ISSN: 0378-1127
DOI: 10.1016/j.foreco.2021.119139

12/02/2021

**Increasing bamboo dominance in southwestern Amazon forests following intensification of drought-mediated fires**

Sonaira Souza da Silva[1,2*], Philip Martin Fearnside[2], Paulo Mauricio Lima de Alencastro Graça[2], Izaya Numata[3], Antonio Willian Flores de Melo[1,2], Evandro Linhares Ferreira[2], Luiz Eduardo Oliveira e Cruz de Aragão[4], Edneia Araujo Santos[1], Maury Sérgio Dias[5], Rodrigo Cunha Lima[5], Pedro Raimundo Ferreira de Lima[1]

[1] Federal University of Acre (UFAC), CEP 69980-000, Cruzeiro do Sul, Acre, Brazil [sonaira.silva@ufac.br; willian.flores@ufac.br; edneiasantos_14@hotmail.com; pedro.f5@hotmail.com]

[2] National Institute for Amazon Research (INPA), Av. André Araújo, 2936, CEP 69067-375, Manaus, Brazil [pmfearn@inpa.gov.br; pmlag@inpa.gov.br; evandroferreira@hotmail.com]

[3] Geospatial Sciences Center of Excellence, South Dakota State University (SDSU), Brookings, SD 57007, USA [Izaya.Numata@sdstate.edu]

[4] National Institute for Space Research (INPE). Av dos Astronautas, 1.751. Jd. Da Granja, São José dos Campos, São Paulo, Brazil [laragao@dsr.inpe.br]

[5] Northern Educational Union (UNINORTE), CEP 69915-901, Rio Branco, Acre, Brazil [maury.play@hotmail.com; rcunhabiologia@gmail.com]

*Corresponding author: sonairasilva@gmail.com; sonaira.silva@ufac.br

Postal address: UFAC, CEP 69980-000, Cruzeiro do Sul, Acre, Brazil

**Abstract**
Since the late 1980s the Amazon rainforest has been affected by major forest fires every 3-5 years, mainly in the southwestern portion of the region. Besides the reduction of forest biomass and changes in structure and floristic composition, these forest fires favor the expansion of bamboo in forests in the southwestern Amazon. However, we know little about the impact of fire on bamboo expansion and changes in forest structure. The goal of this study is to quantify forest degradation by fire in areas with bamboo in the eastern portion of the state of Acre, Brazil, based upon a combination of forest-inventory and satellite remote-sensing data. The forest fires were defined by remote sensing as those in which the crowns of the trees were directly or indirectly affected by fire to the point that they cause a detectable impact on the optical satellite images in the 1984-2016 period. We measured trees and bamboo in 6 ha distributed in twelve 0.5-ha plots (100 m × 50 m) in unburned forest, forest burned in 2005, burned forest in 2010 and forest burned in both 2005 and 2010. Our results show change in the structure of the forest with a reduction in the number of live trees as the number of bamboo stalks increases after the forest fires. The amount of breakage and damage to the trees by the bamboo stems can double or triple with the expansion of the bamboo after fire impact. Bamboo expansion was identified based on an increase of the proportion of pixels with near-infrared channel reflectance values > 3500. The impact of forest fires resulted in incursion and dominance of bamboo stems over an area of 120,000 ha, changing the forest type of this area to "bamboo-dominated forest." Our results clearly show that drought-induced forest fires with anthropogenic sources are capable of shifting species composition in southwestern Amazonia towards bamboo-dominated forest. With future climate scenarios indicating more frequent and extensive droughts due to global warming, which, together with the use of fire for new deforestation and for managing pasture and agricultural fields, can be expected to cause more forests in southwestern Amazonia to be exposed to extensive fires and potential increase in bamboo density. These changes are likely to reduce the ecological value of these forests.

**Keywords**
Forest fires; droughts; forest degradation; bamboo; *Guadua*

## 1. Introduction

A dangerous cycle of forest degradation is taking shape in the Amazon as a result of increased frequency of extreme droughts and associated forest fires drastically increasing tree mortality (Brando et al., 2014; Davidson et al., 2012; McDowell et al., 2018). This modifies the floristic composition of Amazonian forests (Barlow et al., 2016, 2003; Xaud et al., 2013) and exacerbates feedbacks with global climate change (Aragão et al., 2018; Berenguer et al., 2014). Amazonian forest fires almost always have anthropogenic origins. In the state of Acre, as well as in most of the Amazon, fire is used after deforestation as a tool to prepare land for agriculture or pasture, and later to renew these land uses (Barbosa and Fearnside, 1999; Fearnside, 1990; Silva et al., 2018). In years of extreme drought, routine farm fires (even small ones) can get out of control and turn into large forest fires (Nepstad et al., 2004, 2008; Silva et al., 2018).

One of the effects of forest fire in Amazonia is the modification of the forest species composition, which can change drastically in a cascade effect due to increased fire recurrence (Barlow and Peres, 2008). In eastern Amazonia, a reduction of live non-pioneer sapling and frequency and density of lianas (vines) by more than 70% has been reported, jeopardizing the recovery of the forest (Cochrane and Schulze, 1999). In Mato Grosso (in southern Amazonia), tree mortality facilitated invasion of grasses up to 200 m from the edge of the forest (Balch et al., 2013). Another factor in degradation is a synergism between forest fires and natural disturbances, such as windstorms (Marra et al., 2018; Silvério et al., 2019), which increase tree mortality and reduce both forest height and biomass (Silvério et al., 2019). However, there is still no estimate of the spatial or temporal dimension of this degradation.

Studies have hypothesized that ancient forest fires could have completely transformed the vegetation in western Amazonia, leading to bamboo-dominated forest (Keeley and Bond, 1999; Nelson et al., 1994). Large fires in the Amazon occurred in the Holocene as a result of droughts caused by mega-El Niño events (Bush et al., 2008; Meggers, 1994). One piece of evidence supporting the relationship between bamboo and forest fires is the shape of the areas of bamboo-dominated forest, with rounded edges that coincide with the shape of fires (McMichael et al., 2013). This theory is strengthened by the studies of Smith and Nelson (2011) and Griscom and Ashton (2003), who refuted other theories, namely the effects of soils with low permeability and high clay activity or the effect of divides between hydrographic basins. A new theory sought to associate the massive mortality of bamboo every 28 years with the occurrence of large fires, but found no evidence of this link in the spatial and temporal distribution of the fires (Dalagnol et al., 2018).

The southwestern Amazon has the second largest native bamboo forest in the world (Lobovikov et al., 2007). It is estimated that bamboo forests in western Amazonia occupy an area of 11.2 million ha (Dalagnol et al., 2018) to 16.1 million ha (Carvalho et al., 2013). Of the 9.4 million ha of bamboo forest in Acre, 74.5% is classified as having “presence of bamboo” (*Guadua sarcocarpa* and *G. weberbaueri*) (Acre, 2010), known locally as “*taboca*.” Bamboo may be either the main floristic element in the understory or a secondary element (Acre, 2010). There are differences between forest with "presence of bamboo" and forest with "dominant bamboo." Silveira (2001) found forest with "presence of bamboo" to have a tree density of 293 individuals $ha^{-1}$ (DBH > 10 cm), 2884 bamboo stems $ha^{-1}$ (DBH > 2.5 cm), a basal area of trees of 16 $m^2$ $ha^{-1}$ and a richness of 96 tree species $ha^{-1}$. In contrast, forest with "dominant bamboo" has 83 trees $ha^{-1}$ (DBH > 10 cm), 3860 bamboo stems $ha^{-1}$ (in all mature bamboo culms), tree basal area of 4.8 $m^2$ $ha^{-1}$,  and 83 tree species $ha^{-1}$ (Griscom and Ashton, 2006; Griscom et al., 2007). “Bamboo-dominated forests” (with bamboo as the main floristic element) are easily identified both on satellite images (Carvalho et al., 2013) and in the field. These are the forests that may have been affected by past forest fires.

Even in undisturbed forests the effects of bamboo dominance in the forest can be observed in the forest’s structure, biodiversity, regeneration and carbon stock. Bamboo-dominated- forests have lower densities of trees and palms and lower carbon storage, the lower amounts being associated with physical damage to trees, rapid growth and clonal reproduction (Griscom et al., 2007; Griscom and Ashton, 2006; Silveira, 2001; Zaninovich et al., 2017). These forests may also have less animal diversity (Yang et al., 2008). Forest regeneration in bamboo-dominated forests is affected by the reduction of seed rain (Bona et al., 2020). Bamboo-dominated forests produce less litterfall but have thicker layers of litter due to slower decomposition, thus providing and less return of nutrients to the forest (Dantas et al., 2020; Liu et al., 2000). All of these factors show that bamboo strategies promote both the permanence of bamboo as a dominant component of the forest over time and the gradual invasion of adjacent communities.

