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Can forest management be sustainable in a bamboo dominated forest? A 12-year study of forest dynamics in western Amazon

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ABSTRACT

The western Amazon supports the largest formation of neotropical bamboo forests. This forest ecosystem is neglected due to its low commercial timber volume and fragile forest structure that amplifies the damage caused by logging operations. This study was conducted in a lightly logged bamboo-dominated forest in Brazilian western Amazon, with the objective to evaluate the sustainability of the applied forest management regime in terms of tree density, above-ground dried biomass and tree bole volume stocks recovery rates and species groups. The forest dynamics were monitored over a period of 12 years in 10 permanent sample plots of 1 ha. Two main results of this study are important to the establishment of cycle lengths, logging intensities and silvicultural treatments for tropical forest management in bamboo-dominated forest: the rapid increment of the above-ground biomass (AGB) observed in the area after logging, and the slow growth of commercial and logged species. In addition, although no climate data was collected in this study, the reported 2005 and 2010 atypical climate events strongly affected forest dynamics and productivity.

These results indicate that short cutting cycles and light logging intensities, and the rotation of logged species, should produce the appropriate combination in terms of the disturbance frequency and scale to promote sustainable timber production in bamboo-dominated forests.

1. Introduction

The Bambusoideae subfamily (Poaceae) grows naturally from slightly above sea level up to 4500 m and are present in all continents, except Europe and Antarctica. The main centers of diversity are in Asia (eastern and southern) and the Atlantic side of South America (Judziewicz et al., 1999; Ohrnberger, 1999). Due to a large amount of documented uses (over than 1500; Bystriakova et al., 2003), bamboo species are one of the most important non-timber forest products over the World. However, despite their importance, very little is known about bamboo distribution and resources, especially in natural forests (Bystriakova et al., 2003).

The western Amazon supports the largest formation of neotropical bamboo-dominated forest, with an area of about 180,000 km^2 (Nelson, 1994; Griscom and Ashton, 2006). This neglected forest ecosystem (Rockwell et al., 2007) generally has a lower timber volume and forest structure amplifies the damage caused by the felling of trees and the passage of heavy machines for road opening as well as log skidding (D'Oliveira et al., 2004; Veldman et al., 2009). In such forests, succession is arrested (*sensu* Griscom and Ashton, 2003) in a self-perpetuating cycle in which bamboo (*Guadua* spp.) loads and crushes small (DBH < 30 cm) trees (Griscom and Ashton, 2006), resulting in poor timber species establishment and bamboo-dominated regeneration. In southeastern Amazon, especially in the Acre State (Brazil) the establishment of forest management plans in these areas is not rare, although the environmental sustainability of timber production in these areas appears to be questionable (D'Oliveira et al., 2004; Rockwell et al., 2007).

Despite that, the Brazilian forest laws does not provide specific rules to the management of bamboo-dominated forests. Regardless of forest type, the Brazilian law indicates the same silvicultural system, differentiating only cycle length and logging intensity according to log extraction method (CONAMA, 2009), divided in not mechanized (i.e. animal traction), 10-year cycle length and maximum logging intensity of 10 m^3 ha^{-1} and mechanized 25–35 year cycle length and maximum logging intensity of 30 m^3 ha^{-1}.

There is no consensus regarding the sustainability of tropical forest management for timber production among scientists. It is generally accepted that tropical forest management can be considered sustainable when practiced under reduced-impact logging rules (e.g., Nebel et al., 2001; Macpherson et al., 2010; Miller et al., 2011), but to recover the initial harvested volume during the length of a cycle, in addition to considering the impacts of logging operations, silvicultural treatments are required to guarantee the establishment and growth of timber species (e.g., Fredericksen

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and Mostacedo, 2000; Fredericksen and Putz, 2003; Dauber et al., 2005; Wadsworth and Zweed, 2006; Sist and Ferreira, 2007; Villegas et al., 2008). However, some scientists claim that tropical forest management produces irreversible damage in forests, which leads to degradation and conversion to agricultural uses and is only expected to be sustainable in very particular situations, such as under community forest management (e.g., Zimmerman and Kormos, 2012).

The effects of logging operations on tropical forests during the length of a cycle and, hence, on the sustainability of timber production, are difficult to assess due to the complexity of tropical forest ecosystems and the long term over which logging influences forest dynamics (e.g., Huth and Ditzer, 2001). Forest recovery is usually assessed in terms of basal area (e.g., Bonnell et al., 2011), volume (e.g., Silva et al., 1996) or above-ground biomass (AGB – Mazzei et al., 2010) and species composition (e.g. Carreño-Rocabado et al., 2012; Menger et al., 2013). The parameters that affect AGB accumulation and loss are tree growth, in growth and mortality. These parameters are used to estimate forest production and to define logging cycles and logging intensities in tropical forest management (e.g., Macpherson et al., 2010).

