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Evaluation of yield regulation options for primary forest in Tapajós National Forest, Brazil

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Abstract

The sustainability of a range of forest management scenarios were evaluated for the Tapajós region of the Brazilian Amazon using the growth and yield simulation model, Simflora, a derivative of the model SYMFOR developed for application in Indonesia. A simulation of current management regulations based upon a maximum extracted volume of 35 m^3 ha^{-1} and a 30-year cutting cycle was found to be unsustainable. A range of alternative specifications for the control (regulation) of harvested timber yield were compared, along with associated estimates of timber increment and description of the ecological composition of the stand. The alternative scenarios included cutting cycles ranging from 10 to 60 years and maximum yields from 10 to 40 m^3 ha^{-1}.

The maximum commercial volume increment predicted in this study was 0.33 m^3 ha^{-1}. It was observed that the highest rates of volume increment were associated with high logging intensities. The study produced a limited number of potentially sustainable options for the Tapajós forest. The best of these were the combinations of 10 m^3 ha^{-1} yield and a cutting cycle of 30 years or 20 m^3 ha^{-1} with a 60-year cutting cycle. The analysis suggested that the sustainability of both of these options was "marginal" and suggested adopting a precautionary approach of an additional limit for yield to be no more than 33% of standing commercial volume until more data are available.

Analysis of the ecological data from the simulations clearly demonstrated that the composition of the managed forest is likely to differ significantly from that observed in primary forest. The most significant likely change is a reduction in the proportion of trees in the emergent ecological group. This observation raises the issue that stakeholders should not expect tropical forests that are managed for production to ever be identical in structure or composition to primary forests. It also suggests that additional technical measures will be required to promote the regeneration and growth of current emergent species if these are to be maintained in managed forests in the Amazon.

The study concludes that there cannot be a single system of yield regulation or forest management that will fit all contexts (social, ecological, environmental and economic) or management objectives held by various stakeholders in the Amazon.

Keywords: Sustainable forest management; Amazon; Modelling; Timber certification; Brazil; Yield regulation

1. Introduction

The Amazonian rain forest is the world's largest contiguous area of tropical forest (Dubois, 1991; Asner et al., 2004), being recognised for its high biodiversity and importance to global climate (Malhi et al., 2002). Selective logging is one of the main land uses in the Amazon, being very important for the regional economy. From 1996 to 2003, logging occurred at a rate of 10–20 thousand km^2 $year^{-1}$, being responsible for an estimated annual round-wood production of 27–50 million m^3, employing 350 thousand people and generating gross annual revenue of US$ 2.5 billion (Nepstad et al., 1999; Lentini et al., 2003; Asner et al., 2005).

Currently, with very few exceptions, logging activity is part of agricultural frontier expansion and follows the world-wide pattern of the boom-bust cycle (Vincent, 1992; Schneider et al., 2000). In order to avoid the loss of forest cover and its benefits (e.g. watershed, soil and nutrient conservation, and the preservation of biodiversity), sustainable forest management has been proposed as a solution (Schmidt, 1991; Whitmore, 1991; Pearce et al., 2003).

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Definitions of SFM vary widely (Vanclay, 1996; Rice et al., 1998) generally agreeing that today's use of natural forest resources should not compromise its future use in line with the original definition of sustainable development produced by the United Nations Commission on Environment and Development (''The Brundtland Report'', UN Commission on Environment and Development, 1987). Most countries impose regulations to forested lands to ensure this (Vanclay, 1996).

Yield is regulated in Brazil during the approval process of the Sustainable Forest Management Plan and Annual Operating Plans. These documents must present the minimum logging diameter, maximum mean extracted volume and cutting cycle to be used. The minimum DBH of 45 cm is generally applied with a cutting cycle of 25–30 years (Barreto et al., 1998; Grogan et al., 2004). The rule of thumb for maximum mean extracted volume has been more flexible with plans commonly approving 60 m^3 ha^{-1}, however in recent years there has been more adherence to values of 40 and 30 m^3 ha^{-1} so 35 is used for this study. Within a species, up to 90% of the trees above the minimum diameter limit may be harvested.

Growth and yield models are essential tools to evaluate forest characteristics over one or more cutting cycles. The precision of these estimates may, however, be constrained by data used to calibrate the model and assumptions used to develop the model (Vanclay, 1992; Soares et al., 1995). While many models have already been developed to simulate forest growth and ecology, only few models have been developed and applied to support forest policies (van Gardingen et al., 2002).

In the Amazon region, MYRLIN (Nicol et al., 2002) and GEMFORM (Alder, 2000; Marshall and Bird, 2002) were used in Guyana to estimate future yield. In French Guyana, an individual tree spatially explicit model was developed, called SELVA (Gourlet-Fleury and Houllier, 2000) and it was compared to a matrix model called StoMat, concluding that both modelling approaches generate similar predictions and that the current felling regime does not guarantee sustained yields (Gourlet-Fleury et al., 2005). In Bolivia, a simulation model based on diameter distribution, increment and natural mean mortality of commercial species was developed, revealing that complete volume recovery will not be possible under currently prescribed cutting cycles and minimum felling diameter (Dauber et al., 2005). The SYMFOR model originally designed for use in Indonesia (Phillips et al., 2003) was adapted for use in Guyana (Phillips et al., 2002a) and then the Brazilian Amazon (Phillips et al., 2004). This model for Brazil was further adapted for use in this study with the incorporation of new management options and translation into Portuguese to become the model SIMFLORA.

In the Brazilian Amazon, attempts to provide a technical basis for yield regulation were based on mean diameter increment and mortality of commercial species (Barreto and Uhl, 1993; Silva et al., 1995; Vidal, 2004). The initiatives related to forest dynamics modelling in the Brazilian Amazon known by the authors are (in chronological sequence):

(a) Standpro—stand class projections (Silva, 1989).
(b) Inform—diameter class and nutrient cycling hybrid model (Biot et al., 1997).
(c) Cafogrom—cohort model (Oliveira, 2000; Alder and Silva, 2000, 2001; Keller et al., 2004).
(d) Transition matrix used to predict commercial species diameter structure (Cunha et al., 2002).
(e) SYMFOR—individual tree spatially explicit model (Phillips et al., 2004).

Simflora is a framework which includes forest ecology and management models. The ecological model is individual-based and spatially explicit. Further details on its calibration and validation in Brazil and its limitations and assumptions are described elsewhere (Phillips et al., 2004).

