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What loggers leave behind: Impacts on big-leaf mahogany (*Swietenia macrophylla*) commercial populations and potential for post-logging recovery in the Brazilian Amazon

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Abstract

The sustainability of current harvest practices for high-value Meliaceae can be assessed by quantifying logging intensity and projecting growth and survival by post-logging populations over anticipated intervals between harvests. From 100%-area inventories of big-leaf mahogany (*Swietenia macrophylla*) covering 204 ha or more at eight logged and unlogged forest sites across southern Brazilian Amazonia, we report generally higher landscape-scale densities and smaller population-level mean diameters in eastern forests compared to western forests, where most commercial stocks survive. Density of trees $\geq$20 cm diameter varied by two orders of magnitude and peaked at 1.17 ha^{-1}. Size class frequency distributions appeared unimodal at two high-density sites, but were essentially amodal or flat elsewhere; diameter increment patterns indicate that populations were multi- or all-aged. At two high-density sites, conventional logging removed 93–95% of commercial trees ($\geq$45 cm diameter at the time of logging), illegally eliminated 31–47% of sub-merchantable trees, and targeted trees as small as 20 cm diameter. Projected recovery by commercial stems during 30 years after conventional logging represented 9.9–37.5% of initial densities and was highly dependent on initial logging intensity and size class frequency distributions of commercial trees. We simulated post-logging recovery over the same period at all sites according to the 2003 regulatory framework for mahogany in Brazil, which raised the minimum diameter cutting limit to 60 cm and requires retention during the first harvest of 20% of commercial-sized trees. Recovery during 30 years ranged from approximately 0 to 31% over 20% retention densities at seven of eight sites. At only one site where sub-merchantable trees dominated the population did the simulated density of harvestable stems after 30 years exceed initial commercial densities. These results indicate that 80% harvest intensity will not be sustainable over multiple cutting cycles for most populations without silvicultural interventions ensuring establishment and long-term growth of artificial regeneration to augment depleted natural stocks, including repeated tending of outplanted seedlings. Without improved harvest protocols for mahogany in Brazil as explored in this paper, future commercial supplies of this species as well as other high-value tropical timbers are endangered. Rapid changes in the timber industry and land-use in the Amazon are also significant challenges to sustainable management of mahogany.

Keywords: Diameter increment; Forest inventory; Forest legislation; Logging impacts; Mahogany; Simulated population recovery; Sustainable forest management

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1. Introduction

High-value Meliaceae logged for timber in tropical forests across the globe share distinguishing commercial and ecological characteristics: wood whose excellent working properties are matched by exceptional beauty; natural ranges largely coincident with seasonal forests experiencing rapid anthropogenic conversion to other land uses; low-density populations, typically less than 1 commercial tree ha^{-1}; and life histories generally characterized as non-pioneer late secondary, with fast growth rates, wind- or water-dispersed seeds, and low-density advance seedling regeneration in the forest understory requiring canopy disturbance for optimal seedling growth (Lamb, 1966; Pennington et al., 1981; Swaine and Whitmore, 1988). In the neotropics, true mahoganies – the *Swietenias* – have been commercially logged since the 16th century (Lamb, 1966), along with *Cedrela* and, more recently, *Carapa*. The Central African mahoganies *Entandrophragma* and *Khaya* are the principal timber species fueling the region's current logging boom (Hall et al., 2003). And in southeast Asia and tropical Australia, *Toona* and *Chukrasia* are high-value if low-volume staples of the logging industry.

As with nearly all tropical timber species, little is known about regional and local distribution and density patterns characterizing high-value Meliaceae. This means that little empirical basis exists for evaluating the impacts of logging on commercial populations, or for projecting recovery rates and evaluating the sustainability of current harvest practices. This problem pertains even to big-leaf mahogany (*Swietenia macrophylla*), the most widely studied and exploited of the tropical Meliaceae, whose listing on the Convention on International Trade in Endangered Species of Fauna and Flora (CITES) Appendix II in 2002 requires that international trade involve only legally harvested volumes deemed non-detrimental to its role in the ecosystem (Blundell, 2004; Grogan and Barreto, 2005). The concept of non-detriment is generally understood to mean 'sustainably managed' (CITES, 2003).

Aside from descriptive treatments in Lamb (1966), most of what is known about natural big-leaf mahogany populations (henceforth mahogany) has been inferred from stratified inventories at large spatial scales (RadamBrasil, 1974; Richards, 1991; Valera, 1997; Weaver and Sabido, 1997; Schulze and Whitacre, 1999; Weaver and Bauer, 2000), or from a small number of field studies in fixed plots (Gullison et al., 1996; Snook, 2003). Stratified inventory data may accurately describe density and size class frequency distributions at regional or landscape scales, but provide limited insight into local consequences of selective logging. To our knowledge, field studies describing commercial and sub-commercial populations at spatial scales adequate to evaluate forest management practices have so far been conducted at only a handful of sites across mahogany's vast neotropical range (Snook, 1993; Gullison et al., 1996; Baima, 2001; Grogan, 2001). While conclusions and management recommendations drawn from these studies have frequently been projected onto mahogany populations across its range, in fact little is known nor can be usefully said about populations inhabiting forest types dramatically different from those few described (Lugo, 1999; Brown et al., 2003). In consequence, regulatory policy such as the 2002 CITES Appendix II listing may in part be formulated on the basis of assumptions that do not apply to mahogany across much of its range. Meanwhile forest managers in remote regions may find themselves grappling with mahogany populations very different from those described by scientists, if even the most basic management guidelines for mahogany are available to them in the first place.

In this paper we describe and analyze mahogany commercial populations from 100% inventories in large (204–11,370 ha) fixed plots located in four Brazilian states (Pará, Rondônia, Amazonas, and Acre) across southern Amazonia. We examine geographic variation in density and demographic patterns, and assess the impacts of conventional logging practices (Veríssimo et al., 1995) on commercial populations and future harvests at three sites where mahogany was harvested between 1983 and 1996. We use diameter increment and mortality data collected at long-term research sites to simulate population recovery at each site during 30-year cutting cycles following current harvest regulations for mahogany in Brazil. Our objectives are threefold: (1) to demonstrate the variability in density and demographic structure that forest managers may encounter in the field; (2) to quantify impacts of conventional logging practices on commercial mahogany populations; and (3) to examine how patterns described here may impact population recovery under 'one size fits all' management prescriptions.

