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Highlights

- No changes in taxonomic composition, AGB, and seedling density in logged bamboo-dominated forest.
- Low estimates of commercial timber volume in logged and unlogged bamboo-dominated forests.
- Diverse NTFP taxonomic composition potentially allows for multiple use forestry practices.

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Logging in bamboo-dominated forests in southwestern Amazonia: Caveats and opportunities for smallholder forest management

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A B S T R A C T

Guadua sarcocarpa and *Guadua weberbaueri* (Poaceae: Bambuseae) have a negative influence on tree regeneration and recruitment in bamboo-dominated forests of southwestern Amazonia. The lack of advanced regeneration and sparse canopy in this forest type present a considerable challenge for developing sustainable timber management plans. We conducted field studies in the Porto Dias Agroextractive Settlement Project in Acre, Brazil to assess influences of logging in bamboo-dominated forest sites. Taxonomic composition, stand structure, aboveground biomass, commercial timber volume, and commercial tree seedling and bamboo culm density were compared between five logged vs. unlogged sites in different landholdings, using modified 0.5 ha Gentry plots. No differences in taxonomic composition, aboveground biomass, adult and juvenile stem density, or woody seedling and bamboo culm density were detected between paired logged and unlogged sites. Commercial timber volume, however, was reduced by almost two-thirds in logged plots, suggesting that long-term timber management goals in this forest type are compromised since so few future crop trees remained onsite. Our findings indicate that in order to maximize local management objectives, community forest managers must approach logging in bamboo-dominated forests with caution. We suggest an integration of non-timber forest product extraction with low harvest intensity and low-impact logging, tending of natural regeneration, and diversification of commercial species.

1. Introduction

There is substantial debate in the scientific community on exactly what constitutes "sustainable timber management" in the tropics, since many large trees are often removed in the first harvest cycle (Rice et al., 1997; Bowles et al., 1998; Pearce et al., 2003; Sist and Ferreira, 2007; Zarin et al., 2007). Particularly challenging are forests that differ from the idealistic tall, closed-canopy stands of trees (e.g., Mostacedo et al., 1998; Toledo et al., 2001), for which many current logging guidelines were developed (see Pinard et al., 1995; Dykstra and Heinrich, 1996). Forests prone to disturbances (wind damage, fire, logging), or characterized by a discontinuous canopy, create ideal settings for aggressive pioneer plants, such as lianas (Putz, 1991; Gerwing, 2001; Schnitzer et al., 2000), or bamboos (Griscom and Ashton, 2006; Veldman et al., 2009; Larpkern et al., 2011; Medeiros et al., 2013), potentially limiting regeneration and recruitment of commercially valuable tree species. As such, the likelihood of high-grading, or removal of the majority of desirable commercial stems, is increased. Especially for locally rare species, e.g., *Tabebuia* spp. and *Hymenaea courbaril* (Bignonaceae and Fabaceae, respectively; Schulze et al., 2008a), or those exhibiting slow growth rates, e.g., *Tabebuia* spp. (Schulze et al., 2008b), residual stand recovery may take many decades (Zarin et al., 2007). Dauber et al. (2005) determined that even with a low harvest intensity (11.8 m^3 ha^{-1}) and implementation of reduced-impact logging (RIL) techniques, only 22% of the original harvest volume will be replaced in 25 years in a liana-dominated forest in Bolivia. While a recent global meta-analysis of more than 100 case studies estimated a doubling of these replacement volumes to an average 54% for the next harvest (Putz et al., 2012), it is clear that recovery of tropical timber volumes under current cutting cycles is not feasible.

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The arborescent bamboo [*Guadua sarcocarpa* and *Guadua weberbaueri* (Poaceae: Bambuseae)]-dominated forests of southwestern Amazonia are characterized by typically low tree basal areas (Nelson, 1994; Silveira, 2001; Griscom, 2003) and varying *Guadua* culm densities, from low-density scattered culms in *terra firme* forests to stands with an average of 2000 culms ha^{-1} (Londoño and Peterson, 1991; Vidalenc, 2000; Vieira et al., 2005). The two most common species of *Guadua* in southwestern Amazonia, *weberbaueri* and *sarcocarpa*, have tall (~10–20 m) culms that are 8–10 cm in diameter (Londoño and Peterson, 1991). Approximately 40% of the region's total area, including the departments of Madre de Dios, Peru, Acre, Brazil, and Pando, Bolivia, is covered by this forest type (Nelson and Bianchini, 2005; Salimon et al., 2011). Tree species diversity is up to 60% less than forest patches without bamboo, with a tendency towards dominance by pioneer taxa of little commercial value (Silveira, 2001; Griscom et al., 2007). Given *Guadua*'s rapid growth rate (up to 10 cm day^{-1} in height in the rainy season), its interconnected rhizome network, and its ability to use neighboring trees for support (Fig. 1; Silveira, 2001; Griscom and Ashton, 2006, 2007), anthropogenic disturbances tend to enhance its competitive advantages. In other bamboo-dominated forests, bamboo species have been observed to flourish following human disturbances, resulting in a decrease in woody species abundance, richness, diversity, regeneration, and basal area (Whitmore, 1984; Campanello et al., 2007; Larpkern et al., 2009, 2011), all important criteria for sustainable timber management (Putz et al., 2001). D'Oliveira et al. (2004) concluded that of the three major forest types in the Antimary State Forest in Acre, Brazil, bamboo-dominated forest had the lowest timber management potential and suggested that it should only be logged under special circumstances.

