Current knowledge on overall post-logging biomass dynamics in Northern Amazonian forests

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Measurements of the girth of a tree cork buttresses in a permanent sample plot at Cikel.
Photograph P. Sist.

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RÉSUMÉ

NOUVELLES CONNAISSANCES SUR LA DYNAMIQUE GLOBALE DE LA BIOMASSE APRÈS EXPLOITATION EN FORÊT NORD AMAZONIENNE

L'article présente les effets de l'exploitation forestière sur la dynamique de la biomasse aérienne à partir des résultats issus de l'exploitation commerciale au sein de deux forêts : Cikel dans l'Est du Pará au Brésil et Paracou en Guyane française. L'objectif principal a été de comparer l'impact de ce type d'exploitation sur la régénération de la biomasse aérienne dans ces deux forêts dont les caractéristiques sont différentes en termes de structure et de croissance. Dans les deux sites, l'intensité de l'exploitation s'avère être un facteur essentiel déterminant de la perte de biomasse et le temps nécessaire à sa régénération. À Paracou, la régénération de la biomasse aérienne perdue lors des coupes d'abattage de 10 arbres par hectare prendra 45 ans et plus de 100 ans en cas d'exploitation à plus forte intensité (21 arbres par hectare). À la Cikel, la biomasse aérienne se régénérera au bout de 49 ans après exploitation à raison de 6 arbres par hectare et au bout de 87 ans après prélèvement de 8 arbres par hectare. Cette régénération prendra donc autant de temps sur les deux sites, mais avec un moindre nombre d'arbres exploités à la Cikel, les arbres abattus étant de plus grande taille avec une biomasse aérienne individuelle plus importante qu'à Paracou. Après le passage en coupe, l'étude a établi une corrélation directe de la dynamique de la biomasse aérienne avec la structure initiale de la forêt ainsi qu'avec les paramètres de la dynamique forestière : mortalité, croissance et recrutement. L'accumulation de biomasse aérienne par la croissance globale des peuplements après coupe s'avère être un paramètre clé pour le stockage net du carbone, toutefois la contribution du recrutement ne devient significative à Paracou qu'au bout de 10 ans après exploitation. Il s'agit donc de favoriser la croissance des arbres résiduels après la coupe, grâce aux traitements sylvicoles tels que l'éclaircie sélective ou l'élimination de lianes. Alors que les deux forêts sont géographiquement assez proches, leurs capacités de régénération ne sont pas identiques et, en raison de la différence significative de taille des arbres, la forêt guyanaise pourrait tolérer une plus forte intensité d'exploitation.

Mots-clés : biomasse aérienne, impact de l'exploitation, sylviculture, forêt humide amazonienne.

ABSTRACT

CURRENT KNOWLEDGE ON OVERALL POST-LOGGING BIOMASS DYNAMICS IN NORTHERN AMAZONIAN FORESTS

This article presents the effects of logging on the dynamics of above-ground biomass from the results of the post-logging study within two forests: Cikel in Eastern Pará, Brazil and Paracou in French Guiana. The main objective is to compare the impact of commercial logging on the regeneration of the above-ground biomass in these forests whose characteristics differ in terms of structure and growth. In both sites, the intensity of exploitation is a key factor in determining the loss of biomass and the time required for its regeneration. In Paracou, the regeneration of biomass lost during conventional logging of 10 trees per hectare takes 45 years and more than 100 years when operating with higher intensity (21 trees/ha). In Cikel the forest biomass regenerates after 49 years harvesting 6 trees/ha and that takes 87 years after removal of 8 trees/ha. This regeneration needs similar time on both sites but with lower logging intensity at Cikel, in which felled trees are larger with a greater biomass than those of Paracou. This post-logging study has established a direct correlation of the dynamics of the biomass with the initial structure of the forest, as well as with the parameters of forest dynamics: mortality, growth and recruitment. The accumulation of biomass by the tree growth of the two remaining stands is a key parameter for the net carbon storage, while the contribution of recruitment in Paracou becomes significant only after 10 years after felling. Therefore in view to improve the growth of residual trees, it is compulsory to apply adequate silvicultural treatments such as selective thinning or removal of vines. While the two forests are geographically close enough, their regenerative abilities differ and because of the significant difference in size of the trees, the forest could tolerate more intensive harvesting in French Guiana

Keywords: above ground-biomass, logging impact, silviculture, Amazonian rainforests.

