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Balancing Conservation and Economic Sustainability: The Future of the Amazon Timber Industry

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Abstract Logging has been a much maligned feature of frontier development in the Amazon. Most discussions ignore the fact that logging can be part of a renewable, environmentally benign, and broadly equitable economic activity in these remote places. We estimate there to be some 4.5 ± 1.35 billion m^3 of commercial timber volume in the Brazilian Amazon today, of which 1.2 billion m^3 is currently profitable to harvest, with a total potential stumpage value of $15.4 billion. A successful forest sector in the Brazilian Amazon will integrate timber harvesting on private lands and on unprotected and unsettled government lands with timber concessions on public lands. If a legal, productive, timber industry can be established outside of protected areas, it will deliver environmental benefits in synergy with those provided by the region's network of protected areas, the latter of which we estimate to have an opportunity cost from lost timber revenues of $2.3 billion over 30 years. Indeed, on all land accessible to harvesting, the timber industry could produce an average of more than 16 million m^3 per year over a 30-year harvest cycle—entirely outside of current protected areas—providing $4.8 billion in returns to landowners and generating $1.8 billion in sawnwood sales tax revenue. This level of harvest could be profitably complemented with an additional 10% from logging concessions on National Forests. This advance, however, should be realized only through widespread adoption of reduced impact logging techniques.

Keywords Brazilian Amazon · Timber industry · Economic model · Forest policy · Logging

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Logging in the Amazon affects large areas of forest each year, encouraging conversion to other land uses and contributing to forest flammability (Asner and others 2005; Nepstad and others 1999; Mattos and Uhl 1994). When reduced impact logging (RIL) techniques are employed, however, forestry in the Amazon can be both profitable and renewable—while maintaining much of the carbon stock (e.g., see Putz and others 2008; Putz and Pinard 1993), biodiversity, transpiration (important in regional climate stabilization), and cultural values of the forest (Asner and others 2006; Azevedo-Ramos and others 2006; Lima and others 2006; Merry and others 2006; Lentini and others 2005; Holmes and others 2002; Barreto and others 1998; Holdsworth and Uhl 1997). There is also growing evidence to suggest that tropical forests are essential to regional climate stabilization Houghton 2005) and broader strategies to reduce greenhouse gas emissions to the atmosphere (Soares-Filho and others 2006; Phillips and others 2009). While many of these values likely render native forests

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more socially valuable than any cleared use, these values are difficult to estimate and therefore are not integrated into government policies involving Amazon forests; they also play little or no role in the deforestation decision of private landholders. Rather, native forests produce financial returns captured through harvesting by these agents (Bauch and others 2006), and cleared land often has additional value to them such as clearer and more credible property rights (Alston and others 1996). Given that forest clearers do not respond to social values of standing forests, political momentum is building to compensate tropical nations that lower their CO_2 emissions by slowing deforestation and securing their forest estate (Gullison and others 2007). In this context, sustainable timber management is emerging as a land use that can potentially provide the joint benefits of economic profitability and ecosystem services.

So far, Amazon conservation strategies have largely focused on biodiversity and protected areas (Terborgh 1999). In 2004–2005 an impressive political act, the creation of the Terra do Meio Complex and the Sustainable Forest District BR163, placed some 24 million ha in hotly disputed frontier areas under full protection in public forest lands (McCauley 2006; Nepstad and others 2006; Campos and Nepstad 2006). These decrees bring the total area of the Amazon biome in Brazil that is under protection to approximately 43%—more if the designation Area de Proteção Ambiental (APA), the weakest protection category, is included (Soares-Filho and others 2008). Two issues emerge from this act: first, by setting productive land aside the nation incurs an opportunity cost to the economy; and second, if no additional enforcement or planning measures are taken, and there remains profitable land outside of the protected areas, there will continue to be unsustainable land use practices. Unfortunately, little or no information exists regarding either the opportunity costs of protection or the economics of alternative production sites, making it difficult to assess their impacts.

