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Evaluating ipê (*Tabebuia*, Bignoniaceae) logging in Amazonia: Sustainable management or catalyst for forest degradation?

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ABSTRACT

Prized for their dense, rot-resistant wood, *Tabebuia impetiginosa* and *T. serratifolia* (vernacular name = ipê) are among the most valuable Amazonian timbers. We analyzed the geographical extent, spread and trajectory of ipê logging in Brazilian Amazonia, and evaluated harvest pressure on this forest resource. We also examine *Tabebuia* population response to reduced-impact logging, a more ecologically benign alternative to destructive conventional harvest practices in Amazonia. Based on eight years of population monitoring at multiple sites in the eastern Brazilian Amazon, we project second harvest ipê yields in forests logged using RIL under legally allowable (90% of commercial stems) and reduced (70%) harvest intensities.

In recent years ipê harvests have declined or ceased in the majority of old logging frontiers in eastern Amazonia while spreading to new logging frontiers in central and southwestern Amazonia. With current timber market prices, transportation infrastructure and harvesting costs, logging of ipê would be profitable in an estimated 63% of the Brazilian Amazon; in the more remote logging frontiers only logging of ipê and a few other high-value timbers is currently profitable. All populations of *T. impetiginosa* and *T. serratifolia* in northeastern forests showed drastic population declines over multiple RIL harvests in simulations, with no indication of population recovery over the long term. We conclude from study of *Tabebuia* populations in eastern Amazonia and modeling of response to logging that these two species are endangered by logging activity and merit additional protection under forest legislation.

1. Introduction

Since the 1980s logging has been an important catalyst for deforestation in many regions of Amazonia. Much of the deforestation along the southern rim of Amazonia has been facilitated by loggers penetrating primary forests in search of sparsely distributed big-leaf mahogany (*Swietenia macrophylla*) trees, in the process providing access to ranchers and

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farmers who transform forests to pasture and farm fields (Veríssimo et al., 1995; Fearnside, 1997; Asner et al., 2005, 2006). Today, mahogany is recognized as a threatened species under Appendix II of the Convention on International Trade in Endangered Species; significant commercial populations of mahogany exist only in remote regions of Amazonia, primarily in the southwest (Grogan et al., 2008). Meanwhile, the logging industry has migrated from the impoverished landscapes along the so-called arc of deforestation to new forest frontiers in central and western Amazonia, pursuing high-value timbers that occur in these regions and are not subject to the legal protections belatedly bestowed upon mahogany. Many of the characteristics rendering mahogany vulnerable to commercial extinction are shared by other high-value timber species in Amazonia (Grogan et al., 2008).

Efforts to transform an uncontrolled and destructive Amazonian logging industry into an engine for sustainable economic development have achieved tangible, if limited, successes: certified ‘well-managed’ forest area has increased to >5 million ha since Forest Stewardship Council (FSC) certification arrived in the region in the 1990s (primarily in Bolivia and Brazil; FSC, 2007); a growing segment of the timber industry has demonstrated interest in reduced-impact logging (RIL) techniques as an economically viable alternative to haphazard conventional or predatory logging; and big-leaf mahogany was listed on Appendix II of the UN-chartered Convention on International Trade in Endangered Species of Fauna and Flora (CITES) in 2002, necessitating more stringent harvest regulations and tighter controls on timber exports (Grogan and Barreto, 2005). This progress notwithstanding, the vast majority (95–98%) of timber harvesting in Amazonia continues to occur by conventional logging that is often a precursor to forest conversion to ranching or farming (Lentini et al., 2003, 2005; Veríssimo and Barreto, 2004). This boom-and-bust exploitation cycle has been well described elsewhere: loggers migrate to new frontiers as timber stocks in historic logging centers dwindle, instigating new cycles of timber mining, forest clearing, and land conflicts in what were previously intact forests on unclaimed public lands (Uhl et al., 1991, 1997; Veríssimo et al., 1992, 1995, 2002a; Grogan et al., 2002; Veríssimo and Barreto, 2004). The pursuit of high-value timber species for export markets drives much of this expansion into heretofore unlogged regions of Amazonia (Veríssimo et al., 1995; Lentini et al., 2005).

Tabebuia (ipê, pronounced “ee-pay”) are the new mahogany. These are prized neotropical timber species whose dense, rot-resistant wood is exported primarily to North America for use in boardwalks and residential decking. Although the commercial name ipê encompasses several *Tabebuia* species, *T. impetiginosa* and *T. serratifolia* comprise the bulk of ipê extraction from Amazonia and are the focus of this study. Widely advertised on websites for outdoor construction materials, ipê is the most common tropical ‘species’ in the $3 billion residential decking market in the US, and its dominance is expected to continue for the near future as restrictions on chemical treatment of woods reduce market share of temperate zone species (Metafore, 2004). Responding to export prices (FOB – Free On Board) ranging from US$ 400 to 500 per m^3 of sawn timber (Lentini et al., 2005), logging companies profitably extract ipê from remote Amazonian regions where timber harvests would not otherwise be feasible. Meanwhile export markets for *Tabebuia* are well developed and growing: there was a 500% increase from 1998 to 2004 in ipê timber exports from the Brazilian Amazon, and ipê accounted for ca. 9% of the total value of wood exports from the Brazilian Amazon in 2004 (Table 1; SECEX, 2005).

Conventional selective logging in the Brazilian Amazon typically resembles a mining operation characterized by poor planning and execution. Over-exploitation of commercial species combined with excessive damages inflicted on forest stands during harvest can compromise future production potential as well as the ecological integrity of logged forests (Johns et al., 1996; Holdsworth and Uhl, 1997; Uhl et al., 1997; Nepstad et al., 1999; Vidal, 2004). Reduced-impact logging practices mitigate forest-level damages and improve operational cost effectiveness through improved inventory and infrastructural planning (Barreto et al., 1998; Boltz et al., 2001; Holmes et al., 2002). Yet even operating under RIL guidelines, loggers can legally harvest up to 90% of commercial-sized individuals of a given species in Brazil on the assumption that future harvests will be supplied by recruitment of today’s sub-merchantable individuals (juvenile and pole-sized trees, saplings, and seedlings) into commercial size classes during proposed 25–35 yr cutting cycles (Brazil, 2006). Poor logging practices and disregard for basic principles of sustained resource use may lead to depletion and regional commercial extinction of desirable timber species, as has been observed for mahogany throughout much of its natural range (Rodan et al., 1992; Veríssimo et al., 1995; Gullison et al., 1996; Snook, 1996; Grogan et al., 2002; Kometter et al., 2004).

In this paper we describe mounting logging pressure on natural *Tabebuia* populations in the Brazilian Legal Amazon. We examine geographical range, density patterns, population dynamics, and prospects for sustained timber yield at current and hypothetical extraction rates for the two most widely distributed and heavily exploited ipês, *T. impetiginosa* (ipê roxo) and *T. serratifolia* (ipê amarelo). We ask: what is the geographical extent and annual rate of *Tabebuia* exploitation in Brazil-

Table 1 – Timber exports in 2004 from eight states comprising the Brazilian Legal Amazon showing the dollar value of ipê exports[a] and the percent of total ipê exports by dollar value

State	Total exports (US$)	Ipê exports[b] (US$)	Ipê % of total
Acre	5,440,552	124,316	2.3
Amapá	42,311,249	–	–
Amazonas	24,139,739	314,467	1.3
Maranhão	12,681,694	208,458	1.6
Mato Grosso	197,596,200	30,857,124	15.6
Pará	543,441,974	31,811,577	5.9
Rondônia	113,456,363	19,496,032	17.2
Roraima	3,660,606	45,618	1.2
Legal Amazon	942,728,377	82,857,592	8.8

a *Source:* SECEX (2005).

b *Tabebuia* are generally not distinguished commercially by species. Although ipê may refer to any species in the genus, *T. impetiginosa* and *T. serratifolia* are the most commonly logged species in Amazonia.

ian Amazonia? Can ipê populations persist in the face of current exploitation rates? Would reduced-impact logging systems adequately manage these species if widely adopted across this vast region? Finally, we consider ipê logging in the context of regional conservation issues, and propose measures that could reduce logging pressure on these valuable species.