2. The study species in Brazil

Mahogany's natural range in Brazil covers an estimated 159 million ha across seasonal forests of the southern Amazon Basin, from the western state of Acre to Tocantins in the east (Lamb, 1966; Martinez et al., in press). Little empirical data exists describing density patterns and size class frequency distributions across this vast area. The RadamBrasil (1974) Amazonian survey detected mahogany at low densities (0.18 trees ha^{-1}) across its natural range in Brazil. Pre-logging densities of 0.3–2.1 trees ha^{-1} $\geq$30 cm diameter have been documented in southeast Pará (Veríssimo et al., 1995). Population densities at three southeast Pará sites in the present study (Table 1A, C, and D) have been previously reported (Baima, 2001; Grogan, 2001; Brown et al., 2003). Grogan (2001) demonstrated essentially amodal mahogany size class frequency distributions for trees >20 cm diameter and concluded, citing also long-term growth and mortality data, that populations in this region were essentially all-aged and regenerating in relatively small treefall gaps along seasonal streams. Even more robust regeneration and recruitment rates were observed by Baima (2001; see also Brown et al., 2003). These reports contrast with uni- or bi-modal size class frequency distributions observed for populations in Mexico (Snook, 1993, 2003) and in Bolivia (Gullison et al., 1996). These authors proposed that mahogany regenerates in even-aged stands after catastrophic disturbances – hurricanes, fires, or floods – occurring at long return intervals at landscape scales.

Table 1
Description of mahogany inventory sites in the Brazilian Amazon

Site	Municipality, state	Location	History of use	Inventory objective[a]	Area (ha)	Minimum diameter (cm)
A. Fazenda Pataua	Marabá, Pará	5°42′S, 48°56′W	Logged 1983	RES	300	20
B. AIXC	Xikrin Indigenous Area, Pará	6°15′S, 50°47′W	Unlogged	FM	1250	30
C. Faz. Mogno II	Agua Azul, Pará	7°06′S, 50°16′W	Logged 1988–96	RES	859	20
D. Marajoara	Pau d'Arco, Pará	7°50′S, 50°16′W	Logged 1992–94	RES/FM	204	20
E. Pinkaití	Kayapó Indigenous Area, Pará	7°41′S, 51°52′W	Ecological reserve	RES	660	20
F. Faz. Imaculada II	Chupinguaia, Rondônia	12°43′S, 61°00′W	Logged partially	FM	1015	20
G. Faz. São Jorge	Sena Madureira, Acre	9°25′S, 68°38′W	Logging proposed	RES/FM	685	20
H. Faz. Seringal Novo Macapá	Lábrea, Amazonas	8°44′S, 68°59′W	Logging proposed	FM	11370	30

[a] RES = research; FM = forest management.

Methodological and theoretical challenges to the catastrophic disturbance hypothesis are presented by Brown et al. (2003).

Mahogany was logged by the conventional or 'predatory' model in Brazil (Uhl and Vieira, 1989; Uhl et al., 1991; Veríssimo et al., 1992, 1995) until widespread illegality and corruption forced the federal government to place a moratorium on its trade in 2001. This led to changes in forest legislation in 2003 setting strict guidelines for harvest operations involving mahogany (Grogan et al., 2002, 2005b). The conventional logging model, under which an estimated 5.7 million m^3 of mahogany sawnwood was produced between 1971 and 1992 (Grogan et al., 2002), was a high-grading or mining operation: all trees large enough to pay their way out of previously unlogged forests were felled and transported on newly opened roads to sawmill processing centers up to 600 km from the forest of origin (Veríssimo et al., 1995). Working at three study sites in southeast Pará, the region where Brazilian mahogany's population density and wood quality were highest, Veríssimo et al. (1995) found that post-logging volumes of trees ≥30 cm diameter were 6% of pre-logging volumes, with trees as small as 36 cm diameter harvested. Zimmerman et al. (2001) reported that a high percentage of mahogany trees >50 cm diameter had been illegally removed from the Kayapó Indigenous Territory's 3 million ha in the same region. Browder (1987) found that mahogany had been commercially extirpated across most of the western state of Rondônia by the mid 1980s. Significant commercial populations survive today only in remote regions of central and western Pará, southern Amazonas, and western Acre, representing a fraction of mahogany's original commercial stock in Brazil (Grogan et al., 2002; Martinez et al., in press).

3. Methods

3.1. Inventories

Large-scale 100%-area inventories for mahogany trees ≥20 cm (or ≥30 cm) diameter were conducted at eight sites across southern Amazonia in Brazil (Table 1). Inventoried areas ranged from 204 to 11,370 ha. In all regions, mahogany's presence was a pre-condition for site selection. Inventory objectives varied by site, focusing on ecological research at three sites, forest management at three sites, and combined basic and applied objectives at the two remaining sites. Three sites had been selectively logged for mahogany 3–14 years prior to inventory. At three previously unlogged sites, inventories were implemented in preparation for eventual logging under new regulatory guidelines for mahogany in Brazil.

All sites were seasonally dry tropical forests, with <2300 mm annual precipitation and a pronounced dry season lasting 2–5 months during which <100 mm of rain falls per month. Topographic relief was gentle at all sites except G (Table 1), where elevation ranged 75 m within the inventoried area with frequent steep slopes. Soil origins and types ranged widely among sites, with coarser, more freely draining, nutrient-poor soils derived from Precambrian Brazilian Shield bedrock typical at eastern sites (A–E) compared to finer, more water-retentive and nutrient-rich soils derived from Andean alluvium at western sites (F–H). At all sites mahogany demonstrated strong positive spatial association with seasonal streams or sub-surface drainage (Baima, 2001; Grogan et al., 2003a; Grogan unpublished data).

Mahogany trees and stumps were located within grids of forest trails cut at 50-m intervals, except at site E where the inventory grid did not cover the entire area. There, inventory data represent cumulative knowledge of the mahogany population gathered during 12 years of extensive research within a core 660-ha research area.

3.2. Density patterns and size class frequency distributions

Inventory data from three logged sites (Table 1A, C and D) combined live trees with stumps reflecting pre-logging diameters. It was therefore necessary to 'reverse grow' live trees by observed diameter increment rates (see Section 3.4 below) over the time period between logging and the first inventory in order to reconstruct pre-logging mahogany size class frequency distributions comparable to those documented at unlogged sites. This process reduced the total number of trees ≥20 cm diameter at sites A, C, and D relative to inventory data by 20, 5, and 7%, respectively, and shifted observed size class frequency distributions slightly towards smaller size classes. The effect at site A was the most marked because the interval between logging and inventory was longest there (14 years). We acknowledge that trees dying during the interval between logging and inventory are a potential source of error in initial frequency distributions presented here, but observed mortality rates (see Section 3.4 below) indicate that this error is small.

To estimate roundwood volumes, but lacking height data for all trees, we used a single-entry equation developed from a robust sample of plantation-grown mahogany trees in Sri Lanka (Mayhew and Newton, 1998):

$$V = 0.056 - 0.01421 * \text{diam} + 0.001036(\text{diam}^2) \quad (1)$$

where diam = diameter at 1.3 m height on the bole.

Density and estimated roundwood volume are summarized for trees ≥20 cm (or ≥30 cm) diameter, ≥45 cm diameter (the minimum commercial size before 2003), and ≥60 cm diameter (minimum commercial size since 2003). Data are presented per 100 ha because forest management operations in the Brazilian Amazon are typically implemented in 100-ha blocks. This unit area is easy to visualize – picture a square 1 km on a side – and permits density measures to represent whole trees rather than fractions thereof.

3.3. Impacts of conventional logging practices

Logging impacts at sites A, C, and D are presented as percentage of trees and estimated roundwood volume harvested per 100 ha.