Bamboo-dominated forests in this region are a good example of an ecosystem that requires greater taxonomic focus and special management considerations. Relatively few papers have specifically addressed floristic composition (but see Silveira, 2001; Griscom et al., 2007), and indeed, earlier studies tended to disregard *Guadua*-dominated forests as a distinct forest type (see Phillips et al., 1994). This omission may have been the result of the physically impenetrable nature of this particular ecosystem (thus hindering collection expeditions) and the difficulty of distinguishing bamboo-dominated and secondary forests via previous, more limited remote sensing technology (Griscom, 2003; Phillips et al., 2003).

Fig. 1. *Guadua* sp. culm using tree trunk for support via modified branches.

Despite the management complications, bamboo-dominated forests have long played an important role in providing ecosystem services and products for forest residents in southwestern Amazonia. Many forest residents in the Brazilian state of Acre prefer to hunt game animals in this forest type (L. Salgueiro, *pers. comm.*), favor burning areas of bamboo prior to planting subsistence crops such as manioc, corn and beans (Silveira, 2001), and often use bamboo culms for support beams in their houses. Additionally, many animal species prefer bamboo stands, especially during mast fruiting episodes (Silveira, 1999), or are outright obligate bamboo specialists (see Conover, 1994; Kratter, 1997). Even though densities of cash-generating NTFP species such as rubber (*Hevea brasiliensis*, Euphorbaceae) and Brazil nut (*Bertholletia excelsa*, Lecythidaceae) in *Guadua*-dominated forests may be low (Griscom et al., 2007), rubber tappers reportedly favor the quality of latex in bamboo-dominated forests (Silveira, 2001).

Many Amazonian forest-based communities have shifted from local economies based predominantly on NTFPs to those that integrate timber extraction (Kainer et al., 2003; Guariguata et al., 2010; Duchelle et al., 2012; Shanley et al., 2012). To mitigate the much greater ecological impacts which typically ensue from timber vs. non-timber extraction, experimentation is needed, particularly given efforts to curtail carbon emissions that typically increase with logging activities (Putz et al., 2008b; Blanc et al., 2009). Few field datasets for the characterization of aboveground biomass (AGB) exist from this forest type, but typically, *Guadua*-dominated forests have considerably lower AGB values (224 Mg ha^{-1}) than other forest types in the region (322 Mg ha^{-1} for dense forest) (see Vieira et al., 2005; Salimon et al., 2011; D'Oliveira et al., 2013). Nonetheless, their conservation could eventually benefit forest communities through financial compensation from reduced emissions due to deforestation and degradation (REDD) programs (Hall, 2008), as retaining forest carbon is one of many incentives for improving management practices in tropical forests (Putz et al., 2008a). Information on short-term logging impacts on AGB would be valuable to assess how timber management may impact carbon stocks in this forest type (see D'Oliveira et al., 2013).

We present results of a field investigation of logging and management impacts in bamboo-dominated forest sites in southwestern Amazonia. Our objectives were to assess the effects of current conventional logging practices on forest stand structure, timber and NTFP tree seedling densities, and woody plant taxonomic composition. We hypothesized that AGB, commercial timber volume, BA, juvenile and sub-adult tree stem density, and timber species density would all be reduced in logged forest, while there would be an increase in heliophilic genera density in the seedling size class (⩽1 m height), and bamboo culm density due to post-logging canopy openness.

2. Methods

2.1. Study site

The study was conducted in the Porto Dias Agroextractive Settlement Project (S 10°00′39, 9″, W 66°46′26,4″), a 22,145 ha tract of seasonally-moist tropical forest, subsistence agricultural fields and pasture in the Brazilian state of Acre. The landscape is defined by red–yellow latisols of low fertility and gently-rolling to flat topography, with mean annual rainfall and temperature of 1655 mm yr^{-1} (Perz et al., 2013) and 24.5 °C (Vieira et al., 2005), respectively. The Settlement retains a high proportion of forest cover (80%; Pereira, 2007, Franco and Esteves, 2008), most of which

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is dominated by *G. sarcocarpa* and *G. weberbaueri* (CTA, 2001). In late 2004, *G. sarcocarpa* underwent a monocarpic dieoff outside of our plot locations, but in landholdings within the Settlement's southeastern border with Bolivia at the Abunã River (Rockwell et al., 2007). As of 2012, the last time the plots in our study were surveyed, this dieoff had still not occurred in our plots.

Deforestation has largely been avoided within settlement borders, thanks in large part to the historical socioeconomic importance of timber and NTFP extraction. Long-term residents recall that mahogany (*Swietenia macrophylla*, Meliaceae) was selectively removed and transported down the Abunã River from 1900 to 1950, when the Settlement was a privately-owned rubber estate (Stone, 2003). Since designation as an Agroextractive Settlement Project (PAE) in 1989 under the federal authority of INCRA (National Institute for Colonization and Agrarian Reform), timber removal can be qualified by three distinct categories: (1) predatory exploitation, in which neighboring ranchers cut large trees indiscriminately without permission from Settlement residents or federal officials, an activity which has subsided in recent years (D. Alencar, *pers. comm.*); (2) certified operations executed and managed by local residents in concert with a the Community Forest Producers Cooperative, or COOPERFLORESTA (see Humphries and Kainer, 2006); and (3) legal removal by external non-certified operators who were contracted by at least two local landowner associations. The latter has been favored by many residents due to the immediacy and security of timber payments and management simplicity (D. Alencar, *pers. comm.*, Stone, 2003), as opposed to the difficulties of entering the niche market of certified wood (Drigo, 2005). Our study was conducted in one such community known as Mossoró.

