Planting mahogany in canopy gaps created by commercial harvesting

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This paper is dedicated to the memory of Tim Whitmore.

Abstract

Attempts at natural forest management of mahogany (Swietenia macrophylla King) have so far met with limited success, whilst many plantations are beset by the shoot borer Hypsipyla spp. In this paper we present preliminary results of an approach to enrichment planting that aims to balance economic returns (rapid growth and good silvicultural form) with intervention costs and changes to forest structure. Mahogany seedlings were planted in gaps created by selective timber harvesting and that ranged in vertical projected area from 91 to 542 m\textsuperscript{2} (mean = 257 m\textsuperscript{2}). Seedlings grew within the matrix of gap regrowth, with limited control of competing vegetation. Sixty-one percent of seedlings had survived by 4.4 years (equivalent to an annual mortality rate of 10.5\% year\textsuperscript{-1}), and had reached a mean height of 4.5 m. Stocking levels of mahogany were similar to that of naturally regenerated commercial species in unplanted gaps of the same age, but mahogany seedlings were significantly taller. The incidence of shoot borer attack on mahogany stems was relatively low (54.7\%), but, more importantly, most damaged stems (58\%) responded by producing a single replacement leader. The cost of the proposed methodology (US$ 94 per gap over 4.4 years) was low compared to the high value of mahogany timber relative to other species in the forest. The implications of planting mahogany in gaps for forest management and the potential benefits to conservation of the species are considered.

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Keywords: Brazilian Amazon; Canopy gaps; Height growth; Hypsipyla; Silviculture; Swietenia macrophylla

1. Introduction

Mahogany (Swietenia macrophylla King) is one of the world’s most valuable timbers. Yet most mahogany logging in Brazil and elsewhere has been at best poorly regulated and at worst illegal (Rodan et al., 1992; Greenpeace, 2002). Such logging removes most of the commercial-sized trees (Gullison et al., 1996; Snook, 1996), may deplete the genetic variability of the species (Newton et al., 1996), and has acted as a catalyst for deforestation (Veríssimo et al., 1995). The unsustainable nature of this trade resulted in the neotropical populations of mahogany being included in Appendix II of the Convention on International Trade in Endangered Species (CITES) in November 2002. More recently, legislation has been adopted in Brazil that seeks to ensure long-term management of the species. The effects of these measures remain to be seen.

Sustainable management of mahogany in natural forest is seen as an important means of ameliorating these impacts (Jennings et al., 2000). However, several studies have argued that there is little or no regeneration after logging in Bolivia (Quevedo, 1986; Gullison et al., 1996), Mexico (Snook, 1993; Dickinson and Whigham, 1999), and Brazil (Veríssimo et al., 1995; Grogan et al., 2003, 2005). It has been suggested that this is because mahogany regenerates as single-aged stands following catastrophic disturbance, and that selective logging causes insufficient disturbance to provide the conditions necessary for regeneration (Snook, 1996). This view was challenged in a recent review of the available evidence, which concluded that not only there was no evidence that mahogany requires catastrophic disturbance in order to regenerate, but that regeneration is often dense after logging in areas transitional between savannah and high forest (Brown et al., 2003).

Unfortunately, attempts to increase the density of natural regeneration of mahogany through silvicultural interventions have been attempted only rarely, and have met with mixed success (reviewed in Mayhew and Newton, 1998).
In contrast to the limited application of natural forest management of mahogany, the species has been grown in plantations throughout the tropics. Although it has grown rapidly in different types of plantation (monospecific and mixed planting in the open, enrichment planting in lines, etc.) and on different soils, most plantations have been bedevilled by the all but ubiquitous shoot borers, Hypsipyla grandella and H. robusta (Lepidoptera: Pyralidae) (Griffiths, 2001). Shoot borers rarely kill mahogany trees, but they do kill the terminal shoot, as a result of which the tree usually produces several replacement stems. This usually results in trees with low branches and reduced commercial value. The most successful replacement stems. This usually results in trees with low branches and reduced commercial value. The most successful approaches to controlling the species are likely to involve a variety of silvicultural techniques that together: reduce the chance of Hypsipyla locating mahogany trees; reduce susceptibility to attack; promote vigorous vertical growth after attack; and encourage natural enemies of the shoot borer (Newton et al., 1993; Mayhew and Newton, 1998; Hauxwell et al., 2001).

