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The sustainability of timber production from Eastern Amazonian forests

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ABSTRACT

Although the regulations are imperfectly enforced, logging firms in the Brazilian Amazon are subject to forest management regulations intended to reduce environmental damage and protect future forest productivity. Additionally, voluntary best practices firms adopt to achieve environmental performance that exceed regulatory requirements are largely limited to reduced impact logging (RIL) systems that reduce harvest damage relative to conventional logging systems used by a large majority of firms in the region. Existing regulations combined with best practices may not be adequate to ensure sustained yields. This inadequacy is an important issue as Brazil implements an ambitious program of forest concessions on public lands. We analyze the profitability and environmental outcomes of best logging practices and proposed sustainability requirements. We propose two operational definitions of sustainability (the first focusing on sustaining stand-level timber volumes and the other focusing on sustaining species-level volumes within the stand) based on sustaining timber inventories across cutting cycles rather than on sustaining overall harvest yields. RIL is shown to be profitable for loggers and increase the timber available for future harvests. While volume predicted to be available for the second and third harvests are significantly lower than the available timber in the unlogged forest, the second and third harvests are projected to be profitable and have the potential for sustainability despite high opportunity costs. However, as harvesting is repeated into the future, results show the composition of the harvest shifts from higher-value shade-tolerant and emergent species toward a greater reliance on longer-lived, lower-value pioneer species. This shift may create pressure to expand the forest base under management in order to continue to supply high-value species or increase the risk of timber trespass in conservation units and areas under community or indigenous management.

Introduction

Although the regulations are imperfectly enforced, logging firms in the Brazilian Amazon are subject to forest management regulations intended to reduce environmental damage and protect future forest productivity. These restrictions include strict cutting cycles, minimum diameter cutting limits, upper bounds on harvest intensity, the retention of seed trees and individuals of rare species, and protection of riparian buffers and wildlife. Additionally, voluntary best practices firms adopt to achieve environmental performance that exceed regulatory requirements are largely limited to reduced impact logging (RIL) systems that reduce harvest damage relative to conventional logging systems used by the large majority of firms in the region (Zarin et al., 2007). Meanwhile, the Brazilian government is moving forward with an ambitious program of allocating forest management concessions on public lands (Veríssimo et al., 2002a,b). An element of this program is likely to be a new regulatory instrument based on sustainable timber yields.

Several authors have questioned whether the current restrictions combined with best practices are adequate to ensure sustained timber production (Valle et al., 2007; Van Gardingen et al., 2006; Zarin et al., 2007). Few attempts have been made to establish quantitative sustainability objectives that can be applied in practice in Brazil. An exception is Van Gardingen et al. (2006), who found that to achieve sustainable yields in the Tapajós National Forest, loggers must not harvest more than 0.3 m^3/ha/year in combination with no more than one-third of the commercial stock being removed during any single harvest. Yields such as these may in fact be ecologically feasible but not profitable. Studies of the profitability of different forest management strategies have been limited to a few studies of RIL projects (Bacha and Rodriguez, 2007; Barreto et al., 1998; Holmes et al., 2002). These studies

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evaluate the costs and benefits over short periods of time for harvests that remove nearly all merchantable volume. A dynamic approach that incorporates forest responses to different harvest systems and intensities is needed, which we provide in this paper. We also propose and implement two operational definitions of sustainability in the form of harvest constraints requiring sustaining timber inventories across cutting cycles rather than on sustaining overall harvest yields: weakly sustained inventory (WSI) which requires sustaining the overall standing volume of merchantable timber at the end of each harvest cycle and strongly sustained inventory (SSI) which requires sustaining the standing volume of merchantable timber at the species-group level at the end of each harvest cycle.

Identifying the optimal harvest paths under the proposed sustainability requirements requires a two-stage optimization process. First, we identify the harvests and standing timber stocks for a stylized maximum sustainable yield problem. This first stage produces the species-group and stand-level timber inventories that quantify the sustainability constraints. These constraints are then applied in a second stage optimization model to evaluate forest conditions and financial returns under the constraints. We also simulate RIL and CL harvests under the current set of Brazilian forest management regulations to evaluate how well the regulations induce sustainable yields.

Methods

Study site and forest data

The forest inventory data used in the study were collected by researchers from the Instituto do Homem e Meio Ambiente da Amazônia (Imazon) from 1993 and 2003 within a privately owned 205 ha forest block in the Paragominas region of Pará, Brazil (3°S47.5°W). These data have been used in numerous papers in tropical forest ecology and management, as the experiment produced one of the best datasets in Brazilian Amazon for a forest under harvest pressure. Periodic inventories continue to be performed at the site under the supervision one of this study's authors (E.V.).

The forest block, which contains more than 350 tree species, was subjected to three treatments in 1993: an unlogged 25 ha control plot, a 75 ha plot logged using CL techniques by a locally recruited logging crew, and a 105 ha plot logged using RIL by a formally trained crew (Johns et al., 1996). Given that the RIL plot was larger than the CL plot in the experiment, we assume that there is no scale economy for logging that influenced per hectare logging costs. The overall harvest intensities were approximately the same within the CL plot and the RIL plot, but the amount of residual stand damage varied dramatically (Barreto et al., 1998; Johns et al., 1996). RIL practices implemented in the experiment included the following typical RIL practices, adapted from Dykstra (2002):

- Pre-harvest commercial tree inventories and maps
- Pre-harvest planning of roads, skid-trails, and landings
- Pre-harvest vine cutting at least one year before harvesting
- Directional felling, cutting stumps low to the ground, and optimal bucking of stems
- Construction of roads, landings, and skid-trails that satisfy design guidelines
- Conducting post-harvest assessments to provide feedback to forest managers

Using these data, Barreto et al. (1998) examined the relative costs and benefits of following best logging practices and found substantial financial benefits from implementing RIL during a single harvest.

We clustered species into five groups based on ecological traits, such as seed size, seedling shade tolerance, growth potential, wood density, and maximum adult size, based upon a synthesis of published information and field observations made by two of the authors (E.V. and M.D.S) and another experienced researcher (J. Grogan):

1. **Pioneer species** are characterized by small seeds, early reproduction, aggressive colonization of canopy openings, rapid growth, high mortality rates, low wood density, and relatively small adult size. For example, *Cecropia* spp. (Embaúba species primarily) are common in this group. Pioneers include some longer-lived, low-value commercial species used primarily for plywood. Wood density ranges from approximately 0.3–0.5 g/cm^3 in oven-dry mass/fresh volume (Chave et al., 2009; Zanne et al., 2009).
2. **Light-demanding species** have shade-intolerant seedlings and are capable of rapid growth under high-light conditions, but lack classic pioneer characteristics, such as copious early seed production and small adult stature. These species include many plywood and a few sawtimber species, such as *Cordia bicolor* (freijó-branco) and *Sterculia speciosa* (tacacazeira). Wood density in this group is approximately 0.4–0.6 g/cm^3 oven-dry mass/fresh volume.
3. **Intermediate species** have less abundant advance seedling regeneration in the forest understory than shade-tolerant species and generally lower wood density (0.5–0.7 g/cm^3 oven-dry mass/fresh volume) and higher growth rates. Intermediates include species like *Astronium lecointei* (muiracatiara) and *Ocotea caudata* (louro preto).
4. **Shade-tolerant species** generally have large seeds, seedlings capable of prolonged survival in the shaded forest understory, high density wood (0.6–1.0 g/cm^3 oven-dry mass/fresh volume), and low growth rates. Commercial species in this group, such as *Manilkara huberi* (maçaranduba), are used primarily for sawtimber and have medium to high commercial value.
5. **Light-demanding emergents** are characterized by high density wood (0.6–1.1 g/cm^3 oven-dry mass/fresh volume) and a highly skewed diameter distribution with a predominance of very large and old adult trees. Seedlings display shade intolerance, but grow slowly compared to pioneers and light-demanding species. The emergent group includes the highest value timbers species, such as *Tabebuia impetiginosa* (ipê) and *Hymenaea courbaril* (jatobá), which are also some of the most difficult to manage sustainably (Schulze et al., 2008; Zarin et al., 2007).