At site D, some mahogany trees that would have been logged under conventional practices were retained in order to establish a model management project. The site's owner, forest manager, and field crew stated that under conventional practices prevalent across southeastern Pará until the late 1990s, only trees missed by the logging company's *mateiros* (woodsmen responsible for locating merchantable trees in primary forest) would have survived the harvest. These missed survivors were found during post-logging inventories associated with research initiated at the site in 1995 (Grogan, 2001). Because we know of no other 'managed' site east of the Xingu River retaining mahogany trees in this way, we treat this population as logged conventionally – designating retained trees as logged – to illustrate impacts on mahogany populations prevalent across this region. Only 6% of trees ≥20 cm diameter were retained in this way by the logging company and are here treated as logged.

3.4. Post-logging population recovery

3.4.1. Diameter increment and mortality rates

Annualized diameter increment rates were available for surviving trees at logged sites A ($N = 15$, 1999–2001), C ($N = 351$, 1998/1999–2000), and D ($N = 342$ including trees outside the inventory area, 1997–2004). Trees were recensused annually, with measurements taken on the bole at 1.3 m height or at least 30 cm above buttresses where these exceeded 1.3 m height.

Annualized mortality rates, available from sites C ($N = 167$, 1999–2000) and D ($N = 312$, 1997–2005), were calculated according to Sheil et al. (1995):

$$m = 1 - \left(\frac{N_1}{N_0}\right)^{1/t} \quad (2)$$

where N_0 is the number of live stems at time 0 and N_1 is the number of survivors at time t.

3.4.2. Projecting commercial population recovery after conventional logging

Prospects for a second harvest 30 years after conventional logging were assessed at logged sites A, C, and D using observed diameter increment and mortality rates. Thirty years represent the median interval between harvests anticipated under Brazilian forest legislation (25–35 years; Brazil, 2006). Surviving trees were grown at observed increment rates over 30 years to project potential commercial densities and volumes at the time of second harvest. Because short-term post-logging growth rates may over-estimate long-term growth rates due to temporary community-level release associated with forest structural disturbance (Silva et al., 1995, 1996; Poels et al., 1998; De Graaf et al., 1999; Schulze, 2003; Vidal, 2004; Schulze et al., 2005), projections based on available data will likely over- rather than under-estimate long-term diameter growth and volume recovery (Valle et al., 2006).

Mortality was simulated over the first 10 years at observed rates (1.197% year^{-1}, site C; 1.078% year^{-1}, site D), applying the site D mortality rate – the most robust available – at site A for lack of sufficient data there. A more conservative mortality rate of 0.5% was applied during years 10–30, in keeping with current understanding of long-term community-level recovery after logging as above. After removing trees observed to die between recensuses, we assigned mortality by two criteria: trees growing at the slowest increment rates (50%) to cull the weakest individuals, and trees randomly selected from the pool of survivors (50%) to account for stochastic factors causing death.

We assumed that recruitment of new commercial trees (≥60 cm diameter by current regulations) during the first cutting cycle would be possible only by sub-merchantable trees 20–60 cm diameter at the time of first harvest. Mahogany trees 20–60 cm diameter achieving 90th percentile increment rates grew 1.18 cm year^{-1} at site D ($N = 243$, 1997–2004) and 1.17 cm year^{-1} at site C ($N = 351$, 1999–2001), or less than the 1.33 cm year^{-1} necessary for a 19.9-cm tree to reach 60 cm diameter during 30 years. Thirty-year simulations are presented differentiating expected survivors (commercial trees surviving the first cut and subsequent 30 years) from expected recruits (trees growing to commercial size from the 20–60 cm diameter size class).

In these projections and in simulations described below, we do not address recruitment by trees <20 cm diameter at the time of first harvest into sub-merchantable size classes (20–60 cm diameter) because inventories did not include these pole-sized trees.

3.4.3. Simulating commercial population recovery under the 2003 regulatory framework for mahogany

To assess potential long-term impacts of Brazilian legislation regulating mahogany harvests since 2003, we simulated post-logging commercial population recovery at all sites under the new criteria. These stipulate a minimum felling diameter limit of 60 cm; 20% retention rate of commercial-sized trees; and minimum retention density of 5 commercial-sized trees per 100 ha (Brazil, 2003). (For all other timber species, Brazilian forest law stipulates 45 cm diameter minimum felling size and 10% retention rate of commercial-sized trees (Schulze et al., 2005); the minimum diameter felling limit was raised to 50 cm in November 2006.) We randomly selected 80% of trees ≥60 cm diameter for harvest at all sites and applied rules for increment rate and mortality during the first 30-year cutting cycle as described above. At all sites except C, surviving trees were grown over 30 years at increment rates assigned randomly from the pool of observed increment rates by trees at site D in the same 10-cm diameter size class (20–30 cm, 30–40 cm, etc.). The site D mortality rate, the most robust available, was also applied to all sites except C. Site C simulations used diameter increment and mortality rates derived from surviving trees at that site. Each population was resampled 1000 times to account for variation inherent to this method, with median, quartile, and 90th percentile values reported for estimated number of commercial trees and roundwood volume 30 years after the first harvest.

Two additional simulations were performed adjusting retention criteria as follows: (1) retaining the smallest 20% of trees ≥60 cm diameter to account for the expected tendency by loggers to maximize first-cut profits by targeting the largest trees; and (2) retaining the largest 20% of trees to account for expected hollow stems in large trees and to ensure that the most fecund individuals survive the first cut for seed production (Grogan, 2001; Jennings and Baima, 2005).

Commercial population recovery during the first cutting cycle was assessed for all simulations in terms of estimated number of commercial trees ≥60 cm diameter and timber volume per 100 ha. We again assume that recruitment of new commercial trees during the first 30-year cutting cycle would be possible only by sub-merchantable trees 20–60 cm diameter at the time of first harvest. Thirty-year simulations are presented differentiating expected survivors from expected recruits (trees growing to commercial size from 20–60 cm diameter).

4. Results

4.1. Density patterns and size class frequency distributions

Pre-logging landscape-scale densities of mahogany trees ≥20 cm (or ≥30 cm) diameter ranged from 1.4 to 117.7 per 100 ha at eight sites across southern Brazilian Amazonia (Table 2). Commercial densities, whether pre-2003 (≥45 cm diameter) or post-2003 (≥60 cm diameter), ranged from 1.0 to 62.7 and 0.8 to 39.3 per 100 ha, respectively, or considerably lower than 1 tree ha^{-1}. The two highest density sites, C and D, were located in the heart of southeast Pará's famed mahogany belt, a region generally acknowledged by loggers to have harbored Brazil's richest natural stocks. The three lowest density sites – A, B, and H – were located near the northern limits of mahogany's natural range in Brazil (Lamb, 1966; Grogan et al., 2002; Brown et al., 2003; Martinez et al., in press).