Proponents of conservation argue that, regardless of the economic costs incurred, setting land aside is justified when the environmental service benefits provided are taken into consideration (Reid and others 2006; Costanza and others 1997; Pimm 1997). Meanwhile, others, keen to offset some of these potential costs and to control the timber industry, suggest that allowing timber concessions on these some of public lands is an attractive and the best alternative: a perspective that is the basis for the current forest policy in Brazil (Veríssimo and others 1998; Verissimo and others 2002). While protected areas have been shown to be effective barriers against deforestation (Soares-Filho and others 2006; Oliveira and others 2007, Soares-Filho and others 2008), it is less clear whether they are the unique solution for long-term management of the Amazon timber industry and forest estate (Nepstad and others 2002; Merry and Amacher, 2005). Here we argue that the optimal balance of economic development and environmental protection in the Amazon incorporates both protection and sustainable timber production on public and private forest lands. This scenario will deliver a positive synergy whereby pure protection activities can be complemented by logging rather than being in contention. Logging on lands outside of protected areas will also increase the value of private forest land, thereby reducing the likelihood of conversion to other uses. Jointly designed policies that encourage this scenario are therefore crucial in the pursuit of a sustainable future for the Amazon timber industry. Preconditions to this lofty goal are the availability of information about the economics of timber production in the Amazon, widespread adoption of reduced impact logging, and improved monitoring and enforcement, none of which are trivial barriers.

Here we conduct an economic analysis of the Amazon timber industry using a 30-year spatially explicit simulation model that calculates a residual stumpage value on forest lands—a stumpage is defined as a millable log volume of standing tree, the stumpage price is the dollar value per cubic meter, and the stumpage value is the stumpage price multiplied by the available volume—an annual harvest volume and value, and potential tax revenues and forecasts industrial capacity to examine several future forest-sector scenarios. We build on earlier efforts to use a GIS (Geographic Information System) to model the timber industry (Stone 1998). Unlike that other work, our model covers a larger scale and is more detailed in terms of industry behavior. We also incorporate future deforestation estimates and road paving scenarios that affect the availability and profitability of logging—these underlying scenarios were developed under the auspices of the Amazon Scenarios Project (Soares-Filho and others 2006). Our results show how logging expands into previously unharvested areas in scenarios where timber production on both private and public lands is feasible and viable. We show that the forest industry could generate substantial revenue for the Brazilian government from sales taxes on sawnwood complemented by royalties from timber concessions. Frontier governance (Nepstad and others 2002), therefore, must extend beyond protected areas and include conservation action on private lands.

Data and Methods

General

For this research, a 30-year partial equilibrium model of timber harvesting in the Brazilian Amazon was developed—the model follows closely an economic engineering approach where technical parameters, such as processing yield and harvest volumes, are used to bound economic analyses (see Smith 1986; Hyde 1980; Chenery 1949). A residual analysis is used to the calculate standing tree (stumpage) price for each land unit (a raster cell of 2 × 2 km). The stumpage price is equivalent to the net forest rent for the private or public landowner and is constructed by subtracting all costs associated with logging from the delivered gate price collected by the logger at the mill. Although the data used are from conventional logging practices, it is well documented that reduced impact logging can be more profitable than conventional logging (Barreto and others 1998; Holmes and others 2002); as such we may underestimate the potential returns for logging, and thus our model results can be taken as conservative. Furthermore, the logging costs are but one of several costs associated with the delivery of sawnwood to the mill gate. Indeed, transport costs vary across space but can be up to 50% of the total costs, whereas logging (harvest) costs are approximately 7.5% of the total costs—total costs include all processing costs, investment opportunity costs, and taxes (Table 1).

