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

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23 **Abstract**

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

51 **Keywords**

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

54 **1. Introduction**

55 A dangerous cycle of forest degradation is taking shape in the Amazon as a result of
56 increased frequency of extreme droughts and associated forest fires drastically increasing tree
57 mortality (Brando et al., 2014; Davidson et al., 2012; McDowell et al., 2018). This modifies
58 the floristic composition of Amazonian forests (Barlow et al., 2016, 2003; Xaud et al., 2013)
59 and exacerbates feedbacks with global climate change (Aragão et al., 2018; Berenguer et al.,
60 2014). Amazonian forest fires almost always have anthropogenic origins. In the state of Acre,
61 as well as in most of the Amazon, fire is used after deforestation as a tool to prepare land for
62 agriculture or pasture, and later to renew these land uses (Barbosa and Fearnside, 1999;
63 Fearnside, 1990; Silva et al., 2018). In years of extreme drought, routine farm fires (even
64 small ones) can get out of control and turn into large forest fires (Nepstad et al., 2004, 2008;
65 Silva et al., 2018).

66 One of the effects of forest fire in Amazonia is the modification of the forest species
67 composition, which can change drastically in a cascade effect due to increased fire recurrence
68 (Barlow and Peres, 2008). In eastern Amazonia, a reduction of live non-pioneer sapling and
69 frequency and density of lianas (vines) by more than 70% has been reported, jeopardizing the
70 recovery of the forest (Cochrane and Schulze, 1999). In Mato Grosso (in southern Amazonia),
71 tree mortality facilitated invasion of grasses up to 200 m from the edge of the forest (Balch et
72 al., 2013). Another factor in degradation is a synergism between forest fires and natural

73 disturbances, such as windstorms (Marra et al., 2018; Silvério et al., 2019), which increase
 74 tree mortality and reduce both forest height and biomass (Silvério et al., 2019). However,
 75 there is still no estimate of the spatial or temporal dimension of this degradation.

76 Studies have hypothesized that ancient forest fires could have completely
 77 transformed the vegetation in western Amazonia, leading to bamboo-dominated forest
 78 (Keeley and Bond, 1999; Nelson et al., 1994). Large fires in the Amazon occurred in the
 79 Holocene as a result of droughts caused by mega-El Niño events (Bush et al., 2008; Meggers,
 80 1994). One piece of evidence supporting the relationship between bamboo and forest fires is
 81 the shape of the areas of bamboo-dominated forest, with rounded edges that coincide with the
 82 shape of fires (McMichael et al., 2013). This theory is strengthened by the studies of Smith
 83 and Nelson (2011) and Griscom and Ashton (2003), who refuted other theories, namely the
 84 effects of soils with low permeability and high clay activity or the effect of divides between
 85 hydrographic basins. A new theory sought to associate the massive mortality of bamboo every
 86 28 years with the occurrence of large fires, but found no evidence of this link in the spatial
 87 and temporal distribution of the fires (Dalagnol et al., 2018).

88 The southwestern Amazon has the second largest native bamboo forest in the world
 89 (Lobovikov et al., 2007). It is estimated that bamboo forests in western Amazonia occupy an
 90 area of 11.2 million ha (Dalagnol et al., 2018) to 16.1 million ha (Carvalho et al., 2013). Of
 91 the 9.4 million ha of bamboo forest in Acre, 74.5% is classified as having “presence of
 92 bamboo” (*Guadua sarcocarpa* and *G. weberbaueri*) (Acre, 2010), known locally as “*taboca*.”
 93 Bamboo may be either the main floristic element in the understory or a secondary element
 94 (Acre, 2010). There are differences between forest with “presence of bamboo” and forest with
 95 “dominant bamboo.” Silveira (2001) found forest with “presence of bamboo” to have a tree
 96 density of 293 individuals ha⁻¹ (DBH > 10 cm), 2884 bamboo stems ha⁻¹ (DBH > 2.5 cm), a
 97 basal area of trees of 16 m² ha⁻¹ and a richness of 96 tree species ha⁻¹. In contrast, forest with
 98 “dominant bamboo” has 83 trees ha⁻¹ (DBH > 10 cm), 3860 bamboo stems ha⁻¹ (in all mature
 99 bamboo culms), tree basal area of 4.8 m² ha⁻¹, and 83 tree species ha⁻¹ (Griscom and Ashton,
 100 2006; Griscom et al., 2007). “Bamboo-dominated forests” (with bamboo as the main floristic
 101 element) are easily identified both on satellite images (Carvalho et al., 2013) and in the field.
 102 These are the forests that may have been affected by past forest fires.