RESUMEN

NOVEDAD EN CUANTO A LA DINÁMICA GLOBAL DE LA BIOMASA TRAS APROVECHAMIENTO DEL BOSQUE DEL NORTE AMAZONICO

En este artículo se presentan los efectos de la explotación maderera sobre la dinámica de la biomasa aérea gracias a los resultados del estudio de post-tala y acarreo en dos bosques: Cikel en el este de Pará en Brasil y Paracou en Guayana Francesa. El objetivo principal consistió en comparar el impacto de la tala comercial en la regeneración de la biomasa aérea en estos bosques cuyas características difieren en cuanto a la estructura y el crecimiento. En ambos lugares, la intensidad de la explotación resulta ser un factor clave para determinar la pérdida de biomasa y el tiempo necesario para su regeneración. En Paracou, la regeneración de la biomasa perdida durante la extracción de 10 árboles por hectárea tomará 45 años, así como100 años operando con mayor intensidad (21 árboles/ha). En Cikel la biomasa se regenera al cabo de 49 años al talar 6 árboles/ha y unos 87 años cosechando 8 árboles/ha. Esta regeneración se alcanza al mismo plazo en ambos sitios, pero con intensidad de tala menor en Cikel, cuyos árboles comerciales son de mayor tamaño y con más biomasa que los de Paracou. Este estudio de post-tala establece una correlación directa de la dinámica de la biomasa con la estructura inicial de los bosques, así como con los parámetros de la dinámica forestal: mortalidad, crecimiento y reclutamiento. La acumulación de biomasa que proporciona el crecimiento de los árboles residuales resulta ser un parámetro clave para la captura y estoc de carbono, sin embargo la contribución del reclutamiento en Paracou solo llega a ser significativo al cabo de 10 años después de la tala. Por lo tanto, para mejorar el crecimiento post-tala de los árboles residuales se requiere una silvícultura en su favor consistiendo en raleos selectivos o eliminación de lianas. A pesar de la relativa proximidad geográfica de los dos bosques, el potencial regenerativo no es idéntico y debido a la obvia diferencia del tamaño de los árboles, el bosque de Guayana Francesa podría tolerar una valorización mas intensa.

Palabras clave: biomasa aérea, impacto del aprovechamiento, silvicultura, bosque húmedo amazónico.

Introduction

Since the early 1950's, the sustainable management of forest resource for timber production has been seen as a potential tool for the conservation of large areas of tropical forest. Currently, 350 million hectares of tropical moist forests worldwide are designated as production forests, about a quarter of which is managed by rural communities and indigenous people (ITTO, 2005). Due to the high diversity of Amazonian natural forests and limited markets for the timber of most tree species, loggers usually only harvest 1-10 trees per hectare (SIST & NASCIMENTO-FERREIRA, 2007). In the Brazilian Amazon, the potential area dedicated to production forests for logging companies or communities is estimated to be around 70 million ha, while conservation areas already cover about 200 million ha (SIST *et al.*, 2010). The conservation of biodiversity and of the forest ecosystems of tomorrow will mostly take place in both conservation areas as well as in anthropized (logged, domesticated) forests. In the last, conservation of biodiversity and other environmental services will be efficient only if they are well managed which means that logging rules will have to ensure the maintenance of forest services (biodiversity and carbon) and at the same time the production of forest goods (timber and non-timber forests products). The silviculture of tomorrow will therefore have to take into account any compromises between the production of goods (wood, NWFPs) and the preservation of environmental services (SIST *et al.*, 2011). The emergence of new payment for environmental services markets opens up economic development possibilities for the environmental services provided by forests. Of these, carbon storage and biodiversity are by far the ones attracting most attention (PUTZ *et al.*, 2008). In recent years several studies were carried in the Amazon basin to assess the impact of climate change on tree population dynamics and consequently on carbon storage in undisturbed forests (BAKER *et al.*, 2004; MALHI *et al.*, 2006; LEWIS *et al.*, 2006; PHILLIPS *et al.*, 2010). However, an important gap in the current knowledge remains the long-term impact of selective logging on ecosystem services (i.e. Carbon storage and biodiversity) in the Amazon region. In this study, we addressed the question of how logging affects the dynamics of above-ground biomass (AGB) based on the results of forest dynamics monitoring after logging in two different forests of Northern Amazonia (Eastern Pará Brazil, and French Guiana). The main objective is to compare the impact of logging on the recovery rates of AGB in forest with different structure and growth.