Commercial volume is estimated for a land unit using available biomass data from Saatchi and others (2007); see selected calculations below. Initial demand is estimated as the current logging capacity of processing centers. Processing centers are chosen to match municipal seats and are based on data available from the Brazilian Institute of Geography and Statistics (IBGE). A weighting that is quality, market, and location specific is used to estimate sawnwood prices at each processing center. The model works backward from the mill gate to the forest by deducting the processing costs, opportunity costs of investment, taxes, processing yield, transportation costs, and harvest costs (Tables 1 and 2). The resulting value is the net returns per cubic meter in a particular forest land unit in a given location at a given point in time—a social discount rate was assumed to be 5%. As noted above, this is known as a residual or stumpage price—it is the price per cubic meter that a private landowner can charge to contract someone to log the land and is equivalent to the royalty (combined uniform and value-added) that a public land owner would charge in a timber concession. To estimate the total stumpage value for a given area, one need only multiply the stumpage price by the available commercial volume.

Table 1 Selected model variables and values

Variable	Value	Unit
Harvest cost		
New frontier	13.00	$/m^3$
Intermediate frontier	13.00	$/m^3$
Old frontier	11.00	$/m^3$
Processing cost		
New frontier	23.00	$/m^3$
Intermediate frontier	26.00	$/m^3$
Old frontier	20.00	$/m^3$
Processing yield: all frontiers	42.00	%
Transportation cost		
Navigable river*	0.04	$/m^3/km$
Paved road*	0.07	$/m^3/km$
Dirt road log*	0.15	$/m^3/km$
Deforested area	0.24	$/m^3/km$
Logged forest	0.24	$/m^3/km$
Untouched forest	0.60	$/m^3/km$
Conservation area	0.60	$/m^3/km$
Initial capacity for emerging poles	50,000.00	m^3
Distance between old & emerging centers		
Minimum	100.00	km
Maximum	200.00	Km

Sources: Survey data and *Lentini and others (2005)

Applying residual analysis at a landscape level allows construction of a forest rent layer for the entire Amazon. The model begins in year 1 with a known location of processing centers, each of which has a starting capacity to process harvested timber consistent with actual current capacity. If the profitable volume at some time period (given by the rent layer in that time period) on land units around a processing center is greater than the capacity at the processing center at the time period, harvesting occurs such that harvest volume equals capacity. The model becomes dynamic by increasing the capacity for the subsequent year to mimic the expected entry of mills into that processing center; also, all critical underlying parameters are updated annually as harvesting patterns change (Tables 1 and 2). Processing capacity increases and logging expansion occurs until, essentially, profitable accessible wood is no longer present. In other words, if at any location in any period the profitable volume is less than the available capacity, the model allows the processing center to decrease its capacity until the total profitable volume present is harvested, and then the processing center is 'closed.' Processing centers can regain capacity if regrowth of timber in nearby land units occurs, thereby making harvesting profitable again, or if roads are built and deforestation expands, both of which lower the cost of accessing available timber. Each year, the rent layer is recalculated for each land unit as the transportation costs for wood to the mill are adjusted based on changes in the quality of infrastructure and the extent of vicinal roads. In this way, there are several other dynamic layers that support the model: a commercial volume layer, a deforestation model, and a road expansion model (Soares-Filho and others 2006).

Table 2 Market destination and starting prices for sawnwood on three frontiers

	Weighted mean price[a] ($US/m^3)	Export market (%)	Domestic market (%)	Residual market (%)	HV export ($US/m^3)	MV export ($US/m^3)	LV export ($US/m^3)	HV domestic ($US/m^3)	MV domestic ($US/m^3)	LV domestic ($US/m^3)	HV residual ($US/m^3)	MV residual ($US/m^3)	LV residual ($US/m^3)
New	181	77	6	17	323	214	142	150	82	97	117	108	61
Intermediate	191	55	40	5	378	214	191	242	137	101	98	59	50
Old	138	16	60	24	362	218	202	240	135	87	95	83	58

HV high value; *MV* medium value; *LV* low value

[a] Weighted by wood quality (distribution: 20% HV, 40%MV, and 40% LV) and market destination percentage

