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Forest Ecology and Management 236 (2006) 127–135

Forest Ecology and Management

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Review

Identifying bias in stand-level growth and yield estimations: A case study in eastern Brazilian Amazonia

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Received 6 June 2006; received in revised form 22 August 2006; accepted 29 August 2006

Abstract

Commercial volume increment based on permanent plot data has frequently been used to determine cutting cycles and logging intensities that do not deplete forest timber resources, and that are therefore compatible with sustainable forest management. We evaluate three potential sources of increment bias from long-term permanent plot data monitoring forest recovery after reduced-impact logging (RIL) and conventional or predatory logging (CL) in eastern Amazonia: (1) forest monitoring length; (2) minimum diameter at breast height (DBH) included in measurements; (3) defective stems. Short monitoring intervals, inclusion of trees from sub-merchantable size classes, and failure to account for defective stems all lead to overestimates of annual commercial volume increment between first and second harvests. We found that these sources of bias greatly inflated the estimate of volume increment during the projected 30-year cutting cycle. Without controlling for biases, estimated volume increments were 1.14 and 0.18 m^3 ha^{-1} $year^{-1}$ for RIL and CL, respectively; increment corrected for bias decreased to 0.19 and 0 m^3 ha^{-1} $year^{-1}$ over the 30-year period. We propose alternative methods for calculating and reporting commercial volume increment.

Keywords: Amazonia; Commercial volume increment; Permanent plots; Sustainable forest management; Yield regulation

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Contents

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doi:10.1016/j.foreco.2006.08.340

1. Introduction

One of the key features distinguishing 'sustainable' forest management from uncontrolled logging (frequently termed 'timber mining' or 'predatory logging') is the explicit goal of ensuring future timber supply (Rice et al., 1998). Forest managers have historically been concerned with stand-level commercial volume accumulation – referred to as 'increment' throughout this paper – as a simple indicator of sustainable harvest levels. If harvest intensity and volume losses due to damages associated with logging do not exceed the forest's capacity to replenish commercial timber volume between harvests, long-term depletion of timber stocks may be avoided.

Yield regulation is currently a major concern in the Brazilian Amazon, where momentum is building for a large-scale transformation of the timber industry. The Brazilian National Forest Program aims to create 500,000 km^2 of forest concession areas in the Amazon by 2010, with the stated goal of managing forest resources sustainably (Veríssimo et al., 2002). The importance of Forest Stewardship Council (FSC) certification as a market-based incentive for sound forest management in Brazilian Amazonia has increased dramatically over a short interval, with the total certified natural forest area more than doubling during 2003–2004 from 0.5 to 1.3 million ha (FSC-Brasil, 2005). In this context, forest regulations are presently under revision by the Brazilian Ministry of the Environment, with the goal of setting limits on harvest intensity and cutting cycles that are compatible with sustaining timber yields. Changes to forest regulations are to be based on estimated commercial volume increment in Amazonian forests (Freitas, personal communication). Previous applications of this approach have led to predictions that harvests of 30 $m^3\,ha^{-1}$ at 30-year intervals can be sustained based on increment of 1 $m^3\,ha^{-1}\,year^{-1}$ (Silva, 2001).

Efforts to define allowable harvest intensity and cutting cycle length in Amazonia based on estimates of commercial increment are constrained by the paucity of data on forest response to logging. Published studies of increment in logged forests are limited to six sites in the Brazilian Amazon, three of them clumped within the Tapajós National Forest (Flona Tapajós). Permanent sample plots are generally small ($\leq$1 ha) and cover a small total area of forest at each site (Table 1), particularly in light of the heterogeneity of Amazonian forests and the characteristically low densities of many timber species. In Brazil, no plot network has been monitored for a period approaching the projected cutting cycle of 30 years, with most forest monitoring results restricted to the first decade following logging. In light of current data limitations, if commercial volume increment estimates from permanent plots are to be used as primary data for determining sustainable tropical timber harvests, the uncertainties and potential sources of error for these estimates must first be examined.

Stand-level volume increment reported from most tropical mixed forests ranges between 0.5 and 2 $m^3\,ha^{-1}\,year^{-1}$ (Rice et al., 1998). Similar increment ranges have been reported from the Brazilian Amazon (Table 1). Potential sources of increment bias have been mentioned in the literature, though without systematic analysis or discussion of possible corrective measures. Potential sources of bias identified in the literature include:

1.1. Forest monitoring length

Many researchers have reported a decrease in increment over time after logging in the Brazilian Amazon (Silva et al., 1995, 1996; Oliveira, 2000, 2005; Vidal, 2004; but see Higuchi et al., 1997; Table 2) and elsewhere, the decrease attributed mainly to increased competition for light as canopy gaps created by logging close (de Graaf et al., 1999; de Graaf, 2000). This means that increment estimates based on short post-logging observation periods – the case for all Amazonian studies currently available – likely overestimate increment over the course of a complete cutting cycle.