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

115 Acre was the epicenter of the 2005 and the 2010 droughts, which were two of the
 116 strongest droughts ever recorded in the Brazilian Amazon (Lewis et al., 2011). These
 117 droughts, coincided with the years with the highest occurrence of forest fires (Silva et al.,
 118 2018). In 2005 more than 3500 km² of forest burned in Acre, mainly in the eastern region of
 119 the state (Silva et al., 2018). This is the portion of the state with the largest area of open
 120 forests with bamboo and palms, where bamboo is a secondary floristic element (Acre, 2010).

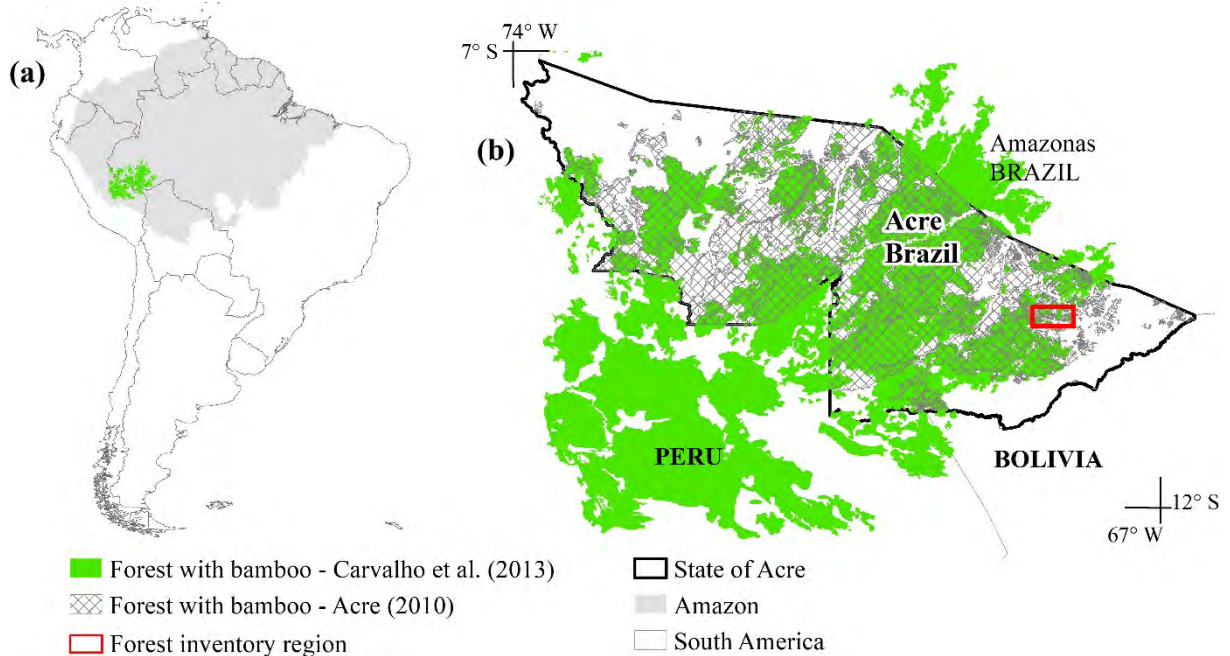
121 In this study we present results on how recent fires have profoundly modified the
 122 structure and floristic composition of forests in southwestern Amazonia. We used remote

123 sensing to evaluate a forest area of 525,000 ha affected by fire between 1984 and 2016 (Silva
 124 et al., 2018) and conducted field studies in the areas in which bamboo expanded during this
 125 period. This provides strong evidence that bamboo is favored by forest fires. Based on these
 126 data, we addressed two questions: (i) What is the magnitude of the structural change in the
 127 “bamboo-dominated forest” affected by fire? and (ii) What is the scale of the expansion of
 128 “bamboo-dominated forest” after fires?
 129

130 2. Materials and methods

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

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



148 Figure 1. (a) Location of the state of Acre in relation to South America and the Amazon
 149 biome, and (b) location of the Amazonian bamboo forest, with the region where the forest
 150 inventory was carried out indicated by the red rectangle. The mapping of bamboo forests by
 151 Acre (2010) is restricted to the state of Acre, unlike that of Carvalho et al. (2013).
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154 2.1. Mapping forest fires

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

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

170 2.2. Identification of open forest with bamboo

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

180
 181 Table 1. Classification in unflooded (*terra firme*) forest types with bamboo based on the
 182 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+) dominance of the forest canopy by bamboo	“bamboo-dominated forest”	10%	1242 to 3860 - bamboo 83 to 430 - trees (Griscom and Ashton, 2006; Rockwell et al., 2014)
Forest with presence of bamboo (B-) 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 300 to 550 - trees (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”		

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184 **2.3. Forest inventory**

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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 (Figure 1b). 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 m².