Selected Calculations

Commercial Volume

The commercial volume available in any cell is given as cubic meters per hectare. The commercial volume map was derived from a biomass map provided by Saatchi and others (2007). To convert biomass to total stem volume, we used the Wood density (t/m^3) and biomass expansion factor (t/ha) data calculated for 3700 coordinate points from the RADAM (Radar na Amazônia) database (MME 1973). The values for these points were spatially extrapolated using Thiessen polygons and then multiplied by the biomass values cell by cell. We assumed that commercial volume equaled 10% of total stem volume (Johan Zweede, Instituto Floresta Tropical, personal communication). Estimated mean commercial volumes range from a low of 8.33 m^3/ha in Mato Grosso to a high of 16.93 m^3/ha in Amapá. Our results show a reasonable distribution of commercial volume throughout the Amazon basin, with notable differences on the frontiers; older logging frontiers have, on average, only 11.43 m^3/ha of commercial volume, compared to 15.09 m^3/ha on newer frontiers. Details on commercial volume are presented in Table 3. The estimate of stem and commercial volume is not corroborated by field data and is an important area of future research to improve the accuracy of the model.

Log Demand and Production Capacity

The demand for logs is determined by the capacity of the mill center located in the city serving as the municipal seat. Initial logging capacity is assigned for each municipality. The total production capacity—equivalent to the quantity demanded by the final forest products market—was estimated by the IBGE (www.sidra.ibge.gov.br IBGE SIDRA Tabela 289, Quantidade produzida na extração vegetal por tipo de produto extrativo, 7.3 Madeira en tora) as approximately 17 million m^3. This initial logging capacity was uniformly increased by 50% (for a total of 25.5 million m^3) to correct for estimation differences between the IBGE data and other published estimates of demand (IBAMA 2002; Lentini and others 2005). Each municipality is allocated one processing center at the municipal seat, and each center comprises many mills and has a variable number of firms associated with it. This is a reasonable assumption, as it mirrors the locations of actual logging centers in the Amazon sufficiently well. Logging capacity at each center is allowed to increase in any given year if the available profitable harvest volume (defined as the harvested volume that is close enough to yield positive stumpage values) is greater than the current capacity.

Table 3 Model results for average per-hectare commercial volume and total forestry potential by State, frontier, and selected land use zones

	CV, mean	CV, SD	CV, min	CV, max	Total area (km^2)	Positive rent area (km^2)	Total CV (million m^3)	Total PV (million m^3)	Total forest stock value (million US$)
State									
Tocantins	2.37	3.12	0.38	24.35		4,576	1.64	1.02	8.97
Maranhão	6.46	8.20	0.65	32.45		18,404	18.30	10.57	90.79
Mato Grosso	8.50	7.84	0.20	35.09		144,824	230.99	106.62	1,237.64
Roraima	11.84	6.01	0.32	33.48		45,764	166.09	51.73	638.38
Acre	11.98	4.52	0.55	39.63		59,384	150.78	73.37	980.85
Rondônia	13.78	7.39	0.32	36.43		59,504	153.01	82.57	1,018.08
Pará	15.02	7.60	0.16	38.57		238,504	1,227.98	339.06	4,212.07
Amazonas	17.60	5.96	0.45	47.02		311,464	2,454.88	541.55	6,638.14
Amapá	17.89	8.93	0.70	38.57		28,568	175.90	42.36	544.85
Total						910,992	4,579.57	1,248.86	15,369.78
Frontier									
New	16.98	6.66	0.32	47.02		502,608	3,484.92	806.67	9,927.88
Intermediate	13.64	6.99	0.24	39.63		274,704	898.31	360.12	4,769.27
Old	6.91	6.98	0.16	36.43		134,164	196.05	82.67	679.98
						911,476	4,579.29	1,249.46	15,377.14
Zone									
Protected areas	15.23	7.07	0.22	47.02	1,783,816	290,056	2,241.12	410.62	4,506.45
Settlements	14.55	8.30	0.20	41.05	283,024	68,472	163.59	91.44	1,294.09
National forests	15.42	6.41	0.66	37.35	220,668	40,640	321.33	61.51	679.47