Acre was the epicenter of the 2005 and the 2010 droughts, which were two of the strongest droughts ever recorded in the Brazilian Amazon (Lewis et al., 2011). These droughts, coincided with the years with the highest occurrence of forest fires (Silva et al., 2018). In 2005 more than 3500 $km^2$ of forest burned in Acre, mainly in the eastern region of the state (Silva et al., 2018). This is the portion of the state with the largest area of open forests with bamboo and palms, where bamboo is a secondary floristic element (Acre, 2010).

In this study we present results on how recent fires have profoundly modified the structure and floristic composition of forests in southwestern Amazonia. We used remote sensing to evaluate a forest area of 525,000 ha affected by fire between 1984 and 2016 (Silva et al., 2018) and conducted field studies in the areas in which bamboo expanded during this period. This provides strong evidence that bamboo is favored by forest fires. Based on these data, we addressed two questions: (i) What is the magnitude of the structural change in the "bamboo-dominated forest" affected by fire? and (ii) What is the scale of the expansion of "bamboo-dominated forest" after fires?.

## 2. Materials and methods

The study was carried out in the Brazilian state of Acre, located in the southwestern Amazon (Figure 1a). Acre has 86% of its territory under native forest cover (14,165,340 ha), considering the total deforestation indicated by Brazil's National Institute of Space Research (INPE) up to 2017. Acre's climate in the Köppen classification is of type Am (Tropical monsoon climate) in the eastern part of the state (representing 29% of the territory) and Af (Tropical climate without a dry season) in the rest of the state (representing 71%) (Alvares et al., 2013). The average annual rainfall in the state ranges from 2500 to 2700 mm and the average temperature ranges from 24 to 26°C.

The predominant forest types are "open ombrophilous forest with bamboo and palms in the understory" (covering 86% of the state), "alluvial forest" (7%), "ombrophilous dense forest" (6%) and "*campinaranas*" (oligotrophic woodlands) (<1%) (Acre, 2010). Our study is focused on the forest with the bamboo in the species *Guadua sarcocarpa* Londoño & P.M. Peterson and *Guadua weberbaueri* Pilg. (Silveira, 2001). The map of bamboo forest developed by Carvalho et al. (2013) indicates that the state of Acre holds the largest area of bamboo forest, accounting for 47% of the total in Amazonia as a whole. Figure 1 shows the region of our forest inventories and the mappings of bamboo forests by Acre (2010) and by Carvalho et al. (2013).

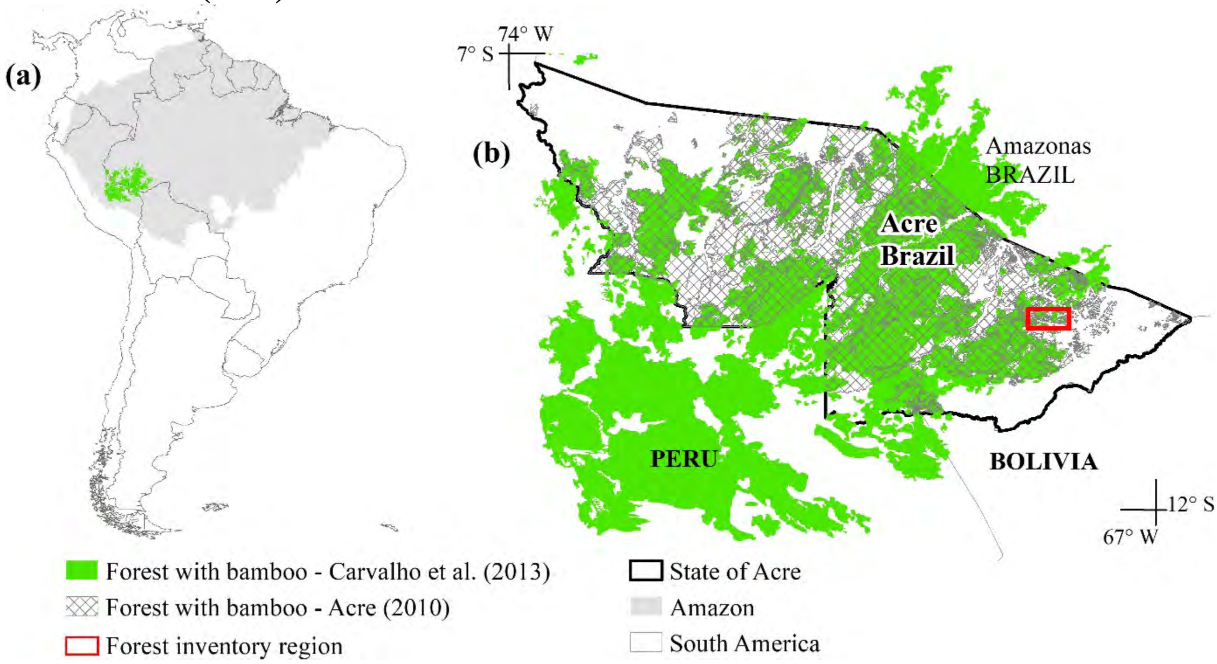


Figure 1. (a) Location of the state of Acre in relation to South America and the Amazon biome, and (b) location of the Amazonian bamboo forest, with the region where the forest inventory was carried out indicated by the red rectangle. The mapping of bamboo forests by Acre (2010) is restricted to the state of Acre, unlike that of Carvalho et al. (2013).

## 2.1. Mapping forest fires

For identification of forest-fire scars in the state of Acre we used the database from the study by Silva et al. (2018). This database was built from a semi-automatic classification using surface-reflectance images from the Landsat satellite from 1984 to 2016. A total of 417 images were analyzed with data between September and December or, for those years with high cloud frequency, from March to June (Silva et al., 2018). The images were processed using CLASlite 3.0 free software, a compact version of the Carnegie Landsat Analysis System (CLAS) (Asner et al., 2009). A subsequent visual audit was performed to exclude misclassified areas. Fire-scars were identified using the burn-scar index (BSI) based on the Alencar (2010) methodology.

This database used as an operational concept of forest fires those in which the crowns of the trees were directly or indirectly affected by fire to the point that there was a detectable impact on the optical satellite images in the 1984-2016 period. The classification had 98% global accuracy; errors of omission were 0.7% and errors of commission were 0.6% based on the analysis of random points and points checked in the field (Silva et al., 2018).

## 2.2. Identification of open forest with bamboo

To identify forests with bamboo we used the database of the Ecological Economic Zoning of the state of Acre (Acre, 2010) (Figure 1b). These data divide the forest with bamboo into: “bamboo-dominated forest” (B+) (where bamboo is the main floristic element) and “forest with presence of bamboo” (B-) (where this is secondary floristic element). There are four subdivisions in the “B-” class,: i) “open alluvial forest with bamboo,” ii) “open forest with bamboo” + “open forest with palms” + “dense forest,” iii) “open forest with bamboo” + “dense forest,” and iv) “open forest with palms” + “open forest with bamboo” + “dense forest” (Table 1). The distinction between B- and B+ in terms of the differences in forest structure is not yet well refined, but we present some general characteristics in Table 1.

Table 1. Classification in unflooded (*terra firme*) forest types with bamboo based on the Ecological Economic Zoning of the State of Acre and literature review.

| Forest type | Classification Acre (2010) | Representation of the area state Acre (%) | Density of bamboo stems $ha^{-1}$ and density of trees $ha^{-1}$ |
|---|---|---|---|
| Bamboo-dominated forest (B+)<br>dominance of the forest canopy by bamboo | “bamboo-dominated forest” | 10% | 1242 to 3860 - bamboo<br>83 to 430 - trees<br>(Griscom and Ashton, 2006; Rockwell et al., 2014) |
| Forest with presence of bamboo (B-)<br>dominance of the forest canopy by trees and palm trees, where bamboo reaches the canopy in a timely manner | “open forest with bamboo” | 58% | 667 to 2800 - bamboo<br>300 to 550 - trees<br>(Castro et al., 2013; Salimon et al., 2011; Silva et al., 2020; Silveira, 2001; Torezan and Silveira, 2000) |
| | “open alluvial forest with bamboo” | | |
| | “open forest with bamboo” + “open forest with palms” + “dense forest” | | |
| | “open forest with bamboo” + “dense forest” | | |
| | “open forest with palms” + “open forest with bamboo” + “dense forest” | | |

### 2.3. Forest inventory

We investigated the impacts of forest fires on the structure of forest based on the change in the densities of trees and palms and of bamboo stems. To obtain these data, we carried out a forest inventory between August 2016 and January 2017 in the western portion of the municipality (county) of Rio Branco, which is the capital of Acre (Figure1b). Three plots were installed in "unflooded open forests with bamboo and palms" (B-) in each of four areas, which were chosen to best represent forest fire between 1984 and 2016: 1) unburned forest (UF), 2) forest burned only in 2005 (BF05), 3) forest burned only in 2010 (BF10) and 4) forest burned in both 2005 and 2010 (BF05-10).

These areas were located at distances of at least 9 km from each other and at least 100 m from a forest edge. In each area three plots measuring 100 m × 50 m were installed along a 1-km transect (0.5 ha/plot, 1.5 ha/area, 6 ha total). The diameter at breast height (DBH) was measured for all trees with DBH ≥ 10 cm. The decisions on the number and size of plots took into consideration economic costs and information from the article by Higuchi et al. (1982), who found little gain in precision with plots above 3000 $m^2$.