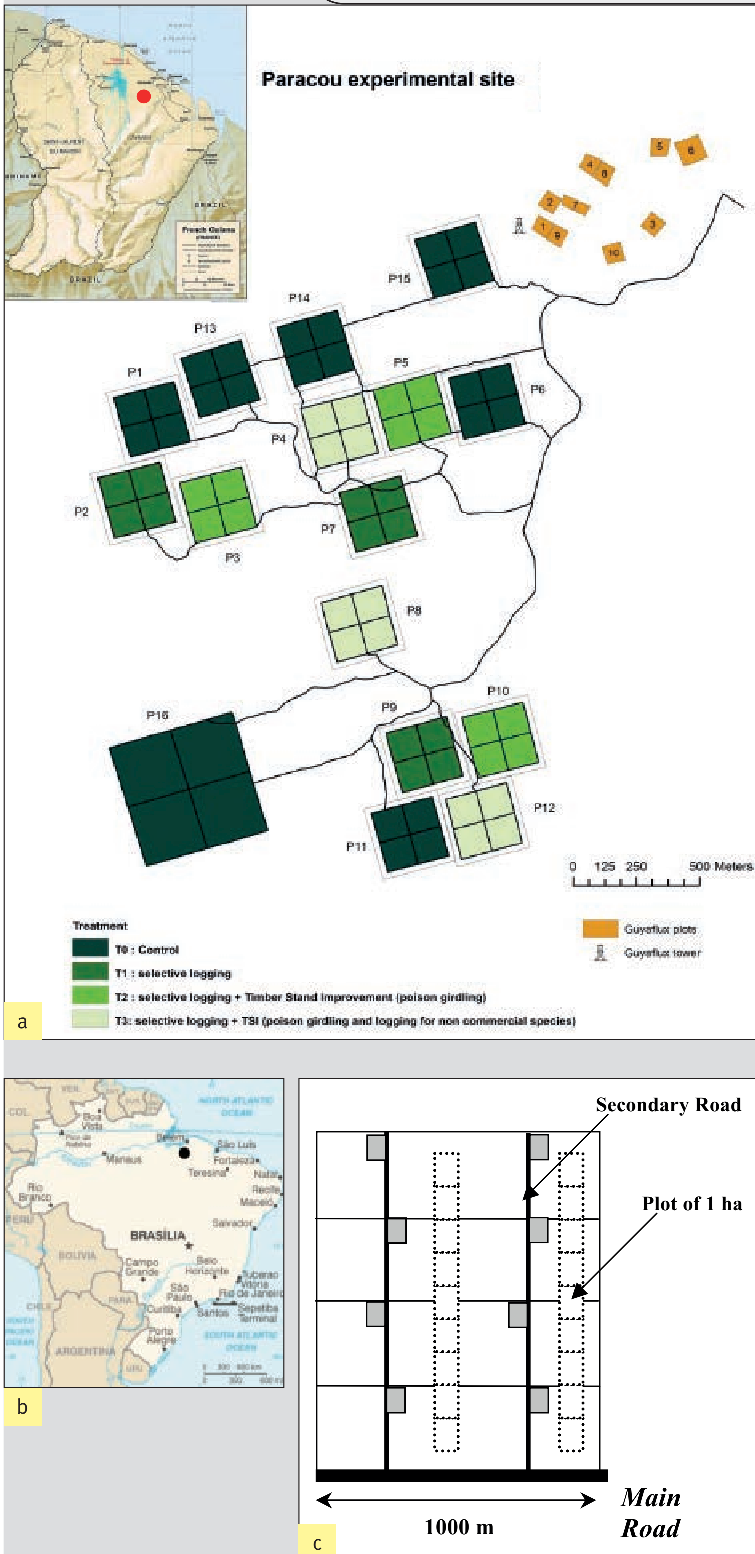

Figure 1.
Location and details of Paracou (1a, red dot) and Cikel (1b, black dot) experimental sites.
1a: geographical location (above) and plot distribution and treatments (below) T0: control, T1: treatment 1 (conventional logging), T2: treatment 2 (logging + timber stand improvement TSI), T3: treatment 3 (logging + Timber stand improvement + logging of non-commercial species).
1c: location of the plots in a 100 ha annual production block logged in 2004 with Reduced Impact Logging techniques (RIL)

Felling a tree buttress according to the techniques recommended by the RIL.
Photograph P. Sist.

