate high revenue and do not involve fire include agroforestry, horticulture, tree plantations, intensive and rotated pastures, and annual crops with chemical inputs. These systems tend to involve costly (often long-term) physical investments, e.g., crops, trees and pastures on land prepared with tractors and chemical inputs, or additional fencing, which can be badly damaged by fire (Hoch et al., 2009; Hoch et al., 2012; Nepstad et al., 2001; Pokorny et al., 2012).

Fire risk and the associated losses depend on the farmer and neighbours' fire use and control choices. If there was no fire risk and we hypothetically set aside other issues such as financial capital access, cultural practices, and access to markets for inputs and outputs, we might expect all smallholders to specialize in land use type B, since it generally leads to higher revenues and because mixing A and B land use types would result in higher fire risk for land use B (Figure 1). However, when there is a high fire risk, a farmer fully specializes in the fire intensive good A. Thus, fire risk has to be below a certain threshold for farmers to be financially motivated to pursue the fire-free land use. Otherwise, they will be trapped in the high fire risk and fire-intensive technology with lower, but less uncertain revenues. This implies that farmers in a given region of common fire risk exposure have an incentive to coordinate on A or B land uses (for example by simultaneously increasing investments in fire control or shifting to fire-free land use types). Coordination to adopt fire-free land uses could lead to higher payouts for all, but without coordination to mitigate fire risk, no farmer has an incentive to adopt higher value land uses.

Capital scarcity (the lack of financial resources) can also explain specialization in A. Here we assume that credit is not available in the short term due to a lack of secure land tenure and high indebtedness, conditions that are common in the study region and the broader Amazon basin (Barbier et al., 2016; Fearnside, 2001; Pereira et al., 2016). If the household is not able to borrow money or to make assets liquid, then they cannot invest in the required technologies to make land use B a viable option, regardless of their fire risk.

Under the above assumptions, the fire risk threshold is higher for (relatively) capital abundant households because the expected revenue produced under full specialization in land use type B is higher. This means that capital abundant households have a higher opportunity cost of switching to A, and thus a potentially higher tolerance to fire losses. Yet, since type B producers have more production value to lose and tolerate higher losses before switching to A (as a result of being more capital abundant), we expect higher losses among type B producers than type A (Figure 1).

## 3. Identification strategy, specification and estimation

In order to estimate the impact of fire risk externalities, we model farm revenue as a function of the variables included in the profit function below. We analyze revenue instead of profits, because as our survey data shows, the latter is often negative in the study region (see Section 4.1).

Several challenges should be considered to achieve causal identification. Little or no access to land and capital markets make revenue and input use – including fire – simultaneous, violating the zero conditional mean assumption. Because fire risk is a function of one's own fire use, fire risk is also endogenous. Last, as discussed in Section 4.2, fire risk is measured with errors, biasing OLS estimates downward.

|  |  | Fire risk: Low | Fire risk: Medium | Fire risk: High |
|---|---|---|---|---|
| Capital availability | Low | Land Use B | Land Use A | Land Use A |
|  | Medium | Land Use B | Land Use A | Land Use A |
|  | High | Land Use B | Land Use B | Land Use A |
| Outcome |  | Little fire use and/or high fire control investments, little or no degraded and flammable landscape | Medium fire use and fire control investments, moderately degraded and flammable landscape | High fire use, low fire control investments, highly degraded and flammable landscape |

**Fig. 1. Economically-optimal land uses for individual smallholder households as a function of capital availability and fire risk.** Land use A is low revenue, fire-intensive, and little exposed to fire risk; land use B is high revenue, less fire-intensive, and highly exposed to fire risk. When fire risk is high, all farmers are expected to reduce risk exposure choosing land use A (such as extensive cattle ranching), and investing little in fire control. As a result, fire risk will stay high. Where fire risk is low, all farmers have greater incentive to pursue land use B (a capital intensive, fire-free practice, such as more intensive ranching or cocoa production), and fire risk will stay low. When fire risk is medium, a mixture of land uses is observed. Low and medium capital farmers choose land use A, but farmers with higher levels of capital have a greater opportunity cost (in terms of potential revenue) associated with not choosing land use B and thus a higher risk threshold to meet before choosing land use A.

The empirical revenue function is defined as:

$$\ln(y_i) = b_0 + b_1 S_{Ai} + b_2 S_{Ai} \sum_{j\neq i} S^q_{Aj} + b_3 S_{Bi} \sum_{j\neq i} S^q_{Aj} \;+ \sum_{k} \gamma_{ki} X_{ki} + \varepsilon_i \tag{1}$$

Where $b_1$ captures the lower revenue of adopting a fire intensive land use type A on the $i^{th}$ farmer's land, $b_2$ and $b_3$ are the fire risk semi-elasticities for each land use type (i.e., the percentage change in revenue for a one unit increase in fire count), fire risk is the sum of the other ($j \neq i$) farmers' fire use, and $X$ is a set of production inputs, household and land specific control variables (see Tables 1 and 2). We test the hypothesis that fire risk is an issue of coordination: a difference in fire risk semi-elasticities between farmers adopting A and B land use types ($b_3 - b_2$), if positive, indicates strategic complementarities in fire use, and the negative coefficient for $b_1$ establishes a lower payoff for land use type A. Turning to the controls, capital stock is possibly endogenous because it is a function of wealth, which is in turn a cumulative function of (unobserved) revenue in the previous years, and because it depends on the level of fire risk. Land availability is assumed to be fixed in the short run and therefore exogenous in this model. Labour is mechanically exogenous; mostly measured through the availability of work in the household, and not the actual labour supplied.

To address reverse causality, we used lagged values of fire risk, which are weakly exogenous to revenue. Capital stock and fire use are also predetermined. Yet, using lagged and predetermined regressors might not be sufficient to achieve identification. If revenue is serially correlated, unobserved lags of revenue are part of the error term. Then, correlation between the error and the lagged values of fire use, fire risk and of capital stock (a cumulative function of revenue) persist, causing endogeneity. We address it by means of instrumental variables and generalized method of moments estimation (IVgmm). Instrumental variables are correlated with the outcome variable, but only through the endogenous variable, therefore providing for exogenous variation in fire use, fire risk and capital stock. Instruments are also expected to address the second problem, the attenuation bias originating from detection error of fire risk. We also address detection error of fire risk using a variety of definitions and robustness tests, as discussed in Section 4.2.

Because we were not able to find exogenous and relevant instruments in the dataset, we generated instrumental variables from heteroskedasticity restrictions using the procedure from Lewbel (2012), generalizing the work of Lewbel (1997) and Rigobon (2003). The method assumes that, for a triangular model composed by equations for the outcome and the endogenous regressors, there are some exogenous variables that are correlated with the error variance in the outcome equation, but not with the covariance of the errors of the outcome and endogenous regressor equations. These variables and the errors can be used to generate valid and exogenous instruments. Detecting homoskedasticity in the outcome equation and heteroskedasticity in the endogenous regressors equation assess the method validity and identification, as we test for (details of the methods and requirements for this application are reported in the SI).

Although non-standard, the Lewbel (2012) procedure is related to other identification methods based on functional form and heteroskedasticity restrictions (Bun and Harrison, 2018; Fiorentini et al., 2003; Klein and Vella, 2009, 2010; Sentana and Fiorentini, 2001), see Lewbel (2018) for a review. This method has also been applied in a variety of fields. Among others, Arcand et al. (2015) identify the impact of financial depth on economic growth, Millimet and Roy (2016) identify the impact of weak environmental regulation in creating pollution havens, Mallick (2012) identifies the impact of microfinance on moneylender interest rates and Eichengreen and Panizza (2016) identify the role of economic growth on primary surplus. To our knowledge, this is the first application to a land use study.

The models are estimated in log-level form, robustness tests for level-level and log-log are reported in the supplementary material and tested against each other with a Ramsey reset test.