For the bamboo inventory, eight subplots measuring 5 m x 5 m were systematically allocated to locations equidistant from each other and 10 m from the main trail, where the DBH was measured for all live bamboo stems. These data were used to calculate the density of bamboo stems $ha^{-1}$ and the diameter distribution of bamboo stems. We identified trees broken by bamboo (trees physically damaged due to the bamboo's need to hang from the trees in order to reach the canopy). The weight of the bamboo stems that accumulate on the trunks of the trees exerts strong pressure, causing breakage (Griscom and Ashton, 2006). We considered trees to be broken by bamboo only when there was clear evidence of accumulation of bamboo stems on the trunk or the formation of arches in the canopy, as illustrated in Figure 2. Although the study by Griscom and Ashton (2006) indicated strong damage to the trees due to bamboo in the Peruvian Amazon, this is the first time that this variable is considered in a forest inventory in the Brazilian Amazon. In the field, we observed that the bamboo was in flowering phase in all of the plots in 2016, and we revisited of some plots in May 2017 and confirmed that the bamboo was dead (Appendix S1: Fig. S1).

Figure 2. Photographic record of trees broken by bamboo considered in this study. Accumulation of climbing bamboo stems can break tree trunks (circles). Photos: S.S da Silva.

Bamboo has an average life cycle of 29 years (Carvalho et al., 2013; Dalagnol et al., 2018). Because the age of the bamboo and its mass mortality after flowering at the end of its life cycle can influence our results, we analyzed the mapping by Dalagnol et al. (2018) in the study area and observed bamboo mortality in 2009 and 2017. However, most of our mapping did not coincide with the mapping by Dalagnol et al. (2018), probably due to the 1-km spatial resolution of the MODIS imagery used in the mapping in that study, while the present study used 30-m resolution Landsat imagery. During the field campaigns in August-October 2016 we recorded bamboo flowering. Flowering is the peak of the bamboo life cycle and occurs just before the bamboo dies.

## 2.4. Analysis

R software (R Core Team, 2020) was used for statistical analyses. To test question (i) ("What is the magnitude of the structural change in the bamboo-dominated forest affected by fire?"), we analyzed the forest-inventory data by comparing the mean differences between UF, BF05, BF10 and BF05-10, representing 10 and 5 years after forest-fire events, in terms of density of tree individuals (number $ha^{-1}$) and density of bamboo stems (number of stems $ha^{-1}$) using the Kruskal-Wallis test and the post-hoc Nemenyi test. We used the Shapiro-Wilk test to compare the diameter distribution of live bamboo stems between the areas. This analysis permits detection of changes in the structure of the post-fire forest. The influence of environmental variables on the results of the forest inventory was performed using the generalized linear model (GLM) following Silva et al. (2020).

To test question (ii) ("What is the scale of the expansion of bamboo-dominated forest after fires, and what are its implications under future climatic conditions?"), we defined the expansion of bamboo as when a forest with the presence of bamboo (B-) becomes a bamboo-dominated forest (B +) in scars from forest fires in 2005 and 2010. This definition was based on the forest-inventory data, which were then associated with the remote-sensing data.

We analyzed the reflectance response in the near-infrared (NIR) channel of Landsat satellite data, corrected by using top-of-atmosphere (TOA) reflectance as indicated by Carvalho et al. (2013) and Dalagnol et al. (2018). Screening identified images from before (July 2003) and after (July 2015) the occurrence of forest fires; images were selected that did not coincide with other bamboo fire and mortality events that occurred in the region between 2016 and 2017 (Appendix S1: Table S1).

The NIR channel has been used to identify forests with bamboo because it allows green vegetation that is dense and uniform (which is characteristic of forest with bamboo) to be distinguished from other types of vegetation (Liu, 2007). Bamboo forests have average reflectance values 25% to 29% higher in the NIR as compared to forests without bamboo (Carvalho et al., 2013; Dalagnol et al., 2018). To avoid confusion errors between "bamboo-dominated forest" and secondary vegetation (*capoeira*), which has similar reflectance values (Carvalho et al., 2013; Hill, 1999), we analyzed 2000 pixels randomly selected from the NIR image for "bamboo-dominated forest," "forest with presence of bamboo" and "secondary forests" without fire impact. The average NIR values of these forest types were 3590, 2852, and 3400, respectively (Figure 3). This analysis allowed differentiation of the thresholds for identification of "bamboo-dominated forest," which are defined by median values above 3500 for NIR reflectance.

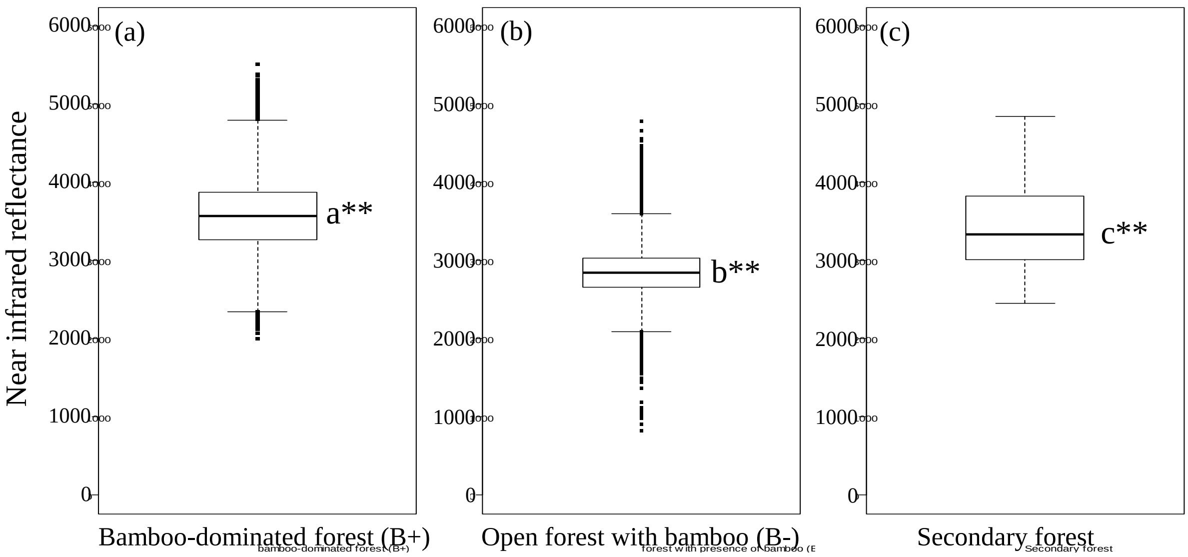


Figure 3. (a) Near-infrared spectral reflectance samples in “bamboo-dominated forest,” (b) “open forest with bamboo” and (c) “secondary forest.” Letters with asterisks indicate forest types with significantly different means based on *post-hoc* Student’s t tests ($p < 0.01$ or **).

We excluded from our analyses forest-fire fragments that coincided with areas deforested before 2016 or that were smaller than 10 ha in area, and we inspected the Landsat time series in this area from 1984 to 2003 in order to determine whether the fire scars were in forest with presence of bamboo (B-). The selection of areas of forest fires with bamboo expansion was done through a change in proportion of pixels with NIR values > 3500 in each area of forest-fire scars, with images from 2003 and 2015 (NIR values extracted 10 and 5 years after the forest fires). Selected areas had the change in the NIR proportion greater than 20% when comparing before and after the two fire events. The cut-off threshold of 20% for the NIR proportion was adopted as a conservative measure seeking to exclude spectral responses of regeneration + sprouting of other pioneer species, and disturbances (either natural or anthropogenic), such as selective logging, extreme droughts, blowdowns, and the periodic mass die-offs of bamboo populations (Nelson et al., 1994; Numata et al., 2017; Silva et al., 2018, 2020). We applied a statistical analysis of repeated measures using the non-parametric Friedman test.

To test the validity of this selection, we generated a 500-m buffer around the scars that were classified as having bamboo expansion and statistically compared the scars with the buffers using ANOVA and a Tukey post-hoc test. Through the combination of field data, forest-fire mapping and spectral analysis, we could express the extent of forest modification after fire.

## 3. Results

### 3.1. Impact of fire on the density of trees and bamboo

Based on the forest-inventory data, we identified the dominance of bamboo in all burned forests (forests burned only in 2005, forests burned only in 2010 and forests burned in both years). We observed an increase of at least 7-fold in the number of bamboo stems $ha^{-1}$ in the burned forests, rising from an average of 667 (±425) stems $ha^{-1}$ in the unburned forest to 5200 (±1262) stems $ha^{-1}$ in the burned forests (Figure 6a, Kruskal-Wallis test, $p = 0.065$). A negative linear relationship was observed between number of bamboo stems and tree density (Figure 4b). For the live-tree density, the mean values for the areas were statistically different from each other (Kruskal-Wallis test, $p < 0.05$), where unburned forests had a mean density of 611 (±66) live trees $ha^{-1}$, which was 50% lower in forests burned only in 2005 (307 ±47 live trees ha$^{-1}$), 56% lower in forest burned only in 2010, 270 (±93) live trees ha$^{-1}$, and 74% lower in forest burned in both years, 157 (±50) live trees ha$^{-1}$.