Smaller 90th percentile diameters at three of five eastern sites (A–E) compared to western sites (F–H) indicate generally smaller mean diameter at eastern sites, especially those situated within the heart of the southeastern mahogany belt. Site-level density of trees ≥20 cm diameter was a statistically significant predictor of both median and 90th percentile diameters (Table 2; linear regression: $P = 0.0421$ and 0.0272, respectively), with higher density associated with smaller mean diameter. Estimated roundwood volumes mirrored these trends, with mean roundwood volume per commercial tree peaking at sites where population densities were lowest (Table 2B and H). The highest estimated commercial volumes of 276.5 and 252.3 m^3 per 100 ha (pre- and post-2003 commercial diameters, respectively) were recorded at site D, where high density compensated for relatively small average tree size.

Size class frequency distributions demonstrated right-hand skew, or a distributional 'tail' of large-sized trees, at all sites except A (Fig. 1). The two highest density sites, C and D, presented pronounced frequency peaks between 40–50 cm and 60–70 cm diameter, respectively, suggesting uni-modality that other researchers have hypothesized arises from episodic recruitment following catastrophic disturbances occurring at long return intervals (Snook, 1993, 2003; Gullison et al., 1996). Unimodal size class frequency distributions allegedly resulting from catastrophic disturbances require relatively uniform growth rates within size classes and positive correlation between growth rate and stem diameter. However, the wide range of observed diameter increment rates within successive 10-cm size classes at sites C and D was comparable to population-wide variation (Fig. 2), indicating mixed-age size classes. Preliminary data from site G in western Amazonia present similar increment distributions within size classes (Grogan, unpublished data).

As site-level median diameter increased, so did commercial-sized trees ≥60 cm diameter as a percentage of observed populations, with 79 and 81% of inventoried trees exceeding the 2003 commercial limit at sites where median diameters were largest (Table 2A and H; Fig. 1). That is, size class frequency distributions at nearly all sites anticipate dramatic impacts on population structures by logging according to minimum diameter cutting limits. Only at site C did sub-merchantable trees represent more than half (77%) of the inventoried population.

4.2. Impacts of conventional logging practices

Loggers harvested 62.5% of commercial trees at the time of logging (≥45 cm diameter) at low-density site A, and 91% at high-density sites C and D (Table 3; Fig. 1). Ninety-five percent or more of trees ≥60 cm diameter were removed at the latter sites. Trees as small as 20 and 30 cm diameter, considerably smaller than the pre-2003 minimum diameter felling limit of 45 cm, were harvested at sites C and D, respectively; 47 and 31% of trees 20–45 cm diameter were taken illegally at respective sites. Conventional logging practices thus eliminated exceptionally high percentages of

Table 2
Characteristics of mahogany populations at eight sites in the Brazilian Amazon

Site	Diameter (cm):			Density (# per 100 ha):			Percent trees	Volume (m^3 per 100 ha):			m^3/tree with 60 cm
	Median	90th %tile	Maximum	≥20 cm	≥45 cm	≥60 cm	≥60 cm	≥20 cm	≥45 cm	≥60 cm	≥60 cm
A. Fazenda Pataua	104.7	141.6	142.5	6.7	5.3	5.3	79.1	68.7	67.6	67.6	12.8
B. AIXC[a,b]	68.0	241.9	249.5	1.4	1.0	0.8	57.1	16.7	16.4	15.8	19.8
C. Fazenda Mogno II	45.1	68.0	121.0	117.7	62.7	27.4	23.3	233.5	189.2	117.1	4.3
D. Marajoara	65.0	102.0	145.0	65.0	51.0	39.3	60.4	286.5	276.5	252.3	6.4
E. Pinkaití[b]	64.4	117.4	180.9	15.8	11.2	8.3	52.9	83.9	80.8	74.9	9.0
F. Faz. Imaculada II[c]	84.4	133.5	170.6	20.4	16.7	14.6	71.5	147.6	145.1	140.7	9.6
G. Faz. São Jorge[c]	81.5	147.4	215.0	11.8	8.6	8.0	68.0	108.5	106.2	104.9	13.1
H. Faz. Seringal Novo Macapá[a,c]	107.0	176.5	274.0	3.6	3.2	2.9	80.6	47.7	47.4	46.7	16.1

The minimum diameter cutting limit was ≥45 cm before 2003; the limit for mahogany since 2003 has been ≥60 cm. The current minimum harvestable density is 5 commercial-sized (≥60 cm diameter) trees per 100 ha (0.05 ha^{-1}). The last column shows mean estimated roundwood volume (Eq. (1)) per commercial tree at each site.
[a] Minimum inventory diameter = 30 cm.
[b] Sites that will not be logged.
[c] Sites partially logged or proposed for logging.

commercial trees as defined by both pre- and post-2003 minimum diameter cutting limits, and further removed substantial percentages of sub-merchantable trees that should have been retained for future harvests.

Logging impacts were generally higher in terms of estimated roundwood volume because trees with large diameters – those facing higher harvest probabilities – contributed disproportionately to total estimated volumes. At sites C and D, 93–95% of