2. Methods

The questions above demand synthesis of several data sources. Geographical distribution and abundance patterns across the Amazon are critical to understanding *Tabebuia* ecology, and also inform analyses of current and potential logging pressure. Population structures from large-scale inventories at sites spanning the Brazilian Amazon and multiple-year observations of population dynamics at a subset of these sites allow for projections of *Tabebuia* population response to logging and ipê timber yields under current and potential harvest regulations. Official statistics on Brazilian ipê exports in different years can be used to identify trends in ipê harvests and to generate estimates of the minimum forest area logged annually to supply export volume. Detailed surveys of timber processing centers across the Brazilian Amazon, including production data, timber prices and extraction and transport costs, show trends in geographical patterns of ipê exploitation and are the foundation for models of the profitability of ipê extraction across the Amazon. In combination, these analyses provide a first assessment of the impact logging has had on *Tabebuia* populations, the potential to regulate sustainable ipê harvests, and the relationship between demand for ipê timber and the spread of logging to new forest frontiers. Below, we detail the sources and methods used to acquire and analyze the datasets for each component of this study.

2.1. *Study species*

Tabebuia impetiginosa and *T. serratifolia* occur from Brazil's Atlantic Forest through the core region of Amazonia, into Central America and up to and including areas of Mexico. Both species are canopy emergent trees attaining heights up to 50 m and stem diameters approaching 2 m. Adult morphology and wood anatomy vary markedly across Brazilian Amazonia in response to as yet poorly understood climatic and edaphic factors. Regional populations along the southern and southeastern Amazonian rim tend to be shorter in stature with less desirable timber characteristics. Both species occur at much reduced stature in central Brazilian *cerrado* (savanna), and again as large trees in remnant Atlantic Forest fragments. *T. impetiginosa* is also common in the vast Pantanal wetland straddling Brazil's border with Bolivia (Hasse and Hirooka, 1998).

Both ipês considered here are deciduous species renowned for spectacular floral displays on leafless crowns (purple and yellow for *T. impetiginosa* and *T. serratifolia*, respectively). Seeds are small, winged, and wind-dispersed, produced annually or supra-annually, with limited dispersal range (ca. 150 m; Schulze, 2003). Germination occurs rapidly with the first rains after dispersal; no year-to-year soil storage is possible. Seedlings are light demanding, requiring some level of forest canopy opening for optimal sustained growth. Reproductive ecology and age or stem size at first fruiting are poorly understood for both species. As well, little is known about age- or size-specific growth and mortality rates by natural populations (Gentry, 1992; Justiniano et al., 2000).

2.2. *Distribution and abundance*

Species distributions in the Brazilian Amazon were mapped based on RadamBrasil (1974) plot-level and sub-region-level data plus collection lists from herbaria (Gentry, 1992; MOBOT, 2005; NYBG, 2005). RadamBrasil is an extensive resource inventory conducted in the 1970s by the Brazilian Ministry of Mines and Energy, covering the entire Legal Amazon and including forest tree ($\geqslant$30 cm diameter) inventories in 2,364 1-ha plots. *Tabebuia* density patterns are estimated based on data from RadamBrasil (1974) and Schulze (2003). Overall species ranges were estimated by plotting all RadamBrasil census plots that contained the species and the locations of all herbarium specimen collections in a GIS database (ArcView 3.2; ESRI, 1999). For both species, known locations spanned the entire Brazilian Amazon, although this does not imply that the species are distributed uniformly within the range. Density patterns within the RadamBrasil dataset were used to tentatively demarcate regions of relatively high, medium and low mean densities. The data provide a coarse view of density patterns, but are limited by the relatively small size and number of sample plots.

2.3. *Population structures and dynamics*

Tabebuia population structures were examined in seven large-scale (204–11,370 ha) inventories at sites that span the Brazilian Amazon (Table 2). While all sites receive <2200 mm of rainfall annually and are seasonally dry during 1–6 months of the year, underlying geomorphology and soil physical and chemical properties vary widely among sites (IBGE, 2003; Schulze, 2003; Grogan and Galvão, 2006). As a consequence, forest structure ranges from tall closed evergreen canopies in eastern forests (sites A–C) to tall open evergreen forests in the southwest (E, G), low broken semi-evergreen forest in the southeast (D), and open semi-deciduous forest in Rondônia (F). At two of these sites (F, G), commercial inventories only included stems >30 cm diameter, and all *Tabebuia* species were lumped under the commercial name ipê; these inventories only provide information on the ratio of commercial to sub-merchantable stems available to loggers. At the remaining sites, *Tabebuia impetiginosa* and *T. serratifolia* (and other *Tabebuia* species) were distinguished, and lower minimum inventory diameters (5 cm or 20 cm for site E) yield more complete information on species populations. At the three eastern sites (A–C), stratified subsampling of smaller size classes provided full population structures, from seedling to adult.

Analyses of population dynamics are based on data from study of *Tabebuia* seedlings, juveniles, and adult trees in unlogged and logged forests at four sites in the eastern Amazonian state of Pará (sites A–C and Moju at 2°11′S, 48°49′W). Forest area included in the study totaled 1625 ha (Table 3). At each site, sample populations were censused for growth,

Table 2 – Tabebuia inventory sites in the Brazilian Amazon

Site[a]	Municipality, State	Location	Inventory area (ha)	Species identification	*T. impetiginosa* density (>30 cm ha^{-1})	*T. serratifolia* density (>30 cm ha^{-1})
A. Fazenda Agrosete	Paragominas, Pará	3° 00' S, 47° 20' W	210	Botanical	0.16	0.31
B. Faz. Cauaxi	Goianesia, Pará	3° 40' S, 48° 20' W	1200	Botanical	0.08	0.10
C. Flona Tapajós km 83	Belterra, Pará	3° 04' S, 54° 15' W	400	Botanical	0.19	0.30
D. Marajoara	Pau d'Arco, Pará	7° 50' S, 50° 16' W	204	Botanical	Not present	0.31
E. Faz. São Jorge	Sena Madureira, Acre	9° 25' S, 68° 38' W	685	Botanical	Not present	0.45
F. Faz. Imaculada II	Chupinguaia, Rondônia	12° 43' S, 61° 00' W	1015	Commercial	All ipê spp = 1.14	
G. Faz. Seringal	Líbrea, Amazonas	8° 44' S, 68° 59' W'	11,370	Commercial	All ipê spp = 0.04	

a Sites A–D inventoried for study of timber species population dynamics (Schulze, 2003; Grogan, unpublished); site E inventoried as part of a study on management of *Swietenia macrophylla* (Grogan, unpublished); sites F and G inventoried for a commercial timber operation (R. Oliveira, unpublished).

mortality and recruitment annually for 3-5 yr beginning in 1993, 1996, or 1997 and at supra-annual (bi- or tri-annual) intervals up through 2005. Short-term (2-yr) data from site D were not included in analyses, but were used along with published rates from other studies for comparison of mean *Tabebuia* growth rates recorded across the Amazon.