CV commercial volume; *PV* profitable volume

Capacity increases are constrained to a maximum of 21% per annum to match historical expansion trends (as described by Stone 1998), and exit of individual mills from the milling center will occur according to available volume. If there is no profitable timber (i.e., no timber close enough to yield positive stumpage values) in the vicinity of a milling center, then it is assumed to be shut down. Once closed, the mill can effectively create an "offspring" center by searching for the lowest-cost access to an available area within a 100- to 200-km radius. If such an area is found, a new center is formed and will begin harvesting. A hundred kilometers is the average harvest outreach of a milling center (Lentini and others 2005). Thus 200 km was established as a maximum bound to ensure that no commercial timber is left unharvested within the offspring centers' areas of influence. A center is allocated an initial capacity of 50,000 m^3, or approximately the demand for three or four mills. In this manner, mills and timber production can migrate into the core of the Amazon forest. Industry migration to new frontiers has been a cornerstone of the Brazilian Amazon industry and one of the reasons for poor technology adoption—it is more cost effective to simply move to another region than to invest in wood-saving technologies.

Entry and exit decisions are based on the stumpage price calculated as described above. We assume a processing yield of 0.40 (i.e., sawnwood is 40% of log volume) and proceed by subtracting a sales tax of 12% applied to the processed volume. We account for the opportunity costs of capital by assuming an interest rate of 16% applied to total production costs—given the recent economic stability in Brazil, this number may be high, which would, however, make our estimate more conservative. Each log is subject to processing and harvesting costs which differ by frontier type (Table 1). These calculations produce a value that can be allocated to transportation; the stumpage price in any given pixel is the residual following subtraction of transportation costs. This stumpage price is then multiplied by the estimated commercial volume to arrive at the profitable harvest volume.

Sawnwood Prices

Sawnwood prices are calculated based on a weighted average for three wood classes (high, medium, and low value) on three frontiers (new, intermediate, and old) for three markets (export, domestic, and residual) (Table 2). Frontiers were defined as new, old, and intermediate using data from a survey of 499 mills conducted in 2004 (for more details on the survey see Merry and others 2006; Bauch and others 2006). Price stochasticity is incorporated by assigning a price that is selected using a triangular function with maximum and minimum values (± one third) to each land unit. While the constant price assumption in this partial equilibrium model is a strong assumption, it is not unreasonable in the absence of research addressing market conditions of the Amazon timber industry. In order to examine the role of the constant price assumption, we ran several scenarios where prices adjust due to change in supply over time following certain demand elasticity assumptions, but these only led to linear changes in the logging expansion results and lower differences between governance forms. We therefore stick with the constant price assumption, which is consistent with small economy assumptions and the fact that Amazon loggers provide a small share of world timber. Indeed, if the industry is export-based and thus a price taker, actions of the Amazon industry will not affect World volume and prices.

A constant price assumption is supported by the structure of our model and data. If the industry holds a large enough market share to influence prices (e.g., is oriented toward supplying domestic demand for timber), an increase in supply should drive prices downward, all else equal. In the case of the Amazon timber industry this issue is further complicated by differences in market share on each of the frontiers. Table 2 shows that the percentage of Brazilian export market share ranges from 77% on new frontiers to 16% on old frontiers, with the reverse being true for domestic market shares. This is consistent with historical trends and prior market incentives; it makes sense that the higher-value, old-growth timber on new frontiers is more likely to be exported and the Brazilian producers harvesting it are more likely to be price takers in the world market than in the domestic one. Thus, since in our model logging expansion occurs primarily on the new frontiers, as is expected, the assumption of a constant price (or nondeclining price) is reasonable.

