Resilience of Above-ground Biomass in Experimental Areas in the Eastern Brazilian Amazon

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ABSTRACT – This study aimed to evaluate the resilience of aerial forest biomass, in four experimental areas in eastern Brazilian Amazon. For all areas after reduced impact cutting, it was evident that there is a great loss of biomass in all tree diametric classes, but much more evident in classes with a diameter above 50cm in the first years after logging. The forest recovered its biomass value due to the growth of the species that remained there. After silviculture treatments with thinning of non-commercial trees after 9 years of exploitation, there is a further decrease in the value of biomass for all diametric classes. After the Tapajos forest fire, there was no significant loss in biomass value between and within treatments.

Keywords: Forest dynamics; silviculture; neotropical forest; low impact forest exploitation.

Resiliência da Biomassa Acima do Solo em Áreas Experimentais na Amazônia Oriental

RESUMO – Este estudo teve como objetivo avaliar a resiliência da biomassa florestal aérea, em quatro áreas experimentais na Amazônia oriental. Para todas as áreas após corte de impacto reduzido, ficou evidente que existe uma grande perda de biomassa em todas as classes diamétricas das árvores, bastante mais evidente nas classes com diâmetro acima de 50cm nos primeiros anos posteriores à extração. A floresta recuperou seu valor de biomassa devido ao crescimento das espécies que ali permaneceram. Após os tratamentos de silvicultura com desbaste de árvores não comerciais passados 9 anos de exploração, ocorre uma nova diminuição no valor da biomassa para todas as classes diamétricas. Após o incêndio na floresta do Tapajós, não houve perda significativa no valor da biomassa entre e dentro dos tratamentos.

Palavras-chave: Dinâmica florestal; silvicultura; floresta neotropical; exploração florestal de baixo impacto.

Resiliencia de la Biomasa Aérea en Áreas Experimentales de la Amazonía Oriental Brasileña

RESUMEN – Este estudio tuvo como objetivo evaluar la resiliencia de la biomasa forestal aérea, en cuatro áreas experimentales en la Amazonía oriental brasileña. Para todas las áreas después de la corta de impacto reducido, fue evidente que hay una gran pérdida de biomasa en todas las clases diamétricas de árboles, pero mucho más evidente en las clases con un diámetro superior a 50cm en los primeros años después de la corta. El bosque recuperó su valor de biomasa debido al crecimiento de las especies que allí se quedaron. Después de los tratamientos de silvicultura con raleo de árboles no comerciales después de 9 años de explotación, hay una nueva disminución en el valor de la biomasa para todas las clases diamétricas. Después del incendio forestal de Tapajos, no hubo una pérdida significativa en el valor de la biomasa entre y dentro de los tratamientos.

Palabras clave: Dinámica forestal; silvicultura; bosque neotropical; explotación forestal de bajo impacto.

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Introduction

The natural ecosystems store large amounts of carbon, both in structure as the ground vegetation (Nellemann & Corcoran 2010).

Resiliency is the ability of an ecosystem to return to its original state or establish its balance, after having undergone a change that is not part of its natural cycle, maintaining its essential characteristic as the taxonomy, structure and function of the ecosystem. However, a forest ecosystem can respond in different ways to disturbances and disturbances (Holling 1973, Thompson *et al*. 2009).

After these forests pass through a reduced impact exploitation, they, over time, are able to return to their natural state and maintain their volumetric stock and consequently their resilience in volume of wood. However, this exploration must be through a forest management plan, to minimize the impacts of the exploration in the area and maintain the floristic diversity, among others (Carneiro *et al*. 2019). The sustainable management of this ecosystem and its resources is seen as an important tool for the conservation of the forest, maintaining its ecological and functional integrity forestry.

In comparison with temperate climate forests, tropical forests are denser and with less seasonal fluctuations in the carbon flow, constituting important carbon stocks that contribute to the stability of the global climate. Forest biomass estimates are important due to their contribution to studies of global changes, since it is a parameter for carbon sequestration estimates and changes in different biomass reservoirs (Brown 1997, Moreira-Burger & Delitti 1999).