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.

233 Bamboo has an average life cycle of 29 years (Carvalho et al., 2013; Dalagnol et al.,
 234 2018). Because the age of the bamboo and its mass mortality after flowering at the end of its
 235 life cycle can influence our results, we analyzed the mapping by Dalagnol et al. (2018) in the
 236 study area and observed bamboo mortality in 2009 and 2017. However, most of our mapping
 237 did not coincide with the mapping by Dalagnol et al. (2018), probably due to the 1-km spatial
 238 resolution of the MODIS imagery used in the mapping in that study, while the present study
 239 used 30-m resolution Landsat imagery. During the field campaigns in August-October 2016
 240 we recorded bamboo flowering. Flowering is the peak of the bamboo life cycle and occurs
 241 just before the bamboo dies.

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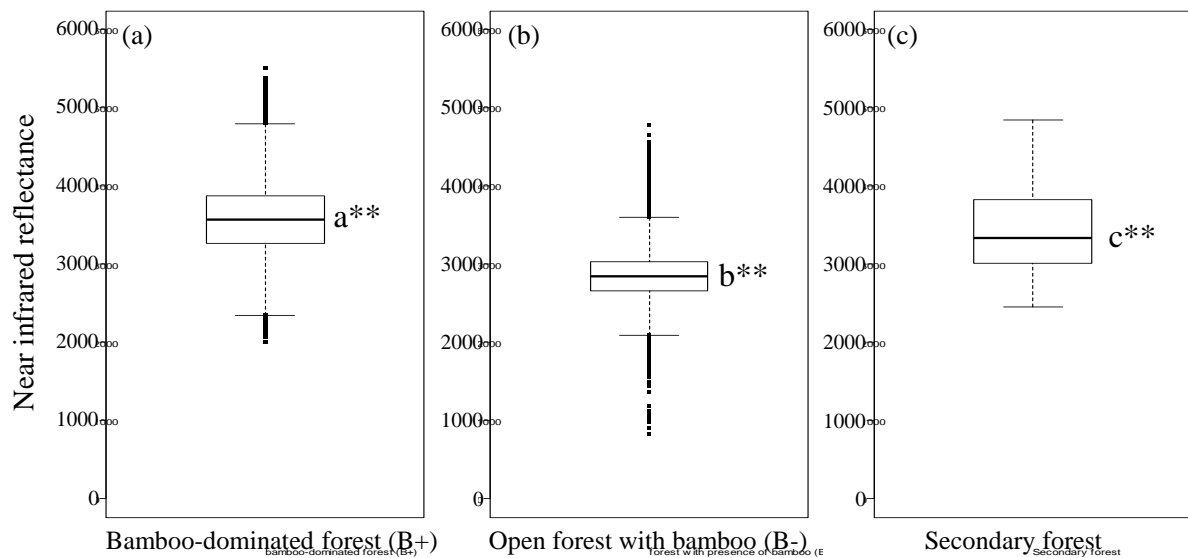
243 **2.4. Analysis**

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

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

259 We analyzed the reflectance response in the near-infrared (NIR) channel of Landsat
 260 satellite data, corrected by using top-of-atmosphere (TOA) reflectance as indicated by
 261 Carvalho et al. (2013) and Dalagnol et al. (2018). Screening identified images from before
 262 (July 2003) and after (July 2015) the occurrence of forest fires; images were selected that did
 263 not coincide with other bamboo fire and mortality events that occurred in the region between
 264 2016 and 2017 (Appendix S1: Table S1).

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



277 Figure 3. (a) Near-infrared spectral reflectance samples in “bamboo-dominated forest,” (b)
 278 “open forest with bamboo” and (c) “secondary forest.” Letters with asterisks indicate forest
 279 types with significantly different means based on *post-hoc* Student’s t tests ($p < 0.01$ or **).
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282 We excluded from our analyses forest-fire fragments that coincided with areas
 283 deforested before 2016 or that were smaller than 10 ha in area, and we inspected the Landsat
 284 time series in this area from 1984 to 2003 in order to determine whether the fire scars were in
 285 forest with presence of bamboo (B-). The selection of areas of forest fires with bamboo
 286 expansion was done through a change in proportion of pixels with NIR values > 3500 in each
 287 area of forest-fire scars, with images from 2003 and 2015 (NIR values extracted 10 and 5
 288 years after the forest fires). Selected areas had the change in the NIR proportion greater than
 289 20% when comparing before and after the two fire events. The cut-off threshold of 20% for
 290 the NIR proportion was adopted as a conservative measure seeking to exclude spectral
 291 responses of regeneration + sprouting of other pioneer species, and disturbances (either
 292 natural or anthropogenic), such as selective logging, extreme droughts, blowdowns, and the
 293 periodic mass die-offs of bamboo populations (Nelson et al., 1994; Numata et al., 2017; Silva
 294 et al., 2018, 2020). We applied a statistical analysis of repeated measures using the non-
 295 parametric Friedman test.