As part of a larger study of commercial species regeneration, *T. impetiginosa* and *T. serratifolia* seedlings and saplings were inventoried in seven logged, 100-ha forest blocks at sites A–C, with at least 60 felling gaps sampled per block and 1 ha of skid trails per block at sites A and B, for a total of 540 gaps and 5.6 ha of skid trails. In 360 one- to three-yr-old logging gaps, seedling presence and density were compared to adult distributions, and overall seedling density per ha in each harvest block was estimated based on this relationship and the distribution of all logging gaps relative to adults (Schulze, 2003). *Tabebuia* seedlings and saplings were tagged and censused annually for growth and mortality in 480 gaps over a period of 6 yr. Experimental introduction of seeds and seedlings into 29 logging gaps at site B provided additional information on seedling growth rates and mortality. Methods and results of post-logging regeneration studies are detailed elsewhere (Schulze, 2003; Schulze, 2008). Here we use information on *Tabebuia* gap colonization and recruitment to model population recovery following logging.

In the presentation and modeling exercises to follow, densities and population structures of the two species are treated separately, while growth and mortality rates are pooled due to lack of significant differences between species.

2.4. *Modeling population response to logging and volume accumulation*

We constructed projection models of second-harvest potential for *Tabebuia* under best-practices RIL by combining data on population structure and dynamics with observations on gap colonization and recruitment rates (Table 4). At three of four study sites we also collected data on logging intensity and impacts on *Tabebuia* populations. Models were applied to representative populations of each species in 1000-ha management blocks at each site. Starting population structures were derived using means from 200- to 400-ha tree samples and 20- to 40-ha juvenile sub-samples.

First-harvest intensity (year 0 in simulations) was assumed to be either 90% of trees ⩾50 cm diameter or 70% of trees ⩾70 cm diameter, with trees smaller than the chosen minimum felling diameter considered sub-merchantable. The higher harvest intensity and lower minimum felling diameter are typical of *Tabebuia* harvests we have observed in eastern Amazonia, and are consistent with Brazilian regulations stipulating 10% seed tree retention. The lower harvesting intensity and higher minimum felling diameter simulates a biologically realistic alternative to current logging practices, and is similar to the approach taken to regulate harvests of threatened big-leaf mahogany in the Brazilian Amazon and elsewhere (Brazil, 2003; Grogan et al., 2008; Grogan and Schulze, 2008).

Commercially defective trees, those with major stem hollows or poor form, may or may not be logged. In RIL operations, hollow trees are often left standing if little

Table 3 – Total sample sizes for Tabebuia impetiginosa and T. serratifolia at three sites[*] in eastern Amazonia

Size class – forest environment	Sample area[a]	Sample # (*Tabebuia* stems)	
		impetiginosa	*serratifolia*
Trees ⩾10 cm diam – unlogged forest	1000 ha	112	128
Trees ⩾10 cm diam – logged forest	625 ha	40	50
Juveniles[b] – unlogged forest	100 ha	9	12
Juveniles – logged forest	10 ha + 590 logging gaps	139	117
Established seedlings[c] – unlogged forest	75 ha	31	44
Established seedlings – 1–6 yr logged forest	5 ha skid trails + 350 gaps	396	591
Established seedlings – 10–15 yr logged forest	240 logging gaps	9	14
1st year seedlings[d] – unlogged forest	15 crown shadows/sp.	2573	2525
1st year seedlings – logged forest	71 logging gaps	398	3131

[a] Area used for quantitative sample of each stem size class. Juveniles and seedlings were added to growth monitoring as encountered outside quantitative sample plots.

[b] Juveniles are stems ⩾2 cm and <10 cm diameter.

[c] Established seedlings are ⩾50 cm height and <2 cm diameter.

[d] 1st year seedlings are those monitored from germination through the end of the 1st year of growth.

[*] Sites A–C used for study of *Tabebuia* population dynamics.

Table 4 – Observed mortality and growth rates for Tabebuia in unlogged and logged forests in Pará, Brazil[*]

Size class – forest environment	Annual mortality rate	Annual growth rate[a]
Trees ⩾10 cm diameter – unlogged forest	0.7%	0.19 (0.33) ± 0.22
Trees ⩾10 cm diameter – logged forest	2.5% (yr 1–3); 1.3% (yr 3–8)	0.31 (0.47) ± 0.28
Juveniles[b] – unlogged forest	9.2%	0.19 (0.32) ± 0.08
Juveniles – logged forest	6.3%	0.43 (0.60) ± 0.27
Established seedlings[c] – unlogged forest	16.4%	0.09 (0.25) ± 0.03
Established seedlings – 1–6 yr logged forest	11.9%	0.36 (0.56) ± 0.30
Established seedlings – 10–15 yr logged forest	9.7%	0.09 (0.14) ± 0.13
1st year seedlings[d] – unlogged forest	81–97%	0.05 (0.10) ± 0.02
1st year seedlings – logged forest	5–22%	0.43 (0.57) ± 0.23

[a] Diameter growth (cm) reported for all size classes except 1st year seedlings (height growth in meters). Numbers in parentheses are 75th percentile values, ± SD.

[b] Juveniles are stems ⩾2 cm and <10 cm diameter.

[c] Established seedlings are ⩾50 cm height and <2 cm diameter.

[d] 1st year seedlings are those monitored from germination through the end of the 1st year of growth.

[*] Growth and mortality data are from sites A–C.

commercial value is expected. However, for high-value species there remains a strong incentive to fell trees with hollows at the base in the hope of obtaining a sound log near the crown (Grogan et al., 2008). It is therefore unclear whether *Tabebuia* trees are more commonly spared or felled in RIL operations when a hollow is detected at the base. Furthermore, minimum seed tree retention requirements may be met with sound or hollow stems; some forest certifiers explicitly require loggers to designate sound trees, but otherwise this aspect of seed tree retention remains an open question in Brazil. In the first round of projections, we assumed that hollows were as common in *Tabebuia* populations as for commercial trees as a group, that hollow trees were not felled, and that all seed trees were free of defect. Before simulating harvests, we randomly selected 25% of trees ⩾50 cm diameter for removal from harvest consideration due to commercially defective (hollow) stems (Holmes et al., 2002; Gourlet-Fleury et al., 2004; Zweede, personal communication). Lacking comparable data on the rate of defect in sub-merchantable populations, we opted for the conservative approach of assuming all sub-merchantable stems were of good form and free of hollows. Inventories from the study sites have found 12–37% of sub-merchantable stems with obvious defects, with an additional unknown fraction possessing cryptic hollows (i.e., undetectable in inventories) that may compromise merchantability if they reach harvestable size (Valle et al., 2006; Schulze and Vidal, unpublished data; Zweede, personal communication). Thus, all of our second harvest projections likely overestimate timber volume to some degree. In subsequent runs, we tested the effect of alternative assumptions about hollows by simulating harvests in which: (A) hollow trees occurred as above, but seed tree retention rules could be met by designating hollow trees as seed trees; and (B) all *Tabebuia* trees were considered defect free (Supplemental Table 1).

Growth and mortality rates of trees surviving the first harvest were modeled under our best estimate of initially elevated post-logging population-level growth (75th percentile annual diameter increment in forest samples, by life stage) and mortality rates, with growth rates declining after 10 yr to the median observed increment, and tree mortality declining after 3 yr and again after 10 yr (Supplemental Table 2). Projected mortality rates for smaller size classes began with observed rates for each class, with rates changing as the cohort was projected to transition from one size class to the next. These growth and mortality patterns provide the most realistic estimate of post-logging population response given currently available data (Silva et al., 1995, 1996; de Graaf et al., 1999; de Graaf, 2000; Oliveira, 2000; Schulze, 2003; Vidal, 2004; Oliveira, 2005). An additional growth scenario was modeled using optimistic assumptions: applying the mean 75th percentile diameter growth rate ($0.42\,\mathrm{cm\,yr^{-1}}$) throughout the projection period, that is, no decline in growth rate over time (total mortality in smaller size classes was also reduced as trees transitioned between size classes more rapidly).