1.2. Minimum DBH of measurement

The influence of the minimum DBH (diameter at breast height) of measurement on increment calculation has been shown in the Brazilian Amazon (Vidal, 2004; Oliveira, 2005; Table 2) and elsewhere (Alder, 1999), indicating that lower minimum DBH of measurement results in higher increment estimates. Published increment estimates use varying minimum diameters, and all incorporate growth, recruitment and mortality in sub-merchantable size classes (Table 1).

Table 1
Published results of increment ($m^3\,ha^{-1}\,year^{-1}$) for logged forests without silvicultural treatment in the Brazilian Amazon

Source	Site (State)	Range of increment ($m^3\,ha^{-1}\,year^{-1}$)	Minimum DBH of measurement (cm)	Maximum monitoring length (years)	Plot size (ha)	Total sampled area (ha)
Silva et al. (1995)	Km 67, RP012–Flona Tapajós (PA)	0.8–2.0	20	11	0.25	9
Silva et al. (1996)	RP011–Flona Tapajós (PA)	1.2–1.9	20	6	0.25	12
Higuchi et al. (1997)[a]	ZF2 (AM)	1.1–1.4	10	9	1.00	15
Oliveira (2000)	CPAF and Pedro Peixoto (AC)	1.0–1.4	20	7	1.00	7
Vidal (2004)[b]	Fazenda Sete (PA)	0.1–2.5	10 and 30	10	24.50	49
Oliveira (2005)[c]	Km 114–Flona Tapajós (PA)	0.5–2.0	20	20	0.25	10

[a] Calculated from data shown in Tables 4–6, pages 108, 110, and 112, respectively.
[b] Results reported by Vidal (2004) are derived from the same dataset as used by this study.
[c] Calculated from data shown in Table 3, page 97.

Table 2
Potential sources of bias identified in the literature

Bias	Increment ($m^3\ ha^{-1}\ year^{-1}$)		Site (State)	Treatment[a]	Source
Monitoring length (calendar years)	2.0 (1981–1987)	1.8 (1981–1992)	Km 67, RP012–Flona Tapajós (PA)	–	Silva et al. (1995)
	2.5 (1983–1989)	1.3 (1983–2003)	Km 114–Flona Tapajós (PA)	OT1	Oliveira (2005)[b]
	0.5 (1987–1991)	1.3 (1987–1996)	ZF2 (AM)	HT1	Higuchi et al. (1997)[c]
	0.0 (1987–1991)	1.1 (1987–1996)	ZF2 (AM)	HT2	
	1.0 (1988–1991)	1.4 (1988–1996)	ZF2 (AM)	HT3	
Minimum DBH of measurement	0.5 (≥10 cm)	0.1 (≥30 cm)	Fazenda Sete (PA)	CL	Vidal (2004)[d]
	2.5 (≥10 cm)	0.9 (≥30 cm)	Fazenda Sete (PA)	RIL	

[a] OT1, logging of all commercial trees (≥45 cm DBH) without post-logging silvicultural treatment; HT1, logging of 32% of commercial basal area (CBA) defined as basal area from trees ≥55 cm DBH from commercial species; HT2, logging of 42% of CBA; HT3, logging of 69% of CBA.

[b] Calculated from data shown in Table 3, page 97.

[c] Calculated from data shown in Tables 4–6, pages 108, 110 and 112, respectively.

[d] Results reported by Vidal (2004) are derived from the same dataset as used by this study.

1.3. Defective stems

More than half of the trees meeting harvest criteria during inventory may be de-selected afterwards due to defects and factors jeopardizing harvest (Holmes et al., 2002). However, no published study explicitly mentions omitting these stems from increment calculations. We consequently expect to find increment bias due to inclusion of these stems in increment calculation.