Matrix models and tropical forests

Matrix models of forest growth and yield are robust predictors of aggregate stand characteristics such as density, basal area, and diameter distribution, while being mathematically tractable (Sist et al., 2003; Vanclay, 2001). Matrix models are particularly advantageous in that they can be used to simulate a range of conditions based upon minimal data requirements (Gourlet-Fleury et al., 2005). Matrix models are often used in forest economics, particularly in tropical contexts where forests are complex and long term data are limited. We chose to implement a matrix model over alternatives because of the easy incorporation of economic factors and ability to rapidly evaluate policy alternatives. It should be noted, however, that while there are many advantages to using matrix models for forest policy analysis, matrix models typically do not capture important spatial aspects of forestry, such as the spatial distribution of commercial trees in the harvest unit, the locations of skid trails and logging decks, or the specific topography and hydrology of the harvest unit that may influence management decisions.

The matrix model

The pre-harvest stand state is given by the vector $\mathbf{y} = [y_{ij}]$ where y_{ij} is the number of trees per ha in species group $i = (1, \ldots, m)$ and size class $j = (1, \ldots, n)$. There are ten size classes each of 10 cm DBH width, beginning with 10.0–20.0 cm DBH and ending with ≥100.0 cm DBH. The 10.0–20.0 cm DBH size class is indexed by $j = 1$, 20.0–30.0 cm DBH is indexed by $j = 2$, and so on with the highest DBH class, ≥100 cm DBH indexed by $j = 10$. The harvest from species group i and size j is given by $\mathbf{h} = [h_{ij}]$. The choice of RIL or CL will influence damage, growth, and recruitment rates. Let s index the choice of harvest system, where $s = 0$ indicates no harvest occurs, $s = 1$ indicates a RIL harvest, and $s = 2$ which indicates a CL harvest. The damage to the residual stand is assumed to be a function of overall harvest intensity and harvest system and is represented by the $mn \times 1$ vector $\mathbf{d}_{st}$:

$$\mathbf{d}_{st} = \left(\sum_{i=1}^{m} \sum_{j=1}^{n} h_{ijt} \right) \mathbf{D}_s \mathbf{y}_t \tag{1}$$

where $\mathbf{D}_s$ is a $mn \times mn$ matrix whose diagonal contains the logging damage coefficient for trees in each species group i and size j under harvest system type s. The damage coefficients are estimated as a percentage of trees destroyed per tree harvested within each species group i and size j under harvest system s. The damage vector includes trees destroyed immediately upon harvest but does not include trees that were damaged during harvest operations and later died. The relatively high mortality rates of these damaged trees are captured within the growth transition matrices. When there is no harvest, $\mathbf{D}_0$ is an empty matrix.

Given a growth interval, θ, the stand state at $t + \theta$ is determined by the population, harvest, and damage at time t according to a modification of the multi-species uneven-aged matrix model presented in Boscolo et al. (1997) and Boscolo and Vincent (2000):

$$\mathbf{y}_{t+\theta} = \mathbf{G}_s(\mathbf{y}_t - \mathbf{h}_t - \mathbf{d}_{st}) + \mathbf{r}_{st} \tag{2}$$

where $\mathbf{G}_s$ is the transition matrix for treatment type s and the vector $\mathbf{r}_{st}$ captures recruitment as a function of stand density, species group, and treatment at time t. The growth matrix is organized as a matrix of transition matrices for each species group i:

$$\mathbf{G}_s = \begin{bmatrix} \mathbf{G}_{1s} & & \\ & \ddots & \\ & & \mathbf{G}_{ms} \end{bmatrix}. \tag{3}$$

Each matrix $\mathbf{G}_{is}$ contains the transition probabilities for each species group i under harvest system s. We estimated the transition parameters using multinomial logit regression (MNL) and the recruitment parameters using ordinary least squares. We chose to implement a discrete choice approach to estimate the transition parameters because this approach permits stochastic and dynamic approaches to simulation, while retaining the linearity of the transition matrix Boltz (Boltz and Carter, 2006). MNL-estimated transition parameters are also likely to be more smoothly distributed across size classes when compared to the proportional estimates of transition parameters typically used in matrix models (Boltz and Carter, 2006).

We set the growth interval θ in our study to ten years, as we had ten years of high quality data available. Ten years also provided a convenient projection interval. Details on the estimation of the transition, damage, and recruitment parameters can be found in Macpherson et al. (2010). The transition probabilities are estimated as a function of DBH to reflect the relative dominance of each tree in its spatial neighborhood, species group to incorporate growth and mortality differences across species groups, and harvest system to incorporate the impact of logging treatment. The damage coefficients are estimated as the percentage of trees killed in each species group, DBH range, and logging treatment. The recruitment of new trees is negatively related to the total number of post-harvest trees per ha, and is also modeled as a function of species group, harvest treatment, and the interaction between species group and harvest system to reflect differential responses to harvest across species groups.

Table 1
Perceived merchantability by species group and harvest system. To be merchantable, a tree must be of a commercial species, of legal size, of good stem form, and not hollow. Perceived merchantability refers to the likelihood that CL loggers do not inspect all trees for hollowness and are likely to perceive more trees as being merchantable than RIL loggers.

Logging system	Species group	Perceived merchantable proportion	
		Initial standing stock	New recruitment
RIL	Pioneer	0.40	0.48
	Light-demanding	0.39	0.46
	Intermediate	0.61	0.73
	Shade-tolerants	0.32	0.38
	Emergents	0.80	0.95
CL	Pioneer	0.45	0.49
	Light-demanding	0.44	0.48
	Intermediate	0.69	0.75
	Shade-tolerants	0.36	0.39
	Emergents	0.90	0.98

To be considered merchantable, a tree must be of a commercial species, of legal size, of good stem form, and not hollow. While both the RIL and CL logger will reject stems with poor form, the RIL logger will test trees for hollowness. We assume hollow trees compose 20% of the initial stand, based on Brown and Lugo (1992). For lack of quality data, we assume that RIL loggers identify all hollow trees, while the CL logger successfully identifies only 50 percent of the hollows, thereby incurring variable harvest costs. We vary this assumption later in the analysis to understand the sensitivity of results to this assumption. The *perceived* merchantable proportion for each species group i is placed within the diagonal of the $mn \times mn$ matrix $\mathbf{M}_s$ (Table 1). The initial pre-harvest perceived standing stock of merchantable timber, $\mathbf{y}_0^m$, is calculated as:

$$\mathbf{y}_0^m = \mathbf{M}_s \mathbf{y}_0 \tag{4}$$

where $\mathbf{y}_0$ represents the initial unlogged distribution of the stand, which is shown in Table 2. Where $\mathbf{d}_{st}^m$ represents the merchantable trees destroyed accidentally during harvest, the logger cannot harvest and incidentally destroy more merchantable stems than exist at time t, or:

$$\mathbf{y}_t^m \geq \mathbf{h}_t + \mathbf{d}_{st}^m. \tag{5}$$

Table 2
Distribution of stems by size (DBH), initial condition of stand, and solutions to maximum even-flow (MEF) problem (stems/ha).