Mossoró is located in the western extremity of Porto Dias, where some of the highest rates of settlement deforestation have been documented (Pereira, 2007, Franco and Esteves, 2008). During the 2005 drought, this area was especially vulnerable to fires that spread from neighboring ranches into the bamboo-dominated forest, which is typically more fire-prone than other types of *terra firme* forest (Smith and Nelson, 2011; Barlow et al., 2012). Since 2005, 12–20 Mossoró residents annually contract a timber company to log trees through the local landowner association, *Associação Agroextrativista São José*. In preparation, an external consultant in concert with several community members trained in tree identification conduct a forest census of all harvestable and future crop trees ⩾45 cm diameter at breast height (dbh). Each year, the size of the management block selected for harvest depends on annual demand vs. long-term management plans and thus, the size of individual management blocks within a single landholding varies from 10 to 30 ha, inhibiting projections of the total number of management blocks (past, current, and future) per landholding. The consultant then submits an annual operating plan to the state environmental agency (IMAC), which has the right to approve, modify or reject the plan based on compliance with federal regulations (e.g., acceptable basal area removed, desired residual stand species distribution, and stream and steep area protection).

Association regulations require that at least one person from the Association (preferably the landowner) accompany the logging crew; however, noncompliance with this rule has led to disputes regarding removal of trees not scheduled for logging or close to water sources, and damage to NTFP stems such as Brazil nut. All timber is extracted using agricultural tractors and transported 30 km to a sawmill owned by the timber company.

During the study period, the contracted timber company paid by logged area rather than by individual trees, and logging intensity varied between 8 and 12 m^3 ha^{-1}. Approximately 20–30 species have been identified by the company as species of commercial interest, but eight species groups tend to be the most heavily exploited: *cumaru ferro* (*Dipteryx* spp., Fabaceae), *cumaru cetim* (*Apuleia leiocarpa*, Fabaceae), *ipê* (*Tabebuia* spp., Bignoniaceae), *cedro* (*Cedrela* spp., Meliaceae), *jatobá* (*H. courbaril*, Fabaceae), *jutaí* (*Hymenaea* spp., Fabaceae), *maçaranduba* (*Manilkara* spp., Sapotaceae), and *cerejeira* (*Amburana cearensis*, Fabaceae). In contrast to the neighboring certified operation that has avoided species with potential NTFP value, this company has on occasion logged *andiroba* (*Carapa guianensis*, Meliaceae) and *copaiba* (*Copaifera* spp., Fabaceae) when encountered, despite their highly-valued medicinal and cosmetic properties (Klimas et al., 2012; Newton et al., 2012; Martins et al., 2013).

2.2. Sampling design

During June–August 2009 following the September 2008 timber harvest, we sampled bamboo-dominated forest in Mossoró in four different landholdings (150–300 ha each). *Guadua* dominance was defined *a priori* as having 10 or more bamboo culms per 100 m^2 of forest (adapted from Griscom and Ashton (2003)). Five sets of paired 0.5-ha plots were installed in four landholdings: 2 sets of paired plots located in one and one pair in each of the remaining three, with at least 300 m between any sets of paired plots.

Each set of paired plots consisted of one plot located in a logged management block (10 ha each) and its corresponding control (unlogged) plot, in an area defined by no logging since 2005, when formalized logging officially began in the community. Unlogged plots were at least 50 m from the edge of management blocks to avoid influence of recent disturbance. Logged plot locations were selected to ensure a comparable logging intensity and skid trail construction between plots. According to landowners' formalized logging plans, management blocks were harvested at an intensity of approximately 10 m^3 ha^{-1}, or 2 trees ha^{-1}. We did not collect data on total number of cut stumps in site, but landowners noted that logging intensity was relatively homogenous within each logging block.

All plot locations (including those deemed "unlogged") had indications of fire damage within the last 10 years as well as signs of selective logging that took place many years prior to the current harvest. Most evidence of undocumented logging activity consisted of widely-dispersed rotted stumps and abandoned boles. These observations were verified by local landowners. According to community residents, a neighboring rancher crossed settlement borders approximately 20 years ago to illegally harvest high-value logs at a relatively low intensity, such as mahogany and Spanish cedar.

All plots were established according to a modified version (Phillips et al., 2001; Baraloto et al., 2011) of the Gentry plot (Gentry, 1982), which consists of ten 10 × 50 m belt transects totaling an area of 0.5-ha (Fig. 2). Although finding a representative 200 × 100 m area (the extent of ground cover needed to install a modified Gentry plot) of *Guadua*-dominated forest can be challenging, the modified plot method is efficient in characterizing both aboveground biomass and floristic composition (see Baraloto et al., 2013). We further modified the protocol in two ways to obtain more information on the regenerating forest community. First, we measured all stems ⩾2.5 cm dbh within the entire 10 × 50 m area of each belt transect. Second, we used a central sub-belt of 2 × 50 m within each 10 × 50 m belt transect to count and measure *Guadua* culms and all tree seedlings (⩽1 m height) of commercially-valuable (timber and NTFP) species. Data from paired logged/unlogged plots were collected to test for the influence of timber harvest on both overall seedling density and individual species density for the seedling size class.