Biases in ecological studies based on permanent sample plots have been evaluated previously, with an emphasis on site selection, measurement methodology, data compilation, and analysis (Sheil, 1995; Sheil and May, 1996; Condit, 1997; Phillips et al., 2002). Our objective is to evaluate biases in timber growth and yield studies, a subject with immediate implications for management of Amazonian forests and one that has received little attention. We examine factors possibly influencing plot-based estimates of commercial volume increment, focusing on the three potential sources of increment bias described above. We use 10-year forest monitoring data from large-scale (24.5 ha) permanent plots from a forest management demonstration site in the eastern Amazon to illustrate the effect of biases that we expect are common to many published increment estimates in the Brazilian Amazon. Finally, we propose an alternative method for calculating and reporting commercial volume increment.

2. Methods

2.1. Study site and data

Paragominas is a county located in Brazil's eastern Amazonian state of Pará (3°17′S, 47°37′W). Predominant soils are oxisols/yellow latisols, on gently rolling terrain. Climate is tropical and highly seasonal, with most of 1700 mm annual precipitation falling between December and May. Vegetation is classified as dense terra firme evergreen forest. Mature unlogged forest has an aboveground biomass of ca. 300 t ha^{-1} and canopy height averaging 25–35 m (Uhl et al., 1988; Holdsworth and Uhl, 1997; Gerwing, 2002).

Data are from a demonstration logging experiment initiated in 1993, in which reduced-impact logging (RIL) was tested for the first time in the Brazilian Amazon and compared to conventional unplanned logging (CL). For the current study, we examine data from two 24.5-ha permanent plots subjected to separate RIL and CL treatments in 1993. Lack of planning in CL leads to severe damage to the residual stand despite selective harvesting. RIL is an alternative operational system that improves harvest efficiency and reduces damage inflicted on stands. For example, despite higher logging intensity in RIL (37 $m^3\ ha^{-1}$) compared to CL (30 $m^3\ ha^{-1}$) at the Paragominas site, RIL resulted in fewer damaged residual trees per tree extracted (35 versus 51 trees for RIL and CL, respectively; Johns et al., 1996). Detailed descriptions of logging characteristics at the study site, such as damage level, cost/benefit evaluation, and forest monitoring results, can be found elsewhere (Johns et al., 1996; Barreto et al., 1998; Vidal, 1998, 2004; Vidal et al., 1998, 2002; Schulze, 2003). All trees ≥25 cm DBH were measured for diameter in 1993 pre-logging, in 1993 post-logging (damage assessment only), and again in 1996, 2000, and 2003.

2.2. Data analysis

In this article, increment is defined as the net annual commercial volume production of the forest, being the result of growth, mortality and recruitment. Commercial volume is the sum of the volume from all trees of commercial species above a given size threshold (in this study either 25 or 45 cm) and meeting other selection criteria (e.g., without commercial defects). For all analyses, we used the simplest method for calculating increment, defined by:

$$I = \frac{V_2 - V_1}{T} \tag{1}$$

where I is the commercial volume increment ($m^3\ ha^{-1}\ year^{-1}$), V_2 the commercial volume at measurement 2 ($m^3\ ha^{-1}$), V_1 the commercial volume at measurement 1 (m^3 ha^{-1}) and T is the time between measurements 1 and 2 (years). Volume (m^3) was estimated as a function of DBH (cm) using Silva and Carvalho's (1984) equation: $\ln(\text{volume}) = -7.7760 + 2.0690 \times \ln(\text{DBH})$.

In the increment formula, volume gains from growth of existing stems and recruitment into the size class of interest, as well as losses due to mortality, are condensed into one increment value for the entire observation period. V_1 and V_2 were always determined in the same way. For example, to calculate 10-year increment for trees ≥45 cm DBH (the legal minimum felling diameter in Brazil), V_1 and V_2 were determined by summing the volumes of trees from commercial species ≥45 cm DBH in 1993 (post-logging) and 2003, respectively.

2.3. Forest monitoring length

To evaluate potential bias attributable to forest monitoring length, increment was calculated for three time periods: 1993–1996, 1993–2000, and 1993–2003. To estimate increment during the full interval between harvests, we assumed a 30-year cutting cycle – the currently accepted norm for forest management in the Brazilian Amazon – and increment from the last measurement period (2000–2003) was used as a proxy for increment during 2003–2023. As an example, if increment for the 1993–2000 measurement period was equal to 0.5 m^3 ha^{-1} $year^{-1}$ and increment for the last measurement period (2000–2003) was equal to 0.3 m^3 ha^{-1} $year^{-1}$, increment for the full cutting cycle is estimated as $[(0.5 \times 7) + (0.3 \times 23)]/30$, yielding 0.35 m^3 ha^{-1} $year^{-1}$. This approach provides a more reliable estimate of increment during the full cutting cycle than use of the mean increment of the entire post-logging monitoring period due to the decrease in increment over time after logging (Silva et al., 1995, 1996; de Graaf et al., 1999; de Graaf, 2000; Oliveira, 2000, 2005; Vidal, 2004).