Size	Initial condition	Cutting cycle for MEF problem (years)			
		30	40	50	60
10–20 cm	351.2	223.1	228.1	232.8	236.3
20–30 cm	88.5	114.3	108.7	105.7	104.7
30–40 cm	32.0	57.6	56.5	54.4	52.1
40–50 cm	13.8	27.9	26.6	26.4	26.0
50–60 cm	6.8	11.9	11.5	11.3	11.4
60–70 cm	3.4	3.0	3.7	4.1	4.4
70–80 cm	1.6	0.6	0.9	1.2	1.4
80–90 cm	1.3	0.3	0.3	0.4	0.5
90–100 cm	1.0	0.3	0.3	0.3	0.3
>100 cm	0.8	0.1	0.1	0.1	0.1
Total	500.5	439.0	436.7	436.5	437.1

As matrix models are often used to project logged stands into the far future, repeated application of a growth matrix estimated on data collected over a relatively short post-harvest period risks over-predicting future volumes. After the post-logging recruitment pulse, evidence shows the growth rates are likely to converge to that of an unlogged forest. This phenomenon was observed within the first decade after logging in the Fazenda Agrosete forest studied here (Valle et al., 2007), in the Tapajós National Forest in the Brazilian Amazon (Silva et al., 1995), and in Suriname (Dekker and De Graaf, 2003). We approximate this decline in growth rate over time in logged forest by applying control forest transition probabilities to RIL and CL populations from the second transition period after each harvest until the transition period after the next harvest. To explain, let γ equal the number of growth intervals between harvest entries. The RIL or CL post-harvest growth transition matrix, $\mathbf{G}_s$, is applied once for the first period after a logging entry and the control transition matrix $\mathbf{G}_0$ is applied until the next logging entry. Similarly, we apply the RIL or CL post-harvest recruitment function, $\mathbf{r}_s$, once during the first period after a logging entry and the control recruitment function $\mathbf{r}_0$ thereafter until the next logging entry. The evolution of the diameter distribution of a stand repeatedly logged using RIL ($s=1$), for example, would be determined by the following iterative procedure:

$$\begin{aligned}
&\mathbf{y}_{\theta} = \mathbf{G}_1(\mathbf{y}_0 - \mathbf{h}_0 - \mathbf{d}_{1,0}) + \mathbf{r}_{1,0}\\
&\mathbf{y}_{2\theta} = \mathbf{G}_0\mathbf{y}_{\theta} + \mathbf{r}_{0,\theta}\\
&\ldots\\
&\mathbf{y}_{\gamma\theta} = \mathbf{G}_0\mathbf{y}_{(\gamma-1)\theta} + \mathbf{r}_{0,(\gamma-1)\theta}\\
&\mathbf{y}_{(\gamma+1)\theta} = \mathbf{G}_1(\mathbf{y}_{\gamma\theta} - \mathbf{h}_{\gamma\theta} - \mathbf{d}_{1,\gamma\theta}) + \mathbf{r}_{0,\gamma\theta}\\
&\ldots
\end{aligned} \tag{6}$$

Commercial volume was calculated using the volume equations reported in Silva et al. (1984). The predicted volumes were averaged across species groups and size and placed into the $mn \times 1$ vector $\boldsymbol{\psi}$, the elements of which are shown in Table 3. The merchantable volume at time t is equal to the transpose of the commercial volume vector multiplied by the harvest vector at time t, or $\boldsymbol{\psi}'\mathbf{h}_t$. The unlogged stand may contain very large commercial trees that will be logged upon first entry, while insufficient time is likely to pass between cutting cycles to allow commercial trees to grow to such large sizes. Because of this concern, we assume all trees with diameters greater than 100 cm DBH have diameters of 110 cm DBH for the purpose of calculating commercial volume beyond the first harvest.

Steady-state solution

Drawing on Buongiorno and Michie (1980), previous multi-species, multi-age studies examining steady-state dynamics typically assume that the overall stand must maintain an equilibrium diameter distribution (*i.e.*, $\mathbf{y}_t = \mathbf{y}_{t+\gamma\theta} = \mathbf{y}^*$) to sustain the equilibrium harvest. Solving for a steady-state harvest in our model requires solving for an equilibrium diameter distribution of merchantable trees (*i.e.*, $\mathbf{y}_t^m = \mathbf{y}_{t+\gamma\theta}^m = \mathbf{y}^{m^*}$). We modified the equilibrium growth constraint of Buongiorno and Michie (1980) to impose the equilibrium conditions on the merchantable sub-stand:

$$\mathbf{y}^{m^*} = \mathbf{G}_0^{\gamma-1}\mathbf{G}_s(\mathbf{y}^{m^*} - \mathbf{h}^* - \mathbf{d}_{st}^{m^*}) + \sum_{i=0}^{\gamma-2}\mathbf{G}_0^{i}\mathbf{M}_s\mathbf{r}_0 + \mathbf{G}_0^{\gamma-1}\mathbf{M}_s\mathbf{r}_s \tag{7}$$

where $\mathbf{I}$ is the identity matrix. The steady state solution identifies the sum of harvest and merchantable harvest damage $(\mathbf{h}^* + \mathbf{d}_{st}^{m^*})$ that maintains the merchantable stand structure $(\mathbf{y}^{m^*})$ while taking into account the growth patterns of trees that recruit after the harvest, $\left(\sum_{i=0}^{\gamma-2}\mathbf{G}_0^{i}\mathbf{M}_s\mathbf{r}_0 + \mathbf{G}_0^{\gamma-1}\mathbf{M}_s\mathbf{r}_s\right)$.

The steady state solution is often difficult to interpret as it is solved independent of initial conditions and depends upon a series of regulation harvests that may take a long period of time to perform. That said the steady state solution contains interesting information about the maximum even-flow yield of the stand. We use this information to establish harvest constraints that require the logger to follow harvest paths that satisfy our proposed sustainability criteria, which will be seen momentarily.

Brazilian forest management regulations

The scenario in which current regulations are applied is called the Brazilian Regulatory Policy (BRP) case. The specific BRP parameters are drawn from a set of regulations enacted in 2009 (Resolução CONAMA 406/2009). The diameter cutting limit constraint used in this study is set at 50 cm DBH across all species groups to reflect the most general case of the current regulations in Brazil, or:

$$\sum_{j=1}^{4} h_{ij} = 0 \quad \forall i. \tag{8}$$

Consistent with Brazilian forest code, we do not apply an upper DBH limit for harvesting trees. The harvest intensity regulatory constraint, 30 m^3/ha per entry, is written:

$$\boldsymbol{\psi}'\mathbf{h}_t \leq 30 \quad \forall t. \tag{9}$$

Lastly, to retain seed trees, Brazilian standards obligate the logger to retain at least 10% of the stems of any given species that would otherwise be authorized for logging, or:

$$\sum_{j=5}^{10} h_{ijt} \leq 0.9\sum_{j=5}^{10} y_{ijt} \quad \forall i, t. \tag{10}$$

While Brazilian forest regulations are unclear on whether the practice is permissible, we assume loggers can satisfy this constraint by leaving hollow stems or stems of poor form.

Table 3
Commercial volume (m^3/stem) and price/tree (price/m^3 in 2004 dollars multiplied by volume/tree) by species group and size (DBH).

Variable	Species group	50–59.9 cm	60–69.9 cm	70–79.9 cm	80–89.9 cm	90–99.9 cm	>100 cm in initial harvest	>100 cm in subs. harvests
Comm. vol.	Pioneer	3.0	4.1	6.0	8.3	9.6	11.9	11.9
	Light-demanding	3.0	4.1	5.8	7.9	10.2	21.3	13.8
	Intermediate	2.9	4.4	6.0	8.1	9.6	17.0	13.8
	Shade-tolerant	3.0	4.3	6.6	8.4	10.4	15.2	13.8
	Emergent	3.0	4.4	6.1	8.1	10.8	19.6	13.8
Price/tree	Pioneer	86.5	114.3	234.7	344.3	418.4	475.7	475.7
	Light-demanding	84.5	110.8	156.4	205.4	275.4	537.5	348.2
	Intermediate	79.7	113.5	153.7	224.3	261.3	490.1	397.8
	Shade-tolerant	87.1	129.9	196.6	275.6	390.0	538.6	489.0
	Emergent	120.3	200.2	282.1	333.9	514.4	1313.0	924.5

Notes: Volumes estimated using volume equations in Silva et al. (1984). Prices based upon the mill prices in the Paragominas region based on economic surveys of mill owners and operators (Lentini et al., 2005).