Study sites and Methodology

Study sites: The results presented in this paper come from two study sites located in the Amazon: Paracou in French Guiana and Rio Capim in Eastern Pará, Brazil (figures 1a and b).

Paracou experimental site is located in a lowland tropical rain forest in French Guiana (5°18'N, 52°55'W; GOURLET-FLEURY *et al.*, 2004). The site receives nearly two-thirds of the annual 3,160mm±161SE of precipitation between mid-March and mid-June, and less than 50 mm per month in September and October. Paracou experimental site gathers 15 permanent plots of 6.25 ha each and one plot of 25 ha in which all stems ≥ 10 cm DBH (Diameter at breast height) were mapped and regularly surveyed (figure 1a). From 1986 to 1988, the plots were logged following a randomized block design, with three blocks of four 250 m x 250 m plots each, in which one plot was kept untouched as reference (identified as control plots in figure 1a) while the three other plots were logged according to one of three different treatments. Treatment 1 was a selective logging which removed an average of 10 timber trees per hectare (DBH ≥ 50 or 60 cm). Treatment 2 was logged as in Treatment 1, followed by timber stand improvement (TSI) by poison girdling of selected non-commercial species, with about 30 trees removed per hectare (DBH ≥ 40 cm). Finally, Treatment 3 was logged as in Treatment 2 for an expanded list of commercial species, with in mean 45 trees removed per hectare (DBH ≥ 40 cm). Tree harvesting in the plots was initiated in October 1986 and was completed in May 1987 while Timber stand improvement (TSI) by poison girdling began in December 1987.

The Rio Capim experimental site is located in Eastern Pará, Paragominas, on the Fazenda Rio Capim owned by Cikel-Brasil Verde group (for more details about the area see: SIST & NASCIMENTO-FERREIRA, 2007; MAZZEI *et al.*, 2010). The area of about 140,000 ha includes large areas of pristine (ca 12,000 ha) and logged terra firme forest (ca 110,000 ha), along with some abandoned pastures (18,000 ha). In 2001, Cikel received Forest Stewardship Council certification for their management of an area of 75,000 ha. Since then, Cikel has been harvesting using RIL techniques (SIST & NASCIMENTO-FERREIRA, 2007) with a minimum cutting diameter of 55cm for all commercial species. The most common harvested species are Manilkara huberi (Ducke) A.Chev., Hymenaea courbaril L., Astronium lecointei Ducke, Parkia pendula (Willd.) Benth. ex Walp., Couratari oblongifolia Ducke & Knuth, and Pouteria bilocularis (Winkler) Baehni. Before logging in 2004, 18 experimental RIL plots, 1ha each were set up in a 100 ha logging block (figure 1b). For comparison, two 0.5 ha control plots was used established in an adjacent area by Fundação Floresta Tropical. In the area to be logged, all trees with DBH ≥ 20 cm (stem diameter at 1.3 m or above buttresses) were identified with a common name, DBH was measured, and the trees were tagged and mapped. In each of these plots (except plot 5 that is henceforth disregarded), trees were also measured in the 10-20 cm DBH class in two randomly located 0.0625 ha (25 m x 25 m) subplots (figure 1b). In the control plots, all trees with DBH › 10 cm were included when the plots were established in 1996 and during the re-measurements in April 2004 and March 2008. In the plots to be logged the initial measurements were made in May 2004 and re-measurements were then carried three months later (October 2004) to assess the logging damage through the record of injured and dead trees (SIST & NASCIMENTO-FERREIRA, 2007). Subsequent plot measurements were made in May 2005, November 2006, February 2008 and March 2010; during the final re-measurement, all trees were identified at least to the generic level.