Changes in plant communities are evaluated by classifying species into different successional groups based on their ability to establish, survive and growth in different shade conditions and the dichotomy between pioneer and climax species could be defined, in a coarse level, as function of species light demanding throughout their existence (Ghazoul and Sheil, 2010). Due to the increase in light in the forest floor, natural gaps are the main driver of opportunities to new recruitment and growth in undisturbed tropical forests (Brokaw, 1985; Denslow, 1987). The fall of trees and skid of logs during forest operations produce gaps which alter the species composition of the managed forests, increasing the proportion of pioneer species in the plant community (e.g. Felton et al., 2006). Thus, pioneer species have been used as an indicator of forest disturbance (e.g. D'Oliveira and Ribas, 2011).

The most common way to obtain consistent results to support the sustainability of timber production in tropical forests is through long-term studies. These studies are expensive and difficult to conduct, but forest dynamics have been studied through permanent sample plots (PSP) for decades (e.g., Sheil, 1998; Malhi et al., 2002; Lewis et al., 2004; Laurance et al., 2009). Despite the limitations of this method, PSP are currently recognized as the best way to conduct monitoring of managed and non-managed tropical forests. In this study, we followed the development of a 70 ha bamboo (*Guadua* spp.) dominated forest in Antimary State Forest in Acre State in the Brazilian western Amazon, from one year before logging (1999) until eleven years after logging. Our objective was to evaluate the sustainability of the applied forest management regime considering the above-ground dried biomass accumulation, tree bole volume recovery and changes on commercial and pioneer species population composition.

2. Methodology

2.1. The studied areas

Antimary State Forest is located between Rio Branco and Sena Madureira in Acre State in the Brazilian western Amazon (68°01′ to 68°23′W; 9°13′ to 9°31′S). Antimary State Forest covers an area of 768.3 km^2 and has approximately 380 inhabitants, or 109 families, who make their living through extractivism (rubber tapping and Brazil nut collection) and shifting cultivation (Fig. 1). The climate falls within Awi (Köppen), with annual precipitation of approximately 2000 mm and an average temperature of 25 °C. Wet and dry seasons can be recognized. The dry season occurs between the months of June and September. Within Antimary State Forest, there are three types of forest: dense tropical forests (forests with a uniform canopy and emergent trees), open tropical forest (with a high occurrence of lianas and palm trees) and *tabocal*, which is an open type of forest dominated by bamboo species locally referred to as "tabocas" (*Guadua* spp.). The area has a topography dominated by gently sloping hills and a maximum altitudinal range of approximately 300 m, and the predominant soils are dystrophic yellow latosols with high clay content (Funtac, 1989).

The forest area studied in this work was the Tabocal annual production unit, an originally bamboo dominated forest with a relatively low timber volume of 157 $m^3\ ha^{-1}$ which was mechanically logged in 2000. Although a light logging intensity of 6.9 $m^3\ ha^{-1}$ (0.29 $m^2\ ha^{-1}$) was applied to fourteen species in the Tabocal annual production unit, the forest damage produced by the logging operations in the area was high (1.91 $m^2\ ha^{-1}$) (D'Oliveira et al., 2004). Considering the entire group of species selected for logging, only 47.2% of the commercial volume was extracted from the area (Table 1). Ten PSP were established and measured one year prior to logging (1999). The PSP were subsequently re-measured one (2001), four (2004), seven (2007) and eleven years after logging (2011).

2.2. Permanent sample plots (PSP)

The PSP are square plots of 1 ha (100 × 100 m), sub-divided into 100 sub-plots of 100 m^2 each (10 × 10 m). In these plots, all trees with a DBH ⩾ 20 cm were tagged, identified and measured. In 20 randomly selected sub-plots in each PSP, all trees with a DBH ⩾ 5 cm were also tagged, identified and measured.

2.3. Tree density, volume and above-ground biomass estimates

Tree density was taken as the number of standing trees per hectare. Stem diameter measurements were used to estimate the above-ground biomass (AGB) value for each measured tree using an allometric equation developed for a similar forest in the Southern Amazon (Nogueira et al., 2008 – Eq. (1)). Stem diameters were employed to calculate the volume (FUNTAC, 1989 – Eq. (2)) of each tree.

$$AGB = \exp(-1.716 + 2.413^{*}\ln(D))/1000 \quad (1)$$

$$V = 0.000308^{*}(D) \wedge 2.1988 \quad (2)$$

where AGB is the above-ground oven-dried biomass expressed in Mg ha^{-1}; D is the DBH expressed in cm, V is the bole volume expressed in $m^3\ ha^{-1}$

2.4. Mean annual above-ground biomass increment

The above-ground biomass (AGB) at any sample time was taken as the sum of the AGB for all trees at that time. Increments in any interval between two sample times (1 and 2) were taken as AGB at time 1 and then subtracting the AGB of trees that had died (death) in the interval and adding the AGB of trees that had been recruited (ingrowth) in the same interval (Eq. (3))

$$AGB = (AGB\_St_{t1} - AGB\_Ing_{t1}) - (AGB\_St_{t0} + AGB\_Mort_{t1}) \quad (3)$$

where AGB_ST_{t1} is the above-ground biomass of the standing trees in a census, AGB_Ing_{t1} is the above-ground biomass of the in growth during the census interval, AGB_ST_{t0} is the above-ground biomass of the standing trees in the previous census, AGB_Mort_{t1} is the above-ground biomass of the trees that died during the census interval.