This study aimed to evaluate options of yield regulation for primary forest in Tapajós National Forest, Brazil. The approach adopted in this study differed from previous modelling studies using data from the Tapajós region (Silva, 1989; Alder and Silva, 2000; Phillips et al., 2004; Keller et al., 2004) in that the application of ecologically-based Simflora model permitted the analysis of a wider range of logging scenarios and criteria of sustainability, moving beyond the consideration of sustained timber yield, towards the objective of sustainable management of the timber resource.

Specific objectives of the current study were to:

- Evaluate the current Brazilian yield regulation system against objective criteria for Sustainable Forest Management.
- Compare the current system with a range of possible alternatives derived through modifications of the length of cutting cycle and maximum harvested volume limit.
- Analyse predicted changes in the ecological composition of forests under simulated management scenarios as a criterion of sustainability.
- Analyse the way that the volume increment responds to management options and provide an estimate of the expected maximum commercial volume increment to be used to set limits for sustainable forest management.
- To apply the yield and ecological analysis to define possible strategies to increase future sustainable yield from the Brazilian Amazon.

2. Methods

2.1. Data

The dataset comes from Tapajós National Forest, in Belterra municipality, Pará State (54°56′5″W and 3°18′46″S). The vegetation consists of typical *terra-firme* (dry-land) high forest, with basal area ranging from 30 to 35 m^2 ha^{-1} ($DBH \geq 5$ cm) and standing volume of 150–200 m^3 ha^{-1} ($DBH \geq 45$ cm). The regional climate is classified as Ami under Köppen system, with mean annual rainfall of 1900–2110 mm and temperature of 25 °C. Soils are classified as yellow latosols and topography is slightly rolling (Silva et al., 1995, 1996; Alder and Silva, 2000; Carvalho et al., 2004).

The series of plots at Tapajós km 114 comprise 60 Permanent Sample Plots, each of 0.25 ha, initially measured

Table 1
Ecological groups used in this study (after Phillips et al., 2004)

	Group name	Dominant members
1	Slow growing mid-canopy	*Lauraceae*, *Sapotaceae*, *Eschweilera blanchetiana*
2	Slow growing understorey	*Duguetia echinophora*, *Sagotia racemosa*, *Theobroma speciosum*
3	Medium growing mid-canopy	*Carapa guianensis*, *Geissospermum sericeum*, *Pouteria bilocularis*
4	Slow growing lower canopy	*Rinorea guianensis*, *Protium apiculatum*, *Neea* spp.
5	Medium growing upper canopy	*Couratari oblongifolia*, *Minquartia guianensis*, *Holopyxidium jarana*
6	Fast growing upper canopy	*Sclerolobium chrysophyllum*, *Parkia multijuga*, *Trattinickia rhoifolia*
7	Fast growing pioneers	*Inga* spp., *Bixa arborea*, *Sloanea froesii*
8	Emergents—climax	*Manilkara huberi*, *Bertholletia excelsa*, *Hymenaea courbaril*
9	Very fast growing pioneers	*Cecropia leucoma*, *Cecropia sciadophylla*, *Cecropia* sp.
10	Very fast growing upper canopy	*Tachigalia myrmecophylla*, *Schyzolobium amazonicum*

Note: There are small differences in the indicative dominant species in the current study compared with those reported by Phillips et al. (2004) resulting from the differences between sites.

in 1981 in unlogged primary forest. These data, with measurements of all trees with a diameter at breast height (DBH) $\geq$ 10 cm, were used to initialize the model. It was necessary to join four plots to create a composite 1 ha plot to be used in the model. Only plots from the same experimental block were joined together, in an effort to avoid within plot variability and to increase the variability between plots. A total of 15 1 ha plots were generated, with mean basal area and tree density (DBH $\geq$ 10 cm) equal to 28 $\text{m}^2\,\text{ha}^{-1}$ and 503 trees ha^{-1}, respectively. Detailed description of the forest and the experiment can be found elsewhere (Silva et al., 1995, 1996; Alder and Silva, 2000; Phillips et al., 2004; Oliveira, 2005).

During the period of 1999–2003, a project sponsored by the International Tropical Timber Organization (ITTO) implemented logging activities in 3200 ha in Flona Tapajós, with the purpose of evaluating systems for sustainable forest management. The ITTO project provided the commercial species list used in their logging trial during 2004 (Dias, pers. comm.). This list contained a total of 105 species suitable for commercial exploitation although only 44 were present in the plots used to initialize the model (see Appendix A for commercial species list and total basal area and tree density by species). In these plots, the mean commercial basal area and tree density (DBH $\geq$ 10 cm) were equal to 8 $\text{m}^2\,\text{ha}^{-1}$ and 73 trees ha^{-1}, respectively. Mean commercial stock, defined as trees from commercial species with stem quality greater than 0.3 and DBH $\geq$ 45 cm, was equal to 56 $\text{m}^3\,\text{ha}^{-1}$.

2.2. Ecological model

The ecological model was calibrated to Tapajós and Jari dataset, with a 5 cm minimum diameter of measurement (Phillips et al., 2004). Afterwards, the ingrowth and mortality submodels were adapted for application to datasets with 10 cm minimum diameter for measurement through a calibration process, to ensure that species composition remained in a dynamic equilibrium below and above the 95 percentile of the cumulative diameter frequency distribution. A summary of the ecological groups is provided as Table 1. The modified ingrowth and mortality submodels parameters can be seen in Table 2.