Harvest and Processing Costs

To accommodate variations in economic conditions on new, intermediate, and old frontiers, the survey data noted above are also used to estimate harvest and processing costs that depend on location. The estimates for harvest cost per cubic meter in new, intermediate, and old frontier firms are $13, $13, and $11, respectively (aggregating all regions within a frontier). Similarly, processing costs per cubic meter of roundwood are estimated at $23, $26, and $20 for new, intermediate, and old frontiers, respectively. While the costs of harvest and milling vary by frontier, transportation costs vary depending on the quality of the terrain over which logs are transported to the mill from each forest land unit harvested. Thus, as areas are harvested or cleared, or as road infrastructure is improved, the cost of access to a given tract of forest declines relative to its starting value. Forest areas that may have been unprofitable can become profitable if the transport cost to the nearest mill is sufficiently reduced. Thus, for each land unit, the model allocates commercial wood to the closest milling center. This effectively simulates competition between adjacent milling centers for a geographic area of influence as new roads are built and logged area expands. As a frontier matures over time from new to intermediate or old, the harvest and processing costs are adjusted correspondingly.

Transportation Costs

Transportation costs are computed using a friction surface calculation in which seven types of surfaces are characterized as having different marginal transport costs (Table 1). Each of these is allocated a cost of traversing the cell containing them in dollars per cubic meter per kilometer. We use both our own and published data to determine these costs. The cost of accessing any individual cell is thus the lowest-cost pathway between it and the processing center. In every annual step of the model, we incorporate an updated layer of roads output by earlier research (Soares-Filho and others 2006). This model is used to deliver a new road surface to our model in each period and is the driver for subsequent road-related changes in transport costs. We also incorporate paving events based on planned paving projects for Amazon highways (Soares-Filho and others 2006). During the 30-year period spanned by the model, there are 58,000 km of new feeder roads created, and 10,600 km of existing dirt roads paved.

Deforestation

Deforestation beyond that attributed to logging is forecasted in each period. This occurs as the land use surface area each year is updated with results from SimAmazonia I (Soares-Filho and others 2006). Both models run simultaneously and are integrated on the same simulation platform (Dinamica EGO; www.csr.ufmg.br/dinamica_ego). Thus, each period begins with a land surface updated with newly logged areas, new and improved roads, and an updated deforestation layer—previously logged areas within a 25-km buffer of main roads increase the probability of deforestation (Asner and others 2006). The total area deforested during the 30-year period spanned by the model is 75 million ha, of which 52% is logged before deforestation takes place.

Validation

We calibrated our model by ensuring that the average distances from harvest location to milling centers match the current harvesting pull of Amazon mills: about 119 km for road and 377 km for fluvial transportation. We then validated the model by cross-tabulating the rent output from year 1 with the logged areas map provided by Asner and others (2005) for the state of Mato Grosso. Finally, we evaluated the spatial fitness of the model using a relative operating characteristic (ROC) method (Pontius and Schneider 2001), which assesses the validity of model predictions of class occurrence by comparing a probability map of likelihood of class occurrence with a Boolean reference map showing actual occurrence. Our model exhibited a ROC coefficient of 64%, which is significantly better than a random model (50%)—especially considering that the reference map was not employed for model calibration.