2.4. Minimum DBH of measurement

To evaluate how the minimum DBH included in plot measurements influences increment estimates, we calculated 10-year increment (1993–2003) assuming two different minimum diameters of measurement: 25 and 45 cm. The 25-cm DBH threshold is the minimum measurement DBH from the dataset while the 45-cm DBH threshold represents the legal minimum logging DBH in Brazil.

We also considered whether volume gain due to recruitment (I_r) into the commercial size class (≥45 cm) might increase over time. This was done by projecting growth and mortality of trees 25–45 cm DBH from commercial species during 2003–2023. Trees 25–45 cm DBH in 2003 were randomly divided into three groups, growing according to 25th, 50th and 75th percentile of the diameter increment distribution. Diameter increment percentiles and mortality rates were species-specific for species with ≥20 individuals; for the remaining species we calculated a single set of growth and mortality parameters based on all trees from the stand. Due to the stochastic nature of growth and mortality, 100 simulations were run for both RIL and CL and averaged results were evaluated.

2.5. Defective stems

Commercially defective stems, defined as trees with hollow stems, bad form, or other commercially undesirable characteristics (from here on referred to simply as defective trees) can correspond to 40% or more of trees meeting harvest criteria in forest inventories. In our study region, ca. 20% of the trees included in commercial inventories have obvious commercial defects (Holmes et al., 2002; Schulze, 2003; Vidal, 2004; Zweede unpublished). In RIL, obvious defects are identified during the inventory while many hollow stems are only identified during hollow testing immediately prior to felling; in the one published example from the study region, more than 50% of the trees originally selected for harvest were later rejected by tree-marking and felling crews (Holmes et al., 2002). RIL protocols for the Amazon currently call for leaving defective stems standing rather than cutting these stems as part of stand improvement. This practice has been adopted to limit the damage to the residual stand per volume of timber extracted and to favour future seed production over the minimal timber production that could be achieved from logging defective stems. Unplanned conventional logging results in felling of some hollow trees – these are then left in the forest since transport to the sawmill is not profitable – yet defective trees can also be expected to accumulate in conventionally logged stands as trees with obvious defects are rejected by sawyers.

Most published studies of defective trees have been conducted in Australia, focusing mainly on hollowed trees from the genus *Eucalyptus* (Gibbons and Lindenmayer, 1996; Ball et al., 1999; Lindenmayer et al., 2000; Whitford, 2002). In the absence of detailed information on hollow trees in the Amazon (i.e., species-specificity, DBH-specificity, relationship to growth or mortality), we assumed that defective trees do not demonstrate different growth or mortality rates from defect-free trees, and that they are randomly distributed among all trees in the study forest. We attributed defect randomly to a given percentage (0, 20 and 40%) of inventoried trees and calculated increment without them. This was done 100 times and increments were averaged by defect percentage. The defect percentages used in simulations represent: (1) a default scenario with no consideration of defect (0%); (2) the minimum possible defect rate based on inventory data (20%); (3) the expected overall defect rate in the study forest given observed high frequencies of cryptic stem hollows (40%).

Although the source data originate from a logging experiment comparing RIL to CL, comparing the effect of logging technique on increment is beyond the scope of this paper. In this sense, our study can be characterized as a mensurative rather than a manipulative experiment (as defined by Hurlbert, 1984), and the 24.5-ha RIL and CL monitored forests are treated only as distinct populations.