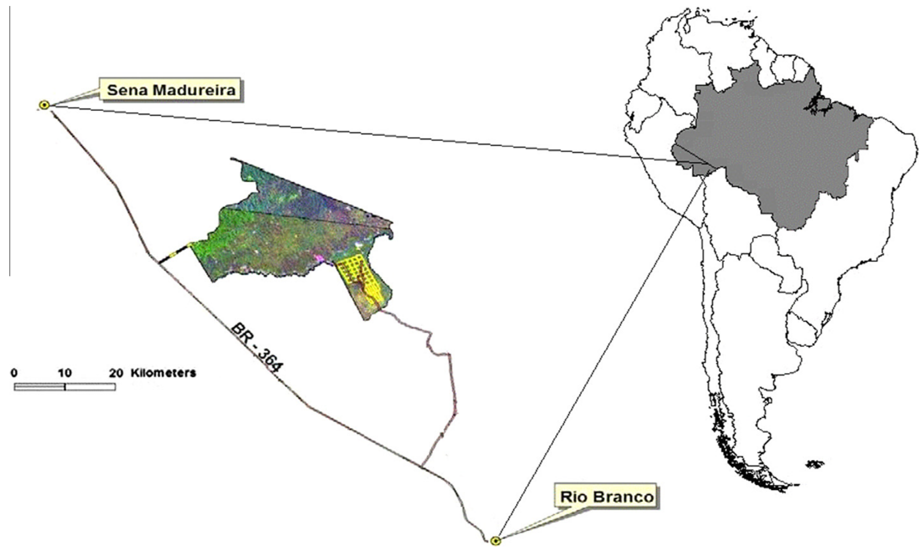

Fig. 1. Location of Antimary State Forest in Acre State, Brazilian western Amazon. The yellow grid areas represent the compartments of the ASF Forest Management project. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Commercial species volume (DBH > 50.0 cm) before and after logging in the Tabocal annual production unit (APU).

Species	Volume before logging (m^3)	Logged volume (m^3)	Volume after logging (m^3)
Apuleia leiocarpa (Vogel) J.F.Macbr.	198.5	198.5	0.0
Aspidosperma macrocarpon Mart.	8.5	8.4	0.0
Aspidosperma vargasii A.DC.	38.7	38.7	0.0
Astronium leicointei Ducke	19.9	19.9	0.0
Astronium sp.	5.3	5.3	0.0
Batocarpus sp.	10.6	0.0	10.6
Cedrela odorata L.	9.6	0.0	9.6
Ceiba pentandra (L.) Gaertn.	132.3	0.0	132.3
Ceiba samauma (Mart. & Zucc.) K.Schum.	26.4	0.0	26.4
Chrysophyllum prieurii A. DC.	12.3	0.0	12.3
Clarisia racemosa Ruiz & Pav.	94.5	0.0	94.5
Cordia goeldiana Huber	4.0	0.0	4.0
Dipteryx odorata (Aubl.) Willd.	82.5	82.5	0.0
Enterolobium schomburgkii (Benth.) Benth.	31.4	31.4	0.0
Hymenaea courbaril L.	3.8	3.8	0.0
Hymenaea oblongifolia Hub.	58.3	0.0	58.3
Hymenaea oblongifolia sp.	2.2	0.0	2.2
Hymenolobium sp.	32.7	32.7	0.0
Hymenolobium sp.	23.6	0.0	23.6
Jacaranda copaia (Aubl.) D. Don.	42.0	0.0	42.0
Mezilaurus itauba (Meisn.) Taub. ex. Mez	8.4	8.4	0.0
Myroxylon balsamum (L.) Harms	3.0	0.0	3.0
Parkia sp.	2.9	2.9	0.0
Handroanthus impetiginosus (Mart. ex DC.)	2.8	2.8	0.0
Handroanthus serratifolius (Vahl) S.O.Grose	28.0	28.0	0.0
Amburana acrea (Ducke) A.C.Sm.	20.0	20.0	0.0
Virola multiflora (*Standl.*) *A.C. Sm.*	99.4	0.0	99.4
Vochysia sp.	22.5	0.0	22.5
Total	1023.9	483.3	540.6
Number of logged species	14		
Total area (ha)	70.0		
Logging intensity (m^3 ha^{-1})	6.9		
Logged volume (%)	47.2		

2.5. Species groups

For this study, we classified pioneer and climax species according to the Swayne and Whitmore (1988) definition and used short-lived pioneer species as an environmental indicator of disturbances (D'Oliveira and Ribas, 2011).

The group of commercial species was composed of the species that were selected for logging in the Tabocal APU in 1999 (Table 1). The volume was estimated considering two classes: stock ($10.0 \leqslant$ DBH $\leqslant 49.9$ cm) and commercial (DBH $\geqslant 50$ cm).