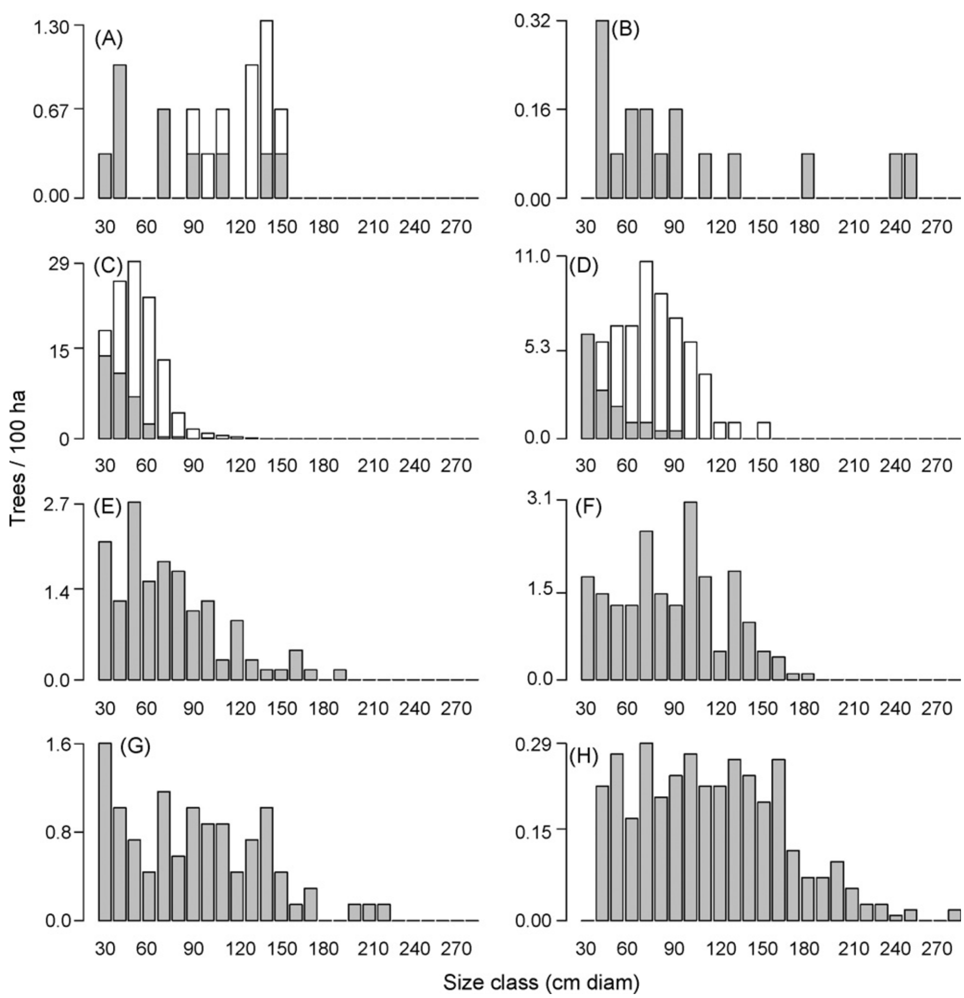

Fig. 1. Mahogany size class frequency distributions by 10-cm size classes at eight sites in the Brazilian Amazon. Panel letters correspond to sites listed in Tables 1–5. Gray columns indicate live trees. In panels A, C, and D, white columns (full or partial) show logged trees. *X*-axis scale indicates the upper limit of a given size class; 30 = 20–30 cm diameter, etc. Note variable *Y*-axis scales.

total estimated volume ≥45 cm diameter was removed by loggers, and nearly 97% of volume ≥60 cm diameter was harvested.

4.3. Post-logging commercial population recovery

4.3.1. Projected commercial population recovery after conventional logging

Projecting observed growth rates by surviving trees over 30 years and subtracting individuals according to mortality rates detailed in Section 3.4., we estimate that commercial densities (currently ≥60 cm diameter) will recover to 9.9–37.5% of pre-logging densities at the three logged sites (Table 4; Fig. 3). The prognosis is best for site A, where initial density was lowest and harvest intensity was lightest; even so, 30 years after logging commercial density is projected to decline from 5.3 to 2.0 trees per 100 ha. Recovery at site C is projected to occur nearly three times as fast as at site D due to the large number of sub-merchantable trees (20–60 cm diameter) surviving the first harvest and growing to commercial size (see recruits, Fig. 3). Projected commercial volume recoveries mirror densities.

4.3.2. Simulated commercial population recovery under the 2003 regulatory framework for mahogany

Harvests of pre-logging populations were simulated for all sites under a minimum diameter cutting limit of 60 cm, randomly selecting 20% of commercial trees for retention, and assigning observed diameter increment and mortality rates from site D to all sites except C, where diameter increment rates were available for surviving trees (Fig. 2b). Median outcomes indicate that second-harvest commercial densities would range from 19 to 51% of first-harvest densities at seven of eight sites under these criteria (Table 5 'Random'; Fig. 4). Only at site C did commercial recovery exceed initial merchantable density (155%). Median outcomes for second-harvest commercial volumes at seven of eight sites ranged from 23 to 50% of first-harvest volumes, again with commercial recovery exceeding initial volumes only at site C (230%).

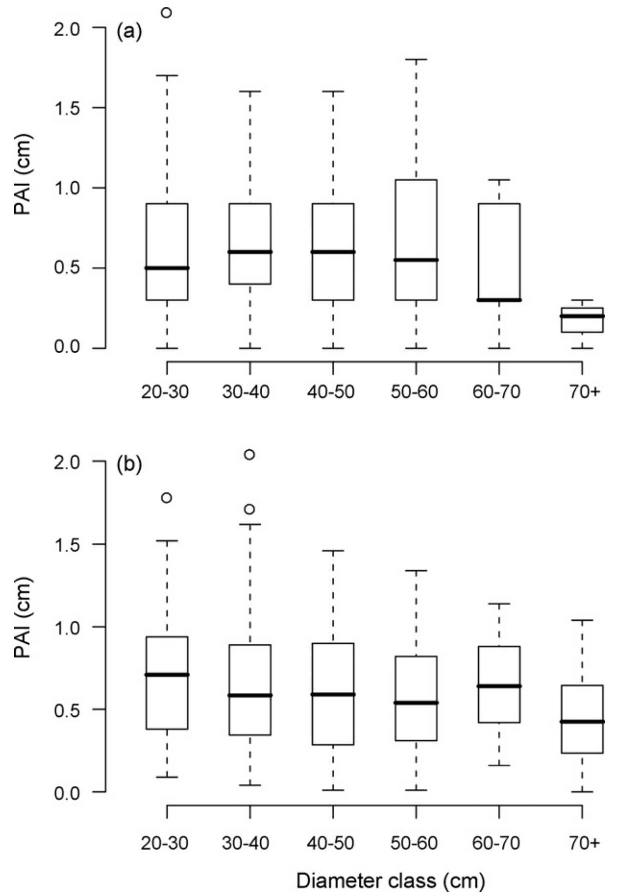

Fig. 2. Observed mahogany diameter increment rates (periodic annual increment, PAI, in cm year^{-1}) by 10-cm size class at (a) site C and (b) site D. Box plots show median values (solid horizontal line), 50th percentile values (box outline), 90th percentile values (whiskers), and outlier values (open circles).

Initial size class frequency distributions strongly influenced simulations. Robust recovery at site C was due to high initial

Table 3
Mahogany harvest intensities under conventional logging practices at three sites in Brazilian Amazonia

Site	Density logged (%)			Volume logged (%)		
	≥20 cm diam	≥45 cm diam	≥60 cm diam	≥20 cm diam	≥45 cm diam	≥60 cm diam
A. Fazenda Pataua	50.0	62.5	62.5	69.2	70.4	70.4
C. Fazenda Mogno II	70.4	90.9	97.0	85.9	92.9	96.9
D. Marajoara	78.4	91.4	95.1	93.4	95.1	96.8

Table 4
Projected 30-year commercial population recovery at three logged sites in terms of number of commercial trees (≥60 cm diameter) and roundwood volume (m^3), based on observed diameter increment and mortality rates

Site	Density (trees per 100 ha)			Volume (m^3 per 100 ha)		
	Harvest			Harvest		
	1st	2nd	% of 1st	1st	2nd	% of 1st
A. Fazenda Pataua	5.3	2.0	37.5	67.6	28.4	42.0
C. Fazenda Mogno II	27.4	7.6	27.6	117.1	31.8	27.2
D. Marajoara	39.3	3.9	9.9	252.3	22.0	8.7