2.3. Sustainability criteria

This study will evaluate forest management sustainability through a four stage criteria:

Table 2
Ecological model parameters for Simflora which were modified from the defaults (Phillips et al., 2004) through further calibration

Mortality submodel

Species groups	m_1	m_2	D_{95}
1	1.8	0.06	41
2	2.9	0.1	15
3	1.1	1	64
4	2	0.6	27
5	0.8	0.17	74
6	2.85	0.2	76
7	3.9	0.85	35
8	0.85	0.006	104
9	4.5	0.6	38
10	4	0.35	78

Recruitment submodel

Species groups	r_1	r_2	r_3	T_I
1	1.58	−0.06	−1.575	37
2	0.54	−0.075	−0.53	75
3	0.96	−0.02	−0.955	28
4	1.62	−0.031	−1.595	38
5	0	−36.727	0.003	41
6	0.0002	−5.644	0.0034	18
7	0.0074	−4.011	−0.043	13
8	0.3	−0.033	−0.3	28
9	0.0074	−1.508	−0.11	5
10	0	−5.028	0.002	14

For the mortality model, the parameter D_{95} describes the 95 percentile of the diameter distribution and m_1 is the mortality rate below D_{95} and m_2 is the coefficient that increases the mortality rate above D_{95}. For the recruitment model the parameters r_1, r_2, and r_3 define the probability of ingrowth with an equation $F = r_1\,\mathrm{e}^{-r_2 I} + r_3$, where I is the mean diameter increment (cm year^{-1}) for a tree with DBH equal to 10 cm. The parameter T_I defines the time required to represents the time required for ingrowth as the number of years required for a tree to grow from seed to a DBH of 10 cm. It is used in the simulation when an area of ground is cleared of seedlings, for example when the soil surface is mechanically scarified and compacted during log extraction. Species groups are defined in Table 1.

(1) constant logged volume over time;
(2) recovery of commercial volume;
(3) recovery of standing total volume;
(4) recovery of the volume of ecological species groups.

These criteria were selected to represent the objectives of key stakeholders. The interest of the logging industry are represented by the requirement for constant logged volume (supply rate to the processing industry) and recovery of commercial volume (long-term sustainability of supply). Criteria three and four were selected to provide links to the ecology of the forest, describing its total volume (biomass) and its species composition. In each case the criteria have the advantage of being quantitative, and hence can be used to make objective comparisons between simulated logging treatments.

It is noted that previous studies have tended to concentrate on the first criterion (e.g. Silva, 1989; Alder and Silva, 2001; Marshall and Bird, 2002; Nicol et al., 2002; Dauber et al., 2005; Gourlet-Fleury et al., 2005).

2.4. Management regimes

The baseline of this study consisted of the simulation of stand dynamics under current forest yield regulation in Brazil, using a cutting cycle of 30 years and a maximum logging intensity of 35 m^3 ha^{-1}. This was implemented with simulated reduced impact logging (RIL) to minimize the environmental impact of harvesting.

Alternative yield regulation scenarios (Table 3) were set by varying the maximum logging intensity and length of the cutting cycle based on the assumption that commercial volume increment was equal or less than 1 m^3 ha^{-1} $year^{-1}$. Four further scenarios were simulated to evaluate stand ecology after a single initial harvest intensity of approximately 10, 20, 30 and 40 m^3 ha^{-1} over a simulation period of 120 years.

2.5. Simulation settings

Each logging scenario described in Table 3 was simulated 20 times for each of the 15 1 ha plots. All scenarios simulated represented reduced impact logging (RIL), with planned skid trails (simulated width of 4 m), directional felling and lianas cut before logging. The minimum DBH for logging was 45 cm and 30% of the trees not logged to allow for typical rates of defects (poor form or hollow), as can be seen in Table 4.

Table 3
Combination of management scenarios used by this study

Logging intensity (m^3 ha^{-1})	Cutting cycle (years)			
	10	20	30	60
10	X	X	X	X
20		X	X	X
30			X	X
35			X	

Table 4
Harvesting parameters used in the Simflora model

Parameters	Values
Firstlogging (years)	0
Dbhthreshold (group 1) (cm)	45
Minquality	0.3
Selectvolume	1
Orderrandom	1
Cutlianas	1
Skidprepradius (m)	5
Skidwidth (m)	4
Maxdbhdamage	40

This resulted in the simulation of Reduced Impact Logging techniques.

3. Results

3.1. Timber yield

The predicted yield resulting from the current Brazilian yield regulation system with a maximum extraction of 35 m^3 ha^{-1} and a cutting cycle of 30 years is shown as Fig. 1. This figure shows that whilst the desired harvest is achieved in primary forest (year 0), this is not sustained for any of the subsequent harvests. The observation that this system does not produce sustainable yield given the current commercial species list is supported by previous modelling studies in the Amazon region (Alder and Silva, 2000, 2001; Phillips et al., 2004).

The results shown as Fig. 1 support the hypothesis that alternative systems of yield regulation are required for forests in the Brazilian Amazon. The current modelling study used the approach of varying the length of the cutting cycle (10–60 years) and maximum harvest intensity (10–30 m^3 ha^{-1}). The most extreme combinations were excluded before simulation leaving the combinations detailed in Table 3 with the resulting predictions of yield shown as Fig. 2.

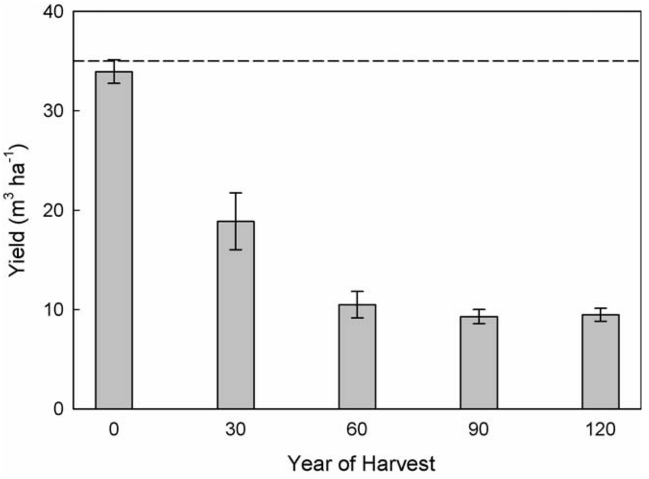

Fig. 1. Predicted yield resulting from the simulation of current Brazilian yield regulation systems with a cutting cycle of 30 years and maximum harvest of 35 m^3 ha^{-1}. Data are the mean calculated from 15, 1 ha composite plots ±1 standard error.