2.6. Statistical analyses

We use repeated measures data analysis to compare the response trends over time regarding the volume and above-ground dried biomass and to compare times within treatments (plots). The model was based on a general mixed model.

$$Y = X\beta + ZU + e \quad (4)$$

where X is a matrix for fixed effects; β is a vector of the fixed effects of unknown parameters; Z is a matrix for random effects; U is a

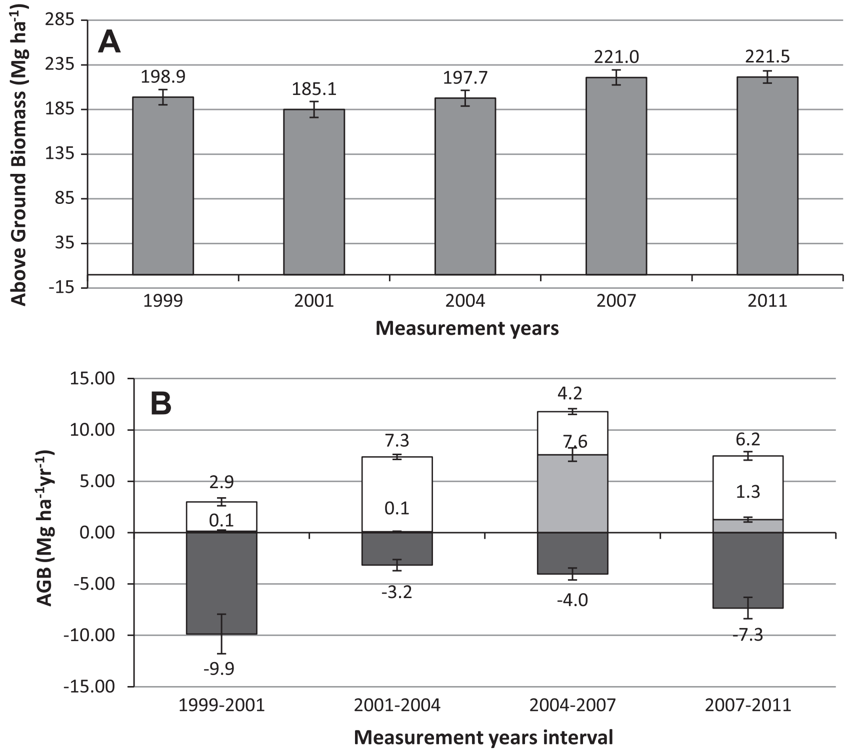

Fig. 2. Mean above-ground biomass (AGB – Mg ha^{-1}) accumulation in the studied years (A) and parameters related to AGB (Mg ha^{-1} yr^{-1}) dynamics: the mean annual growth of living trees (white columns), tree in growth (light gray columns) and tree mortality (dark gray columns) (B) in the permanent sample plots of the Tabocal Annual Production Unit in Antimary State Forest. Error bars represent the standard error ($p < 0.05$).

vector of unobservable random effects; e is a vector of residual random errors.

The repeated measures model is as follows:

$$y_{ijk} = \mu + \alpha_i + \tau_k + (\alpha^*\tau)_{ik} + e_{ijk} \quad (5)$$

where y_{ijk} is the volume (or biomass) of tree j at time k in plot i, μ is the overall mean (of the BA, AGB or volume), α_i is a fixed effect of plot i, τ_k is a fixed effect of time k, $(\alpha^*\tau)_{ik}$ is a fixed interaction effect for plot i at time k, e_{ijk} is the random error at time k in plot i.

To process the data, we used the MIXED procedure (SAS 9.2) with repeated measures. The KR (Kenward–Roger) option was employed to calculate degrees of freedom and compound variance for the covariance structure. If the overall F test was significant ($p < 0.05$), we used post hoc least squares means (LS-means) tests with adjust = tukey to determine significant differences ($p < 0.05$) between years and periods.

3. Results

3.1. Standing tree density

The tree density decreased significantly ($F = 56.65$; $p < 0.001$) over the first two PSP measurements conducted after logging, from 860 ± 22 trees ha^{-1} before logging to 690 ± 18 trees ha^{-1} five years later (lsmeans 1999–2001, *Adjp* = 0.0034; lsmeans 1999–2004, *Adjp* < 0.001). However, in the 2007 measurements, performed seven years after logging, a statistically significant increase in tree density (lsmeans 2004–2007, *Adjp* = 0.0034; 961 trees ha^{-1}) was observed. In the last measurements, conducted in 2011, eleven years after logging (lsmeans 2001–2009, *Adjp* = 0.9971), the tree density was 862 ± 19 trees ha^{-1}, similar to the density of the original forest.