2.3. Forest stand structure measures

We defined seven stand variables to describe forest stand structure of each plot: (1) AGB; (2) mean dbh, measured at 1.3 m above

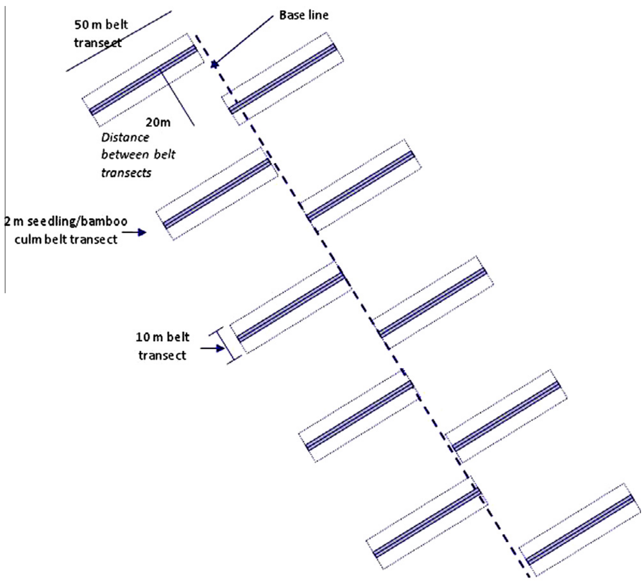

Fig. 2. An example of a modified Gentry plot used in this study (5000 m^2) (adapted from Phillips et al. (2001) and Baraloto et al. (2011)).

ground level; for stems with irregular trunks or buttresses, dbh was determined by measuring above irregularities, or rarely when this was not possible, by visual estimation; (3) mean total height; (4) mean BA per ha (calculated initially by individual tree as $\pi * [(dbh/2)^2]$ ($m^2\ ha^{-1}$) and summed over the plot; (5) mean stem density ha^{-1} for three size classes: (a) 2.5 cm ⩽ dbh < 10 cm; (b) 10 cm ⩽ dbh < 30 cm; and (c) dbh ⩾ 30 cm; (6) bamboo culm density ha^{-1}, and (7) commercial timber volume ($m^3\ ha^{-1}$) (Table 1). Calculations for AGB and commercial timber volume are described accordingly:

2.3.1. Aboveground biomass

We estimated AGB of smaller trees of all species [2.5 ⩽ dbh < 10 cm], including palms, using a model originally developed for a moist tropical forest in southern Mexico (Hughes et al., 1999; Chave et al., 2004):

$$AGB = \frac{WSG \cdot e^{-1.9703+2.1166\ln(\mathrm{dbh})}}{\overline{WSG}}$$

where WSG is the wood specific gravity (in g cm^{-3}) and the overbar indicates the mean value. We used the mean WSG value from southwestern Amazonia calculated by Baker et al. (2004).

We estimated AGB in trees and palms with dbh ⩾ 10 cm, in two ways. First, we used an allometric formula that integrates mean WSG values from southwestern Amazonia (Baker et al., 2004), and total tree height (*H*, in m) and dbh from a pantropical study (Chave et al., 2005):

$$AGB = 0.0509 \cdot WSG \cdot \mathrm{dbh}^2 \cdot H$$

Secondly, we calculated AGB using a dry weight formula for open forests in southern Amazonia (Nogueira et al., 2008a):

$$AGB = \exp(-1.716 + 2.413 * \ln(\mathrm{dbh}))/1000$$

These two approaches gave very consistent results ($r = 0.96$); we only report the former to facilitate comparisons from the literature. Standing bamboo culms were not included in any AGB calculations.

2.3.2. Timber volume

We calculated timber volume (*V*; m^3) for all commercial species with Noguiera et al.'s (2008a) bole-volume allometric equation for open forests in southern Amazonia: $V = 0.000131\ \mathrm{dbh}^{2.507}$, using both a 35 and 45 cm minimum dbh cutoff. Although 50 cm dbh is the legal limit in Brazil for tropical timber species, our 45 cm cutoff mirrored the local community-sponsored forest inventories. Inclusion of the smaller trees (35–45 cm dbh) facilitated assessment of future crop tree potential, albeit assuming they were of desirable commercial form.

2.3.3. Woody taxonomic composition

Parataxonomists from the Federal University of Acre and the local community identified stems on site using vegetative characteristics. Only the most common taxa (e.g., *Rinorea pubiflora*, Violaceae, *Allophylus floribundus*, Sapindaceae) and those

Table 1
Q9 Mean values and test results of paired *t*-tests for basal area (BA), stem densities for three size classes, diameter at breast height (dbh), height, above ground biomass (AGB), timber volume, timber/non-timber forest product (NTFP) seedling abundance, and bamboo culm density in 10 paired 0.5-ha plots.