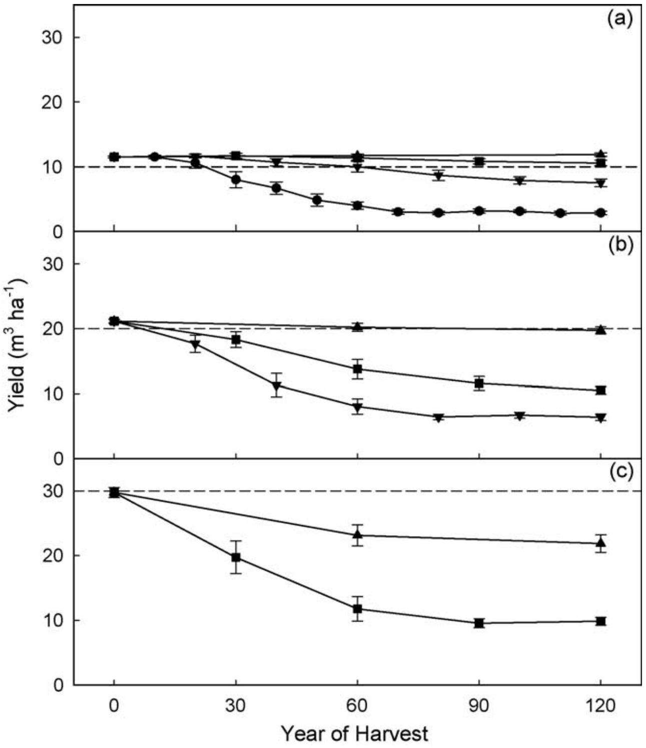

Fig. 2. Predicted yield resulting from the simulation of alternative yield regulation systems. Horizontal dashed line represents the target harvest levels of 10, 20 and 30 m^3 ha^{-1}. Cutting cycles varied between 10 (●), 20 (▼), 30 (■) and 60 years (▲). Data are the mean calculated from 15, 1 ha composite plots ±1 standard error.

Previous studies have suggested that the sustained timber yield from managed natural tropical forests is likely to be less than that which could be extracted initially from primary forests (Alder and Silva, 2001; van Gardingen et al., 2003; Sist et al., 2003; Dauber et al., 2005). The same pattern is observed in the results shown in Fig. 2. A horizontal line would indicate sustained yield. Only a limited number of low-intensity management scenarios sustained the target yield. These were 10 m^3 ha^{-1} combined with either 30- or 60-year cutting cycles and the 20 m^3 ha^{-1} yield with a 60-year cutting cycle. All others produced yields that eventually fell below the target level.

A smaller number of management scenarios were then examined in greater detail with additional criteria for sustainability including the volume of the residual stand and the relative balance of ecological groups in the forest. Four combinations were compared, with volume limits of either 10 or 20 m^3 ha^{-1} and a cutting cycle of either 30 or 60 years.

The volume of the residual stand was used as the second criterion of sustainability (Fig. 3) showing results for both total and commercial volume. These results illustrate the four alternative yield regulation scenarios. For the 30-year cutting cycle there is clear evidence of a decline in commercial volume (a and b). Similar results are observed for total volume (e and f). The longer 60-year cutting cycle demonstrated much less marked declines in commercial volume (c and d) and total volume (g and h). The fact that even low logging intensities (10 m^3 ha^{-1}) together with extended cutting cycles (60 years) do not allow for the complete recovery of commercial stock and total volume reiterates the observation that the structure of the stand of a managed natural forest must be expected to differ from that of primary forest. For this reason the appropriate criteria for sustainability may need to be that the forest comes to a new equilibrium stand structure or characteristics.

Combining the criteria of sustainable yield (Fig. 2) and stand structure is a useful tool to assess sustainability. This is presented as Table 5 showing that only the combination of a 10 m^3 ha^{-1} harvest and 60-year cutting cycle can be considered to be fully sustainable, whilst the 10 m^3 ha^{-1}/30 years and 20 m^3 ha^{-1}/60 years are considered marginal.

3.2. Determinants of yield

In order to assess the determinants of yield further analysis was conducted. The average net increment over a cutting cycle is shown for a number of scenarios as Fig. 4. Two general trends are observed from these results. Firstly, that the increment tends to be higher in scenarios applying heavier harvest intensities. Secondly that increments are lowest after the first harvest and tend to increase in subsequent harvests.

The highest increment observed in Fig. 4 was 0.33 m^3 ha^{-1}. If it is considered that yields should not exceed the stand's potential increment this would imply maximum harvest levels of 3 m^3 ha^{-1} for a 10-year cutting cycle, 10 m^3 ha^{-1} for 30 years and 20 m^3 ha^{-1} for a 60-year cutting cycle. These confirm the results shown in Table 5, which has the 10 m^3 ha^{-1}/30 years and 20 m^3 ha^{-1}/60 years combinations as possible, but with marginal sustainability.

In order to further illustrate the impact of logging intensity on increment, one additional set of simulations were conducted. In this, a single logging was simulated and the regrowth monitored at 20-year intervals over a 120-year period. This was done for two logging intensities, 10 and 40 m^3 ha^{-1} and the results are shown as Fig. 5. This extreme example very clearly

Table 5
Sustainability assessment based on results shown in Figs. 2 and 3

Harvest intensity (m^3 ha^{-1})	Cutting cycle	Sustained yield	Commercial volume	Stand volume	Overall sustainability
10	30	✓	±	±	Marginal
20	30	✓	X	X	Fail
10	60	✓	✓	✓	Fully
20	60	✓	±	±	Marginal

Tick represents likely sustainability, ± is considered marginal and X is failure. The overall rating for sustainability brings together three criteria of yield, combined with commercial and total volume.