In this paper, we describe a technique of enrichment planting in which small numbers of mahogany seedlings are planted within canopy gaps created by timber harvesting. The seedlings grow within the matrix of gap regeneration vegetation, with periodic cleaning confined to maintaining overhead light. The methodology was developed with the full participation of the site’s forest manager (N. Matni) in order to identify a practical balance between competing influences on forest management. These influences include the high economic costs and severe change to forest structure caused by traditional planting methods, against the need for high economic return, which can be achieved by rapid growth and good tree form. The desired outcome of this method is commensurately limited to having at least one marketable mahogany stem available during the next rotation for each tree harvested (of whatever species). The expectations were that (1) the forest gap environment would provide sufficient illumination for silviculturally acceptable growth and survival of mahogany with limited maintenance, (2) the incidence and/or impact of Hypsipyla would be lower than in conventional plantations and (3) there would be economic advantages over leaving the forest to regenerate after logging without seedling enrichment planting in gaps.

2. Materials and methods

2.1. Study area

Research was conducted at Fazenda Pataua (5°42’S, 48°56’W), approximately 570 km south of Belém, in Pará state, Brazil. The forest is approximately 3000 ha in size, and is surrounded by pasture and eucalypt plantations. Precipitation was 1600 mm in 1999 and 2100 mm in 2000, with a dry season of 5 months during which monthly precipitation was <100 mm. The topography is gently undulating, with ridges usually no more than 5–10 m above the courses of the numerous small, seasonal streams that dissect the area. The forest is evergreen with a 25 m canopy surpassed by emergents, most commonly Brazilnut (Bertholletia excelsa Humb. & Bonpl.). The area was logged for mahogany in 1983 and for 21 other species between 1992 and 1998. Mahogany is present at very low density: 0.05 trees ≥20 cm ha⁻¹ and 0.033 logged stumps ha⁻¹ (Jennings and Baima, 2005), and natural regeneration is scarce (0.14 individuals ha⁻¹ between 1 and 20 cm diameter).

2.2. Design and measurements

Fifty gaps created by logging operations during the 1998 dry season (July–October) were selected for the experiment. The most common tree felled to create these gaps was Cedrelina catenaeformis (Ducke) Ducke (Mimosaceae). As the gaps were all recent, natural regeneration was still poorly developed (generally <0.5 m tall). The vertical projection of the canopy gaps was estimated by measuring the diameter of the longest axis and the diameter perpendicular to that, and gap area estimated according to the formula for an ellipse (Barton et al., 1989). Gap size ranged from 91 to 542 m² (mean 257 m², S.E. = 134).

Twenty gaps were randomly allocated as controls and were not manipulated in any way. These effectively control for the null hypothesis that growth, density and species value are higher in the absence of intervention. The other possible type of control – planting mahogany and then not carrying out maintenance – was not done because of its negligible practical value: mahogany stems would have been rapidly overtopped and suffered low growth and high mortality.

Mahogany seedlings were produced from locally collected seeds planted in 2 l polythene sacs filled with a mixture of forest soil, sand and well-rotted manure at a ratio of 3:1:1. They were raised in a field nursery under light neutral shade for 4 months until they were 0.22 m in height (S.E. = 0.05).