296 To test the validity of this selection, we generated a 500-m buffer around the scars
 297 that were classified as having bamboo expansion and statistically compared the scars with the
 298 buffers using ANOVA and a Tukey post-hoc test. Through the combination of field data,
 299 forest-fire mapping and spectral analysis, we could express the extent of forest modification
 300 after fire.
 301

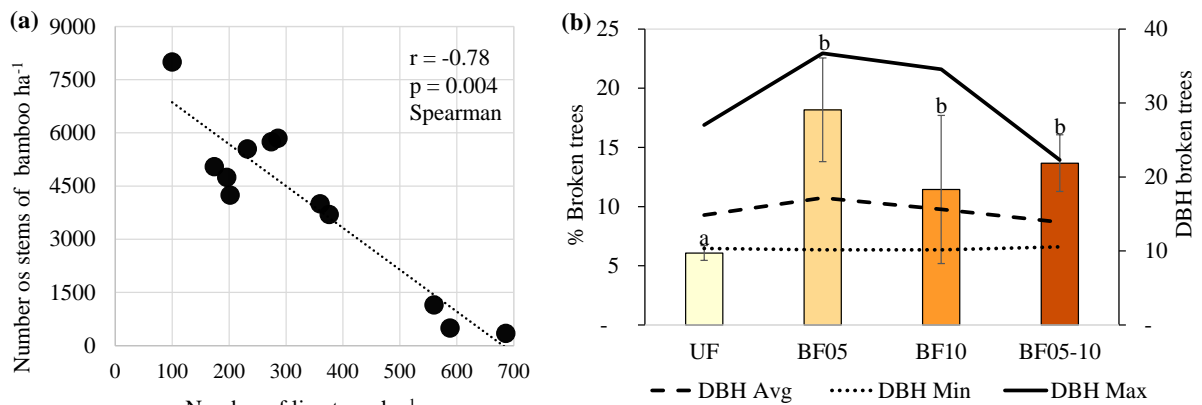
302 3. Results

303 3.1. Impact of fire on the density of trees and bamboo

304 Based on the forest-inventory data, we identified the dominance of bamboo in all
 305 burned forests (forests burned only in 2005, forests burned only in 2010 and forests burned in
 306 both years). We observed an increase of at least 7-fold in the number of bamboo stems ha^{-1} in
 307 the burned forests, rising from an average of $667 (\pm 425)$ stems ha^{-1} in the unburned forest to
 308 $5200 (\pm 1262)$ stems ha^{-1} in the burned forests (Figure 6a, Kruskal-Wallis test, $p = 0.065$). A
 309 negative linear relationship was observed between number of bamboo stems and tree density
 310 (Figure 4b). For the live-tree density, the mean values for the areas were statistically different
 311 from each other (Kruskal-Wallis test, $p < 0.05$), where unburned forests had a mean density of
 312 $611 (\pm 66)$ live trees ha^{-1} , which was 50% lower in forests burned only in 2005 (307 ± 47 live