In intact forests, 6% (±1) of the sampled trees were broken by bamboo, as compared to 18% (±4%) in forest burned only in 2005 (BF05), 11% (±6%) in forest burned only in 2010 (BF10) and 14% (±2%) in forest burned in both years (BF05-10) (Figure 4b). The broken trees had 52% lower height (height = 6.6 ± 3.6 m) than the unbroken trees (height =13.8 ±6.7 m). Only 20% of broken trees were pioneers.

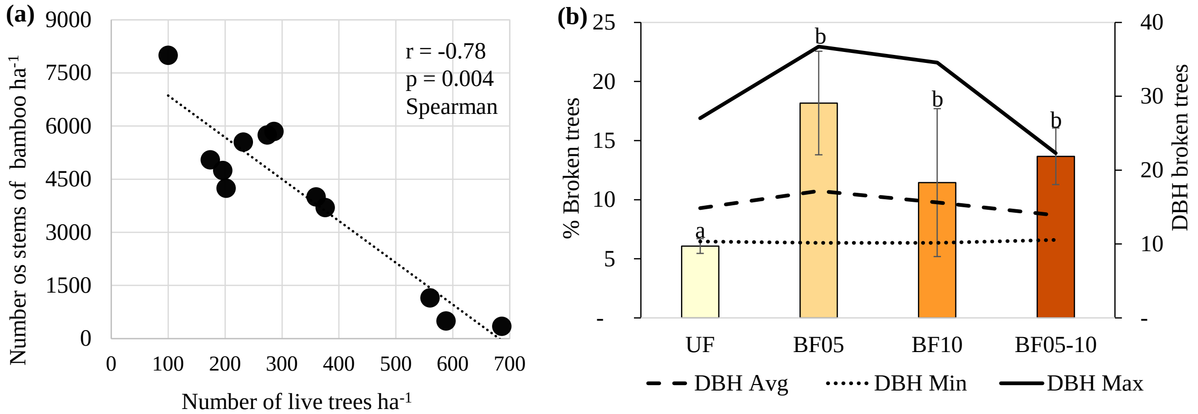


Figure 4. Effects of fire on the expansion of bamboo and the impact of fire on the forest. (a) Negative relationship between the number of bamboo stems and the number of live trees. (b) Percentage of broken trees due to the presence of bamboo and diameter at breast height of broken trees (DBH Max = maximum DBH; DBH Avg = average DBH; DBH Min = minimum DBH). UF = unburned forest, BF05 = forest burned only in 2005. BF10 = forest burned only in 2010. BF05-10 = forest burned both in 2005 and 2010. Bars are means (±SD).

The mean DBH of the bamboo stems for all areas was 4 (±0.54) cm, but the diameter distributions differed among the areas ($p < 0.05$) (Figure 5). In the intact forest, the minimum DBH of bamboo was 3 cm and the maximum was 5.4 cm, whereas in forests impacted by fire, the minimum DBH was 1.1 cm and the maximum was 6.6 cm (DBH ranged from 1.9 cm to 6.0 cm for BF05; from 1.6 cm to 6.5 cm for BF10, and from 1.1 cm to 6.6 cm for BF05-10). In the areas of burned forest we observed a wide range of the DBH values, indicating a young, growing population. Moreover, in the forests burned twice (Figure 5d), the DBH distribution of bamboo was more skewed to the left than in the other treatments, indicating a high number of bamboo stems with low DBH values.

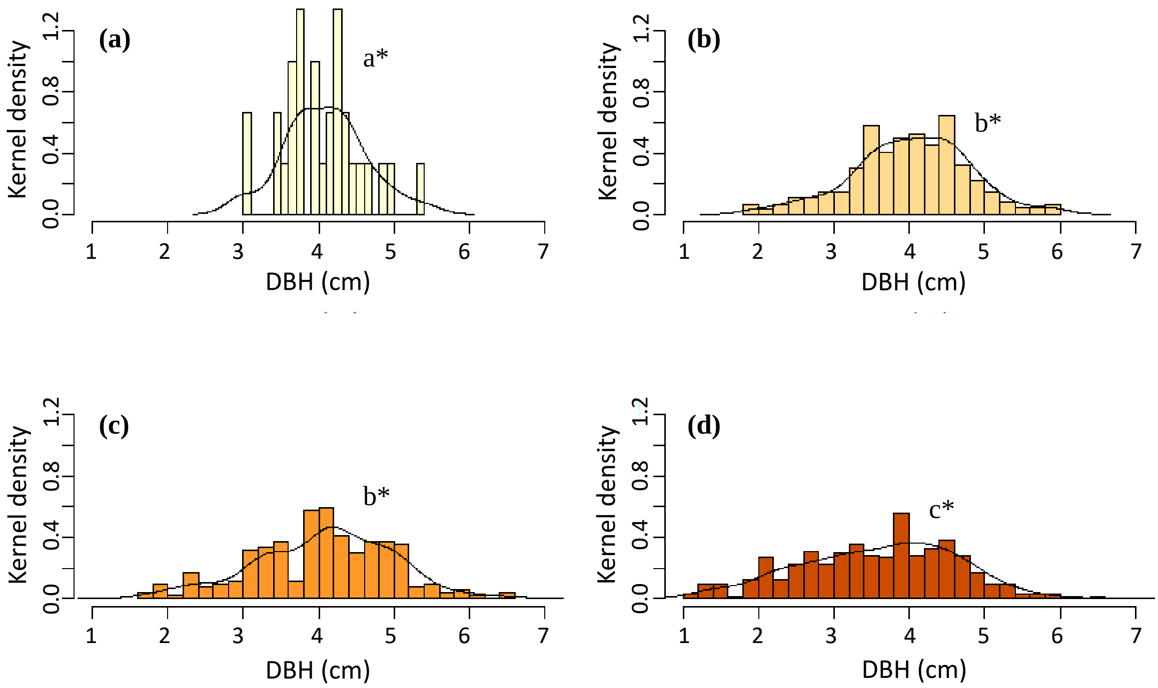


Figure 5. Diameter distribution of bamboo stems in (a) unburned forest, (b) forest burned only in 2005, (c) forest burned only in 2010 and (d) forest burned both in 2005 and 2010. Different letters followed by * are statistically different (Kolmogorov-Smirnov test, $p < 0.05$).

## 3.2. Expansion of forests with dominant bamboo

There was a significant difference ($p < 0.01$) in the average reflectance values in the NIR channel in the same year between the forest-fire scars with bamboo expansion and the 500-m buffers surrounding these scars (Figure 6). The NIR reflectance values in the areas of recent forest fires (2005 and/or 2010) were 11-18% higher than those in the areas of forest fires (Figure 6a and 6c), indicating the dominance of bamboo in the forest canopy. The average NIR reflectance value before the fire (2003 image) was 2900 ±359 in both forest-fire scars with bamboo expansion and in their 500-m buffers. After the fire (2015 image), the average NIR values were 3532 ±637 in the scars and 3160 ±564 in the buffers. There was an average increase by 48% in the proportion of NIR values > 3500 after forest fires, with a maximum increase of 94% (Figure 6e). To validate these results, we analyzed the average NIR values from 1984 to 2003 for forest-fire scars and confirmed that the average NIR values before forest fires ranged from 2584 to 3126 (Figure 6f), these values being below the NIR reflectance values of the same scars after the forest fires.