Methods

In both site the above-ground biomass (AGB) of all living trees with Dbh ≥ 10 cm was estimated before and after logging using allometry developed by CHAVE *et al.* (2005) for moist tropical forests:

$$AGB = \rho \times \exp(-1.499 + 2.148\ln(dbh) + 0.207(\ln(dbh))^2 - 0.0281(\ln(dbh))^3)$$

where ρ is the wood density (g/cm^3); *dbh* is diameter at breast heigh (cm).

For the Cikel site, the value of ρ was obtained from the Brazilian Wood Database compiled by the Laboratorio de Produtos Florestais of the Brazilian Forest Service and the study published by FEARNSIDE (1997) following the recommendations of NOGUEIRA *et al.* (2005). For the Paracou site, wood density values were measured in the field on wood sample for 160 taxa. A total of 57.5% of all stems had wood density measured at the species level, 11.2% at the genus level, 15.9% at the family level and 15.4% at the plot level (for more details see RUSTISHAUSER *et al.*, 2010). Dry biomass was converted into carbon assuming a carbon to dry biomass ratio of 0.5 (BROWN & LUGO, 1982).

Results

Impact of logging techniques and intensities on biomass loss:

Mean logging intensities in Paracou were 10 and 21trees/ha in Paracou (CL and CL+TSI respectively) representing an AGB felled of 57.8 and 86.4 T/ha. At Cikel, logging intensity was much lower with only in mean 6 trees removed per ha although the resulting mean AGB felled of 69.3 T/ha was much higher than in Paracou. This result suggests therefore that trees logged in Cikel were much bigger than those in Paracou.

Not surprisingly, AGB damaged by logging operations increased both with logging intensity (AGB felled) and with logging modalities but without interaction (Ancova analysis shows that the best model is AGB Damaged~AGB felled + logging treatment, AIC=283.34, figure 2). For a given AGB felled, applying RIL techniques rather than conventional logging will reduce AGB damaged by 12.2 T/ha. Using TSI in conventionally logged forests will increase AGB damages by 28.9 T/ha.

AGB dynamics after logging:

AGB total loss (including AGB damaged, felled and thinned) reached 20.7% (87.1 T/ha) of initial AGB stock for CL, 25.7% (104.8 T/ha) for RIL Cikel and 49.6% (219.9 T/ha)