In the model, the recall stumpage price is calculated by subtracting costs of production from the sawnwood millgate price. With a stumpage price and an estimate of commercial volume we are able to estimate the current forest stock and its value. We then run several simulations that incorporate a variety of sectoral and extrasectoral effects, such as infrastructure development, on stumpage prices, harvest volumes, and values over a 30-year period. The model is spatially and temporally sensitive; logging occurs where it is most profitable in any given year. It is also "sustainable" in an economics returns sense by limiting production to 3.33%—equivalent to a 30-year harvest cycle (Silva and others 1995) of total profitable volume in any milling district in any given year. While the 30-year cutting cycle may be debated, it represents a conservative input to the model, restricting our annual harvest allowance of 3.33% of profitable commercial volume, in addition to the fact that there is no allowed reharvesting of previously harvested cells for the 30 years in which the model is run. The opportunity costs of protecting a particular region may not simply be defined by the timber presently located only within it that can no longer be harvested. Rather, the model accounts for 'leakage,' where the opportunity costs of not logging are the forgone logging returns in the area minus the returns from logging in the next best accessible location; i.e., the opportunity costs calculation for each parcel takes into account the possibility that logging will shift to other accessible parcels when the parcel in question is preserved. In economics opportunity costs are calculated by a combination of the impacts on producer and consumer surplus. In this model, however, we are unable to estimate changes in consumer surplus because of our assumption of constant prices. Changes in producer surplus for landowners are equivalent to changes in forest rents as we estimate here. Therefore, opportunity costs are represented by forgone income.

Results

We find that (a) the timber industry has a bright future in sustainable frontier development from an economics returns point of view, but also (b) this future must be jointly constructed between private and public forest management. Indeed, the optimal scenario includes a small percentage of the timber coming from National Forests, but the vast majorities come from private or other government unsettled lands.

How Much Profitable Stumpage Is There?

We estimate there to be 4.5 ± 1.35 billion m^3 of commercial timber volume (stumpage) in the forests of the Brazilian Amazon, of which 1.2 billion currently returns a positive stumpage price (Fig. 1). Uncertainty in the model is introduced through estimates of biomass for the Amazon

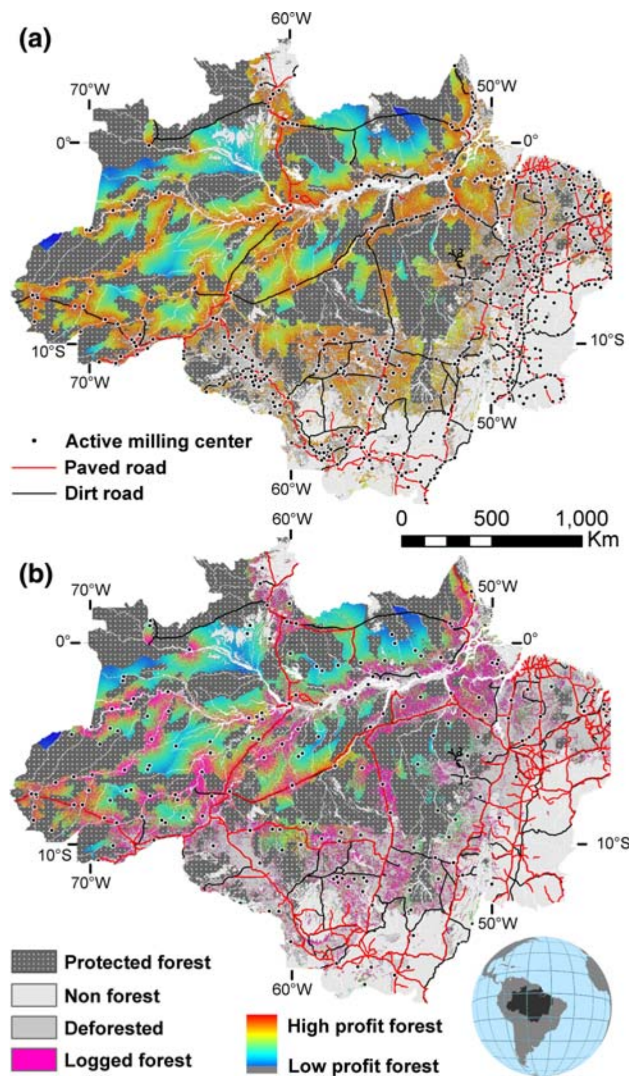

Fig. 1 **a** Year 1 profitable logging area (positive rents). Year 1 estimates are a total of 410 million m^3 of profitable timber stock in the Brazilian Amazon outside of current protected areas. Location of logging centers and initial capacity in year 1 are estimated from IBGE data per municipality. **b** Year 30 logged area and remaining profitable logging area under full protection scenario. Year 30 includes effects of logged forest, new roads, and updated deforestation estimates