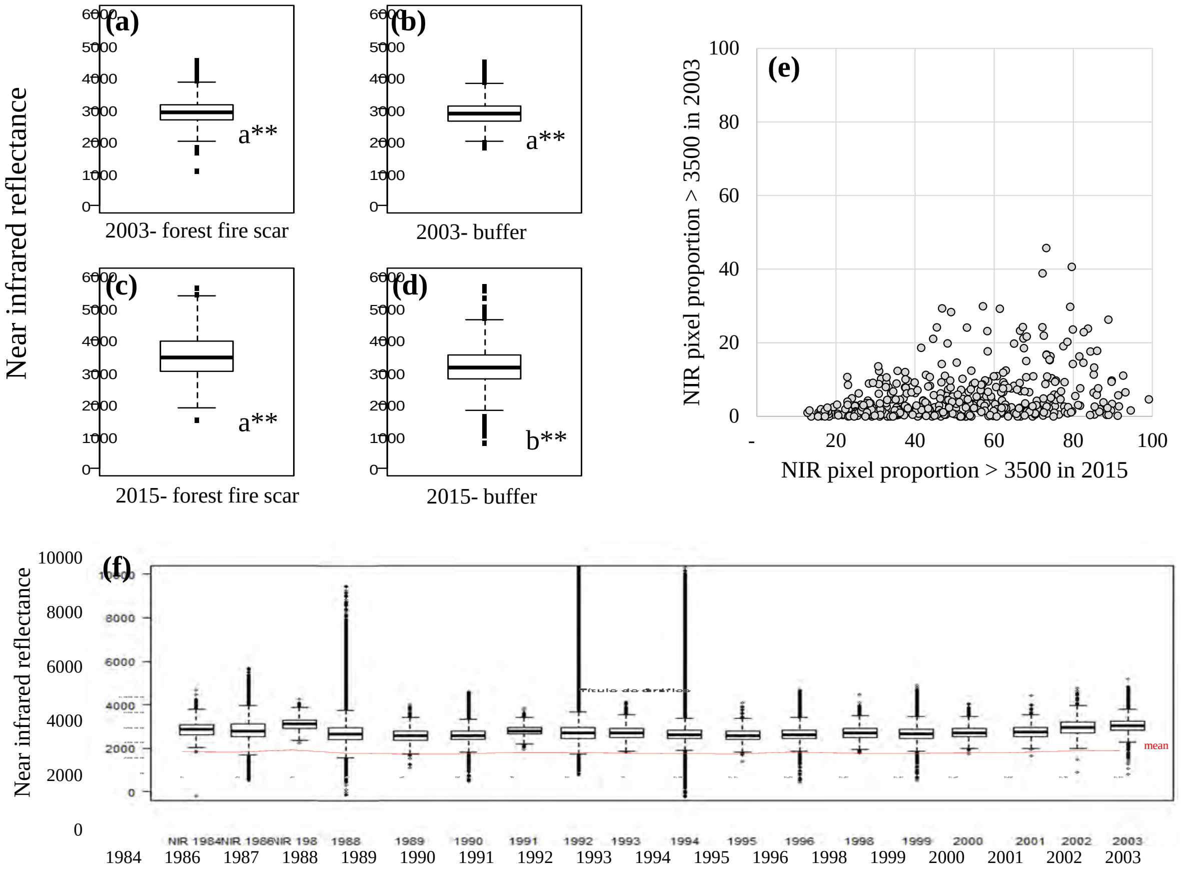


Figure 6. Boxplot of the near-infrared (NIR) reflectance images of forest-fire scars in (a) 2003 and (c) 2015 and in the 500-m buffer surrounding the scars in (b) 2003 and (d) 2015, (e) change in the proportion of NIR values > 3500 in forest-fire scar polygons identified as having expansion of bamboo and (f) annual variation of the average NIR values in the areas where expansion of bamboo-dominated forests were identified. The statistical comparison was performed between the buffer and the scar in the same year because, due to the short life cycle of the bamboo, the spectral response changes over time. Letters with asterisks indicate forest classes with significantly different means based on *post-hoc* Student's t tests comparing forest fire scar and buffer ($p < 0.01$ or **).

Based upon the NIR reflectance analysis, we found that forest fires in 2005 and 2010 in Acre caused an expansion of bamboo areas (or bamboo-dominant forest areas) by 120,000 ha, transforming areas that was "open forest with presence of bamboo" into "bamboo-dominated forest" (Figure 7; Appendix Data1). The largest polygons of forest with expansion of bamboo are in the municipalities of Rio Branco, Xapuri and Sena Madureira. These areas of bamboo expansion can be identified on Google Earth images because of the contrast with surrounding vegetation (Figure 7).

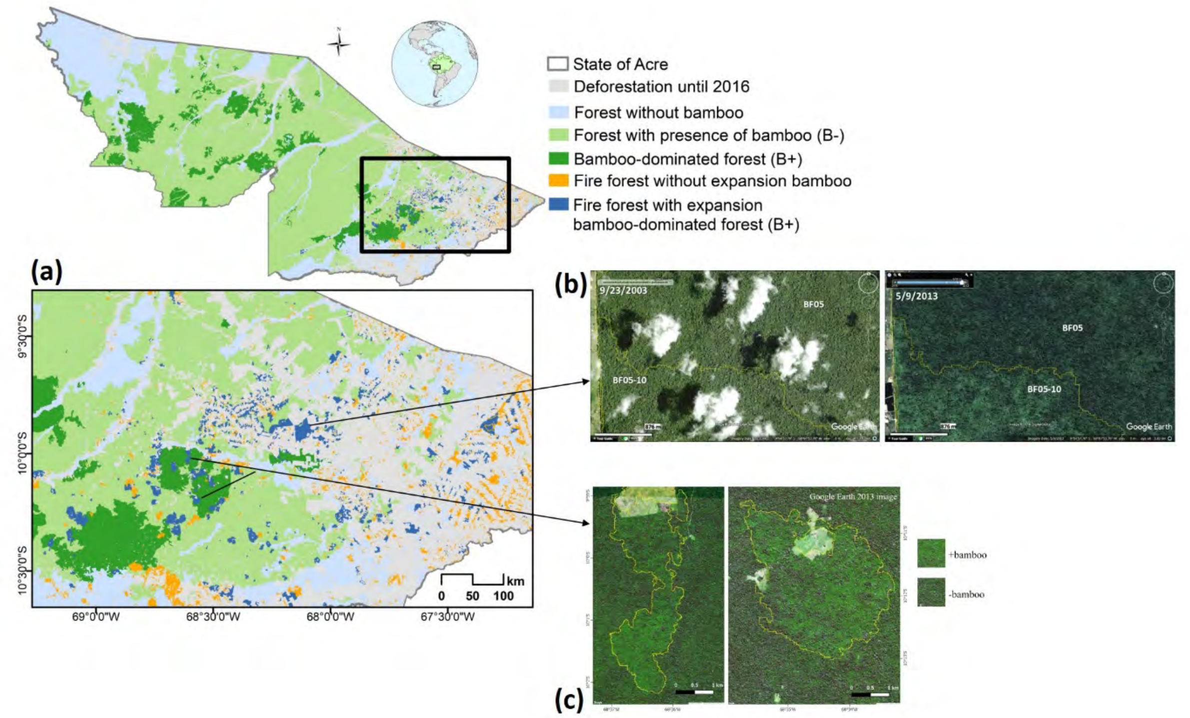


Figure 7. Distinction between areas of forest fires with and without expansion of bamboo in the state of Acre (a). High-resolution 2013 Google Earth image in two 2005 forest-fire polygons in the northern portion of the Chico Mendes Extractive Reserve (b). High-resolution Google Earth image before (September 2003) and after (May 2013) the forest-fire west of the city of Rio Branco (c).

## 4. Discussion

### 4.1. Change in the forest structure with bamboo after forest fires

There have been profound changes in the forest structure in Acre following recent forest fires, as shown by the drastic reduction of the number of tree individuals by up to 70% and by the increase in the number of bamboo stems by a factor of seven as compared to unburned forests based upon forest inventory data covering forest changes up to 11 years after fire. The density of bamboo stems in the burned forests found in this study is greater than that identified in non-degraded bamboo-dominated forest in three studies in the southwestern Amazon: Silveira (2001) in the Chico Mendes Extractive Reserve in Acre, Smith and Nelson (2011) in the municipality of Sena Madureira in Acre, and Griscom and Ashton (2006) in the department of Madre de Dios in Peru.

Our study shows differences in the DBH distribution of bamboo stems between the burned and unburned forests. Although there are few measures of bamboo diameters in forest inventories, this is important information for understanding the structure of these forests (Fadrique et al., 2020; Silva et al., 2020). After the fire, the bamboo launched new stems, but with lower average DBH as compared to the unburned area. These thinner stems may be able to increase in length more rapidly than thicker ones, thus speeding their climb to the canopy. Even when we consider the studies by Silveira (2001) and by Smith and Nelson (2011), who counted bamboo stems considering a minimum DBH of 2.5 cm, the bamboo-stem density after forest fires were at least double. With the impact of fire, the range of DBH values (2.7 cm) of the bamboo stems increased, the average DBH being 2.4 cm in intact forest and 4.8 cm in burned forests. The lower variation among the bamboo stems in the unburned forest shows the maturity and stability of this population.

Bamboo expansion may have been favored by several factors. Bamboo grows rapidly after the reduction of the arboreal component caused by the fire. Bona et al. (2020) showed that bamboo-dominated forest has a smaller seed rain and lower species richness, and Dantas et al. (2020) showed that the litter is thicker in bamboo-dominated forest, which can hinder the regeneration and recovery of the forest trees. Another contributor is the fact that clonal reproduction of bamboo is stimulated by fire, as observed by Smith and Nelson (2011) and Gagnon and Platt (2008). Bamboo has a substantial impact on the forest because the genus *Guadua* is a climbing (semi-scandent) bamboo that depends on adjacent trees for vertical growth, causing breakage and other physical damage to the trees due to the weight of the accumulated bamboo (Ferreira, 2014; Griscom and Ashton, 2003; Silveira, 2001). The bamboo grows with extraordinary speed, with growth rates of 1 to 4 m month$^{-1}$ (Silveira, 2001). Our results show that trees with DBH up to 37 cm were broken by the climbing bamboo.