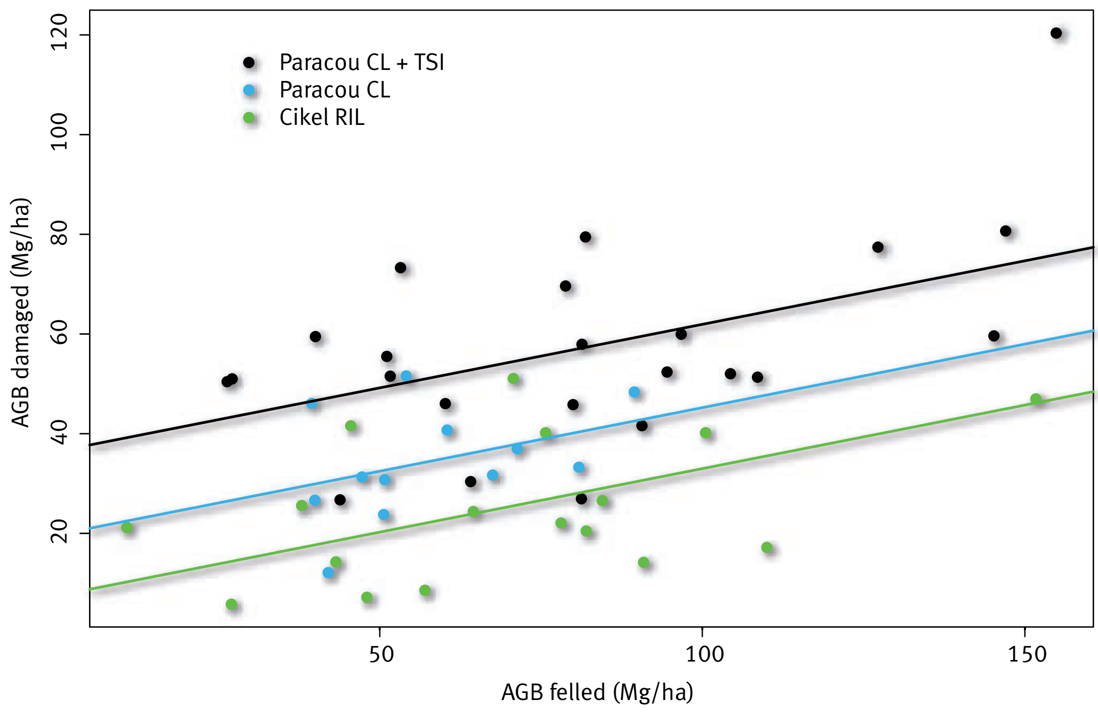

Figure 2.
Above Ground Biomass damaged and felled in 3 logging treatments in Paracou (conventional logging, conventional logging and Timber Stand Improvement) and Cikel (Reduced Impact Logging).

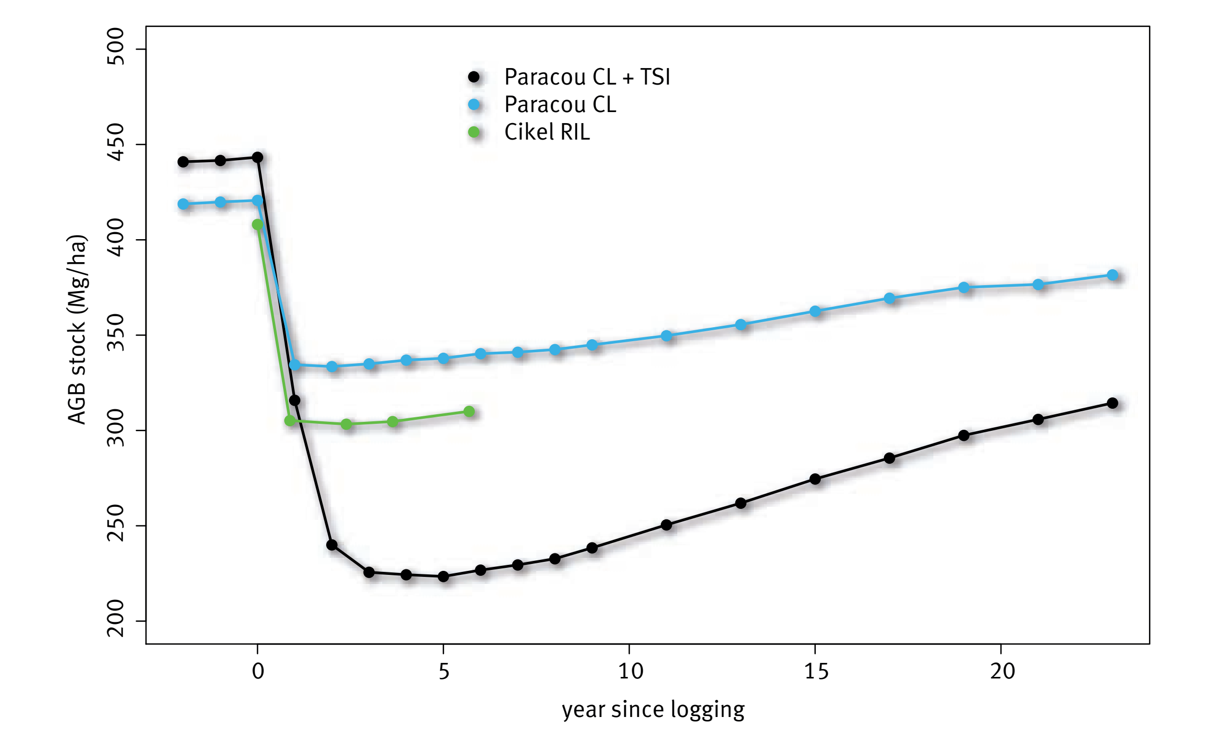

Figure 3.
Temporal evolution of AGB stocked (Mg/ha) in three logging treatments.
CL: Conventional Logging.
TSI: Timber Stand Improvement.
RIL: Reduced-Impact Logging.

for CL and TSI (figure 2). Minimum AGB values were reached 2 years after logging for CL and RIL, but 5 years after logging for CL+TSI (figure 3).