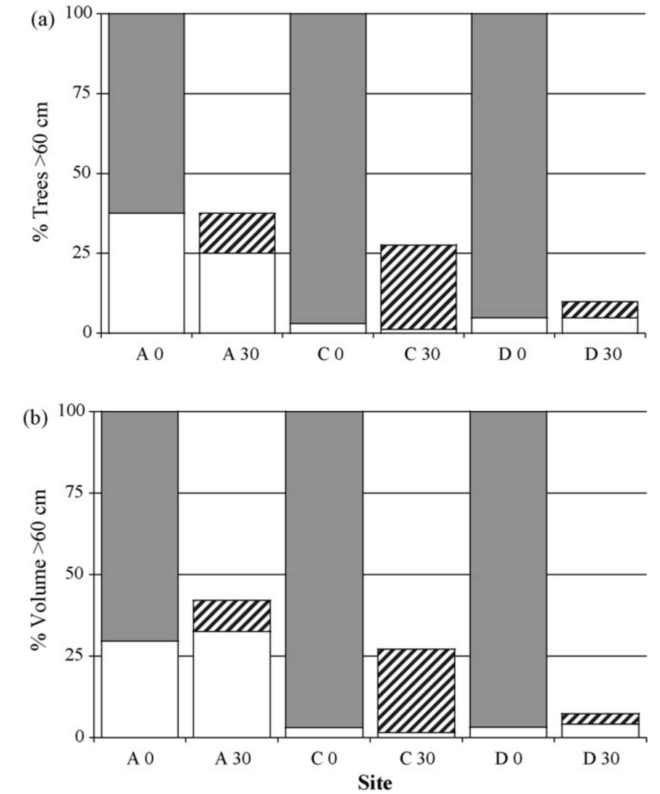

Fig. 3. Logging impacts and projected recovery during 30 years at sites A, C, and D. '0' columns show % surviving the first harvest (white fill) and % logged (gray fill). '30' columns show projected recovery as % of initial (a) densities and (b) volumes, divided into recruits (cross-hatch; trees 20–60 cm diameter at the time of logging growing to commercial size during 30 years) and commercial trees surviving both the first harvest and 30 years of growth (white). See Tables 3 and 4.

densities of sub-merchantable trees (20–60 cm diameter) recruiting to commercial size over the 30-year cutting cycle (Fig. 4). Meanwhile sites where starting densities were low and median diameters were high – A, B, F, G, and H – rebounded

Table 5
Simulated 30-year recovery of commercial-sized mahogany trees (≥60 cm diameter) as % of initial commercial density and volume under three selection criteria: Large = selecting the largest trees for harvest to maximize first harvest profits; Random; and Small = selecting the smallest trees for harvest due to expected hollow boles in large trees and to maximize seed production by larger trees

Site	% Initial density			% Initial volume		
	Selection criteria			Selection criteria		
	Large	Random	Small	Large	Random	Small
A. Fazenda Pataua	25.0	18.8	25.0	16.4	23.0	39.3
B. AIXC[a]	50.0	50.0	50.0	16.2	23.1	73.0
C. Faz. Mogno II	154.9	154.9	153.6	227.1	229.8	235.2
D. Marajoara	46.9	44.4	44.4	44.1	49.7	65.3
E. Pinkaití	54.5	50.9	50.9	37.6	46.5	68.0
F. Faz. Imaculada II	32.4	31.1	30.4	21.5	31.2	46.3
G. Faz. São Jorge	30.9	29.1	29.1	16.7	27.7	46.7
H. Faz. Seringal Novo Macapá[a]	27.4	26.8	27.1	11.2	23.7	44.6

Median values from 1000 replicate runs are shown. See Fig. 5.
[a] Minimum inventory diameter = 30 cm.

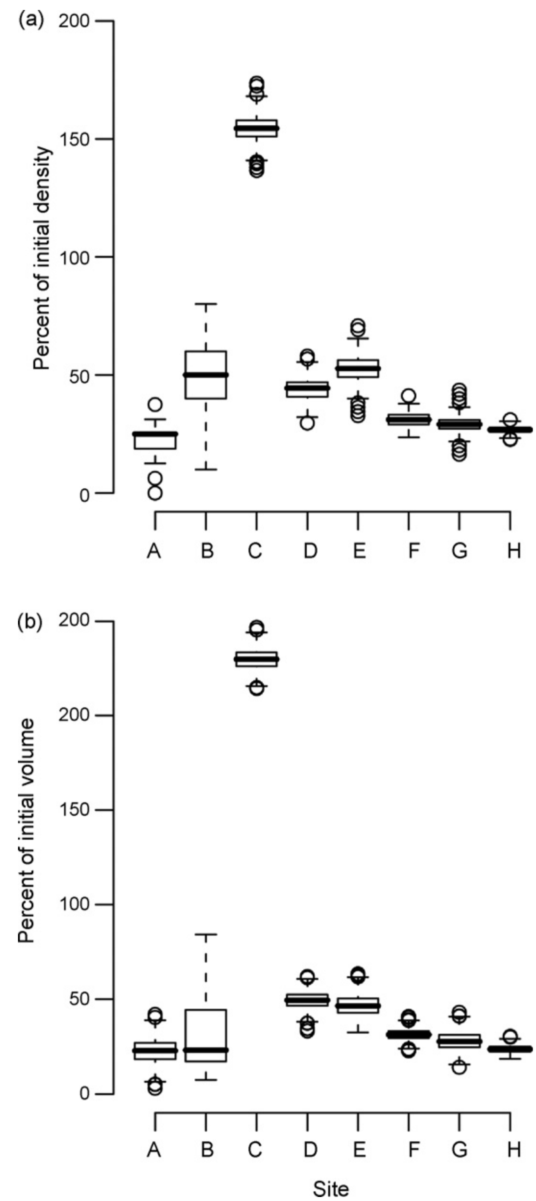

Fig. 4. Simulated mahogany commercial recovery as % of initial commercial (a) density and (b) volume at eight sites (listed in Tables) under Brazil's new regulatory framework for mahogany. Box plots show median simulated values (solid horizontal line), 50th percentile values (box outline), 90th percentile values (whiskers), and outlier values (open circles). Median values for 1000 replicate runs are shown. See Table 5 for values under 'Random'.

slowly at 80% logging intensity, with densities and volumes 30 years after logging estimated to represent only 19–31% of initial densities and volumes (except 50% density at site B; Fig. 4). Subtracting the first-harvest retention rate of 20% from these estimates indicates that real recovery from post-logging densities and volumes can be expected to range from approximately 0 to 30% at seven of eight sites.