**4.2. Expansion of forests with dominant bamboo (bamboo-dominated forests?)**

Our results suggest that the impact of fire with sufficient intensity and magnitude on “open forest with presence of bamboo” (B-) caused the classification of the studied areas to change to "bamboo-dominated forest” (B+). A total of 120,000 ha of forests that had started to have bamboo as their main floristic element were identified. A combined analysis of the field plots with remote-sensing data for both the past and the present, indicates concrete changes in the forest after forest fires. The change in the proportion of the NIR reflectance values > 3500 was confirmed by testing for differences in the NIR values in the areas of forest fires with expansion and in adjacent areas. The average values were generally similar to those identified by Carvalho et al. (2013) (mean NIR = 3400) and Dalagnol et al. (2018) (mean NIR = 3100); we emphasize that the difference in NIR values between MODIS and Landsat images, in addition to the differences in the evaluation dates (which imply differences in the maturity stages of the bamboo populations), can generate substantial differences in results.

The expansion of bamboo in forests affected by the recent fires corroborates the hypothesis that the B+ forest in southwestern Amazonia was formed in connection with ancient fires, as discussed by Keeley and Bond (1999), Nelson et al. (1994), and McMichael et al. (2013). If this evidence is correct, the 1,477,476-ha area of B+ mapped by Acre’s Economic-Ecological Zoning (Acre, 2010) was impacted by ancient fires caused by mega-El Niño events, as discussed by Bush et al. (2008) and Meggers (1994). This could explain the spatial pattern of B+ and the large area occupied by these forests in Acre (Figure 7).

The impact of the expansion of bamboo in the southwestern Amazon may be even greater than our study finds. Brown et al. (2006) showed that in 2005 more than 100,000 ha of forest burned in the department of Pando in Bolivia and 10,000 ha in the department of Madre de Dios in Peru, both of which neighbor Acre. Vasconcelos et al. (2013) identified around 86,500 ha of forest fires in the southern portion of the Brazilian state of Amazonas, which also neighbors Acre. These are regions that Carvalho et al. (2013) identified as being B-.

Records of degradation by forest fire in the Amazon show strong impacts on the floristic composition of forest (Barlow and Peres, 2008; Silva et al., 2020, Xaud et al., 2013). Veldman et al. (2009) and Brando et al. (2014) reported another type of degradation effect: invasion of grasses within the forest after fire and logging. Silvério et al. (2013) argues that profound changes may be occurring due to the invasion of flammable grasses after forest fires, thus promoting subsequent fires. In our study, we found that bamboo dominance can persist after forest fires. This implies persistent degradation over time, especially in an environment characterized by climate change, intensification of land use and forest fires.

The expansion of bamboo forests due to forest fires in Acre is a concern because future climate scenarios indicate an increase in the intensity and magnitude of forest fires

(Faria et al., 2017). Fu et al. (2013) found that the length of the dry season in the southwestern Amazon had increased by two weeks since 1979. In addition to the climate aspect, future human land use will also trigger forest fires in the region. In Acre, expansion of the agricultural frontier is underway in the central portion of the state, and, with increased deforestation and burning (INPE, 2020a, 2020b), this region can be expected to have its remaining forests become dominated by bamboo. The combination of climate change and land-use change will promote favorable environments for the occurrence of forest fires and therefore for the expansion of bamboo forests in the southwestern Amazon (Ferreira et al., 2020).

The impact of increasing bamboo dominance in fire-degraded forests can have important implications for forest recovery over time, especially when associated with other degradation factors such as logging. The combination of bamboo dominance and forest fires reduces biomass stocks and the density and diversity of trees (Ferreira, 2014; Numata et al., 2017; Silva et al., 2020; Ziccardi et al., 2019), which can be permanent. However, because bamboo is dynamic and has a short life cycle (28-30 years), we recommend further research, such as continuous monitoring the forest-inventory plots established in this study, and expanding the forest-monitoring network in other regions in Acre in order to understand forest recovery and the changes in the densities of trees and bamboo. This is also needed in forests in the Brazilian state of Amazonas and in the Peruvian department of Madre de Dios, which were also impacted by forest fires in 2005 and 2010. Plots need to be established in forests where the bamboo died after forest fires. The present study represents only one small step towards understanding the complex interactions after forest fires and the resulting changes in Amazonian forests.

## 5. Conclusions

Forest fires provoke important changes in the forest in the southwestern Amazon: expansion of bamboo-dominated forest (B+). As compared to unburned forest, in burned forest the proportion of pioneer species doubled; the number of live trees was reduced by 50% by the 2005 fire and by 74% by the 2010 fire. This change in the structure of the forest with the expansion of bamboo increased the number of broken trees by 2 to 3 times in relation to the unburned forest.

The impact of forest fires associated with changes in forest structure led to the conversion of “open forest with presence of bamboo” (B-) to “bamboo-dominated forest” (B+) in 120,000 ha, with individual affected areas of up to 5000 ha. This study reinforces the hypothesis that forests with dominant bamboo are related to forest fires. Forest fires have been recorded in Peru and Bolivia that may further increase the impact of the expansion of bamboo in the southwestern Amazon. This study may serve as a guide for further studies in neighboring countries to broaden understanding of bamboo expansion.

Future climate scenarios indicate more intense droughts, which increase the chances of forest fires such as those of 2005 and 2010. This would increase the level of forest degradation due to the association between bamboo and forest fires in the southwestern Amazon.

## Acknowledgments

We are grateful for funding from the State of Acre Research Support Foundation (FAPAC Call 03/2013), the NASA Terrestrial Ecology Program (NNX14AD56G), the National Institute of Science and Technology of the Environmental Services of Amazonia (INCT-Servamb) (CNPq 708565/2009) and the Coordination for Improvement of Higher Education Personnel (CAPES) through the INPA/UFAC Interinstitutional Doctoral Program (No. 459/2013). LEOCA thanks the Brazilian National Council for Scientific and Technological

Development (CNPq: 458022/2013-6 and 305054/2016-3). We thank two reviewers for helpful comments.

**References**

Acre, 2010. Zoneamento Ecológico-Econômico do Estado do Acre: Fase II (Escala 1:250.000), 2nd ed. SEMA, Rio Branco, Acre, Brazil. https://amz.run/4Imc

Alencar, A., 2010. Spatial and temporal determinants of forest fires on the Amazonian deforestation frontier: Implications for current and future carbon emissions (Ph.D.). University of Florida, Gainesville, Florida. https://bityl.co/5aUF

Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.L.M., Sparovek, G., 2013. Köppen's climate classification map for Brazil. Meteorol. Z. 711–728. https://doi.org/10.1127/0941-2948/2013/0507

Aragão, L.E.O.C., Anderson, L.O., Fonseca, M.G., Rosan, T.M., Vedovato, L.B., Wagner, F.H., Silva, C.V.J., Silva Junior, C.H.L., Arai, E., Aguiar, A.P., Barlow, J., Berenguer, E., Deeter, M.N., Domingues, L.G., Gatti, L., Gloor, M., Malhi, Y., Marengo, J.A., Miller, J.B., Phillips, O.L., Saatchi, S., 2018. 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. Nat. Commun. 9, 536. https://doi.org/10.1038/s41467-017-02771-y

Asner, G.P., Knapp, D.E., Balaji, A., Paez-Acosta, G., 2009. Automated mapping of tropical deforestation and forest degradation: CLASlite. J. Appl. Remote Sens. 3, 1–24. https://doi.org/10.1117/1.3223675

Balch, J.K., Massad, T.J., Brando, P.M., Nepstad, D.C., Curran, L.M., 2013. Effects of high-frequency understorey fires on woody plant regeneration in southeastern Amazonian forests. Philos. Trans. R. Soc. B Biol. Sci. 368. https://doi.org/10.1098/rstb.2012.0157

Barbosa, R.I., Fearnside, P.M., 1999. Incêndios na Amazônia Brasileira: estimativa da emissão de gases do efeito estufa pela queima de diferentes ecossistemas de Roraima na passagem do evento "El Nino" (1997/98). Acta Amaz. 29, 513–534. https://doi.org/10.1590/1809-43921999294534

Barlow, J., Lennox, G.D., Ferreira, J., Berenguer, E., Lees, A.C., Nally, R.M., Thomson, J.R., Ferraz, S.F.B., Louzada, J., Oliveira, V.H.F., Parry, L., Solar, R.R.C., Vieira, I.C.G., Aragão, L.E.O.C., Begotti, R.A., Braga, R.F., Cardoso, T.M., Oliveira 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. Nature535, 144–147.. https://doi.org/10.1038/nature18326

Barlow, J.B., Peres, C.A., 2008. Fire-mediated dieback and compositional cascade in an Amazonian forest. Philos. Trans. R. Soc. B Biol. Sci. 363, 1787–1794. https://doi.org/10.1098/rstb.2007.0013

Barlow, J.B., Peres, C.A., Lagan, B.O., Haugaasen, T., 2003. Large tree mortality and the decline of forest biomass following Amazonian wildfires. Ecol. Lett. 6, 6–8. https://doi.org/10.1046/j.1461-0248.2003.00394.x

Berenguer, E., Ferreira, J., Gardner, T.A., Aragão, L.E.O.C., 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. Glob. Change Biol. 20, 3713–3726. https://doi.org/10.1111/gcb.12627

Bona, K., Purificação, K.N., Vieira, T.B., Mews, H.A., 2020. Fine-scale effects of bamboo dominance on seed rain in a rainforest. For. Ecol. Manag. 460, 117906. https://doi.org/10.1016/j.foreco.2020.117906

Brando, P.M., Balch, J.K., Nepstad, D.C., Morton, D.C., Putz, F.E., Coe, M.T., Silvério, D., Macedo, M.N., Davidson, E.A., Nóbrega, C.C., Alencar, A., Soares-Filho, B.S., 2014.