Our assumption of equal growth rates for all stems in a size class is a deliberate simplification of growth patterns. Tree populations display wide variation in growth rates; thus, our projection likely overestimates transition rates among size classes, while underestimating the growth of outstanding individuals. For purposes of estimating volume and population recovery under legal harvests, we favored simple projections over a more sophisticated model with more assumptions. The high-growth scenario simulates the maximum conceivable growth response, as all individuals are essentially considered outstanding specimens, and therefore captures the most optimistic post-logging recovery outcome.

To project second cutting cycle *Tabebuia* timber yields, 90% and 70% harvestable volume of non-defective commercial-sized adults was calculated after 30 and 60 yr (two possible cutting cycles). Commercial stem volume per diameter size class was estimated using the mean of four volume equations:$V = e^{-7.62812+2.1809 \times \ln(\mathrm{diam})}$ (Silva and Carvalho, 1984); $V = 0.0775 + 0.05179 \times (\mathrm{diam}^2 \times \mathrm{CommHgt})$ (Queiroz, 1984 cited in Rolim et al., 2006); $V = \mathrm{BasalArea} \times \mathrm{CommHgt} \times 0.7$(Heinsdijk and Bastos, 1963; Brown et al., 1989); and $V = 0.5179 \times \left(\frac{D}{100}\right)^2 CH + 0.0775$ (Phillips et al., 2004). We present the total harvestable volume in each scenario, although presumably loggers would be subject to the same retention criteria in the second harvest as in the first, meaning actual harvests would be roughly 10% (or 30%) lower than the harvestable volumes we report.

2.5. *Projecting long-term population recovery*

The recovery of *Tabebuia* populations over the long term will be dependent on regeneration in logged forest stands. Projections of growth and recruitment of existing stems as described above demonstrated that low densities, slow growth, and high mortality of existing juveniles in the forest understory result in extremely low recruitment rates to adult size. We assume seedling recruitment to be largely restricted to logging gaps and other disturbed zones within the 100-ha management block (11% of total area). This assumption is based on recorded first-year mortality rates of 90% for seedlings establishing in the understory (with 4-yr mortality of 100% for shaded seedlings; Schulze, 2003). Stems recruiting in logging gaps and other disturbed sites will thus be largely responsible for the eventual completion of a harvest rotation, and for the long-term persistence of *Tabebuia* populations subjected to logging. This recruitment in logging gaps will take longer than the 30- and 60-yr periods relevant to second harvest projections, and therefore was modeled separately from volume recovery.

Three estimates of the time required for seedlings to recruit to commercial size were made by applying the following growth rates observed in logging gaps during 6 yr following harvest: (1) mean growth rate of all *Tabebuia* stems; (2) 90th percentile growth rate; and (3) maximum observed growth rate. Projections of stem sizes at year 15 were also compared to observed sizes of *Tabebuia* stems in 15-yr-old logging gaps. Projections of the number of stems surviving to commercial size in a typical 100-ha management block were then made by applying observed annual mortality rates to three estimates of total seedling number per block based on: (1) overall mean density per hectare; (2) lower 95% confidence interval of mean density; and (3) upper 95% confidence interval of mean density. Observed gap mortality rates were applied for 10, 20 and 30 yr before assuming that rates dropped to those observed for adult *Tabebuia* trees.

2.6. *Exploitation rates and regional logging pressure*

The total ipê roundwood harvest for export in 2004 was estimated by converting reported export weight (158,628,644 kg; SECEX, 2005) to export volume at $850\text{-}1050\,\mathrm{kg\,m^{-3}}$ (Souza et al., 1997; Loureiro et al., 2000). Conversion of export volume to harvested roundwood volume was based on 42% processing efficiency and 36% of processed wood meeting export standards (Lentini et al., 2003, 2005; Sobral, personal communication).

The forest area required to meet this export demand was estimated by dividing per hectare ipê yield into estimated total roundwood harvest volume. Yield per hectare was determined based on estimates of 0.34 commercial-sized trees of *Tabebuia* per hectare (RadamBrasil, 1974); the percentage of commercial-sized trees without defects (50–80%; Holmes et al., 2002; Grogan and Schulze, 2008; Zweede, unpublished data); and 5.3–7.8 $\mathrm{m^3}$ of roundwood volume per harvested tree (diameter- and height-based volume equations as above; diameter distributions and tree heights from this study and Schulze (2003)).

Economic feasibility of *Tabebuia* extraction at regional scales – that is, the extent of their natural ranges that can be profitably logged through conventional selective high-grading – was inferred from spatial models of the economic accessibility of logging in the Brazilian Amazon (Stone, 1998; Veríssimo et al., 1998; Lentini, 2007). These models estimate the feasibility of timber extraction based on prices of logs processed in sawmills subtracting transportation, logging, transaction costs for harvesting activities, and a minimum profit level that loggers will impose over the log price. During modeling procedures, an algorithm developed in a GIS environment (ArcView 3.2a) estimates that a given forest cell is feasible for logging if the difference between logwood prices (at the urban centers where milling occurs) and the costs described above is greater than or equal to zero. Logwood prices for ipê were estimated in 2004 as US$ 42.5 per $\mathrm{m^3}$ on average, ranging from US$ 29 to 73 depending on the region within Amazonia (standard deviation US$ 28.9). Harvesting costs varied between US$ 9.0 and US$ 13.7 per $\mathrm{m^3}$ depending on the region, and transaction costs were assumed to be fixed and equal to US$ 3.9 per m^3 (Barreto, 2002). Minimum profit levels in logging activity were assumed to be 10%, based on an extensive survey carried out in Pará State in 1998 by Veríssimo et al. (2002b). Transportation costs between milling centers and harvestable forests are highly variable in the Amazon, depending on the type of log transport surface (rivers, roads) and extant infrastructure in each region. Modeling accounted for different costs depending on the quality of roads in each region, including expected costs of the construction of new roads to access valuable timber (more details are given in Lentini (2007)). The location of milling centers harvesting *Tabebuia* in 2004 and the economic data used in the modeling were collected in an extensive survey conducted in 143 milling localities (Lentini et al., 2005).

3. Results

3.1. Geographic range and abundance

Both *Tabebuia* are widely distributed across the Brazilian Amazon, typically co-existing within a given region or forest. Both species generally occur at low densities; in the extensive RadamBrasil (1974) forest inventory, average density of trees $\geqslant$30 cm diameter in regions where *Tabebuia* were present was 0.11 and 0.32 trees ha^{-1} for *T. impetiginosa* and *T. serratifolia*, respectively (Fig. 1). Both species occurred at relatively high-density compared to the overall species-level density in RadamBrasil plots in transitional forests of south and southwestern Brazilian Amazonia (Fig. 1). This pattern is supported by Bolivian forest inventory data in which these two species occurred at relatively high densities (mean of 2.5 and 0.45 trees ha^{-1} for *T. impetiginosa* and *T. serratifolia*, respectively; Justiniano et al., 2000). In the large-scale inventories at sites A–G, *Tabebuia* species were present at low densities similar to those found in the RadamBrasil survey, with *T. serratifolia* occurring at highest density at site E in the western state of Acre (Table 2).

3.2. Population structure and dynamics

The frequency distribution of stem diameter size classes, from pole-sized juveniles to large adults, determines timber yields during first and second harvests. Sub-merchantable trees plus commercial-sized trees ($\geqslant$50 cm diameter) surviving the first harvest must comprise the second harvest commonly anticipated after 30 yr of growth. *Tabebuia* population structures in the northeastern Amazon are typically unbalanced towards large diameter size classes, with commercial-sized trees equal to or outnumbering sub-merchantable trees ($\geqslant$20 cm diameter) in six of 10 populations (Fig. 2). In transitional forests in southeastern and southwestern Amazonia (sites D and E), *T. serratifolia* attains a smaller maximum adult size and has a higher ratio of sub-merchantable to commercial stems.