Sustainability constraints

WSI requires that the overall standing volume of merchantable timber at the end of each harvest cycle be undiminished in perpetuity, without respect to the maintenance of volumes of any particular species group. SSI requires that the standing volume of merchantable timber at the species-group level at the end of each harvest cycle be undiminished in perpetuity. While the SSI constraint could be applied at the individual species-level, we target the constraints at the group-level.

The solution for the equilibrium harvest ($\mathbf{h}_t = \mathbf{h}_{t+\gamma\theta} = \mathbf{h}^*$) and size distribution ($\mathbf{y}^m_t = \mathbf{y}^m_{t+\gamma\theta} = \mathbf{y}^{m^*}$) that maximizes an economic objective determines the maximum even-flow (MEF) solution. While the analysis can in principle be extended to an infinite horizon, we assume a concession contract specifies two harvest entries under a fixed cutting cycle, permitting entries at $t = 0$ and $t = \gamma\theta$. Should a subsequent contract be issued, the terminal merchantability constraint maintains the conditions of the stand for the first entry of the subsequent contract at $t = 2\gamma\theta$. Where the pre-harvest merchantable volume at time t equals $\boldsymbol{\psi}'\mathbf{y}^m_t$, WSI requires that the pre-harvest stand-level merchantable timber never diminishes below the equilibrium pre-harvest merchantable volume found by solving the MEF problem:

$$\boldsymbol{\psi}'\mathbf{y}^m_{\gamma\theta} \geq \boldsymbol{\psi}'\mathbf{y}^m_{2\gamma\theta} \geq \boldsymbol{\psi}'\mathbf{y}^{m^*}. \tag{11}$$

Meanwhile, the SSI constraint requires that the merchantable timber never diminishes at the species-group level:

$$\sum_{j=1}^{n} \psi_{ij} y^m_{ij,\gamma\theta} \geq \sum_{j=1}^{n} \psi_{ij} y^m_{ij,2\gamma\theta} \geq \sum_{j=1}^{n} \psi_{ij} y^{m^*}_{ij}. \tag{12}$$

We hypothesize that our approach to constraining inventories greater than or equal to levels found in the steady state induces a series of harvests that regulates the stand toward its optimal size and species distribution. While we do not explicitly examine whether the solution traces the most rapid approach path to the steady state, the management prescriptions are sufficiently simple such that they can be implemented in the field.

Economic variables

For this analysis, we assume prices and costs are constant and in US$2004 (Table 3). About 75% of the stems greater than 50 cm DBH in the Agrosete experimental forest are of commercial species. The prices are derived from responses to economic surveys of mill owners and operators in the Paragominas region (Lentini et al., 2005). While desirable, a more complex treatment of price dynamics over time is not possible due to the paucity of long-term species-level price data in the region. Management costs are classified as either variable or fixed costs and are drawn from Barreto et al. (1998) and Lentini et al. (2005). Variable costs of harvesting a tree in species group i and size j under harvest system s is represented by vc_{ijs} and includes the costs associated with felling, skidding, log deck operations, and transportation. The variable costs are estimated at \$15.64/m^3 for the RIL logger and \$13.48/m^3 for the CL logger. Fixed costs in \$/ha (represented by fc_s) are incurred at each cutting cycle entry for planning, capital costs, and transaction costs and are estimated at \$50.56/ha for the RIL logger and \$13.91/ha for the CL logger. While Boltz et al. (2001) were able to evaluate the role of uncertainty in logging costs in determining that financial returns from RIL were greater than those for CL for a similar Eastern Amazonian forest, our data did not permit a similar examination of the importance of uncertain costs in harvest decisionmaking. We apply a constant real discount rate (r) of 10%, based upon real interest rate reported for the bulk of 2004 by Brazil's National Bank of Economic and Social Development.

Table 4

Inefficiency across logging systems. Operational inefficiencies lead to potential harvest volume lost to poor logging techniques or left in the forest because felled trees could not be found by skidder operators. The deductions for inefficiency are applied as percentage of revenue.

Harvest treatment	Cut hollows	Poor felling and bucking[a]	Lost trees[a]	Waste
RIL	0.000	0.039	0.003	0.042
CL initial harvest	0.100	0.123	0.038	0.261
CL subsequent harvests	0.025	0.123	0.038	0.186

[a] Values derived from Holmes et al. (2002).

The benefits of implementing RIL extend beyond the reduction of damage to the residual stand and minimizing the felling of hollow trees. The operational improvements lead to less timber lost to poor logging techniques or left in the forest because felled trees could not be found by skidder operators (Holmes et al., 2002). Table 4 shows the percentage deductions applied against the RIL and CL loggers' revenues to calculate the variable w_s to incorporate financial losses that results from production inefficiency.

Concessionaire objectives

In each of the seven scenarios that follow, the concessionaire is allowed two logging entries, the timing of which is strictly defined by the cutting cycle with the first harvest at $t = 0$. The cutting cycle length, $\gamma\theta$, varies from 30 to 60 years:

- Maximum even-flow (MEF) harvests for the RIL logger (from which the sustainability restrictions on the WSI and SSI cases are estimated)
- Unconstrained harvests (U) for the RIL and the CL logger (the baseline harvests in which the logger is not bound by any regulations other than the cutting cycle)
- BRP harvests for the RIL and the CL logger
- WSI harvests for the RIL logger
- SSI harvests for the RIL logger

We refrain from modeling the CL case for the WSI and SSI logger because we assume an unconstrained logger is uninterested in implementing an even-flow management regime. The parameter T equals the length of the concession contract, and $\delta = 1/(1 + r)$ represents the discount factor. In each scenario, the logger maximizes net present value (NPV):

$$NPV = \sum_{t=0}^{T} \delta^t \pi_t, \tag{13}$$

where the profit at time t is calculated:

$$\pi_t = \sum_{ij} ((1 - w_s) p_{ij} h_{ijt} - vc_{ijs} h_{ijt}) - fc_s. \tag{14}$$

The objective function of the MEF scenario assumes that the logger seeks to choose the steady-state harvest ($\mathbf{h}^*$) and pre-harvest merchantable stock ($\mathbf{y}^{m^*}$) that maximize the economic objective while satisfying the merchantable harvest constraint (Eq. (5)), the equilibrium merchantable growth constraint (Eq. (7)), the regulatory constraints (Eqs. (8)–(10)), and a non-negativity constraint.

In both RIL and CL cases for the U scenarios, the logger is constrained by the growth model (Eq. (2)), the merchantable harvest constraint (Eq. (5)), the size restrictions on merchantable stems (Eq. (8)), the initial condition of the stand, and a non-negativity constraint. The BRP logger is additionally constrained by the harvest intensity limit (Eq. (9)) and limits on harvesting all trees within

Table 5
Solution of the maximum even-flow (MEF) problem at the species-group level (trees/ha and m^3/ha).