Abrupt increases in Amazonian tree mortality due to drought–fire interactions. Proc. Natl. Acad. Sci. 111, 6347–6352. https://doi.org/10.1073/pnas.1305499111

Brown, I.F., Schroeder, W., Setzer, A., De Los Rios, M., Pantoja, N., Duarte, A., Marengo, J., 2006. Monitoring fires in southwestern Amazonia Rain Forests. Eos Trans. Am. Geophys. Union 87, 253–259. https://doi.org/10.1029/2006EO260001

Bush, M.B., Silman, M.R., McMichael, C., Saatchi, S., 2008. Fire, climate change and biodiversity in Amazonia: a Late-Holocene perspective. Philos. Trans. R. Soc. B Biol. Sci. 363, 1795–1802. https://doi.org/10.1098/rstb.2007.0014

Carvalho, A.L., Nelson, B.W., Bianchini, M.C., Plagnol, D., Kuplich, T.M., Daly, D.C., 2013. Bamboo-dominated forests of the southwest Amazon: detection, spatial extent, life cycle length and flowering waves. PLoS ONE 8, 1–13. https://doi.org/10.1371/journal.pone.0054852

Castro, W., Salimon, C.I., Medeiros, H., Silva, I.B., Silveira, M., 2013. Bamboo abundance, edge effects, and tree mortality in a forest fragment in Southwestern Amazonia. Sci. For. 41, 159–164. https://bityl.co/5aU7

Cochrane, M.A., Schulze, M.D., 1999. Fire as a Recurrent Event in Tropical Forests of the Eastern Amazon: Effects on Forest Structure, Biomass, and Species Composition. Biotropica 31, 2–16. https://doi.org/10.1111/j.1744-7429.1999.tb00112.x

Dalagnol, R., Wagner, F.H., Galvão, L.S., Nelson, B.W., Aragão, L.E.O.C., 2018. Life cycle of bamboo in southwestern Amazon and its relation to fire events. Biogeosciences Discuss. 1–28. https://doi.org/10.5194/bg-2018-207

Dantas, M.A.F., Bona, K., Vieira, T.B., Mews, H.A., 2020. Assessing the fine-scale effects of bamboo dominance on litter dynamics in an Amazonian forest. For. Ecol. Manag. 474, 118391. https://doi.org/10.1016/j.foreco.2020.118391

Davidson, E.A., de Araújo, A.C., Artaxo, P., Balch, J.K., Brown, I.F., C Bustamante, M.M., Coe, M.T., DeFries, R.S., Keller, M., Longo, M., Munger, J.W., Schroeder, W., Soares-Filho, B.S., Souza Jr, C.M., Wofsy, S.C., 2012. The Amazon basin in transition. Nature 481, 321–328. https://doi.org/10.1038/nature10717

Fadrique, B., Veldman, J.W., Dalling, J.W., Clark, L.G., Montti, L., Ruiz-Sanchez, E., Rother, D.C., Ely, F., Farfan-Ríos, W., Gagnon, P., Prada, C.M., García, J.C.C., Saha, S., Veblen, T.T., Londoño, X., Feeley, K.J., Rockwell, C.A., 2020. Guidelines for including bamboos in tropical ecosystem monitoring. Biotropica 52, 427–443. https://doi.org/10.1111/btp.12737

Faria, B.L.D., Brando, P., Macedo, M., Panday, P., Soares-Filho, B., Coe, M., 2017. Current and future patterns of fire-induced forest degradation in Amazonia. Environ. Res. Lett. 119601. https://doi.org/10.1088/1748-9326/aa69ce

Fearnside, P.M., 1990. Fire in the tropical rain forest of the Amazon basin, in: Goldammer, D.J.G. (Ed.), Fire in the Tropical Biota, Ecological Studies. Springer Berlin Heidelberg, Germany, pp. 106–116.

Ferreira, E., Kalliola, R., Ruokolainen, K., 2020. Bamboo, climate change and forest use: A critical combination for southwestern Amazonian forests? Ambio 49, 1353–1363. https://doi.org/10.1007/s13280-019-01299-3

Ferreira, E.J.L., 2014. O bambu é um desafio para a conservação e o manejo de florestas no sudoeste da Amazônia. Cienc. E Cult. 66, 46–51.

Fu, R., Yin, L., Li, W., Arias, P.A., Dickinson, R.E., Huang, L., Chakraborty, S., Fernandes, K., Liebmann, B., Fisher, R., Myneni, R.B., 2013. Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection. Proc. Natl. Acad. Sci. U. S. A. 110, 18110–18115. https://doi.org/10.1073/pnas.1302584110

Gagnon, P.R., Platt, W.J., 2008. Multiple disturbances accelerate clonal growth in a potentially monodominant bamboo. Ecology 89, 612–618. https://doi.org/10.1890/07-1255.1

Griscom, B.W., Ashton, P.M.S., 2006. A self-perpetuating bamboo disturbance cycle in a neotropical forest. J. Trop. Ecol. 22, 587–597. https://doi.org/10.1017/S0266467406003361

Griscom, B.W., Ashton, P.M.S., 2003. Bamboo control of forest succession: Guadua sarcocarpa in Southeastern Peru. For. Ecol. Manag. 175, 445–454. https://doi.org/10.1016/S0378-1127(02)00214-1

Griscom, B.W., Daly, D.C., Ashton, M.S., 2007. Floristics of bamboo-dominated stands in lowland terra-firma forests of southwestern Amazonia. J. Torrey Bot. Soc. 134, 108–125. https://doi.org/10.3159/1095-5674(2007)134[108:FOBSIL]2.0.CO;2

Higuchi, N., dos Santos, J., Jardim, F.C.S., 1982. Tamanho de parcela amostral para inventários florestais. Acta Amaz. 12, 91–103. https://doi.org/10.1590/1809-43921982121091

Hill, R.A., 1999. Image segmentation for humid tropical forest classification in Landsat TM data. Int. J. Remote Sens. 20, 1039–1044. https://doi.org/10.1080/014311699213082

INPE (Instituto Nacional de Pesquisas Espaciais), 2020a. Project PRODES - Monitoring of the Brazilian Amazon Forest by satellite. https://bityl.co/5aTq

INPE (Instituto Nacional de Pesquisas Espaciais), 2020b. Banco de Dados de Queimadas. https://bityl.co/5aTy

Keeley, J.E., Bond, W.J., 1999. Mast Flowering and Semelparity in Bamboos: The Bamboo Fire Cycle Hypothesis. Am. Nat. 154, 383–391. https://doi.org/10.1086/303243

Lewis, S.L., Brando, P.M., Phillips, O.L., Heijden, G.M.F. van der, Nepstad, D.C., 2011. The 2010 Amazon drought. Science 331, 554–554. https://doi.org/10.1126/science.1200807

Liu, W., Fox, J.E.D., Xu, Z., 2000. Leaf litter decomposition of canopy trees, bamboo and moss in a montane moist evergreen broad-leaved forest on Ailao Mountain, Yunnan, south-west China. Ecol. Res. 15, 435–447. https://doi.org/10.1046/j.1440-1703.2000.00366.x

Liu, W.T.H., 2007. Aplicações de sensoriamento remoto. UNIDERP, São Paulo.

Lobovikov, M., Paudel, S., Piazza, M., Ren, H., Wu, J., 2007. World bamboo resources : a thematic study prepared in the framework of the Global Forest Resources Assessment 2005, Non-wood forest products ; 18. FAO, Rome, Italy.