Following Battese (1997) and Klemick (2011), we deal with non-essential inputs in the log-log model by adding a dummy that takes value one when the input is not used, and substituting all zeros with ones in the input variable before log transformation. The dummy for no fire risk is also instrumented with generated instruments.

Results of identification tests of these and of the models for robustness check are reported in the SI.

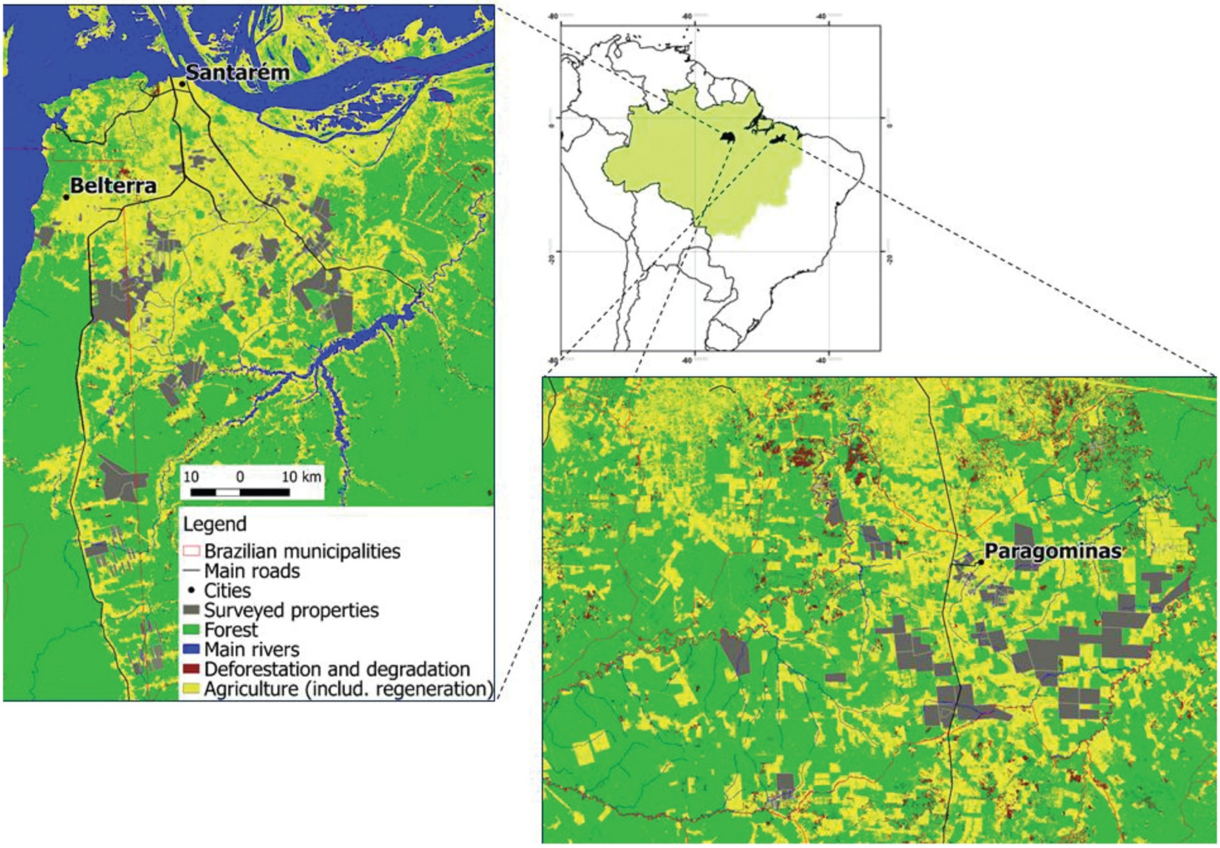

**Fig. 2. Locations of properties sampled in the Eastern Amazon.** The figure to the left shows the study region of greater Santarém, which includes the counties of Santarém, Belterra, and Mojui dos Campos. The figure to the right shows the study region of Paragominas. In total we surveyed 499 properties. Land use maps are obtained through Landsat images classified using a decision tree algorithm described in (Gardner et al., 2013).

## 4. Data and study area

### 4.1. Survey data and study area

Survey and watershed level data were collected in 2010-2011 in the municipalities of Paragominas and Santarém, in the state of Pará, Brazil (Figure 2) (See Gardner et al. (2013). These municipalities are representative of broader trajectories of fire use and persistent rural poverty in Amazonia in a consolidated farm-forest frontier setting. The database has a two-level structure: property and households. 32 households owned more than one property, while others lived together on one property. The first group was discarded because identifying each property's contribution to production was not possible. This in turn would have confounded the impact of fire risk externalities, which is a property attribute. Households that reported no farming activity were also discarded from the analysis. When more than one household lived on the same property, relevant variables were averaged (e.g., for farm size) or summed-up (e.g., for household size and labour). The analysis is conducted only among small farmers, owning up to 4 fiscal lots as defined by the Brazilian law (8.629/93) - 55 ha in Santarém and 75 ha in Paragominas (INCRA, 2013). This is because large landholders are relatively less exposed to neighbors on a per hectare basis and own the means to perform effective fire-fighting. For them, the strategic interaction object of this paper is most likely irrelevant.

### 4.2. Definition of fire risk

As described in the analytical model, fire is a source of risk in two ways: directly, through actual damages and indirectly by reducing the expected revenues associated with investment in a fire-free land use type. We define fire risk as the number of fire occurrences as measured by MODIS FIRMS collection 6 data (NASA, 2018) in a buffer of the property between the beginning of June and the end of May of the following year (approximate beginning of the fire season) of each of the four years preceding 2009 (Figure 3). We only retain fire points with more than 30% confidence. This approach uses the best data publicly available, but is subject to measurement error originating from cloud distortion, detection precision, and from unobserved fire control investments. Measurement error from cloud distortion and detection precision are dealt with by considering a large time frame (4 years), an array of buffer definitions, from 1 to 5 km, and instrumental variables. We generate valid and relevant instruments that satisfies the assumptions of the Lewbel (2012) method for all log-level models with full specification. Since we lack data on fire control, we are forced to assume that all fires contribute equally to fire risk, which is not accurate as fire risk depends on what is burning, unobservable landscape features, as well as on the implementation of appropriate fire control measures. Moreover, risk perception is likely to be driven by risk exposure and previous experiences and might systematically deviate from objective risk (Slovic, 1987). These limitations are discussed below.

### 4.3. Definition of revenue, fire use, and other variables

We define fire users as those respondents who reported using an agricultural fire at least once in the previous four years for consistency with the definition of fire risk and because fire is not used by farmers every year. Land area is measured as property size (instead of farmed area, which might be endogenous). We account for labour as the sum of the labour days provided by the household and by the hired workers on the property normalized for the productivity (as proxied by wage).