Variable	Mean (standard dev.)		Test results
	Unlogged	Logged	
AGB (Mg ha^{-1})			
2.5 cm ⩽ dbh < 10 cm dbh	5.9 (0.8)	5.9 (1.7)	$t = 0.10$, $p = 0.95$
⩾10 cm dbh	113.9 (29.4)	105.3 (32.3)	$t = 0.32$, $p = 0.76$
DBH (cm)			
(ind ⩾ 2.5 cm dbh)	8.8 (0.7)	8.7 cm (0.6)	$t = 0.39$, $p = 0.72$
Height (m)			
(ind ⩾ 2.5 cm dbh)	6.5 dbh (0.5)	6.5 dbh (0.6)	$t = 0.23$, $p = 0.83$
BA ($m^2\ ha^{-1}$)			
(Stems ⩾ 10 cm dbh)	21.3 (2.6)	19.1 (3.8)	$t = 0.99$, $p = 0.38$
Stem densities (stems ha^{-1})			
2.5 cm ⩽ dbh < 10 cm dbh	1216 (255.2)	1194 (281.3)	$t = 0.12$, $p = 0.92$
10 cm ⩽ dbh < 30 cm dbh	269.6 (56.3)	272.8 (88.2)	$t = -0.06$, $p = 0.95$
⩾30 cm dbh	74.4 (12.6)	71.2 (13.2)	$t = 0.42$, $p = 0.70$
Bamboo culms (culm ha^{-1})	1252 (307.9)	1242 (189.7)	$t = 0.12$, $p = 0.92$
Timber volume			
= 35- < 45	68.4 $m^3\ ha^{-1}$ (10.3)	28.2 $m^3\ ha^{-1}$ (5.3)	$t = 6.36$, $p = 0.003^*$
> = 45	57.5 $m^3\ ha^{-1}$ (11.6)	18.7 $m^3\ ha^{-1}$ (4.3)	$t = 5.47$, $p = 0.01^*$
NTFP/timber seedlings	650 st ha^{-1} (411.2)	1014 st ha^{-1} (717.0)	$t = -2.30$, $p = 0.08$

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unambiguous trees of commercial importance (e.g., *B. excelsa*, *H. brasiliensis*) were identified to species. The remaining stems were identified to genera, except for those of unknown scientific classification or those that parataxonomists did not recognize, whereby they were assigned general morphospecies classification or noted as undetermined. Parataxonomists also assessed whether stems were heliophiles (see Poorter et al., 2006) or had timber and/or NTFP value.

2.4. Data analysis

Paired *t*-tests were used to examine differences between logged and unlogged bamboo-dominated forest related to the seven measures of forest stand structure [aboveground biomass (AGB), mean dbh, mean total height, basal area (BA), stem density (⩾2.5 cm dbh), bamboo culm density, and commercial timber volume], timber and NTFP tree seedling densities, and woody plant taxonomic composition. We did not test for a landholding effect due to the high heterogeneity at small spatial scales in this site and the low statistical power associated with such tests. Finally, a Dufrene–Legendre (Dufrene and Legendre, 1997) indicator species analysis tested the potential exclusivity of identified species (or morphospecies) to logged vs. unlogged plots. Analyses were conducted using the R 2.11.1 software platform.

3. Results

3.1. Changes in forest stand structure

3.1.1. Aboveground biomass, basal area, stem density, and bamboo culm density

Across the five sets of paired plots, AGB values 1 year after logging did not differ between logged and unlogged bamboo-dominated forest (Table 1, Fig. 3) for all three size categories. There were also no significant differences in BA, stem densities in the three size classes, mean dbh or height between unlogged and logged sites (Table 1, Fig. 3). Contrary to our expectations, bamboo culm density did not differ between unlogged and logged sites (Table 1). Mean size of bamboo culms was 21 cm in circumference and 20 m in height.

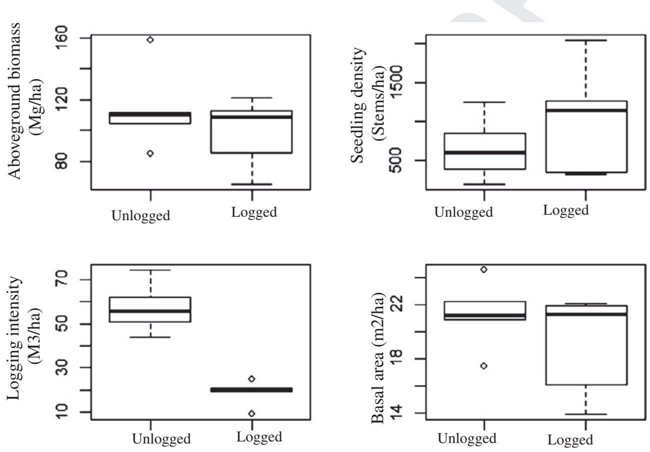

Fig. 3. Contrasting forest structure between 10 paired plots in logged and unlogged bamboo forests, including total aboveground biomass (Mg ha^{-1}), timber and non-timber forest product seedling density (stems ha^{-1}), total timber volume (⩾45 cm dbh) (m^3 ha^{-1}), and total basal area (⩾10 cm dbh) (m^2 ha^{-1}). Box plots represent the first, second (median), and third quartiles, with vertical lines (or "whiskers") demonstrating variability outside the lower and upper quartiles; outliers are represented by the small "o"s. Results of *t*-tests are presented in Table 1.

3.1.2. Timber volume

Across all 10 logged and unlogged plots (5 ha), we observed a total of 56 individuals ⩾ 45 cm dbh and a total of 106 individuals ⩾ 35 cm dbh. One year after harvest, timber volumes for trees of current commercial interest (⩾45 cm dbh) and of large future crop trees (⩾35 cm dbh) were significantly lower (67% and 59%, respectively) in logged plots (Table 1, Fig. 3).