3.2. Above-ground dried biomass and tree bole volume

The AGB presented a significant decrease ($F = 39.95$; $p < 0.001$) after logging, from 198.9 ± 8.5 to 185.1 ± 9.0 Mg ha^{-1} (lsmeans 1999–2001, *Adjp* = 0.0039). In the subsequent measurements, the AGB increased to 221.5 ± 6.8 Mg ha^{-1}, which was significantly higher than was observed in the Tabocal APU before logging (lsmeans 1999–2001, *Adjp* < 0.001) (Fig. 2A). The mean increments of the AGB of living trees ($F = 24.17$; $p < 0.001$) and ingrowth increased drastically from the second to the eighth year after logging (lsmeans iagb99-01 and iagb01-04, *Adjp* < 0.001). In the last measurement interval, the increment of the AGB due to new recruits decreased to 1.3 ± 0.2 Mg ha^{-1} yr^{-1}. The peak of the AGB increment produced by living trees was recorded from the second to the fifth year (7.3 ± 0.7 Mg ha^{-1} yr^{-1}), and although a decrease was observed during the next measurements, tree growth remained high until the final measurement (6.2 ± 0.4 Mg ha^{-1} yr^{-1}). Considering the three measured components (growth, ingrowth and mortality) together, in the first measurement period (1999–2001), the AGB decreased by 13.9 Mg ha^{-1}, mainly due the damage produced by the logging operations. In the next two measurement intervals, the AGB increment increased non-significantly (lsmeans iagb01-04 and iagb04-07, *Adjp* = 0.5655), from 4.50 Mg ha^{-1} yr^{-1} (2001–2004) to 6.93 Mg ha^{-1} yr^{-1} (2004–2007). The value obtained during the final measurement period was 0.20 Mg ha^{-1} yr^{-1}, due to the high mortality observed in the period (Fig. 2B).

The fluctuation of the standing tree volume in the PSP along the studied period followed the same pattern as observed for the AGB. The total volume of all trees (DBH > 5.0 cm) varied significantly ($F = 48.52$; $p < 0.001$; lsmeans 1999–2011, *Adjp* < 0.001), from 157.2 ± 5.7 m^3 ha^{-1} in 1999 to 176.6 ± 5.0 m^3 ha^{-1} in 2011 (increment of 1.6 ± 0.17 m^3 ha^{-1} yr^{-1}) (Fig. 3A). Additionally, for all of the studied tree size categories, the volume at the end of the study

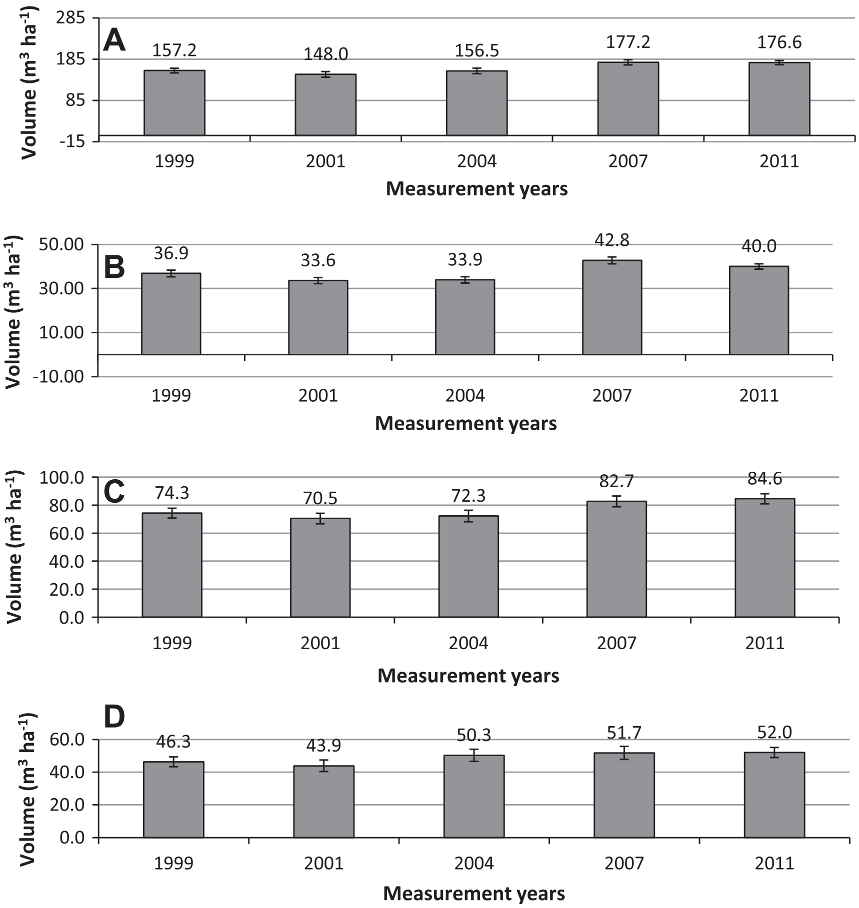

Fig. 3. Mean standing volume ($m^3\ ha^{-1}$) in the years in which PSP measurements were conducted for all trees with a DBH equal to or greater than 5 cm (A), for trees with a DBH below 20 cm (B), for trees with a DBH between 20.0 and 49.9 cm (C) and for trees with a commercial diameter (DBH $\geqslant$ 50 cm) (D) in the permanent sample plots of the Tabocal Annual Production Unit in Antimary State Forest. Error bars represent the standard error ($p < 0.05$).

was significantly higher ($F = 25.21$, $p < 0.001$ (Fig. 3B); $F = 49.15$, $p < 0.001$ (Fig. 3C); $F = 11.79$, $p < 0.001$ (Fig. 3D)) than in the undisturbed forest (Fig. 3B–D). The volume of trees with a DBH equal to or greater than 50 cm (commercial size) presented an increment from 46.3 ± 3.0 in 1999 to 52.0 ± 3.1 $m^3\ ha^{-1}$ in 2011, or an average of 0.47 $m^3\ ha^{-1}\ yr^{-1}$ in this tree size category (Fig. 3D).