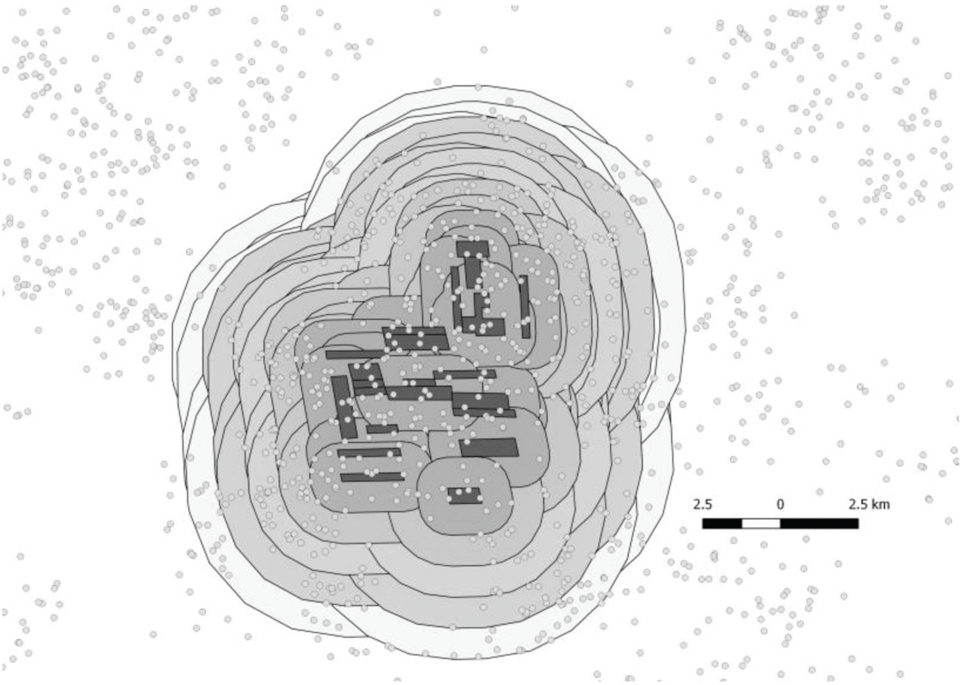

**Fig. 3. Definition of fire risk around Amazonian smallholdings.** Dark polygons are a subsample of the properties analysed, and dots are 2008 fires identified from MODIS FIRMS collection 6. Fire risk is defined as the fire count in a 1 to 5 km buffers around each property (lighter grey).

Quality of labour and farming knowledge are proxied with a dummy for technical assistance and the years of education received by the highest educated member of the household. Household head gender and age are also introduced to account for the household life cycle, which affects the farm productivity (Perz and Walker, 2002).

Quality of land is captured by reported water access, farm slope and a soil quality principal component of acidity, silt and clay composition at the watershed level. Acidity, silt and clay together are indicators of soil quality in the tropical oxisol and ferrasols soils (Reed and Wood, 2016) characterizing our study area. Farm slope was computed in Qgis from the 30m resolution Shuttle Radar Topography Mission (SRTM) digital elevation model, which appears to perform better than other digital elevation models in tropical forested areas (Wong et al., 2014). We include farmer-reported travel time to the nearest city to account for differentiated market access.

Physical capital is measured by aggregating several items into a single variable using a principal component analysis (PCA). Physical capital measure includes the amount of chemical inputs and machinery, cattle stock and the kilometres of wire fences in the property. The capital principal component score is never log-transformed, because it assumes negative values.

## 5. Results

### 5.1. How does fire usage relate to capital availability?

The fire occurrence and farm survey data reveal the severity of fire use and fire risk in the Eastern Brazilian Amazon (Table 1). An average of 5 to 62 fires were detected respectively in the 1 and 5 km neighbourhood of each property in the 4 years preceding 2009. In the same period 78% of farmers used fire for agriculture at least once. Compared to non-fire users, farmers using fire were poorer (with a revenue of 5.7 BRL per day per capita vs 33.46 BRL for non-fire users), have substantially lower capital (chemical inputs and mechanization, pasture fences and own less cattle) and labour, and their land was farther from the market.

### 5.2. How does fire risk influence household revenue and does this impact differ between fire users and non-fire users?

Fire users had substantially higher fire risk than non-fire users. The impact of fire risk on revenue is large and significant for non-fire users, but not significant for fire users. Results for the full specification for a 4km buffer (Table 2, models 1 and 2) show that if fire risk increased by one standard deviation (SD), for instance because of a drought, the farm revenue of non-fire users would fall by 84% $((e^{-0.0287}-1)*29.79)$, compared to near-zero losses for fire users. The difference in fire risk impacts between fire users and non-fire users is highly significant, supporting the hypothesis that fire use decisions exhibit coordination challenges between neighbours that create lock-in.

Fire-intensive land use types have significantly lower revenue as evidenced by the large negative coefficient for "Fire user". If the farmer would convert their land use type from fire-free to fire-intensive, his or her revenue would fall by 63% $(e^{-0.990}-1)$. Yet, due to the damages from nearby fires, using fire might result in a higher revenue than continuing farming without fire. Assuming risk neutrality and holding other factors constant, a 69% increase in fire risk (less than one SD) would entirely offset the benefits of producing without fire, making the farmer indifferent between bearing the losses from fire risk or switching to fire use (Figure 4).

These are conservative estimates of the likely revenue losses associated with non-fire land uses from fire risk for the two study regions. First, due to the large measurement error in fire detection and unobservable risk perceptions, there is likely attenuation bias of coefficient estimates even after IV correction. Second, estimating fire risk impact on revenue rather than profit does not account for the higher input costs of fire-free land use types. Third, fire damages might relate more directly to risk exposure (invested capital inputs), rather than fire use (the result of a risk adapting behaviour). The capital principal component might capture part of risk exposure, and therefore part of the fire risk externality impact related to allocative inefficiency. A more parsimonious specification excluding endogenous controls (capital and labor) is estimated (Table 2, models 3 and 4). OLS – but not IV – estimates of revenue semi-elasticities to fire risk increase in size and

**Table 1**
Summary statistics.

| | N | mean | sd | min | max | N | mean | sd | min | max | N | mean | sd | min | max | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Whole sample | | | | | Fire users | | | | | Non fire users | | | | | t-test p-values |
| Farm revenue 2009 (BRL) | 331 | 11,981 | 31,424 | 2.6 | 291,125 | 258 | 6,157 | 9,473 | 2.6 | 70,602 | 73 | 32,564 | 60,453 | 73 | 291,125 | 0.0000 |
| Per capita per day farm revenue | 283 | 12.08 | 50.61 | 0.0123 | 775.1 | 218 | 5.708 | 12.27 | 0.0123 | 96.71 | 65 | 33.46 | 100.9 | 0.0187 | 775.1 | 0.0001 |
| Log- farm revenue | 331 | 8.144 | 1.581 | 0.956 | 12.58 | 258 | 7.996 | 1.338 | 0.956 | 11.16 | 73 | 8.666 | 2.170 | 4.290 | 12.58 | 0.0013 |
| Fire user | 331 | 0.779 | 0.415 | 0 | 1 | | | | | | | | | | | |
| Fire risk 05-08 (1km) | 331 | 5.405 | 6.798 | 0 | 40 | 258 | 5.806 | 6.914 | 0 | 33 | 73 | 3.986 | 6.213 | 0 | 40 | 0.0433 |
| Fire risk 05-08 (2km) | 331 | 14.92 | 17.07 | 0 | 93 | 258 | 16.21 | 17.97 | 0 | 90 | 73 | 10.36 | 12.45 | 1 | 93 | 0.0094 |
| Fire risk 05-08 (3km) | 331 | 28.04 | 30.68 | 0 | 152 | 258 | 30.25 | 32.70 | 0 | 150 | 73 | 20.22 | 20.45 | 4 | 152 | 0.0135 |
| Fire risk 05-08 (4km) | 331 | 44.00 | 46.35 | 2 | 229 | 258 | 47.31 | 49.60 | 2 | 229 | 73 | 32.27 | 29.79 | 7 | 203 | 0.0142 |
| Fire risk 05-08 (5km) | 331 | 61.99 | 61.70 | 2 | 315 | 258 | 66.23 | 65.97 | 2 | 315 | 73 | 47 | 40.26 | 12 | 261 | 0.0185 |
| Travel time to city (hours) | 331 | 1.965 | 1.185 | 0.0833 | 5.500 | 258 | 2.157 | 1.147 | 0.0833 | 5.500 | 73 | 1.287 | 1.066 | 0.0833 | 5 | 0.0000 |
| Paragominas | 331 | 0.266 | 0.442 | 0 | 1 | 258 | 0.252 | 0.435 | 0 | 1 | 73 | 0.315 | 0.468 | 0 | 1 | 0.2825 |
| Farm size (ha) | 331 | 47.47 | 49.49 | 1 | 300 | 258 | 45.95 | 45.94 | 1 | 300 | 73 | 52.82 | 60.45 | 1 | 283 | 0.2956 |
| Maximum slope | 331 | 22.37 | 11.32 | 4.617 | 57.99 | 258 | 23.09 | 11.51 | 5.186 | 57.99 | 73 | 19.81 | 10.27 | 4.617 | 52.34 | 0.0285 |
| Soil quality | 331 | -0.0365 | 1.232 | -2.402 | 10.22 | 258 | -0.234 | 0.838 | -2.402 | 1.419 | 73 | 0.660 | 1.955 | -1.812 | 10.22 | 0.0000 |
| Water access on farm | 331 | 0.592 | 0.492 | 0 | 1 | 258 | 0.585 | 0.494 | 0 | 1 | 73 | 0.616 | 0.490 | 0 | 1 | 0.6336 |
| Technical assistance | 331 | 0.287 | 0.453 | 0 | 1 | 258 | 0.298 | 0.458 | 0 | 1 | 73 | 0.247 | 0.434 | 0 | 1 | 0.3886 |
| Used tractor 2009 | 331 | 0.236 | 0.497 | 0 | 3 | 258 | 0.116 | 0.321 | 0 | 1 | 73 | 0.658 | 0.731 | 0 | 3 | 0.0000 |
| Capital principal component | 331 | -0.0417 | 2.726 | -2.706 | 18.76 | 258 | -0.666 | 1.694 | -2.706 | 9.397 | 73 | 2.166 | 4.180 | -2.142 | 18.76 | 0.0000 |
| Log of total labour days | 331 | 5.025 | 2.668 | -0.693 | 8.705 | 258 | 4.879 | 2.704 | -0.693 | 8.135 | 73 | 5.540 | 2.488 | 0 | 8.705 | 0.0613 |
| Cattle heads 2009 | 331 | 15.37 | 61.78 | 0 | 840 | 258 | 9.543 | 31.63 | 0 | 350 | 73 | 35.96 | 115.6 | 0 | 840 | 0.0012 |
| Household head male | 331 | 0.828 | 0.361 | 0 | 1 | 258 | 0.824 | 0.369 | 0 | 1 | 73 | 0.839 | 0.337 | 0 | 1 | 0.7587 |
| Household head age | 331 | 51.88 | 12.85 | 23 | 84 | 258 | 52.32 | 13.21 | 23 | 84 | 73 | 50.36 | 11.46 | 30.50 | 73.50 | 0.2505 |
| Household size | 331 | 4.045 | 3.231 | 0 | 20 | 258 | 3.996 | 3.248 | 0 | 20 | 73 | 4.219 | 3.185 | 0 | 17 | 0.6033 |
| Max education in household | 331 | 5.668 | 3.212 | 0 | 16 | 258 | 5.550 | 2.964 | 0 | 16 | 73 | 6.082 | 3.964 | 0 | 16 | 0.2123 |