Variable	Species-group	Cutting cycle (years)							
		30		40		50		60	
		(trees/ha)	(m^3/ha)	(trees/ha)	(m^3/ha)	(trees/ha)	(m^3/ha)	(trees/ha)	(m^3/ha)
Pre-harvest stock	Pioneer	2.8	9.3	2.6	8.7	2.4	8.3	2.3	8.2
	Light-dem.	1.5	5.1	1.6	5.7	1.7	6.3	1.8	6.8
	Intermediate	1.4	4.8	1.6	5.6	1.8	6.6	2.0	7.5
	Shade-tol.	1.3	4.3	1.5	5.1	1.7	5.8	1.8	6.4
	Emergent	1.7	10.5	1.6	10.0	1.6	9.7	1.5	9.6
	Total	8.7	34.0	8.9	35.1	9.2	36.8	9.5	38.6
Harvest	Pioneer	2.8	9.2	2.6	8.7	2.4	8.3	2.3	8.2
	Light-dem.	1.2	4.0	1.3	4.6	1.4	5.1	1.4	5.6
	Intermediate	1.4	4.5	1.6	5.6	1.8	6.6	2.0	7.5
	Shade-tol.	1.3	4.3	1.5	5.1	1.7	5.8	1.8	6.4
	Emergent	0.0	0.7	0.1	0.7	0.1	0.8	0.1	0.9
	Total	6.7	22.7	7.0	24.8	7.3	26.7	7.7	28.6

any species group (Eq. (10)). Meanwhile, the WSI and SSI loggers observe the same constraints as the BRP logger and are constrained by the sustainability constraint (Eqs. (11) and (12), respectively).

Results

Maximum even-flow harvests

We first solve the MEF problem to identify the values of the sustainability constraints. Table 2 shows the size distribution of the optimally regulated stand across cutting cycles. The table also shows how the regulated stand of the MEF condition differs from the initial condition of the stand, depicting the large differences between the initial and idealized market economic conditions. Table 5 shows the distribution of optimally regulated pre-harvest standing merchantable stock and harvests at the species-group level in terms of trees and volumes across cutting cycle lengths. For example, for a 40-year cutting cycle, pre-harvest stand volume cannot drop below 35.1 m^3/ha. The table shows the relative dominance of the pioneer species group in the standing stock and harvest. While the highly valuable emergent class has the most standing merchantable volume in each case, the equilibrium harvests are low, ranging from 7 to 10% of the standing stock of emergents. Meanwhile, harvests from the pioneer group compose more than one-third of the equilibrium harvest at each cycle length. The light-demanding, intermediate, and shade-tolerant groups assume similar proportions in the optimally regulated stand.

Unconstrained and Brazilian Regulatory Policy harvests

Because the unconstrained CL logger mistakenly fells hollow trees, the total felled volume exceeds that of the standing merchantable stock in the first harvest, while the unconstrained RIL logger fells slightly less than the merchantable timber available because some of the valuable timber is lost to damage (Table 6). For each of the U and BRP scenarios, the first harvest for each cutting cycle is essentially the same: to remove all merchantable timber in the unconstrained case and the most valuable permissible timber in the BRP scenarios. The value growth rate of every species group is insufficient to leave timber standing to grow into the next harvest period. The high degree of lost timber in the CL case is evident as the RIL logger is able to recover about 16% more timber, even though the RIL logger logs slightly less.

The timber-related benefits in adopting RIL are evident across all cutting cycle lengths. In the unconstrained scenarios, the logger who adopts RIL will have about 3–4 m^3/ha more merchantable volume in the second harvest than the CL logger. The logger who adopts RIL under the BRP scenario will be able to harvest about 2 m^3/ha more timber in the second harvest. There is little difference between U and BRP scenarios in terms of available timber for the third harvest. During the first harvest, the BRP logger is constrained to leave the lowest-valued merchantable volume standing. In the second harvest, this additional timber is now harvested, incurring relatively more damage in the stand; in a sense, the BRP-constrained logger "catches up" with the U logger.

For each cutting cycle length, the pre-harvest merchantable volume is higher for the third entry than the second. The recruitment pulse stimulated by intense first harvests has pushed through the system to attain commercial size. Also, because the second harvest is relatively light compared to the first harvest, damage rates are relatively low, while the stand still receives a relatively strong positive growth and regeneration effect because of the disturbance.

In the U scenario for the CL logger, for a 40-year cutting cycle, the logger fells more than they sell because the CL logger fells hollow trees, which are not skidded from the forest (Table 7). For the U and BRP cases for both types of logger, Table 7 shows how the composition of the harvest by species group shifts across harvests. The merchantable volume from the valuable emergent group is fully extinguished in the first harvest in the U and BRP cases (Table 7). Because of regeneration challenges and relatively flat diameter distributions in the initial stand, the emergents are unlikely to ever regain volumes that approximate the initial condition.

The shade-tolerant, intermediate, and light-demanding groups are reduced from the first to second harvest, but the intermediate and light-demanding species recover a larger proportion of their initial volume than do the emergent species (Table 7). The dramatic shift in commercial composition toward pioneer species is clearly evident in the chart, with pioneers increasing from about 4% of the harvest to almost 40% in the unconstrained cases. The harvest-induced in-growth of pioneer trees causes waves of pioneers to push through the diameter distribution. Future harvests are likely to be small in comparison to the first harvest and will simultaneously be less valuable per m^3 extracted.

Harvests under weakly sustainable inventories

The WSI and SSI scenarios are modeled for the RIL logger only. Consistent with Eq. (11), for a 40-year cutting cycle, the merchantable volume at time of logging entry cannot decrease below 35.1 m^3/ha, as shown in Table 5. Harvests can vary over time to accommodate this constraint. To satisfy this constraint under the WSI scenarios, the first harvests are light relative to the first U and BRP harvests. By the second harvest, the WSI harvests are larger than the U and BRP harvests (Table 7). At that point, the WSI

Table 6
Pre-harvest standing stock, total felled, and total harvested timber for all cutting cycles (m^3/ha).

Cutting cycle (years)	Scenario	1st entry			2nd entry			3rd entry
		Timber avail. (m^3/ha)	Felled (m^3/ha)	Harvested (m^3/ha)	Timber avail. (m^3/ha)	Felled (m^3/ha)	Harvested (m^3/ha)	Timber avail. (m^3/ha)
30	CL U	41.0	43.4	32.1	8.3	8.1	6.6	12.1
	RIL U	41.0	39.8	38.1	11.4	11.1	10.6	17.7
	CL BRP	41.0	30.0	24.4	16.9	16.8	13.7	12.2
	RIL BRP	41.0	30.0	28.7	18.3	17.9	17.1	17.8
	RIL WSI	41.0	13.1	12.6	34.0	15.0	14.4	34.0
	RIL SSI	41.0	14.9	14.3	31.5	19.2	18.3	29.0
	RIL MEF[a]	34.0	22.7	21.8	34.0	22.7	21.8	34.0
40	CL U	41.0	43.4	32.9	10.4	10.3	8.5	18.2
	RIL U	41.0	39.8	38.1	14.2	13.8	13.2	24.3
	CL BRP	41.0	30.0	22.2	18.3	18.1	14.7	18.2
	RIL BRP	41.0	30.0	28.7	20.3	19.8	19.0	24.4
	RIL WSI	41.0	13.7	13.1	35.1	21.8	20.9	35.1
	RIL SSI	41.0	15.0	14.3	32.9	22.3	21.4	33.6
	RIL MEF[a]	35.1	24.8	23.8	35.1	24.8	23.8	35.1
50	CL U	41.0	43.4	32.1	13.7	13.3	10.8	22.7
	RIL U	41.0	39.7	38.0	17.7	17.1	16.4	28.8
	CL BRP	41.0	30.0	22.2	20.9	20.5	16.7	22.5
	RIL BRP	41.0	30.0	28.7	23.1	22.5	21.5	28.8
	RIL WSI	41.0	13.9	13.3	36.8	25.9	24.9	36.8
	RIL SSI	41.0	19.3	18.4	34.3	16.1	15.4	37.8
	RIL MEF[a]	36.8	26.7	25.6	36.8	26.7	25.6	36.8
60	CL U	41.0	43.3	32.0	17.8	17.1	13.9	26.0
	RIL U	41.0	39.6	38.0	21.6	20.9	20.0	31.9
	CL BRP	41.0	30.0	22.2	24.3	22.6	16.7	26.1
	RIL BRP	41.0	30.0	28.7	26.4	25.6	24.5	31.9
	RIL WSI	41.0	15.4	14.8	38.6	26.6	25.5	38.6
	RIL SSI	41.0	19.0	18.2	34.3	16.1	15.4	37.8
	RIL MEF[a]	38.6	28.6	27.4	38.6	28.6	27.4	38.6

[a] MEF scenario is independent of initial conditions.

logger will encounter 75% more merchantable standing in the second entry than the BRP counterpart and about 33% more at the time of the third hypothetical entry.