3.2. Changes in NTFP and timber seedling abundance

Both timber and NTFP seedlings were abundant, with over 1000 stems ha^{-1} in logged plots (Tables 1 and Fig. 3). This was especially true for *H. brasiliensis* and *Tabebuia* spp. in logged plots and *Tetragastris altissima* in unlogged sites (Tables 2 and 4). Although seedling densities were higher in logged vs. unlogged sites, these differences were not significant at $\alpha = 0.05$ (Table 1; $p = 0.08$), and no significant differences ($p < 0.05$) were found between unlogged and logged stem densities for any of the species.

3.3. Changes in woody taxonomic composition

Of the 331 common local names for woody taxa inventoried, approximately 10% were identified to species and 70% were identified as a morphospecies (i.e., not identified to an individual species, but rather to genus and/or family). We classified between 45 and 60 species/species complexes (defined as a genus with more than one associated species, many of which have yet to be identified using either morphological or molecular traits) with commercial potential (trees ⩾ 2.5 cm dbh), dominated by *Breu vermelho* (*T. altissima*, Burseraceae) and *ipê* (*Tabebuia* spp., Bignoniaceae) (Table 2). Of these taxa, 20 species/species complexes ⩾ 35 cm dbh had current commercial value (see Table 2) according to the local logging company and COOPERFLORESTA. NTFP species were present in all plots, with *açaí* (*Euterpe precatoria*, Arecaceae), *cacau* (*Theobroma cacao*, Sterculiaceae) and *bacaba* (*Oenocarpus bacaba*, Arecaceae) the most prevalent (Table 3).

Recent logging activities also did not influence the 10 most common genera (Table 3) nor the density of heliophilic species of the seedling size class. Based on the indicator species analysis, no species was found exclusively in logged or unlogged sites.

4. Discussion

Our findings contrast sharply with reports from other tropical bamboo forests. Our hypotheses (based on these previous studies) that logging would affect taxonomic composition in the seedling size class (⩽1 m height), seedling density, forest stand structure, aboveground biomass, and bamboo culm density, were not supported by our results. Nonetheless, our pre-logging commercial timber volume was low in comparison to some forest types in the Amazon Basin (e.g., Valle et al., 2007), and decreased considerably following logging.

4.1. Changes in forest stand structure after logging interventions

Our AGB estimates in unlogged bamboo-dominated forest (114 ± 29 Mg ha^{-1}) were considerably lower than those generated by Salimon et al. (2011) and D'Oliveira et al. (2013) in the same region for bamboo-dominated forest (224 ± 50 Mg ha^{-1} and 198.9 ± 8.5, respectively), but similar to estimates calculated by Vieira et al. (2005) for bamboo-dominated forest in the Catuaba Experimental Farm of the Federal University of Acre (95 Mg ha^{-1}). As well, our study site demonstrated evidence of fire intrusion and illegal selective logging from the last two decades, factors which, in concert with the bamboo dominance, could certainly result in

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Table 2
Taxonomic identification and mean stem density ha^{-1} (reported as integers) of several commercially important timber species [⩾35 cm dbh, juveniles (2.5–5 cm dbh), seedlings (⩽1 m height)] in 10 modified Gentry (5000 m^2 each for adult and juvenile stems and 1000 m^2 for seedlings) paired plots in unlogged and logged bamboo-dominated forest.

Species	Brazilian commercial name	Family	Stem (⩾35 cm dbh) density ha^{-1}		Stem (2.5–5 cm dbh) density ha^{-1}		Stem (⩽1 m height) density ha^{-1}	
			Unlogged	Logged	Unlogged	Logged	Unlogged	Logged
Apuleia leiocarpa	cumaru cetim	Fabaceae	<1		3	10	10	36
Aspidosperma vargasii	amarelão	Apocynaceae	<1		18	28	12	56
Astronium spp.	maracatiara	Anacardiaceae	<1		10	22	26	70
Brosimum spp.	manitê	Moraceae	<1		2	<1		
Cedrela spp.	cedro	Meliaceae		<1	2	14		2
Ceiba spp.	samauma	Bombaceae	<1	<1	14	18	12	6
Clarisia spp.	guariuba	Moraceae	<1	<1	5	3		
Dipteryx spp.	cumaru ferro	Fabaceae	<1	<1	5	18	9	76
Hymenaea spp.	jutaí	Fabaceae	<1	1		14	4	46
Hymenaea courbaril	jatobá	Fabaceae	<1		<1	<1		2
Jacaranda spp.	marupá	Bignoniaceae	<1		2	2		4
Manilkara spp.	maçaranduba	Sapotaceae	<1	<1	4	7		2
Myroxylon spp.	balsamo	Fabaceae			4	<1	14	2
Parkia spp.	angico, fava angico	Fabaceae	2	<1	1	1		
Pouteria spp.	abiu, abiurana	Sapotaceae	<1	<1	42	36	4	
Swietenia macrophylla	mogno	Meliaceae	<1			<1		
Tabebuia spp.	ipê	Bignoniaceae	5	3	46	68	134	226
Tetragastris altissima	breu vermelho	Burseraceae	5	2	82	62	236	222
Torresea spp.	cerejeira	Fabaceae	<1		2	1		
Vatairea spp.	sucupira, faveira	Fabaceae	<1		1	<1		10

Table 3
Taxonomic identification and stem density ha^{-1} (reported as integers) of the 10 most common genera (⩾2.5 cm dbh) in 10 modified Gentry (5000 m^2 each) plots in unlogged and logged bamboo-dominated forest (in descending order).