**Table 2**
Estimate Results for different specifications for fire risk defined over a 4Km buffer.

| | (1)<br>OLS | (2)<br>IVgmm | (3)<br>OLS | (4)<br>Ivgmm | (5)<br>OLS | (6)<br>Ivgmm |
|---|---|---|---|---|---|---|
| Fire risk (non-fire user) | -0.0138 | -0.0287*** | -0.0167** | -0.0286*** | | |
| | (0.00883) | (0.00975) | (0.00770) | (0.00882) | | |
| Fire risk (fire user) | 0.00226 | 0.00229 | -5.49e-05 | 0.000298 | | |
| | (0.00192) | (0.00262) | (0.00195) | (0.00254) | | |
| Fire risk (all) | | | | | 0.000420 | -0.000653 |
| | | | | | (0.00224) | (0.00366) |
| Fire user | -0.541 | -0.990** | -0.868** | -1.396*** | 0.0141 | 0.0306 |
| | (0.387) | (0.436) | (0.364) | (0.438) | (0.250) | (0.331) |
| Capital (pc) | 0.175*** | 0.206*** | | | 0.175*** | 0.207*** |
| | (0.0465) | (0.0667) | | | (0.0480) | (0.0706) |
| Labour days | 3.70e-05 | -3.49e-05 | | | 6.47e-05 | 2.53e-05 |
| | (0.000263) | (0.000261) | | | (0.000259) | (0.000259) |
| Farm size | -0.00234 | -0.00259 | 0.00237 | 0.00271 | -0.00240 | -0.00305 |
| | (0.00241) | (0.00314) | (0.00243) | (0.00246) | (0.00237) | (0.00300) |
| Age household head | -0.0205*** | -0.0188*** | -0.0216*** | -0.0195*** | -0.0213*** | -0.0207*** |
| | (0.00648) | (0.00612) | (0.00681) | (0.00641) | (0.00642) | (0.00615) |
| Male household head | 0.567** | 0.597** | 0.592** | 0.591** | 0.552** | 0.546** |
| | (0.258) | (0.245) | (0.254) | (0.246) | (0.258) | (0.246) |
| Household size | 0.0222 | 0.0265 | 0.0209 | 0.0263 | 0.0163 | 0.0165 |
| | (0.0246) | (0.0243) | (0.0234) | (0.0228) | (0.0240) | (0.0236) |
| Education (years) | -0.0257 | -0.0195 | -0.0141 | -0.0113 | -0.0242 | -0.0251 |
| | (0.0284) | (0.0277) | (0.0299) | (0.0292) | (0.0279) | (0.0270) |
| Soil quality | 0.230*** | 0.235*** | 0.295*** | 0.306*** | 0.251*** | 0.256*** |
| | (0.0560) | (0.0461) | (0.0582) | (0.0453) | (0.0570) | (0.0482) |
| Slope | 0.0287*** | 0.0298*** | 0.0300*** | 0.0305*** | 0.0283*** | 0.0295*** |
| | (0.0104) | (0.0108) | (0.0104) | (0.0108) | (0.0102) | (0.0104) |
| Travel time to the city | -0.0292 | -0.00493 | -0.0981 | -0.0715 | -0.0419 | -0.0174 |
| | (0.0788) | (0.0863) | (0.0798) | (0.0805) | (0.0796) | (0.0905) |
| Technical assistance | 0.0544 | -0.0286 | 0.121 | 0.0593 | 0.114 | 0.107 |
| | (0.208) | (0.190) | (0.224) | (0.209) | (0.217) | (0.211) |
| Water access on farm | 0.296* | 0.282 | 0.499*** | 0.491*** | 0.309* | 0.270 |
| | (0.170) | (0.175) | (0.168) | (0.157) | (0.170) | (0.177) |
| Paragominas | -0.267 | -0.151 | -0.186 | -0.149 | -0.258 | -0.189 |
| | (0.254) | (0.261) | (0.249) | (0.259) | (0.251) | (0.261) |
| Constant | 8.633*** | 8.916*** | 8.702*** | 8.977*** | 8.227*** | 8.238*** |
| | (0.603) | (0.630) | (0.636) | (0.667) | (0.565) | (0.580) |
| Observations | 331 | 331 | 331 | 331 | 331 | 331 |
| R-squared | 0.279 | 0.262 | 0.237 | 0.225 | 0.264 | 0.261 |
| Adjusted R2 | 0.243 | 0.224 | 0.203 | 0.191 | 0.229 | 0.226 |
| F-test | 0.0000 | 0.0000 | 0.000 | 0.000 | 0.0000 | 0.0000 |

(*continued on next page*)