3. Results

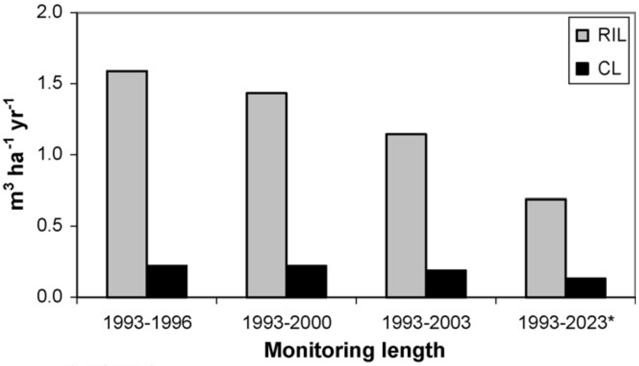
3.1. Forest monitoring length

Increment decreased markedly with each repeated measure. During 1993–1996, increment was 1.59 and 0.22 m^3 ha^{-1} $year^{-1}$ for RIL and CL, respectively. During 1996–2000, increment declined to 1.32 m^3 ha^{-1} $year^{-1}$ for RIL but remained constant for CL. During 2000–2003, increment decreased further to 0.46 and 0.10 m^3 ha^{-1} $year^{-1}$, for the respective treatments. As a consequence, increment was negatively related to the length of forest monitoring (Fig. 1). When increment during 2000–2003 is used as a proxy for increment during the 2003–2023 period, the estimated annual increment over the entire cutting cycle declines from 1.14 and 0.18 m^3 ha^{-1} $year^{-1}$ (based on the average increment during the 10-year post-logging period) to 0.69 and 0.13 m^3 ha^{-1} $year^{-1}$ for RIL and CL, respectively.

3.2. Minimum DBH of measurement

Lowering the minimum DBH of measurement from ≥45 cm to ≥25 cm resulted in higher increments for both RIL and CL (Fig. 2a). This trend was not strong for CL because increment based on trees ≥25 but <45 cm DBH was small (0.01 m^3 ha^{-1} $year^{-1}$). Higher damage rates to residual trees in CL relative to RIL was primarily responsible for this outcome, with damage strongly skewed towards smaller trees (Johns et al., 1996).

Increment is the sum of three elements: I_g (volume gain due to growth by residual trees larger than a given minimum diameter) + I_r (volume gain due to recruitment by trees smaller than the minimum diameter at the time of logging) − I_m (loss of volume due to mortality) (Fig. 2b). Even when increment is restricted to the commercial size class (≥45 cm DBH), annual recruitment into this size class is incorporated into the estimate. However, since I_r exceeds I_g in the commercial size class, increment calculations based on short monitoring periods – the case throughout Amazonia – will only be accurate as an estimate for the full interval between harvests if I_r does not increase substantially over time. Our projections based on trees 25–45 cm DBH from commercial species reveal that a drastic increase in I_r for the remaining 20 years until the second harvest is improbable since the simulated I_r was similar to the observed 10-year I_r (simulated I_r was equal to 0.80 and 0.23 m^3 ha^{-1} $year^{-1}$ for RIL and CL, respectively versus observed 10-year I_r equal to 0.73 and 0.35 m^3 ha^{-1} $year^{-1}$).



* estimated

Fig. 1. Commercial volume increment (m^3 ha^{-1} $year^{-1}$) for trees ≥25 cm DBH by forest monitoring length and logging system (RIL vs. CL). Based on a defect rate of 0%.

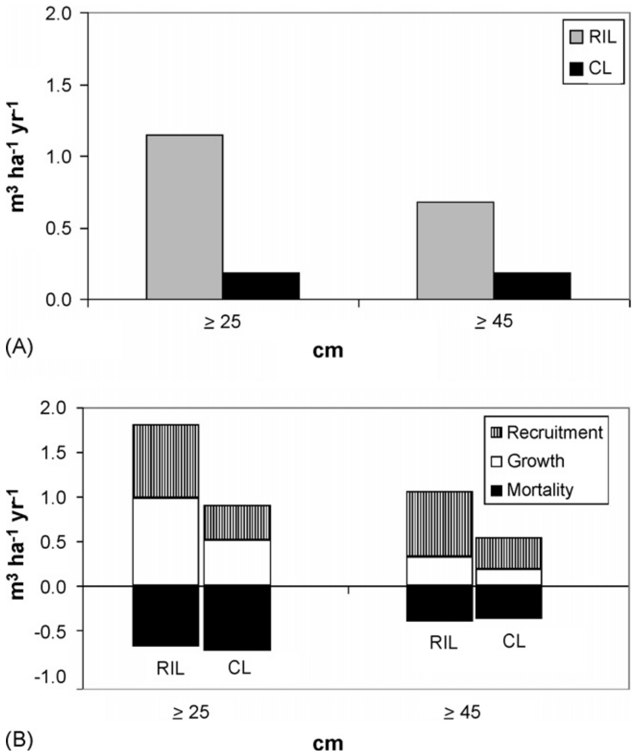


Fig. 2. Commercial volume increment (m^3 ha^{-1} $year^{-1}$) by minimum DBH of measurement and logging system (RIL vs. CL). In (A), increment summarizing growth, recruitment and mortality is shown. In (B), increment shown in (A) is divided into its components (I_g = volume gain due to growth, I_r = volume gain due to recruitment, I_m = volume loss due to mortality). Based on 1993–2003 monitoring interval and a defect rate of 0%.