3.3. Species group

3.3.1. Relative density of pioneer species

The relative density of pioneer species was 7.5 ± 0.8% before logging. In the period from 2001 to 2004, this rate decreased significantly (lsmeans 1999–2004, *Adjp* = 0.047) to 5.9 ± 0.6%, and in the last two measurements, it stabilized at approximately 9% (9.3 ± 1.1% and 9.4 ± 1.1% for 2007 and 2011 measurements, respectively) (Fig. 4). Despite the variation presented across the studied years, the relative density of pioneers was only significantly different from the other periods in 2004 ($F = 8.79$; $p < 0.001$).

3.3.2. Commercial and logged species

Only three species were logged inside the PSP: *Enterolobium schomburgkii* (Benth), *Dipteryx odorata* (Aubl.) Willd. and *Apuleia leiocarpa* (Vogel) J.F. Macbr. The mean volume of these species (DBH > 5.0 cm) before logging was 5.0 ± 1.6 $m^3\ ha^{-1}$, and after

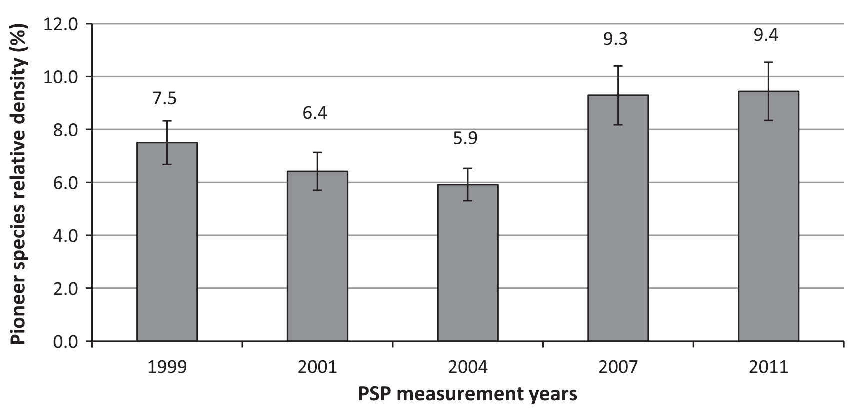

Fig. 4. Mean relative density of pioneer species in the measurement years in the permanent sample plots of the Tabocal Annual Production Unit in Antimary State Forest. Error bars represent the standard error ($p < 0.05$).

eleven years, it was $3.0 \pm 1.1\ m^3\ ha^{-1}$. The number of trees of the commercial species in the PSP was not sufficient to allow any statistical analysis to be conducted (Fig. 5). The volume of all of the managed species in the PSP decreased from 17.0 ± 2.8 to $13.4 \pm 2.2\ m^3\ ha^{-1}$ after logging. From 2001 to 2011, the commercial volume (DBH ⩾ 50.0 cm) of the commercial species increased linearly, to $15.4 \pm 2.4\ m^3\ ha^{-1}$. However, due to the high mean standard error, significant differences in the commercial volume of the managed species could not be verified during the study period ($F = 2.76$; $p = 0.0425$), a linear mean increment of approximately $0.4\ m^3\ ha^{-1}\ yr^{-1}$ was observed (Fig. 6).

4. Discussion

4.1. Forest dynamics

The absolute changes in the AGB across the studied years appear to follow the classical behavior of logged tropical forests, which experience a strong increment in biomass accumulation soon after logging that starts to decrease 5–10 years after logging (e.g., Silva et al., 1995). The commercial timber species of selectively logged tropical forests grow at a slower rate than the rate that is expected to guarantee successive logging cycles (Peña-Claros et al., 2008). This tendency has been reported by several authors (Sist and Ferreira, 2007; Rozendaal et al., 2010; Macpherson et al., 2010; Bonnell et al., 2011) and is the main justification for the application of intermediate silvicultural treatments to avoid productivity losses during the harvesting cycle. However, when the various components of AGB accumulation examined in our study (growth of living trees, in growth and mortality) were considered, we developed a different perspective. In the Tabocal APU, in the last measurement period, the accumulated AGB produced by the growth of living trees and the in growth was higher than that observed in the previous period (2004–2007). Maintenance of tree growth and in growth rates is not characteristic of forests that are stagnating from the perspective of AGB production. The main driver of the low AGB accumulation observed in the last measurement period was a high mortality rate due to natural causes. The Brazilian western Amazon experienced two strong droughts in the years 2005 (Phillips et al., 2009) and 2010 (Brown et al., 2011). In both cases, forest fires and tree mortality were reported. The Tabocal APU did not experience forest fires, but strong wind storms were reported by local families in this area, especially in 2010 (personal communication). Although neither a significant increase in tree mortality nor a decrease in the growth of living trees could be observed in the period from 2004 to 2007, it appears that the effects of the two consecutive droughts potentiated the mortality observed in 2011. This finding agrees with those of Toledo et al. (2011), who stated that the climate is the strongest driver of tree and forest growth. In the present case, the key factor was wind storms, which produced a forest disturbance similar to that produced by logging. Thus, although the forest AGB recorded in the last measurement period was higher than that observed in the natural forest, due to the high mortality rate found in the last measurement interval, it is expected that the forest will continue to accumulate AGB in the coming years.