The WSI harvests at the species-group level tell a slightly different story than the U and BRP harvests. The contribution of the emergent species is higher in the second WSI harvest than that of the U and BRP harvests (Table 7). However, the commercial volume of emergent species is approaching the same low levels as the scenarios not constrained by sustainability concerns. The pioneer group is also assuming a larger role in the harvests. The future quantities of light-demanding and shade-tolerant species under WSI also persist at relatively the same rate as under the BRP set of policies. The difference in species dynamics between the scenarios is that intermediate species undergo light harvests relative to the available volume, implying that the WSI logger's strategy is to use the low-value intermediate species to satisfy the constraint, while the emergent class is gradually eliminated.

Note as an example that the idealized MEF logger applying a 40-year cutting cycle harvests 24.8 m^3/ha of 35.1 m^3/ha standing at each entry. The WSI logger extracts 13.1 m^3/ha of 41.0 m^3/ha in the first entry, then 21.8 m^3/ha of 35.1 m^3/ha in the second entry. In future entries, this harvest is likely to increase gradually until the MEF solution is approximated. This implies the extraction path the logger is following is also one that is likely regulating the stand toward a long-term MEF equilibrium. Although, comparison of the emergent species under the WSI and MEF solutions at year 80 for the 40-year cutting cycle shows that this period of regulation may be very long.

Harvests under strongly sustainable inventories

For each cutting cycle length, the first harvest under the SSI constraint exceeds the first harvest under the WSI constraint (Table 6). The second SSI-constrained harvest volumes under 30-year and 40-year cutting cycles exceed the second harvests of all of the scenarios that are constrained by the initial standing stock (Table 6). Under the WSI constraint, the concessionaire harvests valuable but slow-growing timber, knowing that lower-value species will grow sufficiently to satisfy the stand-level inventory volume constraint. Under the SSI solution, this substitution is not possible, so lower-value but fast-growing timber is harvested first, with very little of the valuable emergent class being removed.

Financial returns

For the RIL logger under a 40 year cycle, following Brazilian policy generates about $80/ha in opportunity costs (Table 8). The WSI scenario presents opportunity costs of about $240/ha compared to the BRP RIL scenario and $320/ha to the U RIL scenario. The SSI scenario presents opportunity costs of about $360/ha compared to the BRP scenario and $440/ha to the U scenario. While the NPV is calculated from the present perspective of the logger, imagine the dynamic perspective of the future logger as the logger approaches the time of the second harvest. The WSI and SSI logger will encounter a significantly richer stand then the counterpart U and BRP loggers. But to maintain the sustainability-constrained stands in perpetuity will always generate opportunity costs and risks of timber trespass.

As mentioned before, the concessionaire who is governed by the SSI constraint is able to harvest more volume than the WSI-constrained concessionaire, but that volume is from relatively low value species. Under a 30-year cutting cycle, the NPV under the SSI constraint is about half of that of the WSI concessionaire. Under a 60-year cutting cycle, the NPV under the SSI constraint is just over two-thirds of the NPV under the WSI constraint. Given the SSI

Table 7
Dynamics of pre-harvest standing stock and total harvest by species group (40-year cutting cycle).

Scenario	Species-group	1st entry		2nd entry		3rd entry
		Timber avail. (m^3/ha)	Harvest (m^3/ha)	Timber avail. (m^3/ha)	Harvest (m^3/ha)	Timber avail. (m^3/ha)
CL U	Pioneer	1.4	1.4	1.4	1.4	7.2
	Light-demanding	5.8	5.2	2.0	1.9	3.4
	Intermediate	16.0	17.5	4.0	4.2	4.1
	Shade-tolerants	7.7	7.8	2.3	2.2	2.8
	Emergents	10.2	11.5	0.7	0.7	0.7
	Total	41.0	43.4	10.4	10.3	18.2
CL BRP	Pioneer	1.4	1.4	1.5	1.4	6.8
	Light-demanding	5.8	0.0	4.0	3.9	3.3
	Intermediate	16.0	9.3	9.6	9.8	4.4
	Shade-tolerants	7.7	7.8	2.4	2.3	2.9
	Emergents	10.2	11.5	0.7	0.8	0.7
	Total	41.0	30.0	18.3	18.1	18.2
RIL U	Pioneer	1.4	1.4	1.8	1.8	6.9
	Light-demanding	5.8	4.5	2.9	2.5	5.0
	Intermediate	16.0	16.0	5.5	5.5	6.7
	Shade-tolerants	7.7	7.7	3.0	3.0	4.5
	Emergents	10.2	10.2	1.0	1.0	1.1
	Total	41.0	39.8	14.2	13.8	24.3
RIL BRP	Pioneer	1.4	1.4	1.8	1.8	6.7
	Light-demanding	5.8	0.0	4.9	4.3	4.9
	Intermediate	16.0	10.8	9.6	9.6	6.9
	Shade-tolerants	7.7	7.7	3.0	3.0	4.6
	Emergents	10.2	10.2	1.0	1.0	1.2
	Total	41.0	30.0	20.3	19.8	24.4
RIL WSY	Pioneer	1.4	1.4	2.0	2.0	6.3
	Light-demanding	5.8	1.7	5.1	3.6	5.6
	Intermediate	16.0	1.0	17.4	5.7	16.9
	Shade-tolerants	7.7	3.6	5.5	5.5	4.9
	Emergents	10.2	6.0	5.1	5.1	1.2
	Total	41.0	13.7	35.1	21.8	35.1
RIL SSY	Pioneer	1.4	0.9	2.1	2.1	6.3
	Light-demanding	5.8	0.0	5.7	3.5	5.7
	Intermediate	16.0	9.1	11.3	11.3	7.5
	Shade-tolerants	7.7	4.3	5.1	4.7	5.1
	Emergents	10.2	0.8	10.0	0.8	9.7
	Total	41.0	15.0	34.1	22.3	34.2
RIL MEF[a]	Pioneer	8.7	8.7	8.7	8.7	8.7
	Light-demanding	5.7	4.6	5.7	4.6	5.7
	Intermediate	5.6	5.6	5.6	5.6	5.6
	Shade-tolerants	5.1	5.1	5.1	5.1	5.1
	Emergents	10.0	0.7	10.0	0.7	10.0
	Total	35.1	24.8	35.1	24.8	35.1

[a] MEF scenario is independent of initial conditions.

harvest is approaching that of the MSY solution, the trade-off between short-term gains and achieving a dynamically optimal and, hence, sustainable path is clear.

As highlighted in Barreto et al. (1998) and Holmes et al. (2002), the comparison of financial returns (Table 8) depends greatly upon relative inefficiency. While the CL loggers harvest more than their RIL counterparts, almost 20% less timber volume actually leaves the forest. For example, the unconstrained CL logger achieves an NPV of $479/ha when applying a 40-year cutting cycle, while the RIL logger earns an NPV of $604/ha, the difference between the two essentially being a result of inefficiency. Meanwhile, the difference between the loggers' respective returns is increased because the CL logger incurs additional marginal harvest costs by harvesting timber that produces no revenues. Given the higher inefficiency level of the CL logger, both the RIL U and BRP scenarios have higher NPVs than the unconstrained CL logger.

Table 8
Net present value (NPV) of scenarios ($/ha in 2004 US dollars).