**Table 2** (*continued*)

| | (1) OLS | (2) IVgmm | (3) OLS | (4) Ivgmm | (5) OLS | (6) Ivgmm |
|---|---|---|---|---|---|---|
| Ramsey test for functional form (p-value) | 0.4453 | | 0.3044 | | 0.7363 | |
| Wald test difference p-value | 0.0732 | 0.0014 | 0.0356 | 0.0012 | | |
| Pagan-Hall_p_value | | 0.693 | | 0.723 | | 0.577 |
| Breush-Pagan Fire risk fire users | | 0.0000 | | 0.0000 | | |
| Breush-Pagan Fire risk non fire users | | 0.0000 | | 0.0000 | | |
| Breush-Pagan Fire risk (all) | | | | | | 0.0000 |
| Breush-Pagan Fire user | | 0.0727 | | 0.0727 | | 0.0727 |
| Breush-Pagan Capital pc | | 0.0000 | | | | 0.0000 |
| Hansen J (p-value) | | 0.694 | | 0.547 | | 0.891 |
| K-P rank test (p-value) | | 0.0000 | | 0.0000 | | 0.0000 |
| F statistic | | 14.47 | | 27.43 | | 23.77 |
| F statistic fire risk Fire users | | 22.49 | | 36.68 | | |
| F statistic fire risk Non-fire users | | 25.15 | | 20.89 | | |
| F statistic fire risk | | | | | | 11.34 |
| F statistic fire users | | 35.94 | | 46.75 | | 41.20 |
| F statistic capital pc | | 14.40 | | | | 26.69 |

Robust standard errors in parentheses; *** $p<0.01$, ** $p<0.05$, * $p<0.1$
Note: All covariates are included in regressions, results for other buffer definitions in the supplementary material.

significance, hinting at potential allocative inefficiencies. Finally, we compare these results to a model without interaction between fire risk and land use types (Table 2, models 5 and 6). Fire risk externalities and the dummy for fire users are both small and insignificant, suggesting that interaction with "fire user" dummy captures the relevant heterogeneity in the impact of fire risk externalities.

### 5.3. How do the impacts of fire risk on revenues compare to other factors?

The size of fire risk impact on non-fire users is large compared to other factors of production, such as labour, land quality, and capital stock (Table 2), which suggests that spontaneous coordination to transition out of fire use is unlikely. For example, a one standard deviation increase in manufactured capital increases revenue by 95% $((e^{0.206}-1)*4.2)$, and a one SD increase in soil quality increases revenue by 52% $((e^{0.235}-1)*1.955)$, while a one SD increase in fire risk among non-fire users reduces farm revenue by 84% $((e^{-0.0287}-1)*29.79)$.

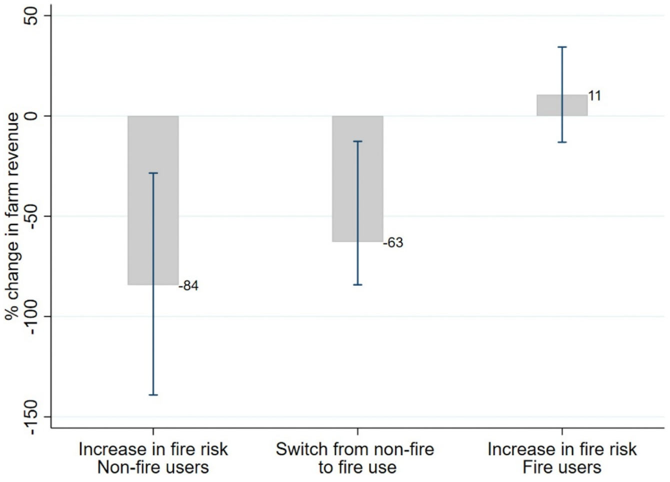

**Fig. 4. Effect of increasing fire risk by 1 standard deviation on farm revenue for non-fire users and fire users, compared to switching from non-fire to fire use.** As the figure shows, a one standard deviation increase in fire risk offsets the benefit of producing a higher yield and fire free land use (B), increasing incentives to produce the more fire intensive land use (A), which is not sensitive to fire risk. If fire risk is too high, there is no incentive to adopt the fire free land use (B). (% changes are calculated based on estimates from model 2 in table 2, for a 4 km buffer definition of fire risk).

Revenue differences were not explained by differences in labour availability. All results are consistently identified for a log-level model across buffers and are robust to covariates exclusion. Impact of fire risk for fire users is significant for a 2 and 3 km buffer, this might be an incidental result, and does not affect our conclusions. Further robustness tests for functional form and exclusion of the exceptional 2005 fires on the definition of fire risk are provided in SI and are supportive of the conclusions established above.

By means of a Ramsey reset test we compare level-level, log-log and log-level specifications across buffer definitions. Level-level is systematically rejected in support of log-level and log-log specifications. Log-level results for fire risk externalities are also similar to log-log estimates (results in the SI).

## 6. Discussion

### 6.1. Fire risk externalities create a vicious cycle

Our results indicate that in the absence of fire risk from neighbouring farms, capital-intensive, fire-free land uses achieve higher yield and revenue than lower capital, fire-intensive land uses. However, under high exposure to fires (the current state of this region), capital-intensive, fire-free land uses are associated with lower revenue than lower capital, fire-intensive land uses. Thus, fire risk reduces the expected revenue of fire-free land uses and incentives to invest in fire control. The continued use of fire-intensive techniques in turn keeps fire risk high, which results in continued fire usage by Amazonian smallholders.

This vicious cycle, which is exacerbated by widespread capital constraints for smallholder farmers (Medina et al., 2015), results in a low-income land use trap that partially explains why 17.5% of households in the North of Brazil earned less than USD 2 per capita per day, and 5.3% earned less than USD 1 in 2014 (IPEA, 2014). Exposure to fire risk from neighbouring properties implies that the low-income land use trap in the Brazil Amazon is economically-rational from an individual land user's perspective and cannot be broken unless coordination for fire risk mitigation is achieved.

We also found that the impact of fire risk on revenue is similar to that of capital, and larger than the one of all other factors. This suggests that fire risk externalities might be one of the most important factors undermining investments in higher value, fire-free intensive production systems among smallholders in the region. Strikingly, a one standard deviation increase in fire risk entirely offsets the increased revenue from fire-free land use types.

### 6.2. Policy implications

Providing subsidies for mechanization (whether for hiring or purchase) and limiting credit to land users who utilize fire are two relatively common strategies for fire risk mitigation that are targeted at individuals. Community level agricultural mechanization programs already exist in the Brazilian Amazon and since 2008 agricultural credit is conditional on compliance with environmental regulations including bans on fire use. Such conditionality – despite being much lower for smallholders (Assunção et al., 2013) – might not achieve more sustainable land uses, if it further tightens capital constraints (lowering tolerance to fire accidents), and disempowers fire users who are already marginalized (Carmenta et al., 2018). Punitive policy measures (i.e., credit exclusion) also exacerbate inequities and the burden of forest degradation and fire control relative to its benefits.

Our results suggest that these "individual focused" policies fail to achieve their goals because transitions to higher value, fire-free land use require coordination. Policies will likely be more effective if they operate on a landscape level, mitigating fire risk in the whole basin of fire contagion. This can be done by targeting contiguous neighbours, settlements or municipalities using direct and indirect incentives – ranging from improved infrastructures and transports to payments for environmental services (PES) – and disincentives, such as bans on uncontrolled fire – command and control (CAC).

In a framed field experiment, also in the Eastern Brazilian Amazon, Cammelli and Angelsen (2019) compare the ability of these two policies to induce coordination for fire risk mitigation. Both policies equally increase the adoption of fire-free techniques, but PES fails to mitigate fire risk because it crowds out fire control investments among the fire users. On the other hand CAC effectiveness is limited by low enforcement capacity by local authorities especially due to measurement error in detection, and budgetary limitations (Morello et al., 2017). Both CAC and PES are likely to suffer from difficulties in defining responsibilities for fire events (Barlow et al., 2012). During drought years fires can spread for tens or hundreds of kilometres, across farms and smallholders' settlements (Alencar et al., 2015; Withey et al., 2018). Such exogenous fire risk hampers coordination locally, reduces incentives for fire control and reduces the scope for conditional payments at the local level (Cammelli and Angelsen, 2019).