Mahogany seedlings were planted in the remaining 30 gaps early in the first wet season after logging (December 1998). Some of the coarse woody debris remaining in the gaps was cut to improve accessibility and facilitate planting. Seedlings were planted at a spacing of 5 m × 5 m and were uniquely labelled. The only criteria for planting were that (1) the planting site should be clear from coarse woody debris or stumps; and (2) the seedling should be within the vertical projection of the gap (i.e., have direct overhead illumination). The number of seedlings planted per gap therefore varied according to gap size, from 6 to 16 (total planted = 290; mean per gap = 9.7; S.E. = 3.2). Natural regeneration within 1 m diameter of the seedling was manually cut back. Soil samples, homogenised from four sub-samples collected from 0 to 20 cm and 20–40 cm depth, were taken from each gap and analysed for chemical composition by the Soil Laboratory at Embrapa Amazônia Oriental, Belém, Pará.

The rationale for this planting methodology was that mahogany seedlings should grow within the matrix of natural gap regeneration (Oliveira, 2000; Snook and Negreiros-Castillo, 2004). Maintenance of the planted gaps was therefore kept to a minimum, manually cutting back only vegetation growing directly above each seedling (such as the fast-growing pioneer species Cecropia spp. and Trema micrantha (L.) Blume), and vegetation within 1 m diameter of the base of the stem. Cut material was left in situ. Maintenance was carried out 3 months...
after planting, every 6 months until April 2000, once more in 2001, and then again in May 2003.

Mahogany seedlings were measured at each maintenance. Height was measured with a rule, or with a telescopic measuring pole for seedlings ≥ 2 m height. The diameter of all seedlings ≥ 2 cm diameter at breast height (dbh) was measured with a steel diameter tape. The crown illumination index (Clark and Clark, 1992; Jennings et al., 1999) of each seedling was estimated before and after maintenance.

A single two-way ANOVA was used to assess the effect of gap, as the crown illumination index is a semi-ordinal scale) and soil nutrients on log-transformed mean seedling height after 4.4 years.

The incidence of shoot borer (H. grandella) on each seedling was recorded, either present or in the past through the characteristic damage to the dead leader. Finally, the number of stems produced by each seedling in response to shoot borer attack was recorded. One gap was not measured on the last occasion due to a serious accident to the researcher, and data from this gap is not reported here.

The annualised mortality rate, \( m \), of planted seedlings, was calculated following the equation of Sheil et al. (1995):

\[
m = 1 - \left( \frac{N_t}{N_0} \right)^{1/t}
\]

where \( N_0 \) and \( N_t \) are the population counts at the beginning and end of the measurement interval, \( t \), in years. Mean annualised absolute height growth rate of seedlings (AGR) was calculated as

\[
AGR = \frac{H_1 - H_0}{t}
\]

where \( H_0 \) and \( H_1 \) are seedling heights at the beginning and end of the measurement interval, \( t \), in years (Hunt, 1978).

Control gaps were measured in May 2003. Stems of all species that have commercial value as sawn wood and/or veneer in the internal or export market were identified, counted, and measured for height, diameter and crown illumination as described above.

### 2.3. Economic considerations

The costs of gap planting were recorded by the forest manager for all phases of the study: seedling production, gap preparation and planting, and maintenance. These costs include materials, labour, consumables, and depreciation of equipment. We have chosen not to make direct economic comparison between planting mahogany and ‘log and leave’ because most methods used in forestry rely on assumptions that are difficult to justify in this study. These include:

- a discounting rate that is stable over decades—problematic in a traditionally volatile economy such as Brazil’s, and even more so as such a rate would cover a time when decreasing oil supply and global climatic change are likely to cause substantial but unpredictable changes to the world’s economies;
- prediction of timber volume at least 30–40 years into the future, based on extrapolation of short-term growth and mortality rates; and
- predictable changes to the relative timber prices of different species.

We believe that such assumptions are unjustified, and therefore decided to simply record timber prices and costs of planting. This is intended as a preliminary indication of the comparison between planting mahogany and ‘log and leave’ only, and it is expected that a more rigorous economic comparison will become possible when volume yields at this site can be more reliably estimated.