Scenario	Cutting cycle (years)			
	30	40	50	60
CL U	481.1	479.2	478.8	478.1
RIL U	606.1	603.7	602.1	600.8
CL BRP	416.7	411.9	410.3	409.6
RIL BRP	526.9	522.4	520.3	519.3
WSI	295.2	286.9	290.3	304.5
SSI	148.1	160.4	212.9	220.5
MEF[a]	278.9	279.4	303.4	328.7

[a] MEF scenario is independent of initial conditions.

With the exception of the SSI-constrained scenario, NPV is mostly invariant to cutting cycle length because the logger harvests all (in the U case) or the most valuable (in the BRP case) merchantable timber for each cutting cycle length. The discounted second harvest contributes very little to the NPV, regardless of volumes harvested. For the WSI scenarios, NPV declines then rises with cutting length because the longer periods of time between harvests permits increases in the allowable cuts in each harvest, shifting slightly toward slow-growing but more valuable species, but exchanges the gains for second harvest returns discounted

Table 9
Revenues and costs for CL and RIL BRP logger, including a breakout of operational losses from inefficiency and sensitivity analysis of CL logger and cutting hollow trees ($/ha for a 40-year cutting cycle).

NPV of revenues and costs (US$2004/ha)	CL BRP			RIL BRP
	Cut hollows (assumptions used in analysis)	Cut hollows (half of assumed rate)	No hollows cut	No hollows cut
Gross revenues	1129.8	1129.8	1129.8	1096.8
Cut hollows	112.1	56.0	0.0	0.0
Poor felling and bucking	139.0	139.0	139.0	42.8
Lost trees	42.5	42.5	42.5	3.3
Net revenues	836.2	892.3	948.3	1050.7
Variable costs (VC) total	410.3	390.0	369.7	476.6
VC attributable to inefficiency	106.5	86.2	65.9	20.0
Fixed costs total	14.2	14.2	14.2	51.7
NPV	411.9	488.0	564.3	522.4

farther into the future. For the SSI scenario, the NPV increases with the length of the cutting cycle as the increasing length permits the concessionaire to harvest more valuable timber in the first harvest, knowing that the volume can recover by the next entry to satisfy the constraint.

In NPV terms, under a 40-year cutting cycle, the CL logger loses about $294/ha due to losses in the harvest operation relative to an operation with no logging waste, which includes losses from cutting hollow trees, poor felling and bucking techniques, and cut trees lost in the forest (Table 9). The CL logger also incurs an extra $107/ha in variable costs due to efforts that produced no timber for sale. By comparison, the RIL logger lost $46/ha in timber volume relative to an operation with no logging waste and incurred an extra $20/ha in extra variable costs associated with this lost timber (Table 9). Meanwhile, the undiscounted returns for the second harvest are $144/ha for the CL logger and $164/ha for the RIL logger. Discounted at 10% over 40 years, these values are $3.7/ha and $4.0/ha, respectively. This comparison shows the relative profitability of improving operational efficiency in the near term over protecting the forest over the long term. One result of this is that firms may imperfectly adopt RIL, selecting to implement only those practices that improve harvest efficiency, rather than protect the forest resource.

Uncertainty

To help evaluate the uncertainty in the analysis, it is important to evaluate three critical sources of uncertainty: the projection model, the discount rate, and the assumptions regarding the proportion of hollow trees logged by the CL logger. Up to now, the projection model has been treated deterministically. Fig. 1A and B shows the 5th and 95th percentile and mean trajectories for commercial volume in the control stand and the stands managed under CL and RIL. We simulated each model 1000 times for 80 years. For background purposes, Fig. 1A depicts a log-and-leave scenario. Fig. 1B shows the results of two harvests. In Fig. 1A, the post-harvest RIL and CL intervals do not intersect during the simulation. The same result is found in Fig. 1B, although, in a sense, the cyclical harvest resets the comparison after the second harvest because the RIL and CL loggers both remove all merchantable timber from the stand. The projections provide additional support that the two competing management techniques do in fact create differential responses from the residual forest.

Close examination of the trends in the 5th and 95th percentiles of the projections shows that the bands between the low and high percentile projections do not widen until several decades into the simulation. The recruitment of new trees is the largest source of uncertainty in the model, as the widening of the intervals occurs when trees that recruited within the simulation begin to attain commercial size. While the transition matrices themselves are stochastic, their contribution to the uncertainty in the projections is relatively small.

The previous section highlighted the role of the discount rate in minimizing the value of future harvests from a present perspective. Referring to Fig. 1B, the uncertainty in the projection model increases later in the projections, when discounted values are already very low, constricting the range of NPVs in the stochastic simulations.

Additionally, in the Brazilian Amazon, tenure stability varies dramatically spatially, and it can be argued that tenure instability is equivalent to a high discount rate, perhaps much higher than the 10% used in this study. That said, because the 10% discount rate is higher than the value growth rate of any species group in the analysis, increasing the discount rate above 10% will have no effects on harvest behavior, only rescale the NPV across scenarios. For the CL and RIL BRP loggers under a 40-year cutting, for example, the growth rates of the merchantable timber are 1.5% and 1.8%, respectively. These rates do not account for species-group level variation, but do indicate that when constant prices are assumed, discount rates must be very low for harvest behavior to be affected.

The financial returns to logging are sensitive to our assumptions about the proportion of merchantable hollow trees the CL logger

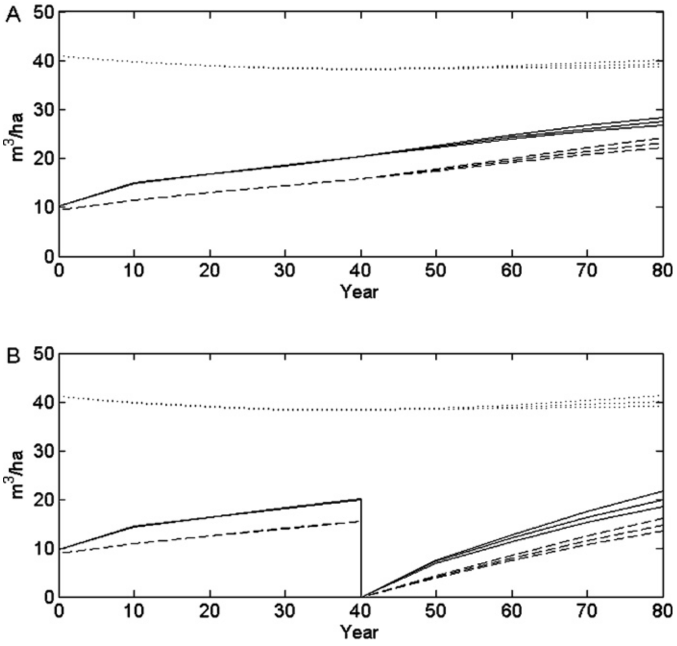

Fig. 1. 80-Year projections of merchantable volume (m^3/ha of merchantable stems >50 cm DBH), mean and 5th and 95th percentiles drawn from 1000 simulations. (A) Log-and-leave scenarios. (B) 40-Year cutting cycle scenarios.

will mistakenly fell. Table 9 shows how financial returns change for the CL BRP logger as the assumed proportion of hollow trees felled falls. The first column shows the results using the assumptions listed in Table 4. The second column halves the assumed number of hollow trees felled by the CL BRP logger. The third column shows the results for CL BRP logger using the same assumptions as used for the RIL logger. NPV increases as the CL BRP logger harvests fewer hollow trees. When the CL BRP logger is assumed to harvest no hollow trees, the NPV for the CL BRP logger exceeds that of the RIL BRP logger. The most important implication of this result is that researchers and enforcement agencies need to gather improved field data on the detailed adoption of forest management, as firms maybe likely to adopt best management practices incompletely, e.g., sawyers might test for hollows but not apply directional felling techniques.