Marra, D.M., Trumbore, S.E., Higuchi, N., Ribeiro, G.H.P.M., Negrón-Juárez, R.I., Holzwarth, F., Rifai, S.W., dos Santos, J., Lima, A.J.N., Kinupp, V.F., Chambers, J.Q., Wirth, C., 2018. Windthrows control biomass patterns and functional composition of Amazon forests. Glob. Change Biol. 24, 5867–5881. https://doi.org/10.1111/gcb.14457

McDowell, N., Allen, C.D., Anderson-Teixeira, K., Brando, P., Brienen, R., Chambers, J., Christoffersen, B., Davies, S., Doughty, C., Duque, A., Espirito-Santo, F., Fisher, R., Fontes, C.G., Galbraith, D., Goodsman, D., Grossiord, C., Hartmann, H., Holm, J., Johnson, D.J., Kassim, A.R., Keller, M., Koven, C., Kueppers, L., Kumagai, T., Malhi, Y., McMahon, S.M., Mencuccini, M., Meir, P., Moorcroft, P., Muller-Landau, H.C., Phillips, O.L., Powell, T., Sierra, C.A., Sperry, J., Warren, J., Xu, C., Xu, X., 2018. Drivers and mechanisms of tree mortality in moist tropical forests. New Phytol. https://doi.org/10.1111/nph.15027

McMichael, C.H., Bush, M.B., Silman, M.R., Piperno, D.R., Raczka, M., Lobato, L.C., Zimmerman, M., Hagen, S., Palace, M., 2013. Historical fire and bamboo dynamics in western Amazonia. J. Biogeogr. 40, 299–309. https://doi.org/10.1111/jbi.12002

Meggers, B.J., 1994. Archeological evidence for the impact of mega-Niño events on Amazonia during the past two millennia. Clim. Change 28, 321–338. https://doi.org/10.1007/BF01104077

Nelson, B.W., Kapos, V., Adams, J.B., Oliveira, W.J., Braun, O.P.G., 1994. Forest Disturbance by Large Blowdowns in the Brazilian Amazon. Ecology 75, 853–858. https://doi.org/10.2307/1941742

Nepstad, D., Lefebvre, P., Silva, U.L., Tomasella, J., Schlesinger, P., Solórzano, L., Moutinho, P., Ray, D., Guerreira Benito, J., 2004. Amazon drought and its implications for forest flammability and tree growth: a basin-wide analysis. Glob. Change Biol. 10, 704–717. https://doi.org/10.1111/j.1529-8817.2003.00772.x

Nepstad, D.C., Stickler, C.M., Filho, B.S., Merry, F., 2008. Interactions among Amazon land use, forests and climate: prospects for a near-term forest tipping point. Philos. Trans. R. Soc. B Biol. Sci. 363, 1737–1746. https://doi.org/10.1098/rstb.2007.0036

Numata, I., Silva, S.S., Cochrane, M.A., d’Oliveira, M.V., 2017. Fire and edge effects in a fragmented tropical forest landscape in the southwestern Amazon. For. Ecol. Manag. 401, 135–146. https://doi.org/10.1016/j.foreco.2017.07.010

R CORE TEAM, 2020. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rockwell, C.A., Kainer, K.A., d’Oliveira, M.V.N., Staudhammer, C.L., Baraloto, C., 2014. Logging in bamboo-dominated forests in southwestern Amazonia: Caveats and opportunities for smallholder forest management. For. Ecol. Manag. 315, 202–210. https://doi.org/10.1016/j.foreco.2013.12.022

Salimon, C.I., Putz, F.E., Menezes-Filho, L., Anderson, A., Silveira, M., Brown, I.F., Oliveira, L.C., 2011. Estimating state-wide biomass carbon stocks for a REDD plan in Acre, Brazil. For. Ecol. Manag. 262, 555–560. https://doi.org/10.1016/j.foreco.2011.04.025

Silva, S.S., Fearnside, P.M., Graça, P.M.L.A., Brown, I.F., Alencar, A., Melo, A.W.F., 2018. Dynamics of forest fires in the southwestern Amazon. For. Ecol. Manag. 424, 312–322. https://doi.org/10.1016/j.foreco.2018.04.041

Silva, S.S., Numata, I., Fearnside, P.M., Graça, P.M.L.A., Ferreira, E.J.L., Santos, E.A., Lima, P.R.F., Dias, M.S.S., Lima, R.C., Melo, A.W.F., 2020. Impact of fires on an open bamboo forest in years of extreme drought in southwestern Amazonia. Reg. Environ. Change 20, 127. https://doi.org/10.1007/s10113-020-01707-5

Silveira, M., 2001. A floresta aberta com bambu no sudoeste da Amazônia: padrões e processos em múltiplas escalas (Tese de Doutorado em Ecologia). UNB, Brasilía.

Silvério, D.V., Brando, P.M., Balch, J.K., Putz, F.E., Nepstad, D.C., Oliveira-Santos, C., Bustamante, M.M.C., 2013. Testing the Amazon savannization hypothesis: fire effects on invasion of a neotropical forest by native cerrado and exotic pasture grasses. Philos. Trans. R. Soc. B Biol. Sci. 368, 20120427. https://doi.org/10.1098/rstb.2012.0427

Silvério, D.V., Brando, P.M., Bustamante, M.M.C., Putz, F.E., Marra, D.M., Levick, S.R., Trumbore, S.E., 2019. Fire, fragmentation, and windstorms: A recipe for tropical forest degradation. J. Ecol. 107, 656–667. https://doi.org/10.1111/1365-2745.13076

Smith, M., Nelson, B.W., 2011. Fire favours expansion of bamboo-dominated forests in the south-west Amazon. J. Trop. Ecol. 27, 59–64. https://doi.org/10.1017/S026646741000057X

Torezan, J.M.D., Silveira, M., 2000. The biomass of bamboo (Guadua weberbaueri Pilger) in open forest of the southwestern Amazon. Ecotropica 6, 71–76.

Vasconcelos, S.S., Fearnside, P.M., Graça, P.M.L.A., Nogueira, E.M., Oliveira, L.C., Figueiredo, E.O., 2013. Forest fires in southwestern Brazilian Amazonia: Estimates of area and potential carbon emissions. For. Ecol. Manag. 291, 199–208. https://doi.org/10.1016/j.foreco.2012.11.044

Veldman, J.W., Mostacedo, B., Peña-Claros, M., Putz, F.E., 2009. Selective logging and fire as drivers of alien grass invasion in a Bolivian tropical dry forest. For. Ecol. Manag. 258, 1643–1649. https://doi.org/10.1016/j.foreco.2009.07.024

Xaud, H.A.M., Martins, F.S.R.V., Santos, J.R., 2013. Tropical forest degradation by mega-fires in the northern Brazilian Amazon. For. Ecol. Manag., The Mega-fire reality 294, 97–106. https://doi.org/10.1016/j.foreco.2012.11.036

Yang, S., Du, Q., Chen, J., Liu, L., 2008. Effect of Phyllostachys heterocycla var. pubescens Spreading on Bird Diversity. J. Zhejiang For. Sci. Technol. 28, 43–46.

Zaninovich, S.C., Montti, L.F., Alvarez, M.F., Gatti, M.G., 2017. Replacing trees by bamboos: Changes from canopy to soil organic carbon storage. For. Ecol. Manag. 400, 208–217. https://doi.org/10.1016/j.foreco.2017.05.047

Ziccardi, L.G., Graça, P.M.L.A, Figueiredo, E.O., Fearnside, P.M., 2019. Decline of large-diameter trees in a bamboo-dominated forest following anthropogenic disturbances in southwestern Amazonia. Ann. For. Sci. 76, 110. https://doi.org/10.1007/s13595-019-0901-4

# Supplementary Material

# Increasing bamboo dominance in southwestern Amazon forests following intensification of drought-mediated fires

Sonaira Souza da Silva[1,2*], Philip Martin Fearnside[2], Paulo Mauricio Lima de Alencastro Graça[2], Izaya Numata[3], Antonio Willian Flores de Melo[1,2], Evandro Linhares Ferreira[2], Luiz Eduardo Oliveira e Cruz de Aragão[4], Edneia Araujo Santos[1], Maury Sérgio Dias[5], Rodrigo Cunha Lima[5], Pedro Raimundo Ferreira de Lima[1]

[1] Federal University of Acre (UFAC), CEP 69980-000, Cruzeiro do Sul, Acre, Brazil [sonairasilva@gmail.com; willian.flores@ufac.br; edneiasantos_14@hotmail.com; pedro.f5@hotmail.com]
[2] National Institute for Research in Amazonia (INPA), Av. André Araújo, 2936, CEP 69067-375, Manaus, Brazil [pmfearn@inpa.gov.br;pmlag@inpa.gov.br; evandroferreira@hotmail.com]
[3] Geospatial Sciences Center of Excellence, South Dakota State University (SDSU), Brookings, SD 57007, USA [Izaya.Numata@sdstate.edu]
[4] National Institute for Space Research (INPE). Av dos Astronautas, 1.751. Jd. Da Granja, São José dos Campos, São Paulo, Brazil [laragao@dsr.inpe.br]
[5] Northern Educational Union (UNINORTE), CEP 69915-901, Rio Branco, Acre, Brazil [maury.play@hotmail.com; rcunhabiologia@gmail.com]

*Corresponding author: sonairasilva@gmail.com; sonaira.silva@ufac.br

Table S1. Data on the Landsat images used to analyze the expansion of bamboo in the areas of forest fires in the state of Acre

| Landsat scene | 2003 | 2015 |
|---|---|---|
| 001/067 | 14-Aug | 30-jul |
| 002/066 | 03-Jul | 06-Aug |
| 002/067 | 03-Jul | 06-Aug |
| 003/066 | 27-Jul | 28-Jul |
| 003/067 | 27-Jul | 14-Sept |

Figure S1. Photographs of flowering (a) and mortality (b) of bamboo in the study area

(a) Photographs in August and November 2016

(b) Photographs in May 2017