PES effectiveness for fire mitigation may be improved by using both landscape (i.e. jurisdictional) and "big push" approaches. Landscape PES schemes increase incentives and capacities for coordination (Battalio et al., 2001; Parkhurst et al., 2002). However, tying payments to collective outcomes when individual action is critical might be perceived as unfair, which could reduce coordination (Drechsler, 2017). The *Big Push* argument (Rosenstein-Rodan, 1961; Sachs and Warner, 1999) states that a minimum level of incentives is needed to overcome coordination failures, which implies that one-time massive PES and CAC incentives are more likely to succeed than smaller step-by-step incentives. Moreover, because of the higher yields associated with fire-free technologies, the outcome of a successful one-time intervention is likely stable over time.

### 6.3. Limitations and future work

Our analysis assumes that fire risk is objective, known *ex-ante* to the farmer who is risk neutral, selfish and a utility maximizer, and that the related losses are also known. However, subjective risk perceptions (Slovic, 1987), subjective beliefs about neighbours' actions, and social norms are likely affecting the farmer's choice, since causing wildfires is never socially approved (Cammelli et al., 2019). Farmers are also likely to have preference for diversification of land use types, as this enhances food security and allows hedging against other risks (e.g. price variations, diseases etc). A farmer perceiving high fire risk, with a preference for diversification and/or concern for neighbours' well-being that cannot invest in fire-free land use types is likely to invest in fire control to prevent burning his or her own crops and/or those of neighbours. In this case, coordination for fire risk mitigation results mainly from fire use with enhanced fire control, rather than a change in land use type. This pattern is indeed largely observed in the data. Fire control is a pragmatic fire risk mitigation strategy in the short term, and a necessary step for a transition out of fire use. Still, too little is known about fire control behaviour, or what is burning. To better understand these dynamics, better distinction of remotely sensed accidental and intended fires is needed (e.g., Cano-Crespo et al., 2015).

We assumed that land uses are discrete and mutually exclusive (production can only be specialized in a low capital, low return, fire-intensive land use or a high capital, high return, fire-free land use). However, some land uses might reside in between the two extreme land use types considered so far. Horticulture, for instance, requires some sunk costs and capital for irrigation, pesticides and fertilizers, but is likely unaffected by accidental fires. Moreover, compared to other systems, horticulture provides more substitutability between capital and labour: cash constrained households can irrigate and weed manually and produce fertilizer on their farm (cf. Cravo et al., 2005). However, these land use types are fairly rare in the Amazon and tend to be constrained to peri-urban zones (Garrett et al., 2017). In general, land use types that do not increase fire risk exposure and offer substitutability between capital and labour potentially pave the way for a transition to fire-free systems, and deserve further investigation. Our results do not necessarily advocate for widespread use of machinery and chemical inputs. These might result in increased incentives to convert forest to agriculture (Morello et al., 2017), health related issues (Pedlowski et al., 2012) and might further concentrate power, capital and land, causing disenfranchisment of poorer households (Patel, 2013). Mechanization offers economies of scale and currently, subsidized credit for buying tractors in Brazil is strongly skewed towards agribusiness (Graeub et al., 2016).

Our analyses only concern the short run. Longitudinal data would allow unravelling long-term dynamics related to land use change, land acquisition, and capital accumulation (cf. Mullan et al., 2017). Additionally, our results might be affected by the high incidence of fires in our two study regions, typical of Amazonian post-frontiers and consolidated frontiers. New studies could assess the replicability of our findings to other parts of the Amazon or elsewhere in the tropics in regions with different landscape, social and climatic features affecting fire ignition and propagation. Except for the Amazon, Andela et al. (2017) found a worldwide decreasing trend of fires, mostly associated with higher GDP and previous land conversion to agriculture. Fire management outside the Amazon might still have features of strategic interaction, but mostly related to preventive fire control investments (Shafran, 2008) and fire-fighting (Orszag and Stiglitz, 2002). The impact of fire risk externalities on farm and homeowner decisions can be substantial. However, the policy implications would be entirely different than in the Amazon.

## 7. Conclusion

Deforestation, forest degradation and persistent poverty remain pressing challenges in the Brazilian Amazon (Alencar et al., 2015; Aragão et al., 2016; Aragao and Shimabukuro, 2010; Medina et al., 2015). These challenges derive from the fact that many smallholders in the frontier and post frontier regions are locked into a pattern of low yield and highly-degrading agricultural practices (Garrett et al., 2017). Numerous factors contribute to the persistence of these types of land use practices, including historical legacies, political instability, market failures and cultural lock-in. Our results indicate that fire risk is also an important factor, because it traps smallholders into choosing low-capital and fire intensive strategies – such as extensive cattle ranching and swidden crops – to avoid major revenue losses when fires occur. Overcoming the high fire poverty trap to move toward higher value land uses – such as agroforestry, horticulture or mechanized agriculture

– is extremely challenging because it requires neighboring farmers to reduce their fire usage simultaneously.

Potential solutions to the problem of persistent uncontrolled fire usage include enforcing fire control and subsidizing the uptake of fire-free agricultural systems that require little initial investments and have good substitutability between capital and labor (e.g., horticulture and mixed cropping). Programs to increase access to loans for machinery or improve community programs for machinery lending or hiring may also be a successful mechanism to reduce fire risk. To overcome fire risk coordination thresholds, these policy interventions must target whole communities, not individual farms, and eventually concentrate incentives in a larger upfront payment (*Big Push*). Group contracts for neighbors accessing PES, transfers, credit and technical assistance would also raise the premium of coordinating for fire risk mitigation.

Though large and coordinated investments toward fire risk mitigation may seem costly and daunting due to their scope and scale, their benefits are likely to greatly outweigh their costs due to synergies between fire control and other development and conservation objectives. Fire mitigation, by freeing people of the vicious cycle of fire risk and low investment, has the potential to achieve a triple-win by simultaneously reducing carbon emissions and forest degradation and improving the incomes of local people.

## Authorship declaration

**Federico Cammelli:** *Conceptualization, Methodology, Validation, Formal analysis, Writing – Original draft, Writing – Review & Editing, Visualization;* **Rachael Garrett:** *Investigation, Resources, Data curation, Writing – Review & Editing, Visualization;* **Jos Barlow:** *Investigation, Resources, Project administration, Funding acquisition, Writing – Review & Editing;* **Luke Parry:** *Investigation, Resources, Project administration, Writing – Review & Editing.*

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2020.102096.

## References

Alencar, A.A., Brando, P.M., Asner, G.P., Putz, F.E., 2015. Landscape fragmentation, severe drought, and the new Amazon forest fire regime. Ecological applications 25, 1493–1505.

Andela, N., Morton, D., Giglio, L., Chen, Y., van der Werf, G., Kasibhatla, P., DeFries, R., Collatz, G., Hantson, S., Kloster, S., 2017. A human-driven decline in global burned area. Science 356, 1356–1362.

Anderson, L.O., Aragão, L.E., Gloor, M., Arai, E., Adami, M., Saatchi, S.S., Malhi, Y., Shimabukuro, Y.E., Barlow, J., Berenguer, E., 2015. Disentangling the contribution of multiple land covers to fire-mediated carbon emissions in Amazonia during the 2010 drought. Global Biogeochemical Cycles 29, 1739–1753.

Aragão, L.E., Anderson, L.O., Lima, A., Arai, E., 2016. Fires in Amazonia, Interactions Between Biosphere. Atmosphere and Human Land Use in the Amazon Basin. Springer, pp. 301–329.

Aragao, L.E., Shimabukuro, Y.E., 2010. The incidence of fire in Amazonian forests with implications for REDD. Science 328, 1275–1278.

Arcand, J.L., Berkes, E., Panizza, U., 2015. Too much finance? Journal of Economic Growth 20, 105–148.

Assunção, J., Gandour, C., Rocha, R., Rocha, R. (2013) Does Credit Affect Deforestation? Evidence from a Rural Credit Policy in the Brazilian Amazon. Climate Policy Initiative, Núcleo de Avaliação de Políticas Climáticas, PUC-Rio de Janeiro.

Barbier, E.B., López, R.E., Hochard, J.P., 2016. Debt, poverty and resource management in a rural smallholder economy. Environmental and resource economics 63, 411–427.