After 2 years, AGB balance (table I, annual flux) became positive for CL and RIL and increased with time to reach max value for a median time value of 15 years. At Cikel, AGB balance increased also constantly during the 6 years following logging activities (table I). AGB balance is higher in Cikel (2.55 T/ha/yr vs 1.55) mainly due to higher AGB growth. AGB balance became positive between 4 and 6 years after logging for CL+TSI and reached also maximum values between 11 and 15 years.

In both sites, tree AGB growth contributed the most significantly to the AGB accumulation after logging while recruitment only represented a small part (max of 26.4%) of the biomass gain (table I). AGB growth showed high and constant values during the recovery except for the last measurement period (19-23 years) where a decrease of the AGB growth was recorded.

In Paracou, recruitment peak was observed between 8 and 15 years after logging. At both sites the highest loss of biomass due to mortality was observed 4 years after logging (table 1) with however a much higher rate in Paracou (-14.78 T/ha/yr) than at Cikel (-6.7 T/ha/yr, table 1).Death AGB fluxes decreased constantly with time in Paracou and after 8 years, values appeared to be close or lower than the ones recorded before logging (table I).

Discussion and Conclusions

In both sites, logging intensity was a key factor that will determine the amount of biomass lost during logging and consequently the time needed to recover the AGB lost during logging. The dynamics of AGB after logging showed similar patterns in both site. First there was a high loss of AGB through mortality due to an over mortality of trees damaged during logging operations. In Paracou, high mortality rates persist for a period of 8 years. At Cikel, four years after logging the mean loss of AGB due to tree mortality in logged plots was still almost twice higher than in undisturbed forest (MAZZEI *et al.*, 2010). The recovery of the AGB in both Paracou and Cikel was strongly correlated to logging intensity (i.e. on the AGB felled by logging). In Paracou the recovery of AGB after conventional logging (mean logging intensity of 10 trees/ha) will require 45 years while in plots with Timber stand improvement with a mean logging intensity of 21 trees/ha, it will take over a 100 years (BLANC *et al.*, 2009). At Cikel comparable results were found as according to the simulation realized by MAZZEI *et al.* (2010), AGB would recover after 49 years for a logging intensity of 6 trees and after 87 years after a logging intensity of 8 trees/ha. For a same AGB recovery period, forest at Cikel will therefore recover from a much lower logging intensity than in Paracou. Indeed, trees felled at Cikel were larger than those felled in Paracou exhibiting therefore a higher individual AGB.

Table 1.
Mean above ground biomass (Standard Deviation) value of gain (growth and recruitment) and loss (death) in Paracou and Cikel.