Finally, diameter growth was lower for trees from commercial species with DBH 25–45 cm (0.42 and 0.31 cm $year^{-1}$ for RIL and CL, respectively) when compared to trees with DBH ≥45 cm (0.49 and 0.33 cm $year^{-1}$ for RIL and CL, respectively). This suggests that the inclusion of a large number of trees from sub-merchantable size classes, even if they are not growing at faster rates, is the main reason for the increase in increment when a lower minimum DBH of measurement is adopted.

3.3. Defective stems

Increment decreases markedly with the elimination of defective trees in both logging systems (Fig. 3). The elimination by defect of a given percentage of trees resulted in an equivalent percentage decrease in increment, as expected since defects were assigned randomly to trees. This result can be arithmetically determined through Eq. (1). If both V_1 and V_2 are multiplied by a given number (D) smaller than one in order to correct for the volume with defect, the resulting increment

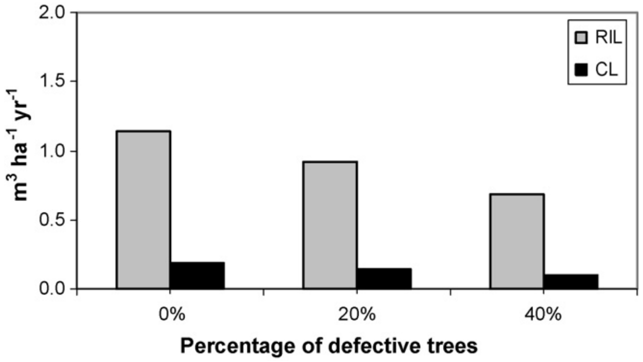


Fig. 3. Commercial volume increment (m^3 ha^{-1} year^{-1}) for trees ≥25 cm DBH by defect rate and logging system (RIL vs. CL). Defect rates were assigned randomly to 0, 20 and 40% of trees. Based on 1993–2003 monitoring interval.

will be equal to the increment calculated without any defect multiplied by *D*.

4. Discussion

Since long-term monitoring data encompassing the entire cutting cycle do not yet exist in Amazonia, current estimation of volume accumulation between harvests must be drawn from short-term measurements of forest response to logging. Increment decreased markedly over time during the first 10 years after logging at the Paragominas site in eastern Amazonia.

A period of severe drought associated with the El Niño-Southern Oscillation (ENSO) occurred in Amazonia in 1997–1998 (Williamson et al., 2000; Schöngart et al., 2004). Negative effects of the ENSO-related drought on tree growth and mortality rates were widely observed (Worbes, 1999; Williamson et al., 2000; Schulze, 2003; Vidal, 2004). In our study area, the 1997–1998 drought suppressed growth in both logged and unlogged forest during the 1996–1998 interval, yet growth in the logged forests continued to decline from 1998–2000 while mean diameter increment in the unlogged forest recovered to pre-1996 values during this period (Vidal, 2004). The ENSO event did not correlate with higher mortality rates in any forest plot. On balance, observed decreases in increment with time since logging appear to be due to post-logging changes in forest structure (e.g., an increase in stand basal area after logging was observed, possibly indicating an increase in competition for growth resources) rather than pervasive climatic factors, and are consistent with post-logging growth patterns observed throughout Amazonia (Silva et al., 1995; de Graaf et al., 1999; de Graaf, 2000; Gourlet-Fleury et al., 2004).

When increment is estimated based on short measurement intervals, projections for 30-year cutting cycles must be adjusted to account for the decline in post-logging increment rates over time. In this study, increment calculated from the most recent measurement interval incorporates this decline to some extent, thus providing a better estimate of increment during the years remaining until the second harvest than would increment calculated from the entire 10-year monitoring period. Clearly this approach is not possible without repeated measures. The method adopted can be considered optimistic in the sense that we implicitly assume that commercial volume increment will not continue to decline with time; rather, the increment between 2003 and 2023 is projected to remain constant and equal to the observed increment between 2000 and 2003. However, even with this optimistic approach, increment during the full cutting cycle might be expected to be lower than currently published increment estimates. On the other hand, this approach attributes a high weight to the last measurement increment. As a consequence, measurement error during the last census period would have a strong influence on increment estimation for the full cutting cycle.