Barlow, J., Berenguer, E., Carmenta, R., França, F., 2019. Clarifying Amazonia's burning crisis. Global change biology. https://doi.org/10.1111/gcb.14872.

Barlow, J., Lennox, G.D., Ferreira, J., Berenguer, E., Lees, A.C., Nally, R.M., Thomson, J.R., Ferraz, S.F.d.B., Louzada, J., Oliveira, V.H.F., Parry, L., Ribeiro de Castro Solar, R., Vieira, I.C.G., Aragão, L.E.O.C., Begotti, R.A., Braga, R.F., Cardoso, T.M., d.O. Jr, R.C., Souza Jr, C.M., Moura, N.G., Nunes, S.S., Siqueira, J.V., Pardini, R., Silveira, J.M., Vaz-de-Mello, F.Z., Veiga, R.C.S., Venturieri, A., Gardner, T.A., 2016. Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation. Nature 535 (7610), 144.

Barlow, J., Parry, L., Gardner, T.A., Ferreira, J., Aragão, L.E.O.C., Carmenta, R., Berenguer, E., Vieira, I.C.G., Souza, C., Cochrane, M.A., 2012. The critical importance of considering fire in REDD+ programs. Biological Conservation 154, 1–8.

Battalio, R., Samuelson, L., Van Huyck, J., 2001. Optimization incentives and coordination failure in laboratory stag hunt games. Econometrica 69, 749–764.

Battese, G.E., 1997. A note on the estimation of Cobb-Douglas production functions when some explanatory variables have zero values. Journal of agricultural Economics 48, 250–252.

Berenguer, E., Ferreira, J., Gardner, T.A., Aragão, L.E.O.C., De Camargo, P.B., Cerri, C.E., Durigan, M., Oliveira, R.C.D., Vieira, I.C.G., Barlow, J., 2014. A large-scale field assessment of carbon stocks in human-modified tropical forests. Global change biology 20, 3713–3726.

Bowman, M.S., Amacher, G.S., Merry, F.D., 2008. Fire use and prevention by traditional households in the Brazilian Amazon. Ecological Economics 67, 117–130.

Brazil (2012) Brazilian Forest Code, Chap. IX, law 12651/2012.

Bun, M.J., Harrison, T.D., 2018. OLS and IV estimation of regression models including endogenous interaction terms. Econometric Reviews.

Cammelli, F., Angelsen, A., 2019. Amazonian farmers' response to fire policies and climate change. Ecological Economics 165, 106359.

Cammelli, F., Coudel, E., Alves, L.d.F.N., 2019. Smallholders' Perceptions of Fire in the Brazilian Amazon: Exploring Implications for Governance Arrangements. Human Ecology 47, 601–612.

Campanharo, W.A., Lopes, A.P., Anderson, L.O., da Silva, T.F., Aragão, L.E., 2019. Translating fire impacts in southwestern amazonia into economic costs. Remote Sensing 11, 764.

Cano-Crespo, A., Oliveira, P.J., Boit, A., Cardoso, M., Thonicke, K., 2015. Forest edge burning in the Brazilian Amazon promoted by escaping fires from managed pastures. Journal of Geophysical Research: Biogeosciences 120, 2095–2107.

Carmenta, R., Coudel, E., Steward, A.M., 2018. Forbidden fire: Does criminalising fire hinder conservation efforts in swidden landscapes of the Brazilian Amazon? The Geographical Journal 185 (1), 23–37.

Carmenta, R., Vermeylen, S., Parry, L., Barlow, J., 2013. Shifting cultivation and fire policy: insights from the Brazilian Amazon. Human Ecology 41, 603–614.

Cochrane, M.A., 2003. Fire science for rainforests. Nature 421, 913–919.

Cravo, M.d.S., Cortelletti, J., Nogueira, O.L., Smyth, T.J., De Souza, B., 2005. Sistema Bragantino: agricultura sustentável para a Amazônia. Embrapa Amazônia Oriental-Documentos (INFOTECA-E).

de Mendonça, M.J.C., Vera Diaz, M.d.C., Nepstad, D., Seroa da Motta, R., Alencar, A., Gomes, J.C., Ortiz, R.A., 2004. The economic cost of the use of fire in the Amazon. Ecological Economics 49, 89–105.

De Sartre, X.A., Taravella, R., 2009. National sovereignty vs. sustainable development lessons from the narrative on the internationalization of the Brazilian Amazon. Political geography 28, 406–415.

Diaz, M.d.C.V., Nepstad, D., Mendonça, M.J.C., da Motta, R.S., Alencar, A., Gomes, J.C., Ortiz, R.A., 2002. O preço oculto do fogo na Amazônia: Os custos econômicos associados as queimadas e incêndios florestais. Relatório Instituto de Pesquisa Ambiental da Amazônia (IPAM)/Instituto de Pesquisa Econômica Aplicada (IPEA)/Centro de Pesquisa Woods Hole.

Drechsler, M., 2017. The Impact of Fairness on Side Payments and Cost-Effectiveness in Agglomeration Payments for Biodiversity Conservation. Ecological Economics 141, 127–135.

Eichengreen, B., Panizza, U., 2016. A surplus of ambition: can Europe rely on large primary surpluses to solve its debt problem? Economic Policy 31, 5–49.

Fearnside, P.M., 2001. Land-tenure issues as factors in environmental destruction in Brazilian Amazonia: the case of southern Pará. World Development 29, 1361–1372.

Fiorentini, G., Sentana, E., Calzolari, G., 2003. Maximum likelihood estimation and inference in multivariate conditionally heteroscedastic dynamic regression models with student t innovations. Journal of Business & Economic Statistics 21, 532–546.

Gardner, T.A., Ferreira, J., Barlow, J., Lees, A.C., Parry, L., Vieira, I.C.G., Berenguer, E., Abramovay, R., Aleixo, A., Andretti, C., 2013. A social and ecological assessment of tropical land uses at multiple scales: the Sustainable Amazon Network. Phil. Trans. R. Soc. B 368, 20120166.

Garrett, R.D., Gardner, T.A., Morello, T.F., Marchand, S., Barlow, J., Ezzine de Blas, D., Ferreira, J., Lees, A.C., Parry, L., 2017. Explaining the persistence of low income and environmentally degrading land uses in the Brazilian Amazon. Ecology and Society 22.

Gibbs, H.K., Munger, J., L'Roe, J., Barreto, P., Pereira, R., Christie, M., Amaral, T., Walker, N.F., 2016. Did Ranchers and Slaughterhouses Respond to Zero-Deforestation Agreements in the Brazilian Amazon? Conservation Letters 9, 32–42.

Gibbs, H.K., Rausch, L., Munger, J., Schelly, I., Morton, D.C., Noojipady, P., Soares-Filho, B., Barreto, P., Micol, L., Walker, N.F., 2015. Brazil's soy moratorium. Science 347, 377–378.

Graeub, B.E., Chappell, M.J., Wittman, H., Ledermann, S., Kerr, R.B., Gemmill-Herren, B., 2016. The state of family farms in the world. World development 87, 1–15.

Hoch, L., Pokorny, B., De Jong, W., 2009. How successful is tree growing for smallholders in the Amazon? International Forestry Review 11, 299–310.

Hoch, L., Pokorny, B., Jong, W., 2012. Financial attractiveness of smallholder tree plantations in the Amazon: bridging external expectations and local realities. Agroforestry Systems 84, 361–375.

INCRA, (2013) Indices basicos 2013 por municipio, http://www.incra.gov.br/sites/default/files/uploads/estrutura-fundiaria/regularizacao-fundiaria/indices-cadastrais/indices_basicos_2013_por_municipio.pdf, last access 20/6/19.

Ioris, A.A., 2016. The paradox of poverty in rich ecosystems: impoverishment and development in the A mazon of B razil and B olivia. The Geographical Journal 182, 178–189.

IPEA (2014) http://www.ipeadata.gov.br, last access 20/6/2019.