Additionally, from a biological perspective, researchers have predicted that over many harvest cycles, the stand is likely to accumulate a proportion of non-merchantable trees far exceeding the proportion of non-merchantable trees in the initial stand (Valle et al., 2006, 2007). In fact, Valle et al. (2007) predict that the commercial volume of a stand logged under RIL will be almost entirely composed by defective stems after 60 years under a 30-year cutting cycle. About one-third of the commercial volume in a comparable stand logged using CL will be composed of defective stems as the CL logger is less selective and removes hollow trees (Valle et al., 2007). While the model used in this paper accounts for the accumulation of hollow trees in the stand, the long term biological and management implications of leaving hollow trees standing is unclear. For example, if genetic attributes are responsible for hollow stems, selective pressure may lead to increased reproduction of hollow trees.

Discussion

While demonstrating the dynamic benefits of RIL, model results exhibit how current best logging practices and current regulatory policies do not guarantee the sustainability of timber harvests. The study also shows the difficulty associated with operationalizing sustainability in practice; sustaining timber yields at the stand-level led to significant opportunity costs while still leading to a stand that is changed in species composition and economically degraded. Over two cutting cycles, the harvests under the proposed definition of sustainability at the species-level were profitable and led to a species-group level merchantable volume distribution approaching the distribution of the maximum sustainable economic yield. To achieve this, the SSI solution essentially protects valuable but slow-growing timber species from harvest, which again creates high opportunity costs and strong incentives for breaking the rules when enforcement is imperfect. For example, species identification is uncertain, likely easy to manipulate, and difficult to monitor and enforce; operators may game species identification in order to circumvent species-level harvest constraints.

If the financial benefits of RIL are evident, it raises the question of why a logger would not adopt RIL practices if the financial benefit is incentive compatible. Putz et al. (2000) write that RIL may not be cost-effective when loggers are restricted from accessing steep slopes or when ground yarding of timber is not permitted during wet conditions. Because the terrain at the experimental forest of this study is relatively flat and did not include any stream buffer areas that firms are required to set aside as reserves, there is a risk that benefits of RIL are over-stated.

Another possibility for the non-adoption of RIL is that loggers may seek to maximize total profit from logging a large area, rather than maximize profits per hectare. For example, because of the greater requirement of RIL activities such as planning or directional logging, it may be possible that RIL is more time-intensive than CL, a cost that the experimental dataset does not capture and, consequently, this study does not reflect.

In cases where the benefits of adoption may otherwise be unambiguous, institutional constraints can also prevent adoption. Survey research in the Brazilian Amazon revealed that many conventional loggers recognize that RIL better protects forest values and is often profitable yet still do not adopt improved practices (Sabogal et al., 2006). Land tenure insecurity may prevent firms from pursuing improved environmental practices. Firms are unlikely to invest in practices that improve the economic value in future decades if they do not expect to have access to those forests decades in the future. Appropriate training, labor, and equipment may also be scarce (Sabogal et al., 2006). Because of the additional training requirements of implementing RIL, there may also be a possibility that increased wage rates and improved working conditions would be required of RIL-trained loggers, creating additional hurdles to implementation. Barriers such as government corruption or inefficiency may also exist making operating conventionally or illegally the only option for operators (Merry et al., 2006).

Many silvicultural practices are currently performed that are not examined here. Practices currently include single or mixed-species reforestation on agricultural, pasture, or secondary forest lands, enrichment planting in logging gaps, secondary forest and the reserve areas of private landholdings, and tending commercially valuable trees (Walters et al., 2005). Because of a lack of data on the impact of silvicultural treatments within this particular site, this study could not incorporate silvicultural practices beyond the practices already included in RIL, such as vine-cutting. The financial cost-effectiveness of such activities is uncertain but promising. Wadsworth and Zweede (2006), for example, performed liberation thinning in a forest similar to the Fazenda Agrosete site and found that the diameter increment of the liberated trees was 20% greater than the comparison trees during the six post-treatment years. The extra volume harvested by the liberation thinning would have paid for the liberation, without considering the increased volumes likely to be available for future harvests (Wadsworth and Zweede, 2006).

Increasing the number of species extracted from tropical forests for commercial purposes may increase the economic value of the forest, reduce impacts upon heavily harvested high-valued species, and reduce the pressure to expand timber production into new forest lands (Plumptre, 1996). As the Paragominas region was central to the early expansion of logging in the Eastern Amazon during the 1980s, regional transportation and forest sector infrastructure is relatively well-developed, implying that the number of species harvested in this region is likely to be relatively high compared to most of the Brazilian Amazon. As mentioned earlier, about 75% of the stems greater than 50 cm DBH in the Agrosete experimental forest are of commercial species. While evaluating the historical trends of timber species use is difficult because of inconsistencies in the species names of low-valued species with few individuals, the increase in the number of species processed in local Paragominas mills of the study region appears negligible during the 12-year study period. Rather than the commercial species list in this region lengthening over time, loggers are reentering logged forests to obtain smaller diameter and defective stems before land conversion.

Because this study is based upon data from the Paragominas region, it may not be appropriate to transfer results to frontier regions, where very few species may be sufficiently valuable to log. We are confident in using the growth and yield model to examine the implications of lower harvests in the WSI and SSI scenarios. However, in a high-grading context where perhaps fewer than one tree per hectare on average is logged, the model is likely to overstate the post-harvest growth stimulation as the model is estimated from higher volume logging impacts.

As harvesting is repeated into the future, results show a shift from higher-value, shade-tolerant and emergent species toward a greater reliance on lower-value pioneer species. The stand-level economics of this shift are clear; the stand becomes less valuable, all else held equal. From a regional perspective, however, assuming a continued demand for higher-value species also translates into higher prices because of an increase in the relative scarcity of the higher-valued species, this shift may create pressure to expand the forest base under management in order to continue to supply the high-value species. Alternative, the shift away from high-value species may increase the risk of predatory logging for high-value species within conservation units as well as areas under community or indigenous management. While the fine-scale model of this study helps to highlight the possibility of this dynamic, a larger-scale market model that accounts for species dynamics is required to examine these issues further.

Conclusion

While it is again shown under the conditions of the study site that RIL is profitable to implement, the bulk of the financial gains are due to operational improvements, rather than through protection of the forest resource. RIL is shown to increase the volumes of merchantable timber available in future harvests, but does not change what is now well-known about logged forests: the structure and composition of the managed forests will be different than that of the primary forest. Perhaps silvicultural techniques in addition to continued development of improved logging techniques will prove to ameliorate this effect in the future.

While volumes of merchantable timber predicted to be available for the second and third harvests are lower than the available timber in the primary forests, the second and third harvests are projected to be profitable and appear to have the potential for sustainability at the stand-level and species-group level. The WSI scenario showed that stand-level sustainability is likely to be possible at lower volumes and lower economic value but that sustainable management under the criteria driving that scenario is viable. The harvests under SSI constraints were profitable but at the expense of harvesting little of the most valuable timber.

Officials are currently planning national and state forests in the Brazilian Amazon and need accurate projections of future timber supplies (Veríssimo et al., 2006). Under current regulations, estimates of supply should account for diminished timber volumes and values in future harvests, rather than assume optimistically that timber volumes are sustainable perpetually at maximum permitted volumes. Realistic projections of timber supply are critical in evaluating how the natural capital of the unlogged forest is converted into economic development, the key issue being whether logging in public forests should be viewed as a one-shot event or as a carefully enforced, repeating series of sustained harvests. The results of this study point at the possibility that logging can be sustained in the Eastern Amazon when broad constraints such as requiring RIL and lengthened and strictly defined cutting cycles that prevent reentry logging are applied.

While this study was performed with the intent of providing analytical support to public forest planning, there is no reason why the results should apply exclusively to public lands. The results apply to private lands equally, although the policy implications may differ across tenures, depending on management objectives for the different lands and public preferences for goods and services delivered from public lands.

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