The conservation of forest biomass is an important way to minimize the greenhouse effect, keep the temperature of the environment in balance and maintain the carbon stock in the forests (Fearnside 2009).

In a forest ecosystem, there are several types of biomass reservoirs such as above-ground biomass, which is formed from the aerial part of the tree, such as the trunk, branches and leaves; the biomass below the ground is formed by the roots of the trees, the litter that is the layer of organic residues deposited in the soil of the forest, the dead trees, and the carbon in the soil (FAO 2010).

The concentration of carbon in tropical forest biomass is between 46 and 52% (Higuchi *et al*. 2004), however, many authors consider that 50% of the value of plant biomass corresponds to the carbon value in it (Brown *et al*. 1989, Houghton *et al*. 2009). The long-lived plants accumulate carbon in the wood and in other tissues until their death and decay, at which time the stored carbon is released into the atmosphere as carbon dioxide, carbon or methane monoxide or is incorporated into the soil as organic matter (Moura 1996).

There are two methods for obtaining the biomass value, the indirect methods of estimating living biomass through mathematical modeling, with allometric equations, where one or more variables, such as diameter in breast height (DBH), height or density of the tree, are correlated with dry biomass (Sanquetta 2002, Silveira 2010). These variables are usually obtained directly in the field, in forest inventories and phytosociological studies. (Brown 1997, Silveira 2010), which makes this method easy and inexpensive compared to the direct method, which consists of cutting all the trees in a parcel and weighing it. However, further studies on the wood densities of tropical forests are needed to obtain more accurate calculations (Carneiro *et al*. 2020).

Within this context, this study aimed to assess the resilience of above-ground biomass in four experimental areas in eastern Brazilian Amazonia.

Material and Methods

The data were collected in four areas distributed in the Eastern Brazilian Amazon, one located in the state of Amapá and other areas the west, the northeast and the southeast in the state of Pará (Figure 1).

Tapajos forest

This area is located in the Tapajós National Forest, close to km 114 of BR 163, Highway Santarém-Cuiabá, between coordinates 2°40'-4°10' of South Latitude and 54°45'-55°30' of West Longitude in the state do Pará. The topography of the region is flat to slightly undulating and the altitude is about 175m above sea level (Carneiro *et al*. 2020). The region's climate is humid tropical, Ami type, with average annual temperature of

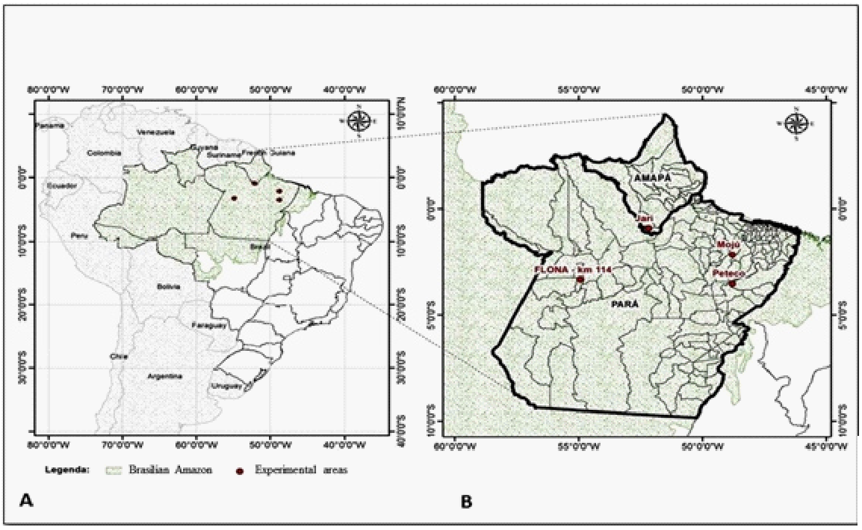

Figure 1 – Location map of experimental areas: A. Map of Brazil in South America B. State of Amapá and Pará with the study areas highlighted.

25.5ºC and average relative humidity of 90% according to the Köppen classification (Alvares *et al*. 2013).