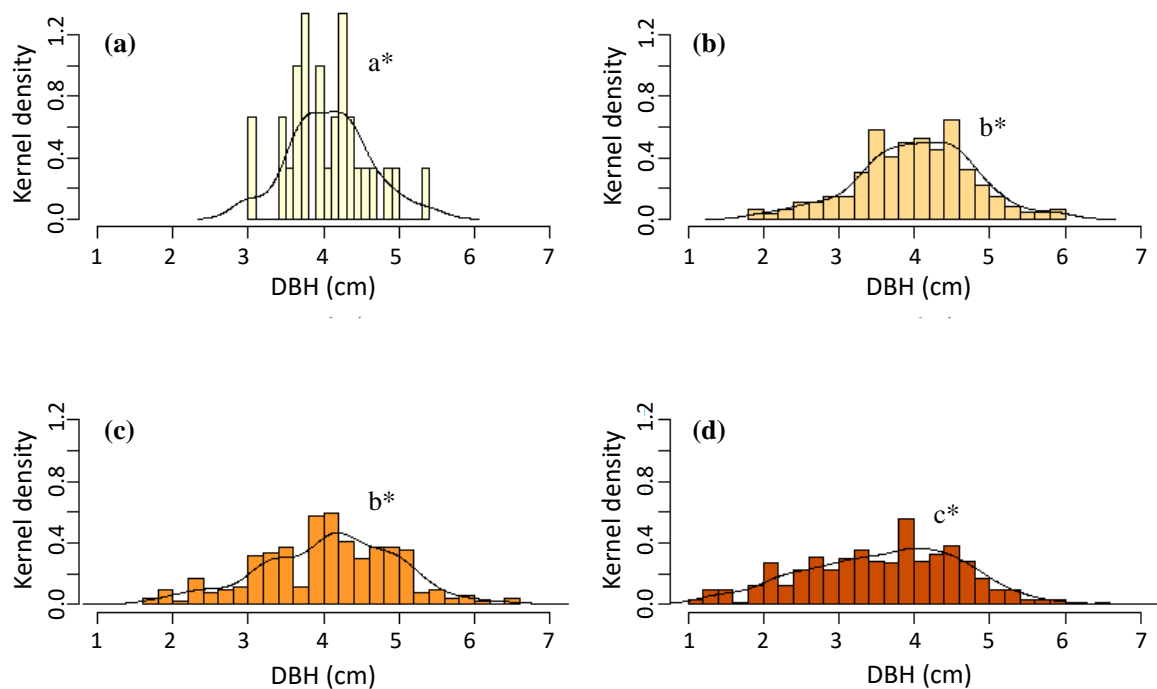
313 trees ha^{-1}), 56% lower in forest burned only in 2010, 270 (± 93) live trees ha^{-1} , and 74% lower
 314 in forest burned in both years, 157 (± 50) live trees ha^{-1} .

315 In intact forests, 6% (± 1) of the sampled trees were broken by bamboo, as compared
 316 to 18% ($\pm 4\%$) in forest burned only in 2005 (BF05), 11% ($\pm 6\%$) in forest burned only in 2010
 317 (BF10) and 14% ($\pm 2\%$) in forest burned in both years (BF05-10) (Figure 4b). The broken
 318 trees had 52% lower height (height = 6.6 ± 3.6 m) than the unbroken trees (height = 13.8 ± 6.7
 319 m). Only 20% of broken trees were pioneers.
 320