### 3. Results

#### 3.1. Planted gaps

All of the planted gaps still contained at least two surviving mahogany seedlings after 4.4 years, with a mean number of seedlings per gap of 6.1 (S.E. = 2.8). Overall seedling survival was 61.4%, equivalent to an annual mortality rate of 10.5% year⁻¹.

Mahogany seedlings had attained a mean height of 4.6 m (S.E. = 2.2) after 4.4 years. More than one in three seedlings (36.3%) reached at least 5 m height, the tallest of which was 12.5 m. The majority of seedlings (74.2%) reached the minimum measurement diameter (2 cm dbh). On a per-gap basis, 8 of the 29 gaps (27.6%) had a mean seedling height in excess of 5 m (Fig. 1). Twenty-one gaps (72.4%) had at least one seedling ≥ 5 m in height, and 27 (93.1%) had one or more seedlings ≥ 2 cm dbh.

A growth function for the mahogany seedlings was derived by linear regression of seedling height at each measurement (Fig. 2). The regression equation was

\[
H_m = 0.990 A + 0.343
\]

where \( H_m \) is the mean height and \( A \) is the age in years. The regression was highly significant and explained most of the variation in the data (\( p < 0.001, R^2 = 99.1\% \)).

### Table 1

Mean pH and concentration of exchangeable cations of soil from 29 planted gaps in a Brazilian rain forest (S.E. in parentheses)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>pH</th>
<th>P (mg/dm³)</th>
<th>K (mg/dm³)</th>
<th>Na (mg/dm³)</th>
<th>Ca (mmol/dm³)</th>
<th>Mg (mmol/dm³)</th>
<th>Al (mmol/dm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–20</td>
<td>3.9 (0.4)</td>
<td>2.3 (1.3)</td>
<td>55.8 (27.4)</td>
<td>26.1 (24.6)</td>
<td>6.9 (7.2)</td>
<td>5.2 (3.4)</td>
<td>23.5 (8.2)</td>
</tr>
<tr>
<td>20–40</td>
<td>4.1 (0.6)</td>
<td>1.5 (1.1)</td>
<td>50.8 (26.9)</td>
<td>21.8 (28.7)</td>
<td>6.4 (5.2)</td>
<td>5.1 (5.1)</td>
<td>22.4 (7.8)</td>
</tr>
</tbody>
</table>
The majority of individuals (73.2%) had a time-weighted crown illumination index of 3, indicating overhead illumination (Clark and Clark, 1992), with the rest scoring either 2.5 (12.8%: no overhead illumination but significant lateral illumination) or 4 (14%: overhead plus lateral illumination). However, all but 5.6% of seedlings had crown illumination scores < 3 at some time, indicating that maintenance operations were not frequent enough to maintain continuous overhead illumination (particularly between the 3rd and 5th year). This is supported by analysis of height increment. Mean absolute height growth rate remained between 0.9 and 1.3 m year\(^{-1}\) over the first 2.5 years, but then declined to 0.6 m year\(^{-1}\) during the final measurement interval (Fig. 3).

Both crown illumination and pH of soil 0–20 cm depth had significant positive effects on mean seedling height (two-way ANOVA, d.f. = 1, \(F = 12.89, p = 0.002\) and d.f. = 1, \(F = 8.21, p = 0.010\), respectively), whilst the concentration of phosphorus in soil 0–20 cm depth (d.f. = 1, \(F = 6.88, p = 0.016\)) had a significant negative effect. Other soil nutrients at this depth (K, Na, Ca, Mg and Al) had no significant effect on height, and no soil variables from 20 to 40 cm depth had any significant effect (Table 1).

The incidence of shoot borer attack was relatively low, with 54.7% of seedlings attacked at some stage over the study period. However, the generally low incidence of shoot borer attack masked considerable variation among gaps (Fig. 4). This variation could not be explained either by the original number of seedlings planted (i.e., mahogany density: linear regression, \(p = 0.061\)), nor canopy illumination (\(p = 0.847\)). Of the trees suffering shoot borer damage, 58% responded by producing a single replacement leader, whilst the rest produced two or more stems.