The three selection criteria for 20% retention of commercial trees – harvesting the largest trees to maximize first-cut profits, random selection as described above, and retaining the largest trees due to expected hollow boles and for seed production – had little impact on simulated second-harvest densities but major impact on volumes (Table 5 'Large', 'Random', and

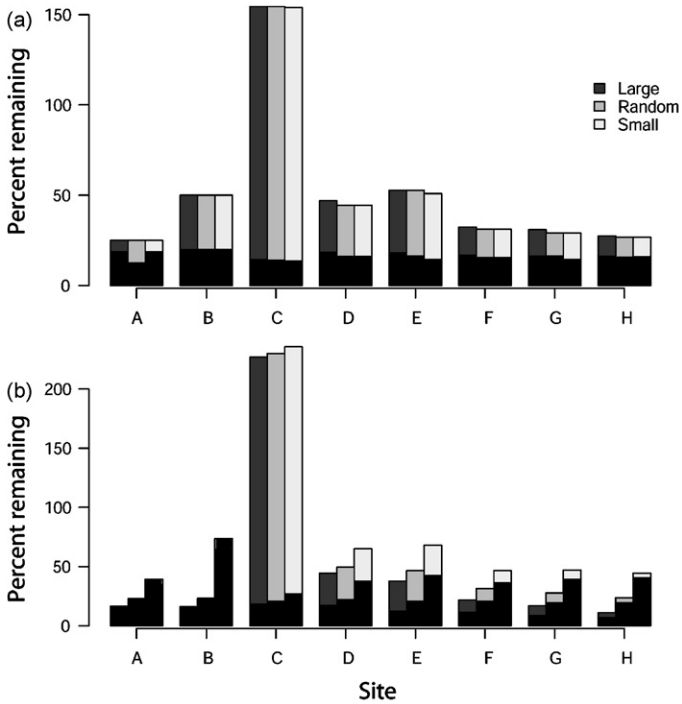

Fig. 5. Simulated mahogany recovery as % of initial commercial (a) density and (b) volume at eight sites (listed in Tables) under three selection criteria: Large = selecting the largest trees for harvest to maximize first harvest profits; Random; and Small = selecting the smallest trees for harvest due to expected hollow boles in large trees and to maximize seed production by larger trees. Black fill at column bases represent trees surviving both the first harvest and 30 years of growth. Median values for 1000 replicate runs are shown. See Table 5.

'Small', respectively; Fig. 5). Consistent density outcomes under these criteria are logical because mortality rates were invariable across simulations. However, removing the largest trees during the first harvest reduced second-cut volume estimates by a factor of four or more at sites where initial populations contained exceptionally large trees (B and H).

5. Discussion

5.1. Density patterns and size class frequency distributions

Compared to natural forest stocking densities reported from sites in Mexico and Central America (Lamb, 1966; Richards, 1991; Valera, 1997; Weaver and Sabido, 1997; Schulze and Whitacre, 1999; Weaver and Bauer, 2000), mahogany occurred at low or extremely low densities at all inventoried sites (Table 2). Even at site C, density barely exceeded 1 tree ha^{-1} for stems $\geq$20 cm diameter. At all sites, trees were aggregated or clumped along the banks of or near seasonal streams; that is, within inventoried areas densities ranged widely within relatively short distances, from nearly 0 up to 5 or more commercial-sized trees ha^{-1} in selected areas at site D, for example. In all regions where inventories were conducted, mahogany's landscape-scale distribution was discontinuous, with extensive forest areas where it did not occur. Based on field visits to mahogany management sites across southern Brazilian Amazonia in addition to those described here, we believe that these data are representative of mahogany densities where it occurred on the landscape, and that reports of average densities up to 1–10 ha^{-1} at regional scales (southern Pará, Rondônia; Barros et al., 1992) over-estimate historic natural stocks in Brazil.

Why were densities highest and mean diameters smallest at two sites (C and D) located in the heart of southeast Pará's mahogany belt? This region is characterized by semi-evergreen transitional forests grading subtly or abruptly into scrub woodlands (*cerradão*) or woodland savannas (*cerrado*) on nutrient-poor, freely draining soils that exacerbate dry season stress on plants. These forests have relatively low and highly irregular canopies subject to frequent small-scale disturbances such as seasonal drought, flooding, and convectional windstorms (Grogan and Galvão, 2006b). These are ideal conditions for mahogany's regeneration and recruitment to adult size in treefall gaps and may help explain relatively high densities observed in this region (Grogan, 2001; Brown et al., 2003). Other high-value timber species such as *Tabebuia serratifolia* (ipê) and *Hymenaea courbaril* (jatobá) also occur at much higher densities while growing to smaller average diameter and height in southeast Pará forests compared to eastern and central Amazonian forests (Schulze, 2003).

Relatively consistent frequency distributions across size classes characterized by right-hand skew (Fig. 1) indicate persistent (if infrequent, considering low densities) recruitment into adult size classes. At two sites where frequency distributions demonstrated apparent modality (Fig. 1C and D), diameter increment rates of individual trees (Fig. 2) were highly variable within all size classes. This suggests multi- or all-aged population structures rather than single-aged populations recruited following landscape-scale catastrophic disturbances occurring at long return intervals (Snook, 1993, 2003; Gullison et al., 1996). Modal size distributions are not in themselves evidence of even-aged populations, as variation in growth or survival between size classes can yield equivalent distributions (Platt et al., 1988; Condit et al., 1998, 2000). Without additional data on individual tree ages and juvenile densities, little else can be inferred about population structures.

5.2. Impacts of conventional logging practices

Logging intensities documented at sites C and D were the norm for mahogany across its range in Brazil before 2003. Minimum diameter cutting limits observed by loggers were determined by harvest costs rather than by forest legislation; mahogany's extraordinary value ensured that trees smaller than the legal minimum cutting diameter were taken, depending on distances to sawmill centers (Veríssimo et al., 1995). Projected 30-year densities and volumes at these sites and at site A, where only 62.5% of commercial-sized trees were logged, demonstrate the importance of initial (pre-logging) size distributions. Where populations were dominated by sub-merchantable trees (site C), post-logging recruitment into the commercial size class (Fig. 3, 'C30') may be robust compared to sites where populations were dominated by commercial-sized trees (Table 2A and D). But after logging intensities reported here, projected 30-year densities and commercial volumes fall far short of starting values. In fact, at two of three logged sites 30-year densities are projected to be lower (2.0–3.9 trees per 100 ha; Table 4) than minimum legally harvestable densities (5 trees per 100 ha), precluding future harvests on this schedule.

We do not address here densities of sub-merchantable trees (20–60 cm diameter) 30 years after logging because recruitment dynamics into this size class remain poorly understood. In our experience, however, a far more pressing issue complicating attempts to manage forests in the Brazilian Amazon or predict future mahogany yields is the absence of long-term forest security. Protecting a forest logged once for mahogany from second and third incursions by loggers seeking secondary timber species – and any high-value mahogany trees surviving the first cut – is almost impossible in remote regions where forest legislation is rarely enforced. Forests logged and supposedly designated as 'management sites' may be bought and re-logged or converted to pasture or agribusiness by new owners. Logged forests are often invaded and converted to small-holder agriculture by landless peasants. And on increasingly fragmented landscapes where forest remnants represent a fraction of remaining land cover, dry season fires frequently spot into heavily logged forests, killing commercial trees including mahogany and further degrading forest structure (Holdsworth and Uhl, 1997; Cochrane and Schulze, 1999). We have worked at other sites where one or more of these fates befell mahogany trees surviving first and even second harvests (Grogan, 2001). Sites C and D have suffered partial burns with extensive tree mortality since we began research activities in the mid 1990s. Site D's legal status is uncertain, and surviving mahogany trees there could be logged in the near future.