321 Figure 4. Effects of fire on the expansion of bamboo and the impact of fire on the forest. (a)
 322 Negative relationship between the number of bamboo stems and the number of live trees. (b)
 323 Percentage of broken trees due to the presence of bamboo and diameter at breast height of
 324 broken trees (DBH Max = maximum DBH; DBH Avg = average DBH; DBH Min =
 325 minimum DBH). UF = unburned forest, BF05 = forest burned only in 2005. BF10 = forest
 326 burned only in 2010. BF05-10 = forest burned both in 2005 and 2010. Bars are means (\pm SD).
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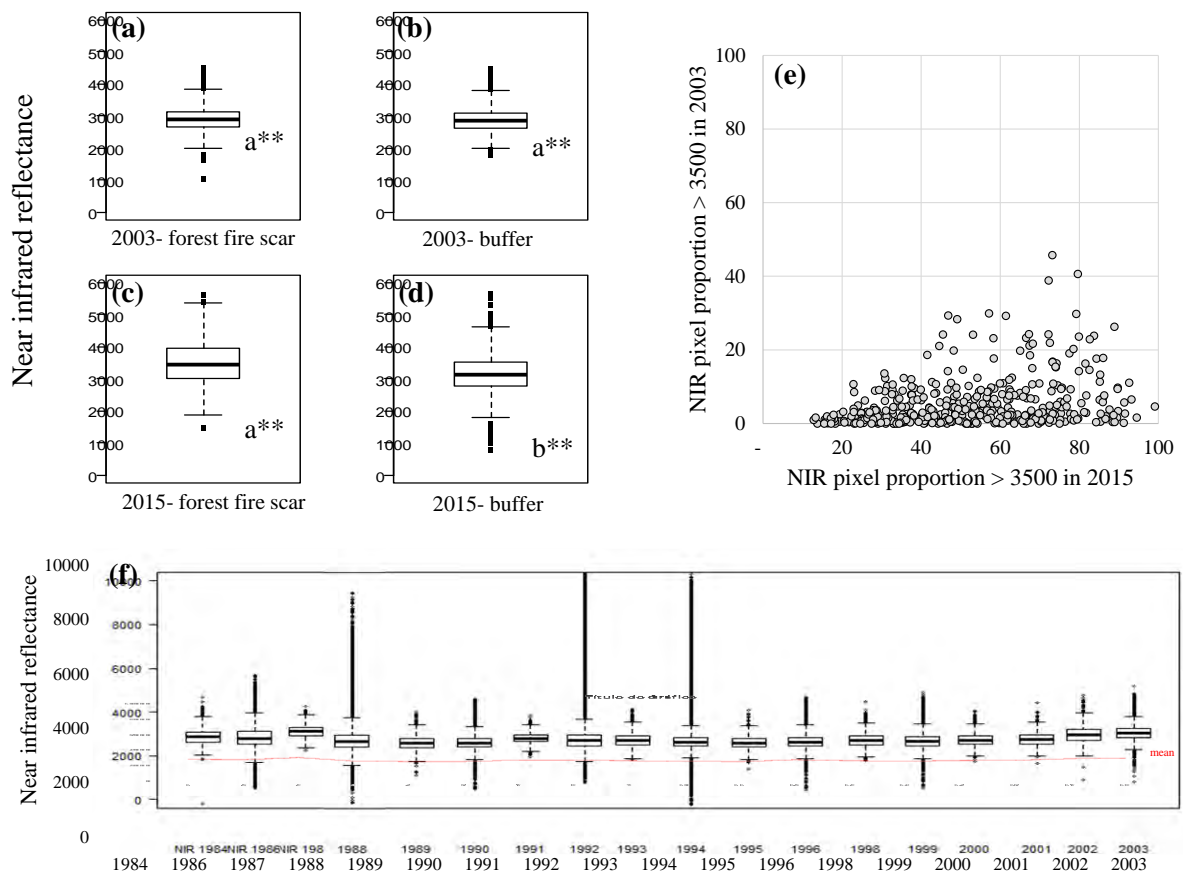
329 The mean DBH of the bamboo stems for all areas was 4 (± 0.54) cm, but the diameter
 330 distributions differed among the areas ($p < 0.05$) (Figure 5). In the intact forest, the minimum
 331 DBH of bamboo was 3 cm and the maximum was 5.4 cm, whereas in forests impacted by fire,
 332 the minimum DBH was 1.1 cm and the maximum was 6.6 cm (DBH ranged from 1.9 cm to
 333 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).
 334 In the areas of burned forest we observed a wide range of the DBH values, indicating a young,
 335 growing population. Moreover, in the forests burned twice (Figure 5d), the DBH distribution
 336 of bamboo was more skewed to the left than in the other treatments, indicating a high number
 337 of bamboo stems with low DBH values.



338
 339 Figure 5. Diameter distribution of bamboo stems in (a) unburned forest, (b) forest burned only
 340 in 2005, (c) forest burned only in 2010 and (d) forest burned both in 2005 and 2010. Different
 341 letters followed by * are statistically different (Kolmogorov-Smirnov test, $p < 0.05$).
 342