The rate at which sub-merchantable trees achieve harvestable size is determined by growth capacity and environmental conditions. Mean growth rates for all diameter size classes of *Tabebuia* are low in both unlogged and logged forests (Table 4 and Supplemental Fig. 1). Sub-merchantable *Tabebuia* trees growing at 90th percentile rates in unlogged and recently logged forests achieve diameter increments of 0.49 and 0.70 cm yr^{-1}, respectively. That is, only sub-merchantable trees of at least 20 cm diameter can achieve commercial size during anticipated 30-yr intervals between harvests. Nine out of ten stems will grow slower than these optimal rates.

While observed mortality rates by *Tabebuia* are low (<1% annually) compared to other tropical timber species, post-logging mortality by surviving trees increases to 2.5% due to stem damage and crown exposure to storm winds (Table 4; Schulze and Zweede, 2006). If mortality rates decline to normal within 10 yr of logging, approximately 28% of surviving trees can be expected to die during anticipated 30-yr intervals between harvests.

Timber production beyond the second harvest will depend on seed production by surviving trees and seedling growth through sub-merchantable to commercial stem size classes. Advance seedling regeneration is rarely present in the forest understory at the time of first harvest due to low growth and high mortality rates in closed forest (Table 4). Height growth rates by *Tabebuia* seedlings in logging gaps are also low (24 ± 15 cm yr^{-1}; ± values indicate SD throughout the text). Even seedlings growing at 90th percentile rates increased heights by only 1 m yr^{-1}. Five years after logging gaps were opened in eastern Amazonia, 90% of seedlings remained in the lower strata of gap vegetation, shaded by faster growing pioneer species (Schulze, 2003).

3.3. Harvest projections: post-logging recovery

After removing 90% of commercial-sized adults in the first harvest – currently allowable under Brazilian forest legislation – commercial volume would not recover to pre-harvest levels within 60 yr under all model scenarios (Table 5). Even under the rapid growth projection, at least 60 yr would be required for an equivalent volume to be extracted in the second harvest. If harvest intensity were restricted to only 70% of harvestable trees and the minimum felling diameter were raised to 70 cm, populations would require less time to recover wood volume, although 30 yr (the cutting cycle widely assumed to be sustainable for Amazonian forests harvested using RIL) would not be sufficiently long to ensure an equivalent harvest of *T. impetiginosa* during the second cut (Table 5).

Assumptions about the defect rate in commercial populations affected total harvestable volume in both the first and second harvest, but did not substantively alter estimates of percent volume recovery between first and second harvests (Supplemental Fig. 2). When all commercial trees were considered sound under the Brazilian regulation scenario (10% retention rate), harvestable volume at year 30 was <21% of first-harvest volume at each of the three sites for both *Tabebuia* species. A similar lack of substantive differences between no-defect and defect projections was observed under all combinations of growth (probable, fast) and harvest (Brazilian legal standard, restricted harvest) scenarios.

In contrast, allowing loggers to meet seed tree retention requirements with defective trees increased projected first-harvest volume and value but reduced second-harvest prospects (Supplemental Fig. 3). This result highlights the large contribution that seed trees retained during the first harvest

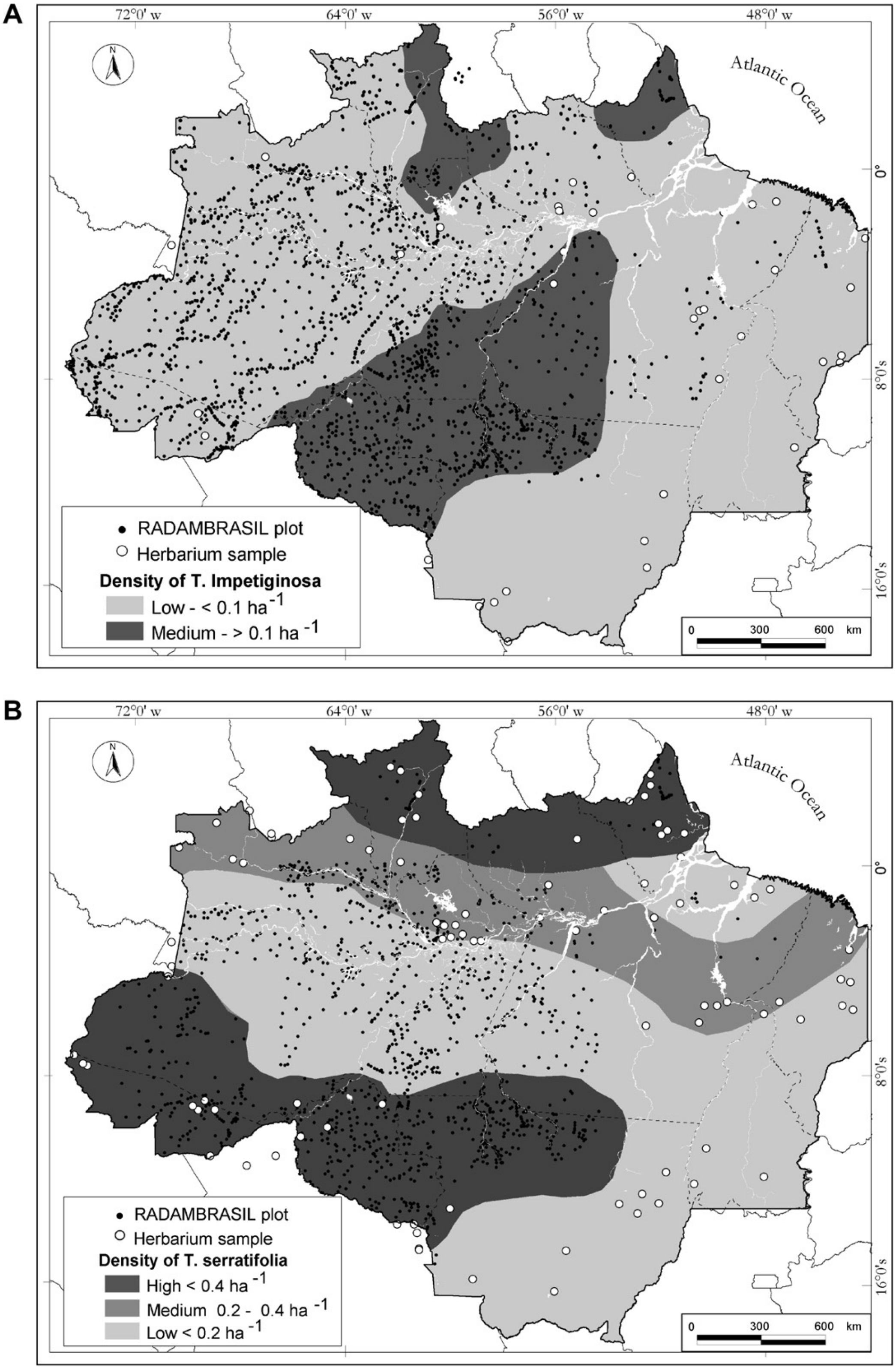

Fig. 1 – Ranges and relative densities of (A) *Tabebuia impetiginosa* and (B) *T. serratifolia* in the Brazilian Legal Amazon. White points represent locations of herbarium collections and black points RadamBrasil inventory samples recording the species.

make to second-harvest volumes; that is, much of the projected second-harvest ipê volume results from this deferred harvest rather than from population recovery. For example, an average of 59% (92.9 m^3 per 1000 ha) of the second *T. serratifolia* harvest in the default scenario (Brazil regulations, probable growth, 25% defect rate, sound seed trees)