### 3.2. Control gaps

Seedlings and saplings of 19 commercial species were found within the control gaps (Table 2), with a mean of 4.2 (S.E. = 2.9) species per gap. None of these gaps contained any natural regeneration of mahogany (note that one naturally regenerated mahogany seedling established in a planted gap). Most commercial species in control gaps were fast-growing pioneer (sensu Swaine and Whitmore, 1988) or light demanding climax species.

A comparison of seedling performance in control and planted gaps is given in Table 3. Unplanted gaps had a mean of 9.1 (S.E. = 6.9) commercial stems, which was not significantly different from the number of mahogany stems in planted gaps (Mann–Whitney \(U\)-test; \(n = 29, 20; W = 670; p = 0.066\)). One gap had no stems of commercial species present.

The mean height of commercial stems was 3.0 m (S.E. = 1.4), significantly shorter than mahogany stems (two-tailed \(t\)-test, \(N = 29, 20; p = 0.002\)). A significantly smaller percentage of naturally regenerated commercial stems had reached 5 m height than mahogany stems (17.5% vs. 36.3%, respectively; Chi-squared test, \(\chi^2 = 21.65, d.f. = 1, p < 0.001\)). Similarly, fewer naturally regenerated stems had reached 2 cm
dbh compared to mahogany stems (38.1% vs. 74.2%, respectively; Chi-squared-test, $\chi^2 = 44.8$, d.f. = 1, $p < 0.001$).

### 3.3. Cost of gap planting and timber values

The cost of producing mahogany seedlings, planting, and maintenance operations was equivalent to US$ 94 per gap (Table 4). This is equivalent to US$ 283–378 per ha (assuming a normal selective felling rate for the Brazilian Amazon of three to four trees per hectare), or US$ 9 per planted seedling and US$ 16 per survivor.

Mahogany has a sawnwood price of US$ 700–1400 per m³ FOB (Association of Timber Exporters of Pará, personal communication, 2006). By comparison, the commercial species found in control gaps have much lower values than mahogany (mean US$ 323 per m³, range US$ 225–390; Table 2). Mahogany – even at the lowest price grade – is therefore at least US$ 310 per m³ (79%) more valuable than the most expensive of the other commercial species, and the costs of gap planting represent only a small fraction of this value differential (8–30%). This suggests that there is considerable potential for economic gain from planting mahogany in felling gaps.

### 4. Discussion

The method reported here was designed to provide a compromise between tree growth, stem quality, impact on forest structure, and financial investment rather than to produce ideal growth conditions for mahogany. It was therefore encouraging that mean height growth of gap-planted mahogany (1.04 m year$^{-1}$) was broadly equivalent to that described from other silvicultural systems. Confidence intervals calculated for the growth function of gap-planted mahogany allow comparison of seedling height with that predicted after 4.4 years by published growth functions for mahogany from different silvicultural systems (Fig. 2). Two of these predicted heights (from conventional monoculture, Neil, 1986; and shade trees in Table 2) were significantly higher for mahogany in planted gaps than for naturally regenerating commercial species in controls (see text for details of statistical tests). The mean standard error about the means is given in parentheses.

Table 3

<table>
<thead>
<tr>
<th>Planted</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean occupancy (number of stems)</td>
<td>6.14 (2.81)</td>
</tr>
<tr>
<td>Stems &gt; 5 m height (%)</td>
<td>36.3***</td>
</tr>
<tr>
<td>Stems ≥2 cm dbh (%)</td>
<td>74.2***</td>
</tr>
</tbody>
</table>

Numbers marked with ** ($p < 0.01$) or *** ($p < 0.001$) are significantly higher for mahogany in planted gaps than for naturally regenerating commercial species in controls (see text for details of statistical tests). The mean standard error about the means is given in parentheses.