In this region, there is a predominance of dystrophic yellow latosol, deep profile and low fertility, characterized by a very clayey texture, and covered by dense forests. The vegetation of the study area is classified as dense ombrophilous forest, characterized by large arboreal individuals and by the presence of woody lianas, emerging palms and epiphytes and uniform tree cover (IBGE 2012, Ivanauskas & Assis 2012).

In 1981, the experiment was implemented with a forest census and using a randomized block design (DBC) with four replications and four treatments, totaling 144ha of area, and 48 permanent rectangular plots of 0.25ha each were installed at the same time. There was a cut of lianas. In 1982, silvicultural treatment took place, with the removal of $73m^3.ha^{-1}$, an average of $12.5trees.ha^{-1}$ belonging to 38 commercial species at the time. In 1983 a T0 treatment was added to a 36ha block, represented by the forest without any intervention. In 1994, twelve years after forestry, silvicultural treatments were applied, eliminating trees of non-commercial species at the time, with the purpose of reducing the basal area of the stand and thereby reducing competition between trees for light, space and nutrients, providing increased survival, growth and establishment of natural regeneration of species of commercial value (Oliveira *et al*. 2005).

At the end of 1996 until the beginning of 1997, there was a fire in the area, reaching 19 of the 60 plots installed, with six plots for T0 treatment (1.5ha), two for T1 treatment, five for treatment T2 and six from the T4 treatment, (Carneiro *et al*. 2019).

Jari forest

This Experimental area is delimited in an area of 500ha of dense forest in the Companhia Florestal Monte Dourado, in Morro do Felipe, municipality of Vitória do Jari, in the state of Amapá. The forest typology is Ombrophilous Dense Forest of upland. The geographical coordinates are 52º20"W and 00º55"S. Temperature is 25.8ºC, of the Ami type, the topography is slightly wavy, the soil type is dystrophic yellow latosol with a heavy clay texture.

In 400ha of forest, three experimental blocks of 48ha were installed, both with borders and tracks with a distance of one km between the blocks and the roads. In the 100ha of forest that were not explored, four blocks of 1ha each were installed, which are used as a control (Carneiro *et al*. 2020).

The experimental design was structured in randomized blocks, with 13 treatments, of which twelve treatments have three repetitions, and the control has four repetitions (Higushi *et al*. 2004, Carneiro *et al*. 2019, Pinheiro *et al*. 2019).

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The experiment started in 1983, with the carrying out of the forest census and the installation of treatments. In 1985, silvicultural treatments aimed at better regeneration and growth of commercial trees for the next harvest, were carried out in the area; in 1994, silvicultural treatments were applied with two types of thinning, one being systematic, with two intensities of reduction of the original basal area in 30% and 50% and the other selective.

Moju forest

This area is located in the municipality of Moju, in the state of Pará, with a total area of 1,050 ha of forest, located between the geographical coordinates 02º08'14" and 02º12'26" south latitude and between 48º47'34" and 48º48'14" longitude West of Greenwich, between km 30 of Highway PA-150 and the Ubá River.

The climate of the region is of the Am type, according to the Köppen classification. The annual rainfall varies from 2,000 to 3,000mm, distributed irregularly, with small dry periods, with the rainiest period between the months of February and April, and the driest from August to October. The relative humidity around 85%. The average annual temperature is 26ºC, the relief of the experimental area is flat, with small undulations, with slopes of up to 3% (Lopes *et al*. 2001, Silva *et al*. 2001).

The dystrophic yellow latosol with different textures predominates in the area, also occurring red-yellow podzolic soils, slightly moist glei and soil plinth (Lopes *et al*. 2001, Silva *et al*. 2001).

The forest typology of the experimental area is dense ombrophilous forest of upland It has trees ranging in size from 25 to 35m in height with the presence of some palm trees in the understory (Lopes *et al*. 2001, Silva *et al*. 2001).