Years since logging	Paracou CL	Paracou CL+TSI	Cikel RIL
		Above Ground Biomass growth (T/ha/yr)	
[-2 -0]	4.50 (1.5)	4.07 (0.8)	
[0 -2]	5.12 (0.8)	4.90 (0.8)	6.33 (1.1)
[2 -4]	6.20 (1.0)	6.07 (0.7)	7.47 (1.1)
[4 -6]	5.57 (0.9)	5.99 (1.0)	6.91 (1.4)
[6 -8]	5.88 (0.9)	6.40 (1.2)	
[8 -11]	5.83 (1.1)	6.53 (1.1)	
[11 -15]	5.58 (0.8)	6.70 (1.1)	
[15 -19]	6.17 (1.1)	7.37 (1.2)	
[19 -23]	4.84 (1.2)	6.42 (1.3)	
		AGB recruitment (T/ha/yr)	
[-2 -0]	0.36 (0.3)	0.25 (0.2)	
[0 -2]	0.33 (0.1)	0.34 (0.1)	0.66 (0.6)
[2 -4]	0.68 (0.3)	0.85 (0.3)	0.87 (0.6)
[4 -6]	1.10 (0.6)	1.56 (1.1)	0.80 (0.4)
[6 -8]	0.55 (0.3)	1.24 (0.4)	
[8 -11]	0.98 (0.3)	2.34 (0.9)	
[11 -15]	1.17 (0.3)	2.01 (0.5)	
[15 -19]	0.67 (0.2)	1.06 (0.3)	
[19 -23]	0.35 (0.1)	0.62 (0.2)	
		AGB death (T/ha/yr)	
[-2 -0]	-3.85 (2.4)	-3.14 (2.5)	
[0 -2]	-49.85 (13.1)	-106.89 (25.9)	-65.67 (21.4)
[2 -4]	-4.97 (2.3)	-14.74 (6.4)	-6.71 (4.99)
[4 -6]	-5.13 (3.9)	-6.34 (3.5)	-5.16 (2.28)
[6 -8]	-5.62 (4.2)	-4.66 (2.0)	
[8 -11]	-4.50 (2.0)	-2.95 (1.3)	
[11 -15]	-3.33 (1.7)	-2.70 (0.9)	
[15 -19]	-3.71 (1.6)	-2.71 (0.9)	
[19 -23]	-3.12 (1.6)	-2.80 (0.9)	
		AGB Balance (T/ha/yr)	
[-2 -0]	1.02 (3.2)	1.18 (2.6)	
[0 -2]	-44.39 (12.7)	-101.65 (26.1)	-58.67 (25.7)
[2 -4]	1.91 (2.9)	-7.83 (6.4)	1.62 (6.1)
[4 -6]	1.55 (3.9)	1.21 (3.5)	2.55 (5.0)
[6 -8]	0.81 (4.2)	2.98 (1.9)	
[8 -11]	2.30 (1.6)	5.92 (2.1)	
[11 -15]	3.42 (2.1)	6.02 (1.5)	
[15 -19]	3.13 (1.5)	5.72 (1.4)	
[19 -23]	2.08 (1.7)	4.24 (1.4)	

Forest road at Cikel in responding to the RIL techniques requirements (limited width of the road).
Photograph P. Sist.

Accumulation of AGB by growth play an important part in the net balance of Carbon storage after logging in both sites while recruitment only showed significant contribution at Paracou 10 years after logging. It would be therefore essential to promote the growth of the remaining trees after logging. This can be done through the implementation of silvicultural treatments such as selective thinning and liana cutting around the remaining potential crop trees. The positive impact of silvicultural treatments on growth of remaining trees has been clearly demonstrated in several studies (PEÑA-CLAROS *et al.*, 2008; VILEGAS *et al.*, 2009).

This study showed that AGB dynamics after logging was directly correlated to the original structure of the forest (initial AGB and size of trees) and the dynamics parameters involved such as mortality, growth and recruitment. Although Paracou and Cikel are relatively closed in distance, their capacity of recovery is slightly different. Indeed, because of a significant difference in tree size, the results suggest that forests in French Guiana can sustain higher logging intensities than those at Cikel.

At the Amazon basin regional scale, only a few isolated studies on the dynamics of logged Amazonian forests have been published (SIST & NASCIMENTO-FERREIRA, 2007; MAZZEI *et al.*, 2010; BLANC *et al.*, 2009). These studies clearly demonstrated that forest dynamics vary considerably in the region. For example, mean stem diameter growth rates recorded during the first four years after logging in East Pará (0.33 cm/year) were higher than those recorded over 18 years post-logging in French Guiana (0.20 cm/year, BLANC *et al.*, 2009; GOURLET-FLEURY *et al.*, 2004) but similar to those observed in the Santarém region of central Pará over a 25 year post-logging period (0.36 cm/year; OLIVEIRA, 2005). Still lacking is an analysis of multiple response variables across a broad gradient of sites to identify any trends in response of different forests across the region. Moreover, several studies at the regional scale demonstrated that Amazonian rainforest exhibit a rather large variability in structure and species composition along an East-West Gradient (TER STEEGE *et al.*, 2006, MALHI *et al.*, 2006). For example, MALHI *et al.* (2006) demonstrated that AGB is the highest in the moderately seasonal, slow growing forest of Central Amazonia and the Guyanas (up to 350 T/ha) and declining to 200-250 T/ha at the Western, Southern and Eastern margins. Given these large differences in floristic composition, forest structure and dynamics, within the Amazon region, forest management guidelines should be adapted to these different forests to ensure sustainability. For this, it is essential to better understand how forest response to logging varies across the region.

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