<table>
<thead>
<tr>
<th>Name</th>
<th>Family</th>
<th>Ecological group$^a$</th>
<th>Mean number of individuals per gap</th>
<th>Gaps occupied (%)</th>
<th>Value (US$ per m³)$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virola sp.</td>
<td>Myristicaceae</td>
<td>LDC</td>
<td>2.05</td>
<td>70</td>
<td>150–330</td>
</tr>
<tr>
<td>Jacaranda copia (Aubl.) D. Don</td>
<td>Bignoniaceae</td>
<td>P</td>
<td>1.45</td>
<td>40</td>
<td>350$^1$</td>
</tr>
<tr>
<td>Trattinnickia rhoifolia Willd.</td>
<td>Burseraceae</td>
<td>LDC</td>
<td>0.95</td>
<td>45</td>
<td>350$^1$</td>
</tr>
<tr>
<td>Simarouba anara Aubl.</td>
<td>Simaroubaceae</td>
<td>LDC</td>
<td>0.85</td>
<td>30</td>
<td>275</td>
</tr>
<tr>
<td>Aupleia molaris Spruce ex Benth.</td>
<td>Caesalpinaceae</td>
<td>LDC</td>
<td>0.65</td>
<td>20</td>
<td>275–360</td>
</tr>
<tr>
<td>Parkia pendula (Willd.) Bent. ex Walp.</td>
<td>Mimosaceae</td>
<td>LDC</td>
<td>0.45</td>
<td>15</td>
<td>350$^1$</td>
</tr>
<tr>
<td>Goupia glabra Aubl.</td>
<td>Celastraceae</td>
<td>P</td>
<td>0.40</td>
<td>20</td>
<td>225</td>
</tr>
<tr>
<td>Cedrelinga catenariaformis (Ducke) Ducke</td>
<td>Mimosaceae</td>
<td>LDC</td>
<td>0.30</td>
<td>20</td>
<td>225</td>
</tr>
<tr>
<td>Schefflera morototoni (Aubl.) Maguire, Steyerm. &amp; Frodin</td>
<td>Araliaceae</td>
<td>P</td>
<td>0.30</td>
<td>30</td>
<td>No data</td>
</tr>
<tr>
<td>Schizolobium amazonicun Huber ex Ducke</td>
<td>Caesalpinaceae</td>
<td>P</td>
<td>0.30</td>
<td>10</td>
<td>350$^1$</td>
</tr>
<tr>
<td>Parkia gigantocarpa Ducke</td>
<td>Mimosaceae</td>
<td>LDC</td>
<td>0.25</td>
<td>20</td>
<td>350$^1$</td>
</tr>
<tr>
<td>Symphonia globulifera L.f.</td>
<td>Clusiaceae</td>
<td>STC</td>
<td>0.25</td>
<td>25</td>
<td>No data</td>
</tr>
<tr>
<td>Astronium lecointei Ducke</td>
<td>Anacardiaceae</td>
<td>LDC</td>
<td>0.20</td>
<td>10</td>
<td>320</td>
</tr>
<tr>
<td>Ceiba pentandra (L.) Gaertn.</td>
<td>Bombacaceae</td>
<td>LDC</td>
<td>0.20</td>
<td>15</td>
<td>350$^1$</td>
</tr>
<tr>
<td>Sterculia species K.Schum.</td>
<td>Sterculiaceae</td>
<td>LDC</td>
<td>0.15</td>
<td>15</td>
<td>350$^1$</td>
</tr>
<tr>
<td>Trattinnickia burseraeformia (Mart.) Willd.</td>
<td>Burseraceae</td>
<td>LDC</td>
<td>0.15</td>
<td>10</td>
<td>390</td>
</tr>
<tr>
<td>Hymenaea sp.</td>
<td>Caesalpinaceae</td>
<td>LDC</td>
<td>0.15</td>
<td>10</td>
<td>350$^1$</td>
</tr>
<tr>
<td>Aspidosperma sp.</td>
<td>Apocynaceae</td>
<td>LDC</td>
<td>0.05</td>
<td>5</td>
<td>No data</td>
</tr>
<tr>
<td>Parkia multijuga Benth.</td>
<td>Mimosaceae</td>
<td>LDC</td>
<td>0.05</td>
<td>5</td>
<td>350$^1$</td>
</tr>
<tr>
<td>Vatairea paraensis Ducke</td>
<td>Fabaceae</td>
<td>LDC</td>
<td>0.05</td>
<td>5</td>
<td>350$^1$</td>
</tr>
</tbody>
</table>