The experiment was started in 1995 in 200 ha of forest monitored by the forest census. In 1997, low impact silviculture was carried out avoiding the loss of trees that would not be commercialized, as well as the lowest impact on the soil and the sustainability of the forest. An average of 3.3trees.ha^{-1} were extracted, corresponding to a volume of $23m^3.ha^{-1}$, which represented 69% of the planned volume, $33.5m^3.ha^{-1}$, with a total of 31 species mined cutting diameter (DMC) of 65cm. Forest inventories were carried out in the years 1998, 2010 and 2015. In this area, there were no silvicultural treatments after exploitation (Carneiro *et al*. 2019).

PETECO forest

The area is located on the Rio Capim farm (3º30' and 3º45' south latitude and 48º30' and 48º45' west longitude), owned by the company Cikel Brasil Verde Madeiras Ltda., in the municipality of Paragominas, in the state of Pará. The forest typology is dense ombrophylous forest upland. The climate is Aw, the temperature is around 27.2ºC, the topography is slightly wavy and the predominant soil type is the yellow latosol, where 36 permanent plots of 0.25ha in 108ha were established at random, divided into three treatments, consisting of 12 plots each, totaling a sample area of 9ha (Francez 2013).

The exploration was carried out uniformly, with the exception of the control area, according to the guidelines established in the company's management plan. An average of 4.0trees.ha^{-1} were extracted from 16 commercial species, equivalent to $17.8m^3/ha^{-1}$. Six measurements were made, one in 2003, months before the logging that was carried out in the same year, and another five after logging in the years 2004, 2005, 2007, 2008 and 2011 (Carneiro *et al*. 2019).

Analysis of variance

The analysis was performed for repeated measures, seeking to show differences over time. Considering the F test to report the existence of differences in the average biomass between the years studied. Subsequently, tests were used for the paired comparisons to verify the existence of a difference in the biomass average.

Quantity of aerial biomass

The wood density was taken from Carneiro *et al*. (2020). For the calculation of above-ground biomass-BAS, it was used to key the Chave *et al*. 2005.

$$BAS = DM * exp\left(-1{,}499 + 2{,}148 * ln(DAP) + 0{,}207 * \left(ln(DBH)\right)^2 - 0{,}0281 * \left(ln(DBH)\right)^3\right)$$

Where:

DM = the value of wood density in g/m3;

DBH =diameter of tree at breast height in centimeters.

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Results

Tapajos forest

Table 1 shows the average amount of biomass in ton per hectare (t/ha) in each treatment per year. The results provided by the F test showed that in 1981, a year before logging, there was no statistical difference in the average number of biomass between treatments. In the following years, after the forest harvest, the difference between treatments at the level of 5% was verified in the years 1983, 1989 and 1995, highlighting that in 1987 there was a p-value of 5.7%. From 2008, 12 years after the forest fire and 14 years after the silviculture treatments, it is observed that there is no statistical difference between the treatments by the F test.

In 1983, a difference was observed only between T0 and T4. In 1989, statistical differences in the T0 treatment in relation to T1, T3 and T4 were identified. In 1995, there was only difference between treatments T2 and T3.

Table 1 – Comparison of the average amount of biomass (t/ha) in the treatments and between years in the experimental area of the Tapajós flona.

Year	Average amount of biomass					Homogeneity	F
	T0	T1	T2	T3	T4	P-value	P-value
1981	0.00	29.54	24.42	26.93	24.62	0.058	0.581
1983	27.53	22.08	24.03	20.29	19.61	0.836	0.031
1987	27.99	22.02	25.80	20.93	20.19	0.856	0.057
1989	32.04	22.67	27.26	21.58	21.13	0.454	0.004
1995	26.86	24.56	28.90	19.80	20.86	0.658	0.022
2008	29.37	29.41	27.37	20.87	24.80	0.125	0.104
2012	27.44	26.56	25.54	21.95	19.12	0.096	0.120

To assess the differences in relation to the year prior to exploration, Table 2 presents the results of tests via anova with repeated measures comparing the average biomass of each year, with the average biomass of 1981 per treatment.

It can be observed that in the T0 treatment there was no difference in the average annual biomass in relation to 1981. In the T1 treatment, the difference exists from 1983 to 1995 in relation to 1981, when there is no statistical difference in the biomass of 2008 and 2012 in relation to to 1981. In T2, the only difference occurred in 1995. In T3, there is a difference from all the years studied in relation to 1981 and in treatment T4 the difference occurs in 1983, and 2012 in relation to 1981.