Considering the average AGB of other APU in Antimary Forest (e.g., $232\ Mg\ ha^{-1}$ – D'Oliveira et al., 2012), the mean AGB ($221.5\ Mg\ ha^{-1}$) observed during the last measurements is still

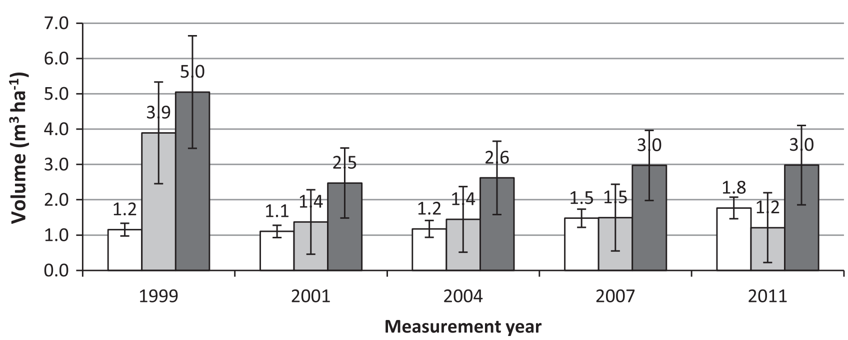

Fig. 5. Future crop trees (DBH < 50.0 cm – white columns), commercial trees (DBH ⩾ 50 cm – light gray columns) and the total (dark gray columns) volume ($m^3\ ha^{-1}$) of the logged species in the permanent sample plots of the Tabocal annual production unit in Antimary State Forest. Error bars represent the standard error ($p < 0.05$).

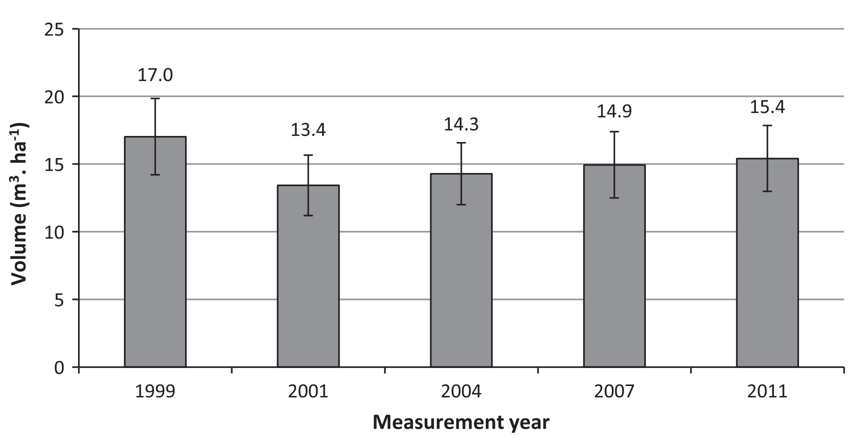

Fig. 6. Volume of commercial (DBH ⩾ 50 cm) species in the permanent sample plots of the Tabocal annual production unit in Antimary State Forest. Error bars represent the standard error ($p < 0.05$).

low, and it is very likely that once the forest is released from bamboo dominance, both the tree density and above-ground biomass will continue to increase until they are similar to the adjacent forests. In addition, recent studies indicate that forest productivity is rising in tropical forests (e.g., Baker et al., 2004, Laurance et al., 2009) in response to increasing CO_2 fertilization.

Although the observed relative density of the pioneer species at the end of the study period was not significantly different from that found in the forest before logging, the increase in the populations of these species after 2004 is an indicator of the effect of the natural disturbances that occurred in the area between 2004 and 2011.

4.2. Implications for forest management

There are two main results of this study that must be considered in the establishment of cycle lengths, logging intensities and silvicultural treatments for tropical forest management: i. the rapid AGB increment observed in the area after logging, ii. the slow growth of commercial and logged species. In addition, although no climate data was collected in this study, the 2005 and 2010 atypical climate events (Brown et al., 2011; Phillips et al., 2009) strongly affected forest dynamics and productivity.