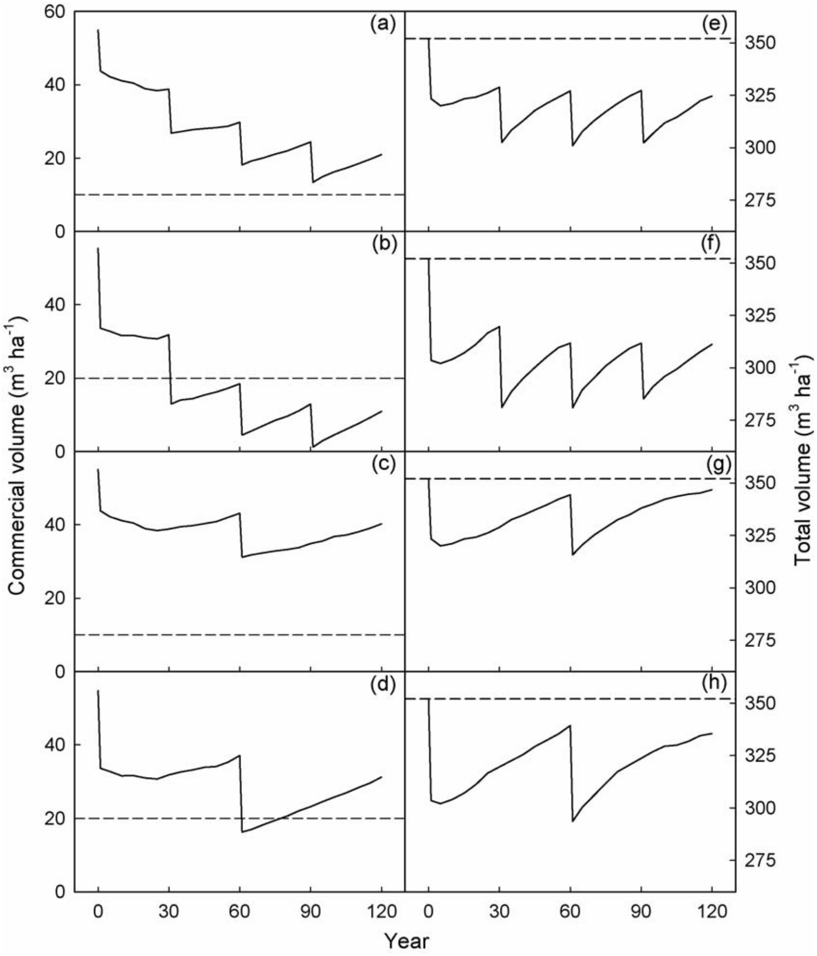

Fig. 3. Commercial and total stand volumes from simulations of alternative yield regulation systems. Commercial volume (a–d), dashed line represents target harvest level (10 and 20 $m^3\ ha^{-1}$). (a and b) 30-year cutting cycle, (c and d) 60-year cutting cycle. Total volume (e–h) corresponding with those shown as (a–d), dashed line represents the initial stand volume.

illustrates that high logging intensity results in significantly higher rates of commercial increment or regrowth.

The results presented here have identified an upper limit to timber harvesting for the Tapajos region of the Brazilian Amazon which is equivalent to 0.33 $m^3\ ha^{-1}\ year^{-1}$.

3.3. Ecological analysis

Simulation models such as SYMFOR have the advantage of being able to examine many aspects of the response of forest stands to simulated logging. The analysis presented in this paper has examined the impact of logging on predicted yield and the residual stand volumes. SYMFOR also contains significant ecological information. The version for the Brazilian Amazon was defined using 10 ecological species groups (Phillips et al., 2004). This information can be used to examine predicted changes in species composition following logging. The 10 $m^3\ ha^{-1}$ simulation presented in Fig. 5 were used to evaluate changes in ecological species groups following harvesting. Fig. 6 shows changes in the total volume for six important ecological species groups including the pioneer, upper canopy and emergent species. The trends are as would be expected from the ecological literature, with an initial increase in the two pioneer groups (c and e) which are then slowly replaced by fast growing upper canopy species. It is extremely important to note that significant differences in species composition should be expected even 100 years after a single logging event.

The emergent or climax species (Fig. 6d) do not show significant recovery over the period of the simulation. This is a reflection of the relatively low rates of recruitment and growth observed in the Tapajós dataset. This group also demonstrates very limited response to environmental competition in the model, specifically growth rates are not expected to increase significantly after canopy opening through logging. The simulation based on available data suggests that logging will reduce the prevalence of the emergent species to be replaced by faster growing species in the upper canopy (Fig. 6b and f).

The analysis of changes in species within the main ecological groups was supplemented with the same analysis comparing commercial and non-commercial trees in the stand. For this analysis, a commercial tree was defined as one that could potentially be harvested, by belonging to the commercial species group, having a DBH greater than 45 cm and a relative stem quality greater than 0.3. This simulation (Fig. 7) shows that whilst the volume of non-commercial trees has completely

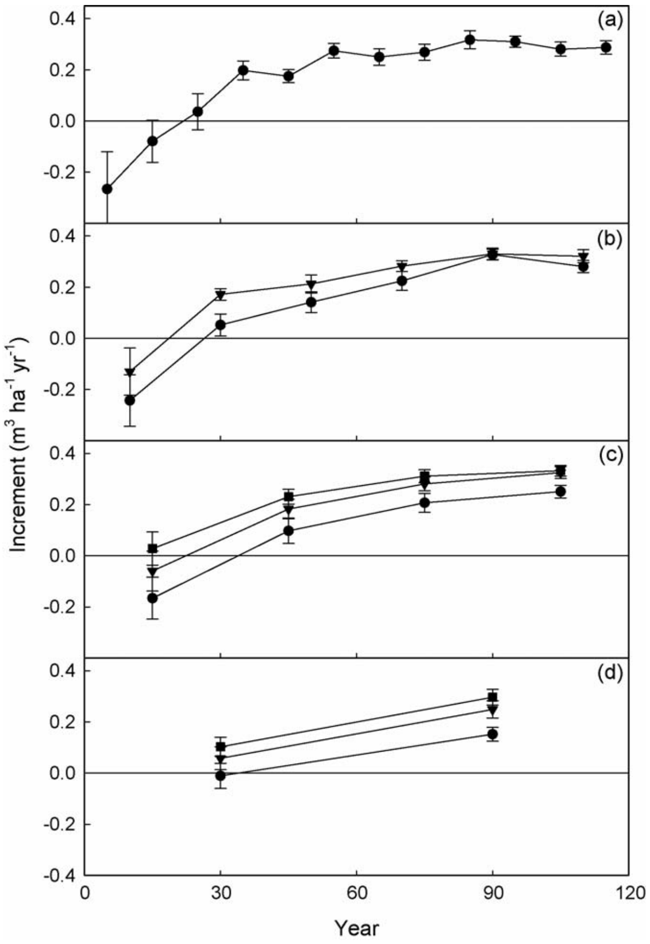

Fig. 4. Net commercial increment resulting from a repeated simulated logging with maximum harvest of 10 (●), 20 (▼) and 30 m^3 ha^{-1} (■). Cutting cycles are 10 (a), 20 (b), 30 (c) and 60 (d) years. Data are the average over each cutting cycle ±1 standard error. Other details as for Fig. 1.

recovered after 40 years, commercial tree volume has not fully recovered even after 120 years. The main reason for this is that the logging operation is designed to extract commercial trees from the forest, but the observation that the current commercial species group (Appendix A) has a predominance of relatively slow growing species (Fig. 6) will contribute to the slow rate of recovery.