$^a$ Ecological groups are based on the knowledge of local foresters: P, pioneer; LDC, light demanding climax; STC, shade tolerant climax.

$^b$ Values are for sawn timber FOB except those marked$^1$ where prices are for plywood as no export market for sawnwood exists. Species for which no export market exists are marked ‘no data’. Prices were kindly provided by the Association of Timber Exporters of Pará (AIMEX) and Nordisk Timber Ltda.
cocoa plantations, Llera and Melandez, 1989) were within the 95% confidence intervals of our growth function. The third (conventional monoculture; JICA, 1982) was above the upper confidence interval, but as this point has no associated error, it is not clear whether this represents significantly greater growth. Indeed, Mayhew and Newton (1998) consider height growth of 1 m year\(^{-1}\) to be acceptable for mahogany in plantations. The mean height growth reported here represents a significant improvement over that reported from gap and skid-trail planted mahogany where no maintenance was carried out (mean height = 3.31 m after 5 years; Oliveira, 2000). Maintaining rapid growth is critical, because once suppressed, mahogany quickly loses the capacity to respond to subsequent increased light levels with rapid growth (Grogan et al., 2005).

Increased height growth could almost certainly be achieved by more frequent maintenance, as many stems were overtopped and shaded by pioneer vegetation during the longer intervals between maintenance. Although it would increase costs, a twice-yearly maintenance regime for the first 3 years, followed by annual cleaning as necessary, may well be warranted. Additional improvements to the methodology could be gained by reducing costs through direct seeding (Negreros-Castillo and Hall, 1996), through improved nursery practices (Mexal et al., 2002), or by using provenances more resistant to the shoot borer (Newton et al., 1999).

Table 4
Cost of producing mahogany seedlings, planting and maintenance over 4.4 years

<table>
<thead>
<tr>
<th>Operation</th>
<th>Cost (US$ per gap)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seedling production</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seed</td>
<td>0.49</td>
<td>80% seed germination, 10% seedlings discarded</td>
</tr>
<tr>
<td>Materials</td>
<td>1.54</td>
<td>2 l plastic sacs, manure</td>
</tr>
<tr>
<td>Labour</td>
<td>0.80</td>
<td></td>
</tr>
<tr>
<td>Sub-total</td>
<td>2.83</td>
<td></td>
</tr>
<tr>
<td>Planting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petrol (chainsaw)</td>
<td>5.00</td>
<td>Equipment: truck, chainsaw, manual digger, machetes</td>
</tr>
<tr>
<td>Diesel (truck)</td>
<td>8.00</td>
<td>One driver, one chainsaw operator, four field assistants</td>
</tr>
<tr>
<td>Equipment depreciation</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>Labour</td>
<td>12.40</td>
<td></td>
</tr>
<tr>
<td>Sub-total</td>
<td>25.59</td>
<td></td>
</tr>
<tr>
<td>Maintenance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel (truck)</td>
<td>8.00</td>
<td>Truck, chainsaw, manual digger, machetes</td>
</tr>
<tr>
<td>Equipment depreciation</td>
<td>0.12</td>
<td>One driver, two labourers</td>
</tr>
<tr>
<td>Labour</td>
<td>5.07</td>
<td></td>
</tr>
<tr>
<td>Sub-total</td>
<td>13.19</td>
<td>Maintenance repeated five times</td>
</tr>
<tr>
<td></td>
<td>65.97</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>94.38</td>
<td></td>
</tr>
</tbody>
</table>