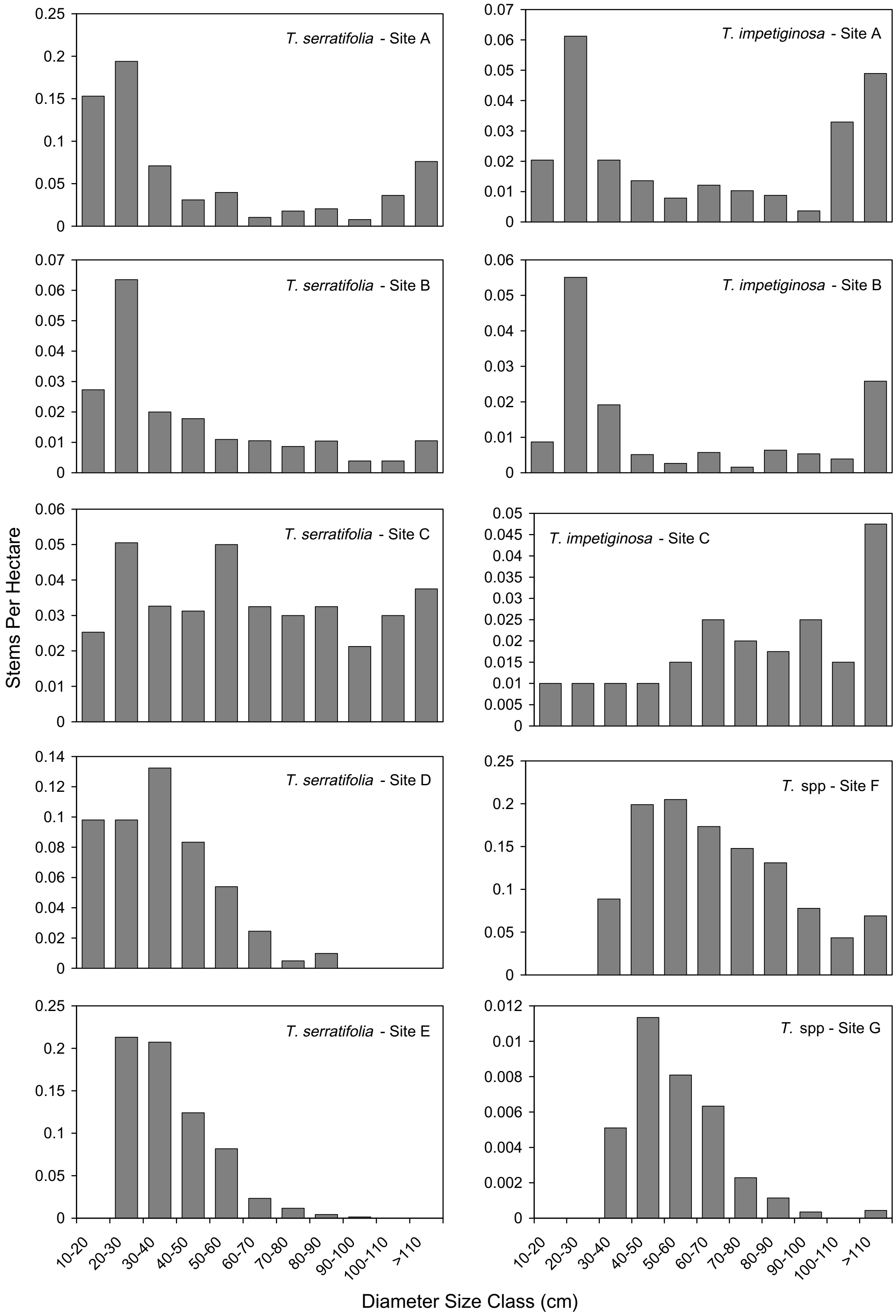

Fig. 2 – Timber species population structures by stem size class intervals, means from seven sites in the Brazilian Amazon.

is furnished by first-harvest seed trees that survive to the second cut. When loggers avoid deferring this harvest by designating commercially defective stems as seed trees, projected second-harvest volumes fall to as low as 2% of first harvest volumes (range 2–3% for *T. impetiginosa*, 4–12% for *T. serratifolia*). However, given higher net present values under 'defective seed tree' scenarios (Supplemental Fig. 2), there will be a strong financial incentive to avoid reserving

Table 5 – Estimated timber volume available from commercial-sized trees of Tabebuia impetiginosa and T. serratifolia at second harvest as a percent of the volume extracted during the first harvest at sites in eastern Amazonia

	Harvest intensity (%)	Minimum felling diameter (cm)	Years after 1st harvest	% First-harvest volume at estimated growth rates	
				Probable (%)	Fast (%)
T. impetiginosa	90[a]	50	30	12.4–13.6[b]	12.9–14.3
			60	12.6–15.9	16.6–35.9
	70[c]	70	30	43.1–49.9	43.8–51.3
			60	40.3–49.3	48.9–62.0
T. serratifolia	90	50	30	15.2–24.1	16.5–26.2
			60	18.5–29.8	29.3–63.7
	70	70	30	41.9–57.3	43.5–60.2
			60	42.8–61.7	58.4–99.0

Based on observed initial population structures, and estimated growth and mortality rates of trees ⩾10 cm diameter and juveniles ⩾50 cm tall.

a Estimated first-harvest volume extracted at 90% rate varied by site from 357 to 832 m^3 per 1000 ha for *T. impetiginosa* and 269 to 1270 m^3 per 1000 ha for *T. serratifolia*.

b Estimates were calculated for each site separately and are presented here as ranges.

c Estimated first-harvest volume extracted at 70% rate varied by site from 263 to 654 m^3 per 1000 ha for *T. impetiginosa* and 174 to 913 m^3 per 1000 ha for *T. serratifolia*.

commercially sound seed trees, to the extent that this is legally or technically feasible.

3.4. *Regeneration and population recovery*

Observed *Tabebuia* regeneration following logging at study sites in eastern Amazonia was patchy, with low overall seedling and sapling densities in the high-light disturbed zones within logged forest (5.7 ± 3.8 stems ha^{-1}). Only at the highest observed seedling densities and the lowest possible mortality rates would a sufficient number of stems survive post-logging gap succession to eventually yield densities of at least three commercial-sized trees per 100 ha (Fig. 3a), the minimum density necessary to allow harvest under current regulations (Brazil, 2006). This population-level recovery through seedling recruitment to commercial size classes would require approximately 100 yr (Fig. 3b).

3.5. *Exploitation rates and regional harvest pressure*

Based on Brazilian government data tracking timber exports (SECEX, 2005), we estimate that 1,104,000 m^3 of ipê roundwood were harvested in 2004 to generate 167,000 m^3 of export-grade timber. These estimates are comparable to mahogany volumes extracted from Brazilian Amazonia during the 'mahogany rush' of the late 1980s and early 1990s (Browder, 1987; Veríssimo et al., 1995; Grogan et al., 2002). At landscape-scale densities recorded by RadamBrasil (1974) and Schulze (2003), approximately 649,000 ha of forest were selectively logged in 2004 to meet this export total (assuming a defect rate of 25%, mean values of 6.6 m^3 $tree^{-1}$ harvested, and 950 kg m^{-3}; minimum and maximum area estimates derived from extremes of these three values were 373,000 and 1,354,000 ha, respectively). This estimated forest area represents ca. 40% of the total forest area logged annually in Brazilian Amazonia (Nepstad et al., 1999; Asner et al., 2005).