These observations have three very important implications for sustainable management of the Amazon forests. Firstly, that the species composition of managed forests *will be different* from that observed in primary forests. For this reason, maintenance of species composition (volume or number of stems) is not a suitable criterion for sustainable forest management. The second implication is that there is likely to be a shift in the species composition of trees suitable for harvesting in subsequent harvests. This has very important implications for the timber processing industry which may have to adapt to changes in timber supply. The shift towards species with higher growth rates, typically light demanding or responding species is likely to produce timber with lower density. Finally, the prediction that the proportion of emergent species in the stand will decrease, means that additional specific measures will be required to promote the regeneration of these species.

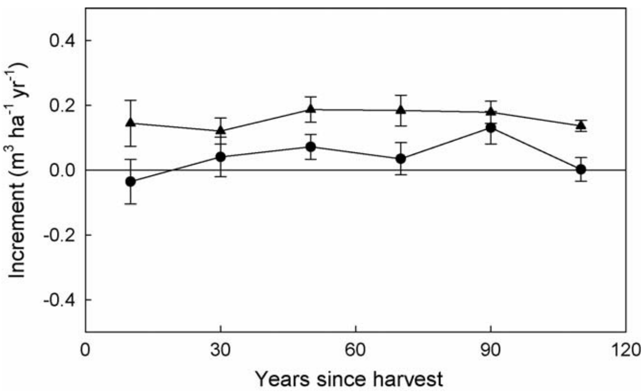

Fig. 5. Net commercial increment resulting from a single simulated logging with maximum harvest of 10 (●) and 40 m^3 ha^{-1} (▲). Data are the average over each 20-year period ±1 standard error. Other details as for Fig. 1.

4. Discussion

4.1. Implications for forest management in the Amazon

Forest managers need to explore means to increase the productivity of the forests to meet their economic objectives, whilst also meeting demands from society to adapt to new social and environmental norms. In addition, the benefits associated with timber certification schemes provide incentives for change. Managers have a much wider range of options available than those explored in the current study. Previous work with the equivalent model for Indonesia (SYMFOR) (Phillips et al., 2003) suggested that adjusting the list of commercial species would be an effective way of increasing harvested yield (van Gardingen et al., 2003). One of the main reasons for the much higher yields observed in Indonesia is that the commercial species groups constitute a much higher proportion of total stand volume (van Gardingen et al., 1998; Phillips et al., 2002b) than that observed in the Tapajos dataset. Also, the growth rates modelled in the current study tend to be much lower than those modelled for Southeast Asia (Phillips et al., 2003) and they tend to be less responsive to canopy opening. The implications of slow growth rates of Amazonian trees has been discussed in relation to carbon cycling (Vieira et al., 2005). The findings from the current study leads to the suggestion that the most appropriate way to *increase the productivity* of forests in the Brazilian Amazon will be to look for opportunities to enhance the range of species utilised commercially. This conclusion is also supported by the results of an independent study using the Tapajós data (Keller et al., 2004).

The current study demonstrates that changes in species composition should be an expected outcome over the timeframe of standard logging cycles in selective logging systems. This conclusion is supported by the analysis of (Vieira et al., 2005) who concluded that recovery of species composition could take many centuries in the Amazon region. The study of (Keller

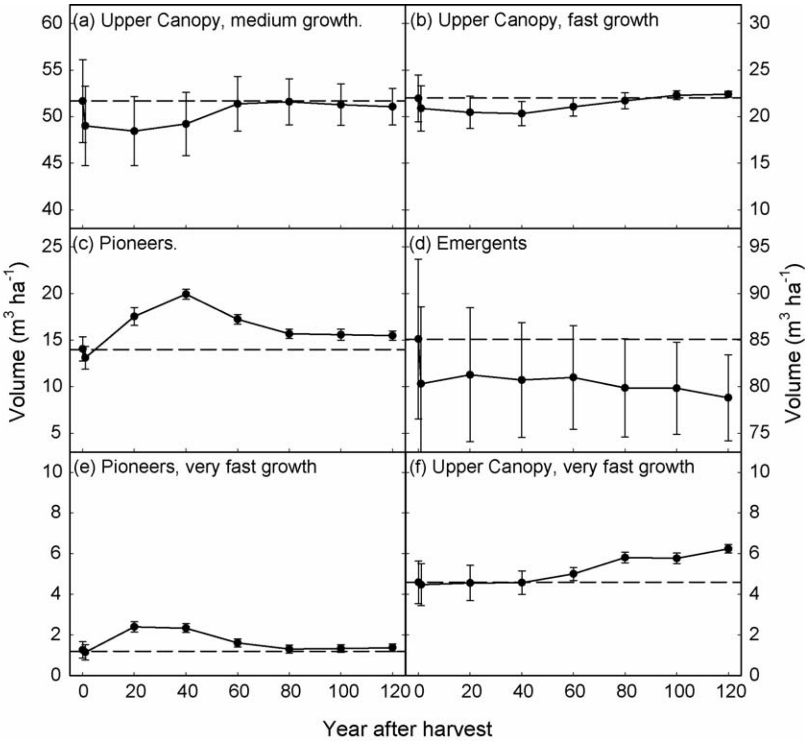

Fig. 6. Changes in the total volume in selected ecological (Table 1) and commercial groups (Appendix A) following a single logging with 10 m^3 ha^{-1} intensity. Horizontal dashed line represents initial volumes. Other details as for Fig. 1. Note differences in vertical scale between groups.

et al., 2004) also showed that timber predicted yields were only sustainable for the Tapajós region when lesser known species are utilised, in that study, after the third simulated harvest on 30-year cutting cycle.

A significant challenge for forest managers and other stakeholders is to define guidelines on what level of change in species composition is acceptable in relation to the various services provided by managed forests. It is important to recognise that utilisation of new species implies that the timber processing industry may need to adapt to changing patterns of supply. There are potentially significant real costs associated with such change, and it is important for potential changes in supply to be factored into future investment decisions in the processing industry. In the absence of adaptation by the processing industry it may be very difficult to market new species.