When forest monitoring intervals span less than a decade, they may not capture the decline in growth rate that has generally been observed 8–10 years following logging disturbance (de Graaf et al., 1999; de Graaf, 2000). For example, increment estimated for the 30-year cutting cycle at the Paragominas site using data from 7 years (1993–2000) would still be nearly twice that estimated using data from 10 years (1993–2003). Increasing the length of forest monitoring and the number of repeated measures are both essential to overcome this bias. Currently all logged forest increment data in the Brazilian Amazon are derived from 11 or fewer years of forest monitoring, with the exception of treatment OT1 from Oliveira (2005; Table 1). To our knowledge no attempt has been made to correct for this bias.

Minimum DBH of measurement is a variable with a more subtle effect on increment calculations. Lowering the minimum DBH of measurement results in higher increment estimates. However, increment calculated for trees ≥45 cm DBH implicitly includes trees recruiting annually into this size class, making it unnecessary to lower the minimum DBH of measurement in order to account for trees that will reach the commercial size class by the time of the second harvest. Yet all published increments in the Brazilian Amazon are calculated for trees either ≥10, ≥20, or ≥30 cm DBH (Table 1), potentially overestimating increment.

With this recommendation for applying increment calculations consistent with the size class of interest (i.e., commercial-sized stems), we note one important caveat. Eq. (1) used to calculate increment – summarizing growth, recruitment, and mortality into one number – is particularly vulnerable to changes in recruitment rates over time. However, simulations indicate that we are not underestimating increment at the study site.

Our simulations of different defect rates suggest that exclusion of defective trees should result in a substantial reduction of increment estimates. However, because our simulations assumed that defect rate bears no relation to stem size, growth or mortality rate, doubt remains as to the appropriate defect rate for use in increment calculations. On one hand, evidence that the proportion of hollow trees increases with tree size (Lindenmayer et al., 2000) suggests that the proportion of defective commercial-sized stems in second and subsequent harvests should be lower than in first harvests characterized by high frequency of large and very old trees. On the other hand, RIL protocols for the Amazon currently call for leaving defective stems standing rather than cutting them

(Holmes et al., 2002). The natural consequence of this practice is that most residual commercial-sized trees will be defective and therefore should not be included in increment calculations. Because it is difficult to identify all defective trees without invasive hollow testing (e.g., with a chainsaw), it is therefore difficult to accurately predict the incidence of stem hollows at the time of second harvest based on typical inventory and permanent plot data. However, at a minimum, trees identified before logging as hollow or defective should be removed from increment calculations, as well as trees expected to be rejected during subsequent harvests.

An important assumption in our analysis is that timber markets will remain static, a common assumption in yield projections (e.g., Dauber et al., 2005; van Gardingen et al., 2006). However, it is widely recognized that as transportation infrastructure evolves and high-value species are commercially depleted, many formerly non-commercial stems, rejected at the time of first harvest because the species or bole form were unmerchantable, become commercially viable (Stone, 1998). These changes affect commercial volume increment. For example, previous studies from the Brazilian Amazon have demonstrated the positive impact on increment estimates of expanding the commercial species list (increasing the number of species considered commercial) between first and second harvests (Silva et al., 1995, 1996). The absence of information on how, where and when these changes will occur highlights the importance of monitoring both timber market and forest dynamics when engaging in long-term growth and yield projections.

Our increment calculation – prior to adjustments for declining increment rates over time, the sample minimum DBH (25 cm), and defective stems – falls within the range usually reported for mixed tropical forests (Rice et al., 1998). However, we have identified three biases that, when analyzed separately, lead to overestimation of long-term stand-level increment. When analyzed jointly, their effect on increment estimation is cumulative. Controlling sequentially for each bias resulted in an estimate of commercial volume increment over a 30-year period for RIL and CL, respectively, of 1.14 and 0.18 m^3 ha^{-1} $year^{-1}$ (no correction), 0.69 and 0.13 m^3 ha^{-1} $year^{-1}$ (controlling for monitoring length), 0.32 and 0 m^3 ha^{-1} $year^{-1}$ (controlling for monitoring length and minimum DBH), and 0.19 and 0 m^3 ha^{-1} $year^{-1}$ (controlling for monitoring length, minimum DBH, and defective stems). As a consequence, instead of the original estimated recovery of 93 and 15% of the logged volume in RIL and CL during the first 30-year cutting cycle, the joint effect of the three identified biases reduced estimated recovery to 15 and 0%, which substantially modifies any yield regulation prescription derived from these data (Fig. 4).