Table 2 – Statistical significance of the annual comparison tests with the base year (1981) in the experimental area km 114.

Comparisons with 1981	Significance by Treatment (P- Value)				
	T0	T1	T2	T3	T4
1983 x 1981	0.65	0	0.87	0	0.03
1987 x 1981	0.8	0	0.55	0.01	0.05
1989 x 1981	0.13	0	0.21	0.02	0.13
1995 x 1981	0.46	0.03	0.05	0	0.1
2008 x 1981	0.73	0.96	0.2	0.01	0.94
2012 x 1981	0.62	0.19	0.62	0.03	0.02

Jari forest

Table 3 shows the average biomass per year for each treatment. It is observed in each year that there was little difference between treatments. A formal comparison test between treatments was performed using the Kruskal-Wallis non-parametric ANOVA due to the small sample size in each treatment. There was no evidence of statistical difference between treatments at the 5% level of significance in any of the years studied.

Table 3 – Comparison of the average amount of biomass (t/ha) in treatments and between years in Jari's experimental area.

Treatment	1984	1986	1988	1990	1994	1996	2004	2011
T0	95.76	96.79	98.16	94.26	96.24	96.56	91.46	89.66
T1	125.96	112.54	112.48	108.71	114.44	116.54	124.09	127.5
T2	130.39	90.15	91.1	92.66	96.3	96.4	94.97	107.63
T3	111.95	89.78	90.56	82.15	86.95	79.78	83.91	87.59
T4	120.42	92.32	94.79	93.69	98.55	96.81	103.71	98.05
T5	113.25	97.44	97.23	99.95	101.7	97.32	102.13	102.55
T6	123.3	113.32	115.13	113.83	120.62	109.6	106.79	103.53
T7	137.65	129.31	127.89	128.35	129.66	123.02	115.01	121.44
T8	124.13	100.48	101.01	99.15	104.6	106.37	111.85	113.43
T9	110.32	96.48	96.56	97.67	102.41	99.21	99.39	100.6
T10	124.21	100.67	102.76	100.58	104.35	96.27	95.47	98.22
T11	130.06	96.97	97.68	97.96	100.62	97.5	96.91	106.66
T12	124.06	98.55	98.68	98.52	104.77	105.43	112.9	119.07

The preview into each treatment evidence one decrease in the average biomass over the period studied in the treatment T0. In the other treatments, a loss is observed in 1986 due to forest exploitation in 1995 and slight growth over the period, but only the T1 treatments managed to return to their 1984 average. The formal comparison was performed using the Friedman non-parametric test, which detected differences in biomass (P value <0.05) over the period studied in treatments T1, T3, T4, T7, T8, T9, T11 and T12.

Moju forest

For the Moju area, due to the absence of treatments, only ANOVA was performed for repeated measures, seeking to show differences over time (Table 4). In the visualization of the averages, there is a reduction in biomass in 1998 and 2004 compared to 1995 and a growth from 2010 to 2015. The sphericity test was initially performed to assess the assumption of circularity in the variance-covariance matrix. The results pointed out in the Huynh-Feldt and Greenhouse-Geisser tests confirm the sphericity hypothesis and the F test reports the existence of differences in the average biomass between the years studied. The tests for the paired comparisons had verified the existence of difference in the average biomass in the years of 1998, 2004, 2010 and 2015 in relation to the 1995.

Table 4 – Comparison of the average amount of biomass (t/ha) between years in the Moju experimental area.

Year	Average	Sphericity	F
1995	13.81	Huynh-Feldt = 0.515	P-value = 0
1998	12.54		
2010	14.79		
2015	16.08		

PETECO forest

The ANOVA revealed no statistically significant differences between treatments for each year (Table 5).

Table 5 – Comparison of the average amount of biomass (t/ha) in treatments and between years in the experimental area of PETECO.