343 3.2. Expansion of forests with dominant bamboo

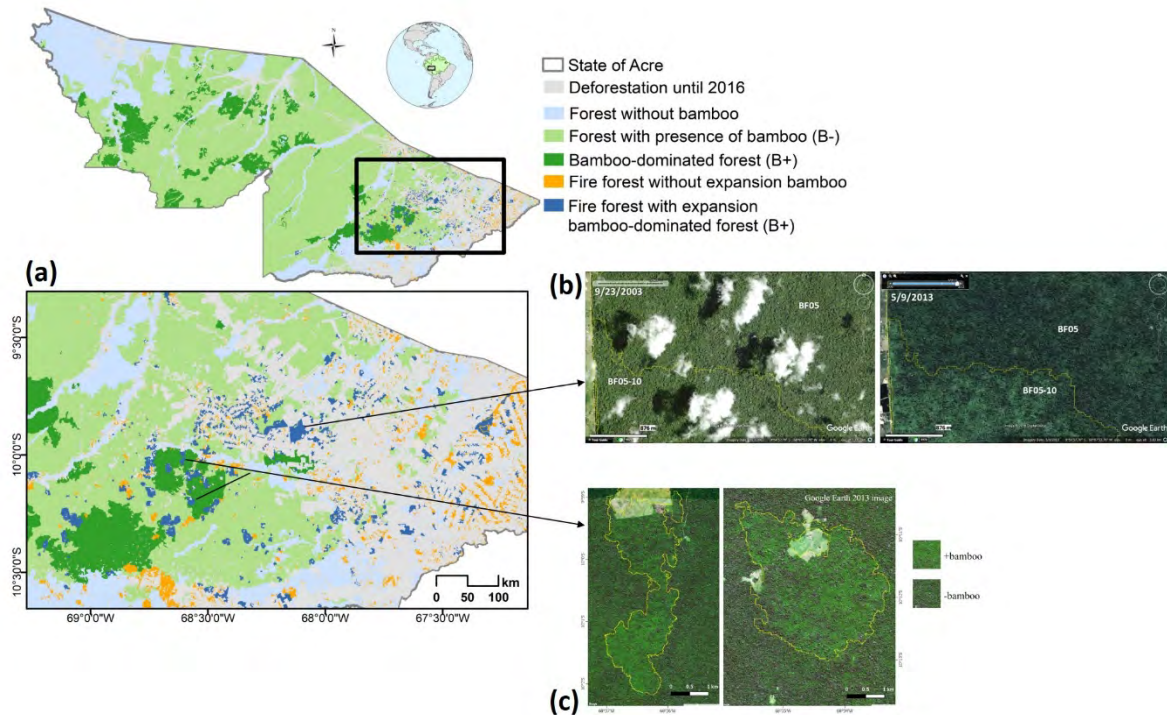
344 There was a significant difference ($p < 0.01$) in the average reflectance values in the
 345 NIR channel in the same year between the forest-fire scars with bamboo expansion and the
 346 500-m buffers surrounding these scars (Figure 6). The NIR reflectance values in the areas of
 347 recent forest fires (2005 and/or 2010) were 11-18% higher than those in the areas of forest
 348 fires (Figure 6a and 6c), indicating the dominance of bamboo in the forest canopy. The
 349 average NIR reflectance value before the fire (2003 image) was 2900 ± 359 in both forest-fire
 350 scars with bamboo expansion and in their 500-m buffers. After the fire (2015 image), the
 351 average NIR values were 3532 ± 637 in the scars and 3160 ± 564 in the buffers. There was an
 352 average increase by 48% in the proportion of NIR values > 3500 after forest fires, with a
 353 maximum increase of 94% (Figure 6e). To validate these results, we analyzed the average
 354 NIR values from 1984 to 2003 for forest-fire scars and confirmed that the average NIR values
 355 before forest fires ranged from 2584 to 3126 (Figure 6f), these values being below the NIR
 356 reflectance values of the same scars after the forest fires.



357
 358 Figure 6. Boxplot of the near-infrared (NIR) reflectance images of forest-fire scars in (a) 2003
 359 and (c) 2015 and in the 500-m buffer surrounding the scars in (b) 2003 and (d) 2015, (e)
 360 change in the proportion of NIR values > 3500 in forest-fire scar polygons identified as
 361 having expansion of bamboo and (f) annual variation of the average NIR values in the areas
 362 where expansion of bamboo-dominated forests were identified. The statistical comparison
 363 was performed between the buffer and the scar in the same year because, due to the short life
 364 cycle of the bamboo, the spectral response changes over time. Letters with asterisks indicate
 365 forest classes with significantly different means based on *post-hoc* Student's t tests comparing
 366 forest fire scar and buffer ($p < 0.01$ or **).

367

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



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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).

382 4. Discussion

383 4.1. Change in the forest structure with bamboo after forest fires

384 There have been profound changes in the forest structure in Acre following recent
385 forest fires, as shown by the drastic reduction of the number of tree individuals by up to 70%
386 and by the increase in the number of bamboo stems by a factor of seven as compared to
387 unburned forests based upon forest inventory data covering forest changes up to 11 years after
388 fire. The density of bamboo stems in the burned forests found in this study is greater than that
389 identified in non-degraded bamboo-dominated forest in three studies in the southwestern
390 Amazon: Silveira (2001) in the Chico Mendes Extractive Reserve in Acre, Smith and Nelson
391 (2011) in the municipality of Sena Madureira in Acre, and Griscom and Ashton (2006) in the
392 department of Madre de Dios in Peru.

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

405 Bamboo expansion may have been favored by several factors. Bamboo grows rapidly
 406 after the reduction of the arboreal component caused by the fire. Bona et al. (2020) showed
 407 that bamboo-dominated forest has a smaller seed rain and lower species richness, and Dantas
 408 et al. (2020) showed that the litter is thicker in bamboo-dominated forest, which can hinder
 409 the regeneration and recovery of the forest trees. Another contributor is the fact that clonal
 410 reproduction of bamboo is stimulated by fire, as observed by Smith and Nelson (2011) and
 411 Gagnon and Platt (2008). Bamboo has a substantial impact on the forest because the genus
 412 *Guadua* is a climbing (semi-scandent) bamboo that depends on adjacent trees for vertical
 413 growth, causing breakage and other physical damage to the trees due to the weight of the
 414 accumulated bamboo (Ferreira, 2014; Griscom and Ashton, 2003; Silveira, 2001). The
 415 bamboo grows with extraordinary speed, with growth rates of 1 to 4 m month⁻¹ (Silveira,
 416 2001). Our results show that trees with DBH up to 37 cm were broken by the climbing
 417 bamboo.