Klein, R., Vella, F., 2009. A semiparametric model for binary response and continuous outcomes under index heteroscedasticity. Journal of Applied Econometrics 24, 735–762.

Klein, R., Vella, F., 2010. Estimating a class of triangular simultaneous equations models without exclusion restrictions. Journal of Econometrics 154, 154–164.

Klemick, H., 2011. Shifting cultivation, forest fallow, and externalities in ecosystem services: Evidence from the Eastern Amazon. Journal of Environmental Economics and Management 61, 95–106.

Lewbel, A., 1997. Constructing instruments for regressions with measurement error when no additional data are available, with an application to patents and R&D. Econometrica 65, 1201–1213.

Lewbel, A., 2012. Using heteroscedasticity to identify and estimate mismeasured and endogenous regressor models. Journal of Business & Economic Statistics 30, 67–80.

Lewbel, A., 2018. The Identification Zoo-Meanings of Identification in Econometrics. College Department of Economics, Boston.

Mallick, D., 2012. Microfinance and moneylender interest rate: Evidence from Bangladesh. World development 40, 1181–1189.

Medina, G., Almeida, C., Novaes, E., Godar, J., Pokorny, B., 2015. Development conditions for family farming: Lessons from Brazil. World Development 74, 386–396.

Millimet, D.L., Roy, J., 2016. Empirical tests of the pollution haven hypothesis when environmental regulation is endogenous. Journal of Applied Econometrics 31, 652–677.

Morello, T.F., Parry, L., Markusson, N., Barlow, J., 2017. Policy instruments to control Amazon fires: A simulation approach. Ecological Economics 138, 199–222.

Mullan, K., Sills, E., Pattanayak, S.K., Caviglia-Harris, J., 2017. Converting Forests to Farms: The Economic Benefits of Clearing Forests in Agricultural Settlements in the Amazon. Environmental and Resource Economics 1–29.

NASA (2018) MODIS Collection 6 Active Fire Product User's Guide Revision B. http://modis-fire.umd.edu/files/MODIS_C6_Fire_User_Guide_B.pdf.

Nepstad, D., Carvalho, G., Cristina Barros, A., Alencar, A., Paulo Capobianco, J., Bishop, J., Moutinho, P., Lefebvre, P., Lopes Silva, U., Prins, E., 2001. Road paving, fire regime feedbacks, and the future of Amazon forests. Forest ecology and management 154, 395–407.

Nepstad, D., Lefebvre, P., Lopes da Silva, U., Tomasella, J., Schlesinger, P., Solorzano, L., Moutinho, P., Ray, D., Guerreira Benito, J., 2004. Amazon drought and its implications for forest flammability and tree growth: A basin-wide analysis. Global change biology 10, 704–717.

Nepstad, D., McGrath, D., Stickler, C., Alencar, A., Azevedo, A., Swette, B., Bezerra, T., DiGiano, M., Shimada, J., da Motta, R.S., 2014. Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. science 344, 1118–1123.

Nepstad, D.C., Moreira, A.G., Alencar, A.A., 1999. A floresta em chamas: origens, impactos e prevenção de fogo na Amazônia. Programa Piloto para a Proteção das Florestas Tropicais do Brasil. Banco Mundial, Brasília.

Orszag, P., Stiglitz, J., 2002. Optimal fire departments: Evaluating public policy in the face of externalities. The Brookings Institution Jan 4, 2002.

Palm, C., Vosti, S.A., Sanchez, P.A., Ericksen, P.J., 2005. Slash-and-burn agriculture: the search for alternatives. Columbia University Press.

Parkhurst, G.M., Shogren, J.F., Bastian, C., Kivi, P., Donner, J., Smith, R.B., 2002. Agglomeration bonus: an incentive mechanism to reunite fragmented habitat for biodiversity conservation. Ecological Economics 41, 305–328.

Patel, R., 2013. The long green revolution. The Journal of Peasant Studies 40, 1–63.

Pedlowski, M.A., Canela, M.C., da Costa Terra, M.A., de Faria, R.M.R., 2012. Modes of pesticides utilization by Brazilian smallholders and their implications for human health and the environment. Crop Protection 31, 113–118.

Pereira, R., Simmons, C.S., Walker, R., 2016. Smallholders, agrarian reform, and globalization in the Brazilian Amazon: Cattle versus the environment. Land 5, 24.

Perz, S.G., Walker, R.T., 2002. Household life cycles and secondary forest cover among small farm colonists in the Amazon. World Development 30, 1009–1027.

Pokorny, B., Johnson, J., Medina, G., Hoch, L., 2012. Market-based conservation of the Amazonian forests: Revisiting win–win expectations. Geoforum 43, 387–401.

Pollini, J., 2009. Agroforestry and the search for alternatives to slash-and-burn cultivation: From technological optimism to a political economy of deforestation. Agriculture, Ecosystems & Environment 133, 48–60.

Pollini, J., 2014. Slash-and-Burn Agriculture. Encyclopedia of Food and Agricultural Ethics 1648–1657.

Reed, S.C., Wood, T.E., 2016. Soil Phosphorus Cycling in Tropical Soils: An Ultisol and Oxisol Perspective. In: Lal, R., Stewart, B.A. (Eds.), Soil phosphorus. CRC press.

Rigobon, R., 2003. Identification through heteroskedasticity. Review of Economics and Statistics 85, 777–792.

Rosenstein-Rodan, P.N., 1961. Notes on the theory of the 'big push'. Economic Development for Latin America. Springer, pp. 57–81.

Sachs, J.D., Warner, A.M., 1999. The big push, natural resource booms and growth. Journal of development economics 59, 43–76.

Schwartz, N.B., Uriarte, M., Gutiérrez-Vélez, V.H., Baethgen, W., DeFries, R., Fernandes, K., Pinedo-Vasquez, M.A., 2015. Climate, landowner residency, and land cover predict local scale fire activity in the Western Amazon. Global Environmental Change 31, 144–153.

Sentana, E., Fiorentini, G., 2001. Identification, estimation and testing of conditionally heteroskedastic factor models. Journal of econometrics 102, 143–164.

Shafran, A.P., 2008. Risk externalities and the problem of wildfire risk. Journal of Urban Economics 64, 488–495.

Silva, C.V., Aragão, L.E., Barlow, J., Espirito-Santo, F., Young, P.J., Anderson, L.O., Berenguer, E., Brasil, I., Foster Brown, I., Castro, B., 2018. Drought-induced Amazonian wildfires instigate a decadal-scale disruption of forest carbon dynamics. Philosophical Transactions of the Royal Society B: Biological Sciences 373, 20180043.

Simmons, C.S., Walker, R.T., Wood, C.H., 2002. Tree planting by small producers in the tropics: a comparative study of Brazil and Panama. Agroforestry systems 56, 89–105.

Slovic, P., 1987. Perception of risk. Science 236, 280–285.

Smith, L.T., Aragao, L.E., Sabel, C.E., Nakaya, T., 2014. Drought impacts on children's respiratory health in the Brazilian Amazon. Scientific reports 4, 3726.

Sunderlin, W.D., Angelsen, A., Wunder, S., 2003. Forests and poverty alleviation. State of the World's Forests, pp. 61–73.

Withey, K., Berenguer, E., Palmeira, A.F., Espírito-Santo, F.D., Lennox, G.D., Silva, C.V., Aragao, L.E., Ferreira, J., França, F., Malhi, Y., Barlow, J., 2018. Quantifying immediate carbon emissions from El Niño-mediated wildfires in humid tropical forests. Philosophical Transactions of the Royal Society B: Biological Sciences 373, 20170312.

Wong, W.V., Tsuyuki, S., Loki, K., Phua, M., 2014. Accuracy assessment of global topographic data (SRTM & ASTER GDEM) in comparison with lidar for tropical montane forest. In: Proceedings of the 35th Asian Conference on Remote Sensing. Nay Pyi Taw, Myanmar. pp. 27–31.