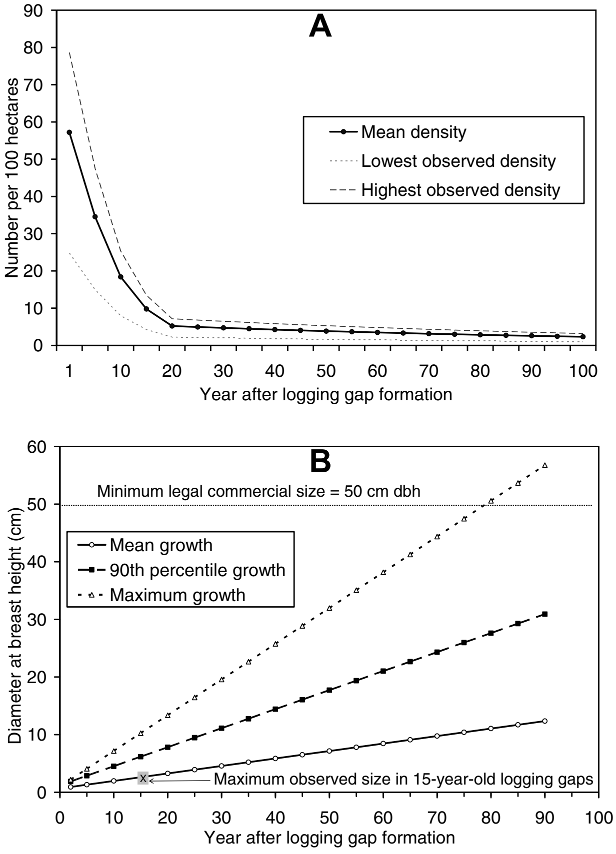

Fig. 3 – Projection of *Tabebuia* (A) survival and (B) recruitment in logging gaps based on observed sizes, densities, growth and mortality in 2-year-old logging gaps in RIL stands at three sites (A–C) in Pará, Brazil. The X in (B) represents the maximum observed size of a *Tabebuia* sapling observed in a survey of 180 15-year-old logging gaps.

Sawmill surveys in 2004 revealed that ipê timber was being extracted from 93 of the 143 milling localities in Amazonia, while most timber processing centers where ipê logging was not recorded (41 of 50) were located in old frontier areas of eastern Pará and north-central Mato Grosso (Fig. 4). Of these 50 milling localities, 80% were still producing ipê timber in 1998, suggesting that by 2004 ipê was exhausted in these regions. With few exceptions, ipê timber was an important product in the western logging frontiers in 2004. Sawmill surveys indicate a wave of ipê logging moving from the original eastern logging centers west into more remote regions over time. Where access and infrastructure are poor and the pool of harvest species restricted, ipê species dominate selective harvests. In well-developed logging centers with large species lists, ipê is absent from or a small component of harvests.

Ipê's role as a critical resource in new logging frontiers is predicted by models of logging profitability. Even though *Tabebuia* occur at extremely low densities, these species can be extracted profitably from all but the remotest 36% of Brazilian Amazonia, corresponding to approximately 178 million km^2 (Fig. 4). Over most of the Amazon, economic barriers are now insufficient to prevent pursuit of new sources of high-value ipê timber to replace dwindling production in old sawmill centers.

4. Discussion

Tabebuia impetiginosa and *T. serratifolia* populations in the Amazon present considerable challenges for sustainable management. Both species generally occur at densities much lower than shade-tolerant timber species such as *Manilkara huberi* (Schulze et al., 2005), and as low as the threatened mahogany (0.18 trees ha^{-1} in RadamBrasil (1974)). Moreover, population structures are weighted towards large, very old adults, meaning relatively few young trees are present in stands. This pattern is typical for light-demanding long-lived timber species in the Amazon, including mahogany (Gullison et al., 1996; Jennings et al., 2001; Grogan et al., 2002), and is frequently cited as a major limitation for sustainable timber production (e.g., Fredericksen and Putz, 2003). In the case of *Tabebuia*, unfavorable population distribution patterns are compounded by slow median and maximum growth rates. Thus, in many Amazonian forests, ipê presents a 'perfect storm' of unfavorable ecological characteristics from the perspective of the forest manager concerned with sustained timber production.

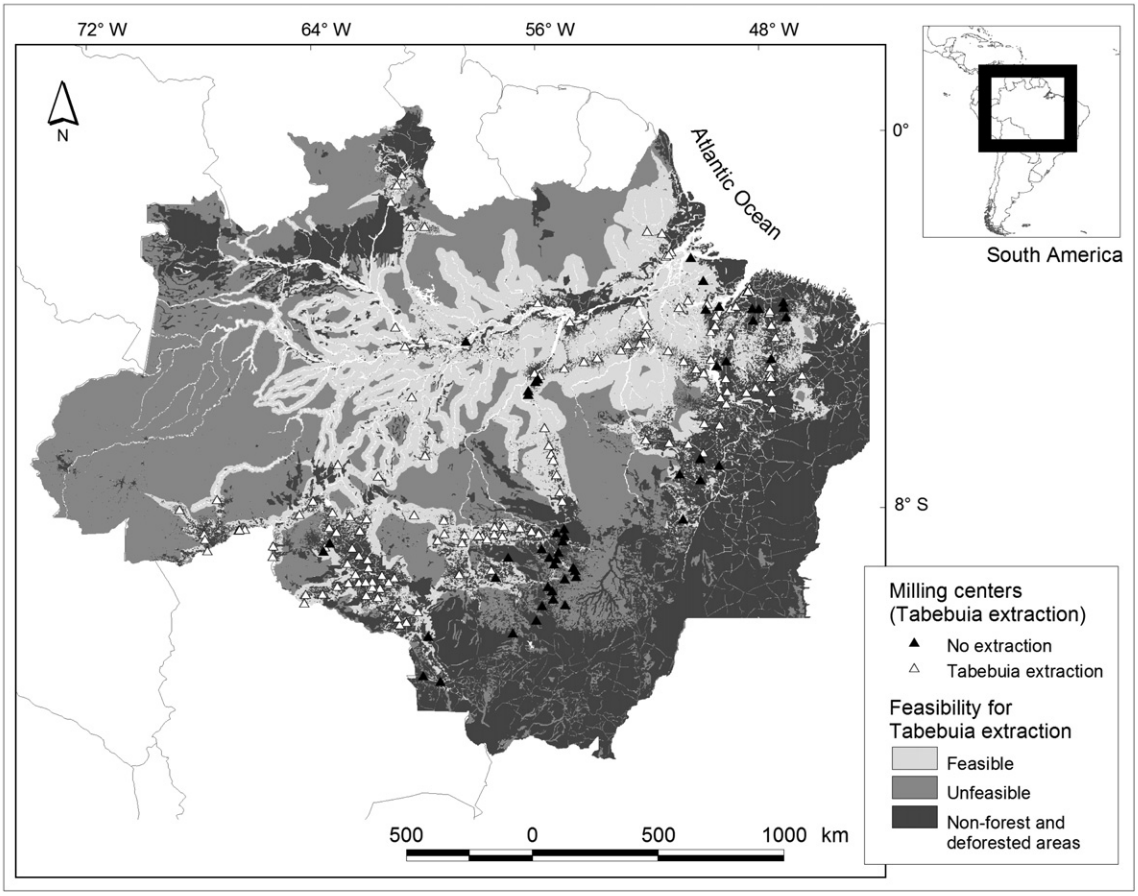

Fig. 4 – Map of the Brazilian Legal Amazon showing urban centers processing (white triangles) and not processing (black triangles) ipê timber in 2004. The majority (80%) of the milling centers not processing ipê in that year, all located closer to the eastern and southern borders of Amazonia, were processing ipê timber in 1998. The map also shows areas where the extraction of ipê species is profitable based on prices of sawn ipê timber and transportation costs between forests and logging centers. Medium gray areas represent regions where transport limitations currently render extraction of ipê timber unprofitable. Although the ranges of *Tabebuia impetiginosa* and *T. serratifolia* encompass the entire Legal Amazon, these species are not present in all forests in the region and understanding of species' distribution patterns remains limited.