5.3. Prospects for future harvests under the 2003 regulatory framework for mahogany

Simulation results must be regarded with caution considering our reliance on diameter increment and mortality rates from site D as proxies for post-logging population dynamics at other sites except C. It is possible, for example, that mahogany growth rates on richer western Amazonian soils (sites F–H) are faster, on average, than in southeastern Pará, and that mortality rates are lower. However, in the absence of long-term site-specific data, we believe that the substitutions and resampling methods employed here offer reasonable approximations of near-term (30-year) dynamics, especially considering the conservative mortality rate (0.5%) applied during years 10–30.

Simulations demonstrate the degree to which post-logging recovery depends on pre-logging size class frequency distributions (Brown et al., 2003; Schulze et al., 2005). Considering these simulations' baseline 20% retention rate, commercial population recovery during 30 years through recruitment by sub-merchantable trees into the commercial size class plus growth by surviving trees was negligible or slow at seven of eight sites. Only at site C, where initial density of sub-merchantable trees was exceptionally high, did second-harvest prospects exceed those of the first harvest. Ignoring for the moment post-logging seedling regeneration and recruitment by pole-sized trees to sub-merchantable and eventually commercial size, current harvest regulations will lead to marked depletion of commercial densities and volumes over anticipated 30-year harvest intervals.

Loggers can be expected to meet retention rate requirements by retaining individuals with the least commercial value: small trees with low volumes, or hollow trees with little or no salvageable value. Adjusting selection criteria to favor retention of the largest trees to account for hollow stems and maximize seed production appears at first glance to ameliorate impacts on second-harvest commercial volumes, which simulations predict could represent 39–73% of initial volumes at seven of eight sites under this scenario (Table 5 'Small'; Fig. 5). The incidence of heartrot or stem decay in mahogany increases with tree size; 68% of trees ≥60 cm diameter surviving conventional logging at site D were hollow to some degree, with 100% of trees >90 cm diameter hollow at the base (Grogan, 2001). Corresponding rates were 48 and 59% at site G in western Amazonia (Grogan, unpublished data). This means that forest managers could select trees for retention based solely on whether they show signs of heartrot – the largest trees nearly always will – and still log many hollow trees hoping to salvage undamaged sections of the upper bole or primary branches (under conventional logging practices, all trees are felled under this premise, even those unlikely to yield commercial volumes). By this selection criterion, estimated second-harvest volumes will be dominated by large hollow trees with little commercial value aside from seed production and as a genetic resource. Thus apparent commercial 'recovery' under this selection criterion may grossly over-estimate commercial volumes in 30 years.

Simulated recovery of commercial mahogany stocks during the first 30-year cutting cycle until the second harvest may tell only half of the story if the rotation period – the time required for mahogany to recruit to commercial size from seed – is 60 years or more (Snook, 1993; Gullison et al., 1996; Grogan, 2001). If pole-sized trees, saplings, and seedlings are present at the time of first logging at sufficient densities to boost commercial densities and volumes during second and third cutting cycles (leading to third and fourth harvests), then current harvest regulations may be sustainable. However, except at site C, where densities of stems <20 cm diameter in heavily logged forest were exceptionally high (Baima, 2001; Brown et al., 2003), we have not observed advance regeneration within seed dispersal distance of adult trees at sufficient densities to ensure long-term population recovery (Grogan et al., 2005a). Post-harvest mahogany seedling densities in logging gaps have been reported to be low (Grogan et al., 2003b, 2005a) to nearly absent in southeast Pará (Veríssimo et al., 1995). Reasons for this include low seed production rates and supra-annual production cycles, dispersal limitations, pre- and post-germination seed mortality factors, and high seedling mortality in the forest understory beneath closed canopies (Grogan and Galvão, 2006a). It is therefore unlikely that prospects for harvests beyond those simulated here will improve without silvicultural interventions at the time of logging, in particular outplanting nursery-grown seedlings into logging gaps with follow-up tending during the years after logging (Lopes et al., this volume).

Finally, simulations reported here further ignore the reality that original (pre-logging) commercial densities of mahogany at two sites (Table 2B and H) are lower than the legal minimum of 5 trees per 100 ha, while at three other sites (A, E, and G) commercial densities are marginally higher than the legal limit. Following current harvest regulations for mahogany, commercial population recovery during 30 years would be sufficient to allow second harvests at only two sites (C and D). Regrettably, recovery at either site is unlikely since both have already been conventionally logged.

6. Management implications

High-density populations like those at sites C and D in southeastern Pará – the most conducive to forest management, given abundant or relatively abundant sub-merchantable stems – were commercially extirpated by the mid 1990s. Commercial stands of mahogany in the Brazilian Amazon survive mostly in the western states of Acre and Amazonas, with remnant intact populations also possibly persisting in central Pará's Terra do Meio, southwestern Pará, and northwestern Mato Grosso (Grogan et al., 2002). Remaining commercial stands are likely to be characterized by low landscape-scale densities and populations dominated by large commercial-sized trees (sites F–H). Similar dramatic reductions in commercial mahogany populations have been documented in Peru and Bolivia (Kometter et al., 2004).

Given this, the new 'one size fits all' harvest protocols for mahogany will yield sharply reduced commercial densities and volumes of mahogany 30 years after logging. Simulated second-harvest volumes presented here mask non-commercial volumes represented by hollow trees and by legal minimum density requirements. More ominously, mahogany's extraordinary value makes protecting trees that have survived logging nearly impossible over timeframes relevant to forest management. We are pessimistic that forests at several sites in the current study will persist long enough for second harvests to occur in the face of wildfires and socioeconomic pressures to convert forests to pasture or agriculture.

The 2003 regulatory framework nevertheless represents significant improvement over conventional practices towards sustainability as required by the 2002 CITES Appendix II listing, so long as its provisions are respected by the logging industry. If retention rates and minimum diameter cutting limits can be enforced, the new framework's most important innovation may be the requirement that artificial regeneration – nursery-grown seedlings – be outplanted into logging gaps and tended during subsequent years to augment low background densities of natural regeneration. Minimum investment in technical extension aimed at improving nursery, outplanting, and tending practices could pay large dividends during third harvests and beyond.

However, management protocols remain ambiguous on key questions such as: (1) Will original (pre-logging) density values determine 20% retention levels in 30 years, or will 80% of commercial-sized trees be harvestable at the time of second harvest even if populations have not recovered to pre-logging densities? (2) Are hollow trees retained for seed tree purposes harvestable after 30 years? (3) At what landscape unit of measurement does the minimum density rule (5 trees per 100 ha) apply, and will this rule be enforced? Whether long-term commercial production can occur or not at present harvest schedules will depend in no small degree on answers to these questions.

Other high-value Meliaceae in the neotropics and Old World face logging pressures similar to those described here under conventional or 'predatory' models, and similar obstacles to population recovery (Valera, 1997; Kageyama, 1998; Hall et al., 2003). The Brazilian regulatory framework for mahogany is the most stringent we have seen for any tropical timber species under active exploitation. More typically in other regions and for other species, retention rules are less strict, minimum diameter cutting limits may be lower, and sub-merchantable trees continue to be logged with impunity (Schulze et al., 2005). Without tightened harvest protocols improving on those for mahogany in Brazil as explored in this paper, future commercial supplies of high-value tropical timbers are endangered.

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