Silvicultural treatments, such as thinning, have also been proposed and tested as an alternative to increase yield in the Amazon Basin (de Graaf, 1986, 2000; Jonkers, 1987; Hendrison, 1990; Silva et al., 1995, 1996; de Graaf et al., 1999; van der Hout, 1999; Schulze, 2003; Vidal, 2004). However, to date, the results of experimental silvicultural treatments have produced varying results. Some results even reveal that thinning can impact negatively on the increment of commercial volume, often explained by the high mortality after thinning (Oliveira, 2005). At present, there is only a single example of silvicultural treatment being applied at an operational scale in the Brazilian Amazon (Graaf, 2000). The absence of appropriate data limits the possibilities for further simulation studies of silvicultural treatments at this time.

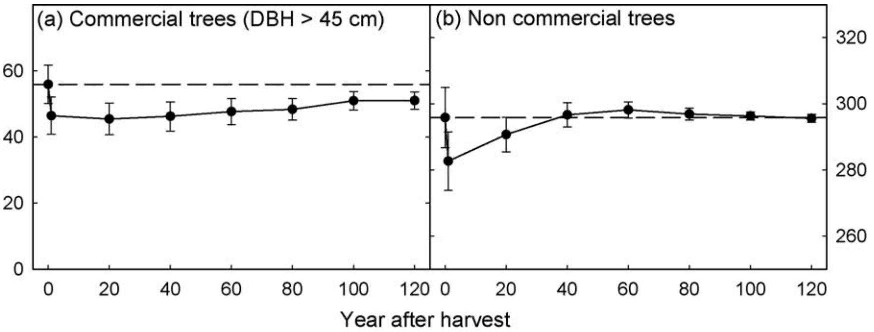

Fig. 7. Changes in the total volume for commercial and non-commercial trees following a single logging with 10 m^3 ha^{-1} intensity. Horizontal dashed line represents initial volumes. Commercial trees include all individuals from the species listed in Appendix A with a DBH greater than 45 cm and stem quality greater than 0.3 at each point in the simulation. Non-commercial trees represent all other trees in the stand. Other details as for Fig. 1.

The Legal Brazilian Amazon occupies nearly 5 million square kilometres, with a consequent high spatial heterogeneity in respect to ecological, environmental social and economic characteristics. For example, market conditions vary both spatially and temporally; proximity to processing sites or timber markets may increase the number of commercial species whilst conversely high transport costs may restrict logging to high value species. Similarly, as transport infra-structure evolve and high-valued timber becomes scarce, other previously non-commercial species become financially atractive (Veríssimo et al., 1995, 1998; Stone, 1998).

In addition, difficulties in estimating parameters and natural population fluctuations imposes the need of constant monitoring of data used to determine management regimes (Sutherland, 2001). It is unlikely that the results from this study will be applicable for the entire Brazilian Amazon and monitoring in Tapajós will remain essential and obtaining data from new sites, highly desirable. The absence of information relevant to forest management for much of the other areas of the Brazilian Amazon raises the question of how to proceed when data are limited.

The United Nations Conference on Environment and Development produced the ‘‘Rio Declaration’’ which adopted the concept of the precautionary approach or principle (UNCED, 1992). Extending these concepts to the results of the current study suggests that a realistic option would be to include some form of safety margin into forest management plans. For instance, even if the results presented here support logging of 10 m^3 ha^{-1} every 30 years, this should only be allowed if the 10 m^3 ha^{-1} do not represent more than one third of the commercial stock of the area, guaranteeing this way that at least three logging will be possible.

Tropical forest stakeholders are very diverse (Sheil et al., 2004), ranging from communities utilising a few hectares to large commercial operations including large privately owned forested lands, such as the half a million hectares forest under management owned by the Grupo Orsa Florestal. Apart from land size, marked differences may be seen in relation to land ownership. Although legal forest management is currently done predominantly on private lands, a drastic increase in the proportion of public lands under legal forest management is likely to occur if the Brazilian National Forest Program achieves its objective to create 500,000 km^2 of forest management concession area by 2010 (Veríssimo et al., 2002).

These differences makes it necessary to state that there should not be a unform set of limits applied for yield regulation for the Amazon since there is a need to adapt management to address all contexts (social, ecological, environmental and economic) and the variety of different objectives for forest management, as also discussed by Zarin et al. (in prep). For instance, the Forest Stewardship Council (FSC) began the project Small and Low Intensity Managed Forests (SLIMF) after recognizing that the realities and needs of small-scale forest management are far different from large-scale operations (FSC, 2005). Also, privately-owned forests management regimes are likely to be adapted to enhance yield and hence profitability, albeit at a potential loss of some environmental services. In contrast the management of publicly-owned forested land may need to place greater emphasis on aspects such as biodiversity and other services provided by the forest.

5. Conclusions

The simulation of growth and yield from the Tapajós region in this paper has suggested that the sustainable yield for current management practice may be as low as 0.33 m^3 ha^{-1} $year^{-1}$, or 10 m^3 ha^{-1} over a 30-year cutting cycle. This is considerably lower than levels currently being discussed for legislation in Brazil. There is no doubt that such an approach to sustainable management will be unwelcome to some parts of the forest industry. The move towards forest certification provides an opportunity to encourage these groups to adopt sustainable practices. There are two ways that industry could adapt their practice to be able to justify higher levels of extraction. The first will be to seek to diversify the selection of species that are harvested. This study provides a very clear indication that forest managers should try to develop markets for the faster growing upper canopy trees that respond well to the disturbance following logging. This approach will be extended as part of a future research study. The second action that commercial operations should invest in, is to develop their own research capacity to collect site-specific data describing the growth and potential yield of their forest. This could then be used, where appropriate, to justify higher levels of extraction to both certifying and legislative organisations.

The nature of the results produced by the application of Simflora to study management of the Tapajos region has helped to link forest ecology and management and illustrate some basic but very important principles applicable to tropical forests. Arguably, the most important is that the structure of a managed ‘‘natural’’ forest will differ from that of the original primary forest. Species composition, size distribution and probably maximum volume and basal area will all be different over time scales that are realistic for forest managers. This is an important message for legislators, certifiers and environmental groups who should not expect managed forests to return to a state equivalent to that of primary forests. Whilst it is possible to reduce the impact of logging, it is not possible to remove it. *How much change is acceptable should be a matter for public debate*.

The pragmatic option is to develop a mosaic of land use and management which should include reserves of primary forest to protect biodiversity and environmental services that are most sensitive to logging. A similar message is also relevant to the forest industry which needs to be aware that the types and characteristics of timber being produced by the forest will change in second and subsequent harvests. The costs and time-scales involved with investment decisions means that actions should be taken now to prevent an imbalance between demand and supply from the legally managed Amazon.