Genus	Family	Stem density ha^{-1} (unlogged)	Stem density ha^{-1} (logged)
Rinorea	Violaceae	233	143
Pseudolmedia	Moraceae	78	77
Inga	Fabaceae	67	50
Pouteria	Sapotaceae	43	38
Metrodorea	Rutaceae	41	28
Casearia	Salicaceae	20	44
Cecropia	Cecropiaceae	27	36
Acalypha	Euphorbiaceae	29	34
Oenocarpus	Arecaceae	22	35
Euterpe	Arecaceae	30	25
Pausandra	Euphorbiaceae	39	16

lower biomass values. What remains clear is that AGB values from all three of these local studies are lower than estimates from central and eastern Amazonia (233–446 Mg ha^{-1}; Anderson et al., 2009), perhaps due to low wood density and because trees are shorter at any given diameter than at least their central Amazonian counterparts (Nelson et al., 2006; Nogueira et al., 2008b). The longer dry season in Acre (Brazil, ANA, 2006), continuous damage by the mass loading prevalent in bamboo forest (Griscom and Ashton, 2006), and convective downbursts common to the region (Nelson et al., 2001; Garstang et al., 1998) may further explain these differences.

AGB values, though, did not differ significantly between logged and unlogged sites, suggesting one of at least two possibilities: our sample size (5 sets of paired 0.5 ha plots) was too small to capture the contrast between logged and unlogged sites, or the logging survey team chose the richer stand to exploit, in terms of harvestable trees. Additionally, our census 1 year after logging may have been too early to detect the changes observed in other studies, especially juvenile tree stem densities and taxonomic composition (e.g., Uhl and Vieira, 1989; Baraloto et al., 2012). Furthermore, evidence of both fire and illegal logging was found in many of our plots (including those designated as "unlogged" in terms of recent logging activities), and this disturbance may mask the effect of more recent select logging activity, as observed in logging concessions in the dry tropical forest of eastern Bolivia (see Mostacedo et al., 1998; Toledo et al., 2001).

Our measured timber volume was low (Table 1, Fig. 3) compared to other locations in Amazonia, even for our unlogged sites. Our volumes of commercial species (⩾10 cm dbh) prior to harvest (70.6 m^3 ha^{-1}) was about half of that reported for Paragominas (134 ± 19 m^3 ha^{-1}) (Valle et al., 2007). Without pre-formal logging data, though, it is difficult to say whether the large differences in commercial volume is the result of the most recent logging intervention (in 2008) or the combined result of the formal logging and previous clandestine activities. If the forest is truly experiencing a second cutting cycle, current and future timber volumes would be much lower than those accumulated over the centuries prior to the first harvest of these previously old-growth forests (Putz et al., 2012). This lack of pre-logging metrics is one of the limitations of our study. Nonetheless, we submit that this type of "background disturbance" is common across the Amazon Basin, especially in those areas with a long history of human habitation and road access (Heckenberger et al., 2003; Perz et al., 2013; Baraloto et al., in preparation). These forests should be included in scientific discussions, as exploited and degraded forest is becoming increasingly the norm across the tropics (Putz et al., 2012).

4.2. Logging impacts on regeneration

Logging has been shown to enhance tree regeneration due to canopy openings and soil scarification in other forest types (e.g., Gullison et al., 1996; Fredericksen and Mostacedo, 2000; Fredericksen and Putz, 2003). And indeed, studies conducted in recently disturbed bamboo-dominated sites have found similar results (see Larpkern et al., 2011; Montti et al., in press). Accordingly, densities of timber tree seedlings (e.g., *Tabebuia* spp., *Astronium* spp.) tended to be higher (by 36%) in our logged vs. unlogged sites ($p = 0.08$, Tables 1 and 2, Fig. 3), although the influence of location in a logged site was not statistically significant ($p \leqslant 0.05$). It is possible that the sample size ($n = 5$) was too small to reflect a strong influence of logging in this particular response variable. As well, given that bamboo culm density did not vary between logged and unlogged sites (see Table 1), canopy openness caused by stem removal and

temporary culm dieback was (at least 1 year after logging interventions) not as pronounced to have a lasting effect on regeneration rates. Even so, it is interesting to note that *Tabebuia* regeneration was especially abundant – an important result, as it has been classified as a genus of special concern in previous studies (Schulze et al., 2005, 2008b). In contrast to these cases (from the Brazilian state of Pará), *Tabebuia* presents one of the most vigorous populations of all of the timber genera for all size classes – reinforcing the need for regionally based management prescriptions generated from long-term dynamics data.

4.3. Logging impacts on taxonomic composition

Bamboo-dominated forests in southwestern Amazonia are highly heterogenous across the Amazonian landscape. Our species and genera composition differed from other southwestern Amazonian *Guadua* forests, and even from other stands located in Acre, Brazil (see Silveira, 2001; Griscom et al., 2007). *Pseudolmedia* (Moraceae) was identified as a bamboo disassociate in Madre de Dios, Peru (Griscom, 2003), whereas it was the second most common genus in our study (Table 3). In fact, most of the abundant genera in our study were not found in *Guadua*-dominated forest in the Tambopata River Basin (approximately 400 km to the southwest of our study site). Despite dominance by the same two bamboo species, these compositional differences might be explained by the large geographic distance between study sites; forest composition will necessarily vary by topography, soil, climate, and disturbance regimes (Phillips et al., 2003; Bachman et al., 2004). We also found striking differences between our data set and that of Silveira's (2001), collected approximately 120 km away in the Chico Mendes Extractive Reserve. None of the five most common genera corresponded between sites, although Silveira (2001) listed *Hevea* as one of the 10 most common genera (individuals ⩾ 10 cm dbh), a similar result to our study. What these comparisons suggest is that bamboo-dominated forests in southwestern Amazonia are highly heterogenous across the landscape.