These results have important implications for Amazonian forest policy. At a minimum, this study suggests hypotheses regarding potential biases that are easily testable on other datasets. The same factors that produced overestimates in this study may apply to other published volume increments for the Brazilian Amazon. It is likely that overestimates of true increment – related to measurement interval, minimum stem diameter, and defective stems – are the norm.

Three suggestions regarding post-logging forest volume increment follow from these results. First, in the absence of long-term forest monitoring data and modelling tools that can provide long-term estimates for regional forests, it is important to use increment from the last measurement period as a proxy for increment during the remaining years before the second harvest. This would account for the fact that, without silvicultural treatment, increment will tend to decline to the level of unlogged primary forest. Second, commercial volume increment (which already includes recruitment) should be calculated only for the commercial size class (≥45 cm DBH) since this is effectively the population of interest. Finally, defective stems, both those rejected in the first harvest but persisting as commercial-sized trees as well as those expected to be rejected during subsequent harvests, should be discounted from volume increment calculations.

Our evaluation of increment calculation is in no way a critique of this monitoring approach. Indeed, a great deal of knowledge about tropical forest dynamics has been derived from these plots (Sheil and May, 1996). However, yield regulation based on currently published increments will not guarantee sustainable timber production.

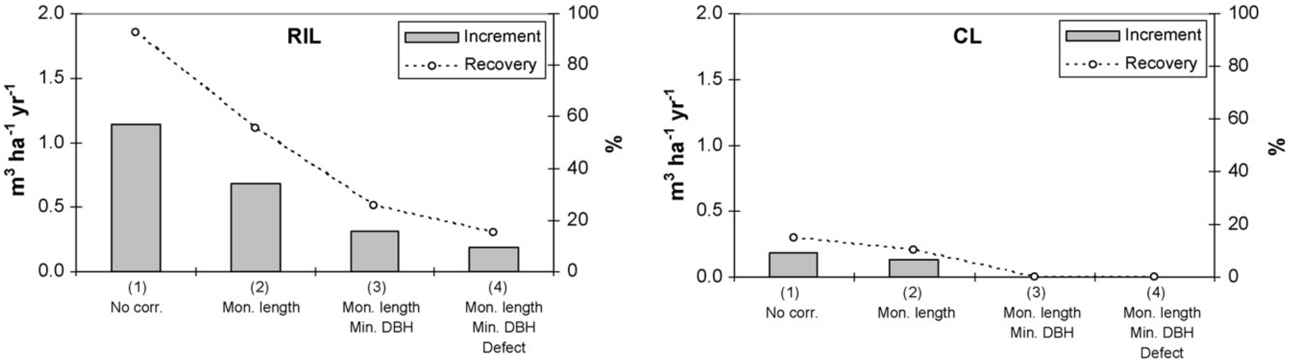


Fig. 4. Commercial volume increment (m^3 ha^{-1} $year^{-1}$) for RIL and CL incorporating biases: (1) No corr. = no correction, commercial trees ≥25 cm DBH during 1993–2003; (2) Mon. length = monitoring length, estimated 30-year increment by trees ≥25 cm DBH adjusted by 2000–2003 increment; (3) Mon. length + Min. DBH = (2) adjusted by minimum DBH of measurement (≥45 cm); (4) Mon. length + Min. DBH + Defect = (3) adjusted by 40% defective stem rate. Logged volume recovery (%) is based on a 30-year cutting cycle and observed logging intensity of 37 and 30 m^3 ha^{-1} for RIL and CL, respectively (Johns et al., 1996).

Acknowledgements

This publication was possible due to the support from the General Administration Office through the Latin America and Caribbean Department of the United States Agency for International Development—USAID, under the terms of the International Cooperation Agreement no. 512-A-00-03-00026-00. The views and opinions expressed are the authors' opinions and do not necessarily reflect United States Agency for International Development official positions. Additional funding was provided by a grant from Projeto Dendrogene (EMBRAPA/DFID), and The Milton and Miriam Handler Foundation. We thank Todd Fredericksen, Ian Thompson, Daniel Zarin and two anonymous reviewers for reviewing this article. This project received logistic support from the Fazenda Agrossete owners, Mr. Pérsio Lima and Mr. Thales Lima. This work would not have been possible without the help of many people in the field. We especially thank Frank Pantoja, Rodney Salomão, Damião Farias, Manuel Farias, Miguel Lopes, Marcelo Galdino de Almeida, Eliana Farias, Manuel Vitorino, Miguel Alves, and Waldemir Ribeiro da Cruz.

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