4.1. *Can 30-yr cutting cycles be sustained?*

One frequently cited benefit of reduced-impact logging (RIL) is that cutting cycles of 30 yr will be possible when RIL is employed, compared to 100 yr or more when logging is unplanned (Uhl et al., 1997). The widely held assumption that 30-yr cutting cycles will be sustainable is based on stand-level volume increment from a limited number of small plots in Amazonia (Barreto et al., 1998; Alder and Silva, 2000; Keller et al., 2004; Valle et al., 2006). These estimates do not consider logging impacts on timber species populations or population recovery rates. Given *Tabebuia* population dynamics at our eastern Amazonian sites, it is not possible to maintain timber production at current harvest levels on 30-yr cutting cycles, or even at substantially reduced logging intensities with the current log-and-leave RIL model. Similar population structures (Fig. 2), slow growth rates (Dauber et al., 2003; Supplemental Table 3), and poor regeneration at other Amazonian sites (Fredericksen and Mostacedo, 2000; Justiniano et al., 2000; Heuberger et al., 2002) indicate that our results are broadly applicable across *Tabebuia* ranges in Amazonia (population dynamics may be quite different outside Amazon forests, such as in cerrado and pantanal regions). New silvicultural models will be necessary to sustainably manage *Tabebuia* and similar timber species.

4.2. *Will populations persist under logging pressure?*

In order to predict long-term effects of logging on *Tabebuia* populations, we must understand seedling dynamics in disturbed areas (logging gaps and skid trails) within logged forests. Given low densities of sub-merchantable trees, saplings, and seedlings in unlogged forest, seedling performance in logging gaps will largely determine these species' capacity to recover from logging disturbance. Even under the best regeneration scenario – the highest observed seedling densities in logging gaps and lowest observed mortality rates – only one ipê tree per 10 ha could be expected to survive to adult size, and this only after a century or more of growth.

A more probable scenario is that only the rare individual establishing in the right location in a gap with appropriate conditions will survive and recruit to commercial size in logging gaps that are left to natural successional processes. We therefore cannot assume that natural regeneration following logging will be sufficient to enable population recovery from the initial harvest. Thus we conclude that sustainable logging of *Tabebuia* will require some combination of enrichment planting and long-term silvicultural tending of established seedlings in high-light environments within logged stands.

Demand for ipê timber is responsible for the logging of a vast region of Amazonia each year, much of this logging is in new frontier regions, and the expansion of ipê logging into previously intact forest regions will likely increase as demand for ipê increases and supplies from established logging centers dwindle. Ipê harvest volumes in 2004 were comparable to mahogany volumes extracted from Brazilian Amazonia during the 'mahogany rush' of the late 1980s and early 1990s (Browder, 1987; Veríssimo et al., 1995; Grogan et al., 2002). Accurate estimates of total annual ipê consumption, including domestic and clandestine production, are not available; it is likely, however, that the total area of forest logged for ipê in 2004 was greater than our estimations from export data. Because ipê stocks have been largely depleted in old frontier regions such as eastern Pará state (Veríssimo and Barreto, 2004), most current production must come from new logging frontiers in western Pará, southern Amazonas, northwestern Mato Grosso, and Acre.

Similar to mahogany since the early 1970s, *Tabebuia* logging is lucrative in primary forests at great distances from established wood processing centers, drawing industrial timber operations into the core of the Amazon Basin (Veríssimo et al., 1992, 2002; Lentini et al., 2003, 2005). Planned or ongoing projects to extend the network of all-weather roads into the core of Amazonia (Laurance et al., 2001; Nepstad et al., 2004) would remove most of the remaining economic barriers to ipê extraction.

A general expansion of export-oriented forestry has been observed in Brazil (Lentini et al., 2005) and is predicted to continue as Amazonian timber fills the void left by depletion of southeast Asian timber stocks (Nepstad et al., 2004). We emphasize that the vast majority of logging in Amazonia does not following RIL protocols or even the legal standards used as the basis for the projections presented here (Schulze et al., 2008). That is, deleterious impacts on populations harvested by conventional or predatory logging practices are undoubtedly higher than we report here due to higher intensity harvests, absence of seed trees, and greater damage inflicted on the residual stand (Johns et al., 1996; Holmes et al., 2002).

4.3. *Ipê logging as a catalyst for forest degradation and clearing*

In recent years there has been a clear shift in the geographical range of ipê logging, as stocks in older eastern frontiers were exhausted and logging operations spread to central and western Amazonia. Even without planned expansion of the transportation network, the majority of the Brazilian Amazon is already financially accessible to ipê logging. Left to market forces, ipê logging will continue to spread to unlogged forest regions wherever these species can be profitably harvested. As logging roads and sawmills penetrate new regions they provide access and incentive for colonists and land speculators to follow (Fearnside, 1997; Laurance et al., 2001). This dynamic has been well documented for Amazonia (Asner et al., 2006), and in much of the so-called 'arc of deforestation' the pursuit of big-leaf mahogany served as the catalyst for the process of land-clearing, serial logging and burning that has resulted in a landscape where islands of degraded forest (heavily logged and in many cases repeatedly burned) persist precariously within a matrix of used and abandoned pastures and agricultural fields (Holdsworth and Uhl, 1997; Gerwing, 2002). With ipê as a new catalyst, the wave of forest degradation and clearing powered by largely unregulated logging now threatens to wash across the heart of Amazonia. The implications of uncontrolled logging of ipê extend well beyond the potential depletion of commercial stocks of *Tabebuia* species, and could undermine government efforts to achieve forest conservation by bringing order to the Amazon frontier.

4.4. *Regulation of ipê logging*

Industrial logging is depleting *Tabebuia* populations throughout Amazonia. Illegal harvest of high-value species such as *Tabebuia* continues to drive expansion of logging frontiers into regions previously inaccessible to logging. Current best-practices forestry, even if uniformly adopted, would not alleviate the pressure on *Tabebuia* populations because harvest intensities and silvicultural systems under RIL have not been adjusted to species-level population dynamics. Solving these problems will require eliminating incentives for illegal logging of ipê while improving standards for legal management of this renewable resource.

In Brazil, concern about populations of high-value species has led to specific legal protection for Brazilnut (*Bertholettia excelsa*), virola (*Virola duckei*), and more recently, mahogany (Brazil, 1994, 1999, 2003). Brazilnut and virola were protected through domestic government policies, whereas protection for mahogany stemmed from concern over international trade of a threatened species. Mahogany's recent listing on CITES Appendix II forced the design and adoption of management requirements more stringent than for any other timber species in Amazonia, while making it more difficult to market illegal wood (Blundell, 2004). This has slowed the spread of uncontrolled mahogany logging into new regions and raised hope that *S. macrophylla* might still be sustainably managed within some portion of its natural geographic range (Grogan and Barreto, 2005).

Like mahogany, the two species of *Tabebuia* discussed here merit greater protection than provided by current generic forestry laws in Brazil and other Amazonian countries. The ecological similarities between *Tabebuia* and *S. macrophylla* are striking. *Tabebuia* appear as vulnerable to uncontrolled logging as mahogany. The growing international demand for and rising value of ipê timber is creating pressure on this forest resource that may soon rival the pursuit of 'green gold', as mahogany is widely known. International demand facilitates much of this uncontrolled logging and is one factor (albeit indirect) in the expansion of illegal logging into the heart of Amazonia. Clearly, eradication or drastic reduction of illegal logging – possible through improved monitoring and enforcement as well as market avoidance of wood of uncertain origin – is fundamental to conserving forest resources, including *Tabebuia*. However, protecting *Tabebuia* populations will require development of higher standards for ipê management – reduced harvest intensity and requirements for management of regeneration – much like those for the threatened mahogany. *Tabebuia* species may also warrant consideration for international regulatory protection under the CITES charter. Unsustainable logging of mahogany was not slowed in Brazil until systematic efforts to restrict harvest, transport and trade were implemented at the national and international levels (Grogan and Barreto, 2005). These efforts came too late for most mahogany populations and forests within the species' range (Grogan et al., 2008). Will we repeat history with ipê?

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biocon.2008.06.003.

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