4.4. Implications for smallholder management

Bamboo-dominated forests present a significant management challenge, and should only be logged under certain circumstances (D'Oliveira et al., 2004). Our study demonstrated low standing timber volumes, yet we hesitate to propose complete avoidance of logging activities. Forest residents may not have the option of moving their timber operations to bamboo-free areas, and commercial logging is not likely to decrease in the near future given the widespread demand for Brazilian tropical wood (Pereira et al., 2010).

Perhaps the best management option is to restrict logging to just after the increasingly predictable (see Carvalho et al., 2013) monocarpic events when bamboo seedlings are most vulnerable and the rhizome network is still immature (Griscom, 2003). In the Antimary State Forest in Acre, Brazil, (D'Oliveira et al., 2013) discovered that individual bamboo genets did not recover following a cyclical 27–28-year synchronous mortality event during a dry season timber harvest. Yet, organizing a landscape-scale timber harvest to coincide with periodic bamboo dieoffs may be impractical, particularly for smallholders and communities who log small areas.

To even sustain our observed low timber harvests volumes, timber management will need to be more sophisticated in these bamboo forests, including early assessment of individual species populations for all size classes. For example, some species (e.g., *T. altissima*, *Tabebuia* spp.) were abundant at both seedling and adult stages, while others (e.g., *Dipteryx* spp.) were plentiful as seedlings but not as juveniles or adults (Tables 2 and 4). Smallholders could feasibly cut back bamboo culms and maintain advanced regeneration to add value to logged, low volume forests and encourage timber seedlings to attain commercial size by the third harvest (Schulze, 2008). Albeit expensive, enrichment planting and tending of select species could help attend to this objective.

Rural communities are not solely driven by profit maximization targets as are industrial firms, having a more comprehensive view of the forested ecosystem they call home (Schmink, 2004). They are open to diverse management options and could integrate a suite of NTFPs into management plans. Stem densities of açaí (*E. precatoria*) (27 individual ha^{-1}) were comparable with other regional *terra firme* forests (Zuidema and Boot, 2000), and some community members have already marketed *E. precatoria* fruits (D. Alencar, *pers. comm.*). *H. brasiliensis* is also common at the adult and seedling stages (see Table 4), suggesting great potential for sustainable rubber management. Most community members in Porto Dias long-abandoned traditional rubber tapping, but the highly successful natural rubber condom factory Natex and the forthcoming *Granulado Escuro Brasileiro* factory present novel local latex market outlets. The latter will produce processed natural latex, a primary ingredient for the pressurized gas and automotive industries. Diversification of forest-based (NTFPs, environmental service payments, adding value to forest products, timber) and

Table 4
Taxonomic identification and mean stem density ha^{-1} (⩾2.5 cm dbh and ⩽1 m height) of non-timber forest product taxa in 10 modified Gentry (5000 m^2 each) plots in unlogged and logged bamboo-dominated forest.

Species	Brazilian commercial name	Family	Stem density ha^{-1} (⩾2.5 cm dbh)		Stem density ha^{-1} (⩽1 m height)		Timber value
			Unlogged	Logged	Unlogged	Logged	
Acacia sp.	cipó-unha-de-gato	Fabaceae	<1	<1	<1	<1	
Astrocaryum aculeatum	tucumã	Arecaceae	<1	2			
Astrocaryum murumuru	murmuru	Arecaceae	13	8.4			
Bactris sp.	pupunha	Arecaceae		<1			
Bertholletia excelsa	castanheira	Lecythidaceae	7	6	6	6	
Copaifera spp.	copaiba	Fabaceae		<1		<1	X
Dipteryx spp.	cumaru ferro	Fabaceae	4	3	9	76	X
Euterpe precatoria	açaí	Arecaceae	30	25			
Hevea brasiliensis	seringueira	Euphorbiaceae	12	23	20	110	
Hymenaea courbaril	jatobá	Fabaceae	<1			2	X
Maximiliana maripa	inaja	Arecaceae	<1	2			
Oenocarpus bacaba	abacaba, bacaba	Arecaceae	21	34			
Oenocarpus bataua	patauá	Arecaceae	<1	1			
Qualea tesmannii	catuaba	Vochysiaceae	4	3	4	3	X
Theobroma sp.	cupuí	Sterculiaceae	<1	<1			
Theobroma cacao	cacau	Sterculiaceae	20	18			
Theobroma obovatum	cupuaçu-bravo	Sterculiaceae	1	1			

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nonforest-based (wage labor, perhaps small-scale cattle and agriculture) livelihood strategies coupled with an emphasis on community perspectives and capacities to manage their forests (see Amaral and Neto, 2000; Stone-Jovicich et al., 2007; Lima et al., 2008) are central to long-term maintenance of forest cover and forest-based livelihoods. Additionally, combined efforts on the part of all stakeholders, including open communication and negotiation between forest communities and contracted companies (see Menton et al., 2009), as well as cooperative, government, and non-governmental actors, is needed to attain sustainable forest management goals for bamboo-dominated forests.

5. Uncited references

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