Brazilian legislation (IBAMA, 2006) prescribes a minimum 25-year cycle length to achieve maximum timber extraction of 20 m^3 ha^{-1} (30 m^3 ha^{-1} in a 35-year cycle). Thus, despite the low logging intensity applied to the Tabocal APU, in less than half of the cycle, the forest had not only recovered all of its original AGB but also presented a significantly higher AGB. This result demonstrate that the basal area growth and biomass accumulation observed in Amazon undisturbed forests (Baker et al., 2004; Lewis et al., 2004; Laurence et al., 2009) can also occurs in managed forests and supports the potential of managed forests as carbon sinks.

The mean annual volume increment found in the group of the commercial species (0.4 m^3 ha^{-1} yr^{-1}), following the observed linear tendency, will reach the same value found in the forest prior to logging in the next four years. Although the sampling intensity was high (14%), it was not sufficient to obtain the required data to allow robust individual or even commercial species group analyses. Nevertheless, our results appear to agree with those of other studies (e.g., Mazzei et al., 2010; Macpherson et al., 2010) indicating that logged species require longer cycles to recover than are employed today (10–35 yr). Even under the low logging intensity applied, some species were heavily logged (e.g., *Apuleia leiocarpa* and *Dipteryx odorata*), with most of their commercial-sized trees being extracted. This happened because in contrast to the situation today, the forest legislation in place in 1999 did not yet prescribe the preservation of 10% of the commercial population of the logged species as seed trees. However, considering the entire list of commercial species included in the Tabocal APU forest management plan, at the end of the 25-year cycle, an available volume of approximately 20 m^3 ha^{-1} is expected for harvesting. In addition, the number of commercial species has increased in the last 20 years, which favors species rotation in successive cycles, diminishing the pressure that occurs when only a few species are present and allowing the recovery of heavily logged species in periods longer than the prescribed cycle lengths.

The relatively low mean AGB observed prior to the logging of the Tabocal APU (e.g., when compared with other APU in ASF – D'Oliveira et al., 2004, 2012) and the strong AGB increment verified after logging, which resulted in a significantly higher AGB at the end of the study period, support the conclusion that the logging of the forest acted as an silvicultural treatment that ended the dominance of bamboo and favored forest development. It is generally accepted that logging creates conditions that favor the growth of the residual trees (Silva et al., 1996; Carvalho et al., 2004; D'Oliveira and Braz, 2006; Toledo et al., 2011), and this effect increases with an increasing logging intensity (e.g., Peña-Claros et al. 2008; Villegas et al., 2008). In the present study, although the harvesting intensity was low, considering the forest structure, the logging damage was relatively high (14.2 m^3 ha^{-1} – D'Oliveira et al., 2004) and produced a sufficient disturbance in the forest to guarantee a consistent increase in the AGB during the study period.

The observed atypical climate events of 2005 and 2010 also had effects that can be linked to basal area reduction silvicultural treatment, producing additional disturbances in the forest and maintaining high forest productivity without compromising the establishment and growth of timber species eleven years after logging. However, such events cannot be controlled, and it is expected that they will produce much more damage to the forest compared to the degree to which they promote its recovery. The impacts generated in the forest by logging operations alone usually do not persist over long cycles, and intermediate silvicultural treatments are necessary to maintain forest productivity (e.g., Wadsworth and Zweed, 2006). Low intensity logging could be considered as an economic alternative to intermediary silvicultural treatments to avoid forest productivity declines. The use of short cutting cycles and a light logging intensity (e.g., D'Oliveira and Braz, 2006) appears to represent an appropriate combination regarding the disturbance frequency and scale (sensu Connell, 1978). In the case of this particular area, considering the high AGB and bole volume (0.8 m^3 ha^{-1} yr^{-1}, DBH > 50.0) observed during the study period, a logging intensity of 10 m^3 ha^{-1} together with a 15-year cycle length, associated with logged species rotation and seed tree retention to avoid the risk of overexploiting the timber stocks of slow growing species (e.g., Schongart, 2008), should be a suitable alternative for sustainable timber production in western Amazonian bamboo-dominated forests. Additionally, the concept of commercial species has been changing in the Amazon. Most of the trees that reach a DBH of 50 cm are now considered to have some commercial use. Thus, the observed volume increment (1.6 m^3 ha^{-1} - yr^{-1}) can be considered high, facilitating the rotation of the harvested species and short logging cycles.

Regional indices represent a good approach for conducting long-term production estimations and they have been used on national polices to establish cycle lengths and logging intensities (e.g. IBAMA, 2006). However, climatic variations and site peculiarities can dramatically alter the dynamic parameters that determine the growth and development of tropical forests (e.g. Toledo et al., 2011). In the last twenty years Amazon experienced four atypical climate events (1997, 1998, 2005 and 2010) which resulted in high mortality and biomass loss (Phillips et al., 2009; Laurence et al., 2009; Brown et al., 2011). Thus, considering the logging cycle lengths practiced in the region from 10 to 30 years, the effect of atypical climate events which happens in between these cycles, must be considered on the estimates of forest productivity.

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