Year	Species average			Homogeneity	F
	T0	T1	T2	P-value	P-value
2003	27.16	28.77	29.88	0.150	0.746
2004	27.43	25.93	25.16	0.079	0.742
2005	26.99	26.06	25.35	0.054	0.858
2007	27.48	24.73	26.08	0.441	0.651
2008	27.98	25.09	26.31	0.429	0.622
2011	28.23	26.52	26.08	0.463	0.764

Discussion

For all areas after low-impact logging, the great loss of biomass was evident in the first years after logging. Santos *et al*. 2018, observed in the Tapajós national forest that the largest stocks of biomass are found in the classes of 30 ≤ DBH ≤ 60cm and DBH ≥ 90cm, despite the large number of individuals 10 ≤ DBH ≤ 30cm, individuals in the middle classes and higher concentrate a large accumulation of biomass. After seven years, the forest is recovering the value of biomass due to growth, both in height and in diameter of the species that remained there. After silvicultural treatments, there is a decrease in the value of biomass due to the death of non-commercial trees with considerable diameter and height, according to their treatments. Sist *et al*. (2014) and D'Oliveira & Braz (2006) observed that the opening of clearings and the entry of light due to the fall of large trees in the environment favor the development of trees in the shade of large trees. After the fire in the Tapajos forest, it was evident that there was no significant loss of aerial biomass, between and within the treatments, so much so that, 12 years after the fire, the forest showed no statistical difference between them.

Also Sist *et al*. (2014) observed that, when directing the harvest to the largest trees, commercial exploitation generates an immediate reduction in carbon stocks, with significant consequences on the net balance of forest biomass. Santos (2016) observed that large trees represented 55% of the initial total biomass of the plots of his study in the Jari forest in Amapá, West *et al*. (2014) showed that before the reduced impact exploration, 29% of the above-ground biomass was stored in trees with a diameter greater than 60cm. Sist *et al*. (2014) observed that trees with a diameter greater than 60cm represent 9.3% of the density of the trees; however, they collect an average of 49% of the total aerial biomass. In 30, 26, 18 and 8 years after logging, silvicultural treatments and accidental fire it was evident that the forest recovers the value of existing biomass before logging, however the speed of this dynamic depends on the intensity of logging and the quality of management reduced impact forestry. Mazzei *et al*. (2010) observed that the overall above-ground biomass gains in the logged forest 2 to 4 years after logging were double of those observed in the primary forest.

In the eastern Amazon, the use of reduced impact exploration techniques has substantially reduced the effect of selective logging on residual forest biomass, favoring the increase in above-ground biomass recovered after 16 years of monitoring (West *et al*. 2014). Santos (2016), found that the cutting intensity directly interferes with forest productivity. However, plots with a longer evaluation period, approximately 12 years, showed good development in above-ground biomass after exploration, mainly due to the low intensity of local exploration of these plots and the longer observation time in relation to the other plots.

In French Guiana, during the 20 year observation period, after conventional logging, that is, without planning, the plots explored have not recovered their initial carbon stock above the ground (Blanc *et al*. 2009).

Sist *et al*. (2003) evaluate that only the low impact exploration techniques, although an essential part of the solution, are not sufficient to guarantee the sustainability of the management, they are useful only under a moderate extraction regime and that does not exceed the limit of 8 ha-1 trees. Restricting felling and cutting intensity is essential, both from the point of view of the growth and survival of remaining trees and, in the long run, for the ecological sustainability of the forest (Sist *et al*. 2003, Mazzei *et al*. 2010, Putz *et al*. 2012, Carneiro *et al*. 2019 and Pinheiro *et al*. 2019).

Conclusion

The analyzes showed that the forest is able to recover its initial stocks of aerial biomass after 8 years of low impact exploration, in places with low exploration intensity.

In places with high exploration intensity, after seven years it is already possible to notice the growth in the value of biomass. In areas with less exploitation intensity two years after exploitation, it is already possible to notice the growth in the value of biomass.

Silvicultural treatments for the maintenance of biomass are not an option.

The growth of post-harvest biomass with reduced impact is greater, reflecting a good recovery of biomass stocks.

The high intensity of exploitation in some treatments resulted in severe biomass losses, contributing to a longer recovery time for above-ground biomass.

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