The incidence of shoot borer attack (54.7%) was lower than that reported from most other silvicultural systems, where 60–100% of trees between 3 and 5 years old are typically attacked (Mayhew and Newton, 1998; Newton et al., 1999). In common with many other reports of variable shoot borer attack, reasons for the relatively low incidence of attack and variation in incidence among gaps were not ascertainable from this study, which focused on silvicultural results rather than biological mechanisms. Shoot borer attack is determined by a number of interdependent factors (Mayhew and Newton, 1998; Hauxwell et al., 2001), but given the low density of mahogany within the forest and growth of mahogany seedlings within a matrix of natural gap regeneration, we hypothesise that it may have been due to a combination of reduced apparency of mahogany stems within dense gap regeneration, and perhaps a high incidence of natural enemies of *Hypsipyla*.

Perhaps more important than the incidence of attack was the high proportion of attacked stems (58%) that responded with a single strong leader (’host recovery’ in the terminology of Mayhew and Newton, 1998). This response is likely to be the result of the gap environment in which the seedlings grew, which, compared to conventional plantations, provided less total illumination, direct overhead illumination, and limited (mostly indirect) lateral light.
Whilst we recognise that it may be imprudent to draw too many conclusions on the basis of evidence gathered over a short time period, we believe that early indications from this study are encouraging. The method described above has the potential to secure at least one mahogany stem for each tree harvested; mahogany growth was equivalent to that found in other silvicultural systems and superior to that of naturally regenerating commercial species; and the costs of the intervention are likely to be outweighed by the high value of mahogany timber compared to other species in the forest. It should also be borne in mind that many planted gaps will be able to support more than one mahogany stem plus stems of other commercial species because the vertical projection of a felling gap is much larger than the crown diameter of logged trees (falling trees typically take down numerous other and usually smaller stems). This means that the comparisons made here likely underestimate the benefits of planting and maintaining mahogany.

Mahogany occurs in a wide range of population densities and size structures in the Brazilian Amazon (Brown et al., 2003). In forests such as the site used here, mahogany’s population density is so low that there is little prospect that management through natural regeneration will be commercially viable. This leaves forest managers with the options of either managing the forest for other species present, which are of lower value and yield lower economic returns, or investing in conventional enrichment planting (such as line planting), which is expensive, causes severe modification to forest structure, and in which mahogany often suffers badly from Hypsipyla.

The gap-planting technique described here provides a third option. Planting mahogany in gaps created by logging would, given typical logging rates in the region, result in three and four planted gaps per hectare. If each gap yielded an average of one marketable stem, this would result in a hugely valuable resource to the forest owner. The indication from results presented here are that it would also accelerate regeneration, potentially resulting in trees reaching a larger size within a fixed rotation period. The technique would also increase the population density of mahogany in the forest here, by at least 60 times. As mahogany begins to produce fruit at approximately 30 cm dbh (Gullison et al., 1996; Jennings and Baima, 2005), a size well below legal felling limits, this could provide a significant (albeit temporary) increase in seed rain and therefore regeneration. Increasing population density is particularly important in the management of light demanding climax species such as mahogany, as they are vulnerable to loss of genetic diversity through harvesting (Jennings et al., 2001). As long as locally produced seed, collected from a range of trees, is used to produce seedlings, the proposed methodology could also play a role in maintaining population-level genetic diversity. Providing forest managers, including indigenous communities, with workable options for managing mahogany in situ is a potentially important step (Jennings et al., 2000; Zimmerman et al., 2001) in reversing the depressing trends of deforestation (INPE, 2005) and degradation (Asner et al., 2005) in the Brazilian Amazon.

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