In summary there are four main messages that come out of this study:

1. Estimates of the maximum sustainable yield of forests in the Brazilian Amazon will need to be reduced for current forest management practices. A *maximum* level of

$0.33\ \mathrm{m^3\ ha^{-1}\ year^{-1}}$ combined with a maximum logging intensity of 33 % of total commercial volume (at the time of harvesting) is suggested based on a combination of data analysis and the application of the precautionary principle. We do, however, recognize that yield regulation should be adaptable to the different contexts (social, ecological, environmental and economic) and the variety of objectives for forest management within the Brazilian Amazon.

2. Improved forest management practice should be able to increase the level of sustainable yield. The most promising immediate option will be to diversify the range of species utilised for timber production.
3. The relative importance of slow-growing emergent species is predicted to decrease in response to harvesting. This is mainly a result of the poor observed regeneration of these species in managed forests and slow subsequent growth rates. Additional measures will be required to promote the establishment, growth and survival of emergent species in managed forests in the Amazon if the presence of these species is to be maintained to meet ecological and economic objectives.
4. Stakeholders need to recognise that sustainably managed forests will have different structural characteristics and species compositions compared to primary forests. This has implications for legislators, environmental groups, forest certifiers and the forest industry.

It is highly unlikely that a single management prescription or regime for natural forests in the Amazon will meet the diverse needs of all stakeholders. Future management of the Amazon will need to adopt a more flexible approach to adapt to the differences in land tenure, extent of managed areas and management objectives. It is essential that future management regimes should recognise the constraints imposed by the ecology of the region since sustainable management will only be possible when our understanding of forest ecology, management and economics come together. There is still time to implement sustainable forest management practices for the Amazon. All stakeholders have a responsibility to work together towards this objective. The results from this study can stimulate and support debate and decisions towards that end.

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Appendix A

Commercial species list, with ecological group and mean tree density ($\mathrm{trees\ ha^{-1}}$) and basal area ($\mathrm{m^2\ ha^{-1}}$) by species ($\mathrm{DBH} \geq 10\ \mathrm{cm}$). On average there were 73 commercial stem per hectare ($\mathrm{DBH} > 10\ \mathrm{cm}$) corresponding to a basal area of $8.3\ \mathrm{m^2\ ha^{-1}}$. The ecological groups are defined in Table 1.

Family	Genus	Species	Ecological group	Number of stems ($\mathrm{trees\ ha^{-1}}$)	Basal area ($\mathrm{m^2\ ha^{-1}}$)
Anacardiaceae	*Astronium*	*Gracile*	8	1.6	0.22
Anacardiaceae	*Astronium*	*Lecointei*	3	0.1	0.01
Bignoniaceae	*Jacaranda*	*Copaia*	6	0.9	0.07
Bignoniaceae	*Tabebuia*	*Impetiginosa*	8	0.5	0.17
Bombacaceae	*Ceiba*	*Pentandra*	8	0.1	0.10
Boraginaceae	*Cordia*	*Bicolor*	3	3.0	0.15
Boraginaceae	*Cordia*	*Goeldiana*	3	0.7	0.04
Burseraceae	*Trattinickia*	*Rhoifolia*	6	1.3	0.13
Caesalpiniaceae	*Dialium*	*Guianensis*	5	1.3	0.09
Caesalpiniaceae	*Hymenaea*	*Courbaril*	8	1.3	0.42
Caryocaraceae	*Caryocar*	*Glabrum*	8	0.5	0.17
Caryocaraceae	*Caryocar*	*Villosum*	8	0.3	0.24
Celastraceae	*Goupia*	*Glabra*	8	0.9	0.31
Euphorbiaceae	*Glycidendron*	*Amazonicum*	3	1.1	0.04
Fabaceae	*Dipteryx*	*Odorata*	8	0.1	0.02
Fabaceae	*Hymenolobium*	*Excelsum*	8	0.5	0.05
Flacourtiaceae	*Laetia*	*Procera*	3	0.7	0.05
Guttiferae	*Symphonia*	*Globulifera*	3	0.8	0.05
Lauraceae	*Mezilaurus*	*Itauba*	5	0.1	0.03
Lauraceae	*Mezilaurus*	*Lindaviana*	3	2.6	0.12
Lecythidaceae	*Couratari*	*Oblongifolia*	5	8.1	1.05
Leguminosae	*Apuleia*	*Molaris*	6	0.2	0.04
Leguminosae	*Enterolobium*	*Maximum*	3	1.5	0.09

Appendix A (*Continued*)

Family	Genus	Species	Ecological group	Number of stems (trees ha^{-1})	Basal area (m^2 ha^{-1})
Leguminosae	*Eperua*	*Schomburgkiana*	3	1.3	0.07
Leguminosae	*Hymenaea*	*Parvifolia*	5	0.7	0.07
Leguminosae	*Ormosia*	spp.	4	2.6	0.07
Leguminosae	*Parkia*	*Multijuga*	6	1.6	0.15
Leguminosae	*Schyzolobium*	*Amazonicum*	10	0.2	0.03
Meliaceae	*Carapa*	*Guianensis*	3	10.7	1.17
Mimosaceae	*Dinizia*	*Excelsa*	8	0.1	0.00
Mimosaceae	*Enterolobium*	*Schomburgkii*	6	0.6	0.11
Mimosaceae	*Parkia*	*Pendula*	8	0.1	0.01
Moraceae	*Bagassa*	*Guianensis*	8	0.2	0.11
Moraceae	*Brosimum*	*Lactescens*	3	2.7	0.17
Moraceae	*Brosimum*	*Parinarioides*	8	1.0	0.13
Moraceae	*Clarisia*	*Racemosa*	5	0.5	0.04
Myristicaceae	*Virola*	*Melinonii*	3	6.4	0.41
Rubiaceae	*Capirona*	*Huberiana*	3	0.5	0.02
Sapotaceae	*Manilkara*	*Huberi*	8	5.1	1.02
Sapotaceae	*Manilkara*	*Paraensis*	8	1.5	0.18
Sapotaceae	*Micropholis*	*Venulosa*	1	1.5	0.06
Sapotaceae	*Pouteria*	*Bilocularis*	3	7.3	0.68
Simaroubaceae	*Simaruba*	*Amara*	6	0.5	0.07
Vochysiaceae	*Vochysia*	*Maxima*	6	0.1	0.03

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