418

419 **4.2. Expansion of forests with dominant bamboo (bamboo-dominated forests?)**

420 Our results suggest that the impact of fire with sufficient intensity and magnitude on
 421 “open forest with presence of bamboo” (B-) caused the classification of the studied areas to
 422 change to “bamboo-dominated forest” (B+). A total of 120,000 ha of forests that had started
 423 to have bamboo as their main floristic element were identified. A combined analysis of the
 424 field plots with remote-sensing data for both the past and the present, indicates concrete
 425 changes in the forest after forest fires. The change in the proportion of the NIR reflectance
 426 values > 3500 was confirmed by testing for differences in the NIR values in the areas of forest
 427 fires with expansion and in adjacent areas. The average values were generally similar to those
 428 identified by Carvalho et al. (2013) (mean NIR = 3400) and Dalagnol et al. (2018) (mean NIR
 429 = 3100); we emphasize that the difference in NIR values between MODIS and Landsat
 430 images, in addition to the differences in the evaluation dates (which imply differences in the
 431 maturity stages of the bamboo populations), can generate substantial differences in results.

432

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

440

441 The impact of the expansion of bamboo in the southwestern Amazon may be even
 442 greater than our study finds. Brown et al. (2006) showed that in 2005 more than 100,000 ha of
 443 forest burned in the department of Pando in Bolivia and 10,000 ha in the department of Madre
 444 de Dios in Peru, both of which neighbor Acre. Vasconcelos et al. (2013) identified around
 445 86,500 ha of forest fires in the southern portion of the Brazilian state of Amazonas, which
 446 also neighbors Acre. These are regions that Carvalho et al. (2013) identified as being B-.

447

448 Records of degradation by forest fire in the Amazon show strong impacts on the
 449 floristic composition of forest (Barlow and Peres, 2008; Silva et al., 2020, Xaud et al., 2013).
 450 Veldman et al. (2009) and Brando et al. (2014) reported another type of degradation effect:
 451 invasion of grasses within the forest after fire and logging. Silvério et al. (2013) argues that
 452 profound changes may be occurring due to the invasion of flammable grasses after forest
 453 fires, thus promoting subsequent fires. In our study, we found that bamboo dominance can
 454 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.

455

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

455 (Faria et al., 2017). Fu et al. (2013) found that the length of the dry season in the southwestern
 456 Amazon had increased by two weeks since 1979. In addition to the climate aspect, future
 457 human land use will also trigger forest fires in the region. In Acre, expansion of the
 458 agricultural frontier is underway in the central portion of the state, and, with increased
 459 deforestation and burning (INPE, 2020a, 2020b), this region can be expected to have its
 460 remaining forests become dominated by bamboo. The combination of climate change and
 461 land-use change will promote favorable environments for the occurrence of forest fires and
 462 therefore for the expansion of bamboo forests in the southwestern Amazon (Ferreira et al.,
 463 2020).

464 The impact of increasing bamboo dominance in fire-degraded forests can have
 465 important implications for forest recovery over time, especially when associated with other
 466 degradation factors such as logging. The combination of bamboo dominance and forest fires
 467 reduces biomass stocks and the density and diversity of trees (Ferreira, 2014; Numata et al.,
 468 2017; Silva et al., 2020; Ziccardi et al., 2019), which can be permanent. However, because
 469 bamboo is dynamic and has a short life cycle (28-30 years), we recommend further research,
 470 such as continuous monitoring the forest-inventory plots established in this study, and
 471 expanding the forest-monitoring network in other regions in Acre in order to understand forest
 472 recovery and the changes in the densities of trees and bamboo. This is also needed in forests
 473 in the Brazilian state of Amazonas and in the Peruvian department of Madre de Dios, which
 474 were also impacted by forest fires in 2005 and 2010. Plots need to be established in forests
 475 where the bamboo died after forest fires. The present study represents only one small step
 476 towards understanding the complex interactions after forest fires and the resulting changes in
 477 Amazonian forests.

478

479 **5. Conclusions**

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

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

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

497

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507

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Supplementary Material

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

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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 2

Figure S1. Photographs of flowering (a) and mortality (b) of bamboo in the study area 3

1 Table S1. Data on the Landsat images used to analyze the expansion of bamboo in the areas of
2 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

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

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(a) Photographs in August and November 2016

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(b) Photographs in May 2017