(Saatchi and others 2007; Houghton and others 2001), which claim accuracy within 30%. Access to this stumpage is constrained by processing capacity, however, is currently estimated as between 20 million and 25 million m^3 per year. The total estimated stumpage value of this total stock at today's prices—assuming adequate processing capacity—is \$15.4 billion (Table 3). The two states with the largest standing forest stock are Amazonas and Pará, with 541 million and 339 million m^3 of profitable stumpage respectively. Of this profitable volume, 65% can be found on the new frontier, 29% on the intermediate frontier, and the remaining 6% on the old frontier; stumpage prices are estimated on average as \$12.31 per m^3 on new frontiers, \$13.24 on intermediate, and \$8.22 on old frontiers. Finally, only 23% of the total stumpage on new frontiers shows a positive price, whereas that number increases to approximately 40% for intermediate and 42% for old frontiers, respectively. These results suggest that there is better access on older frontiers but perhaps greater potential for long-term growth on the new frontiers, as would be expected.

One-third of the profitable timber stock of the Brazilian Amazon (410 million m^3) is located in all protected areas. Fifteen percent (61 million m^3) of this stock is found within the 22 million ha of national forests—national forests (called FLONAS in Brazil) are federal public forests that are designated for sustainable use, including timber concessions. By comparison, smallholder settlements in the Brazilian Amazon cover approximately the same area as national forests but hold some 91 million m^3 of profitable volume. In direct comparison, settlement areas hold 3.6% of commercial volume but 7.3% of profitable volume, while national forests are the opposite, with 7% of commercial volume but only 4.9% of total profitable volume. Furthermore, the total stumpage value for National Forests is estimated to be only 52% of that found in settlement areas. The average stumpage price found in settlement areas was \$14 per m^3, whereas both national forests alone and total protected areas had average stumpage prices of \$11.00 per m^3. As landowners in protected areas, the government is eligible to earn the stumpage value associated with harvest on protected areas. Our estimates here suggest that the combination of uniform and sales tax levied on logs should not exceed \$11.00 per m^3. An important caveat here is that fees affect harvest decisions. Therefore should the government charge less than this fee, it will be providing an incentive to log protected areas. Furthermore, the distribution and level of uniform and value-added royalties will also affect stand-level decisions.

What Does the Future Hold?

When harvested volume is forecast in a 30-year dynamic simulation we are able to incorporate changing economic scenarios. The primary one is due to the timber industry, in the very act of logging, reducing the transportation costs to a region and increasing profitability beyond the current harvest areas, thereby bringing more forest land into profitable status. When combined with an expansion of infrastructure at the national and state levels and increases in production capacity, we see an increasing potential profitable stock and flow in the industry.

Our simulation results presented below include four basic scenarios: (S1) full access to logging in the entire region; (S2) full access to logging in approximately 22 million ha of national forest in addition to land beyond the borders of protected areas; (S3) no access to logging in protected areas; and (S4) the role of smallholders in the logging industry—we also consider a scenario that allows logging in state forests (Flotas) but find no additional production, suggesting little impact of the state forest system on future optimal logging patterns. These scenarios allowed us to examine whether a sustainable future for logging in the Brazilian Amazon is possible and plausible, address the opportunity costs of protected areas, and address whether the current federal forest policy based largely on National Forest concessions is the optimal solution from a sustainable production standpoint. In no scenario run does the annual percentage harvest exceed 3.08%—calculated by dividing current harvest by available profitable harvest. We also assume that a well-managed forest estate will be part of an overall improvement in frontier governance during the next 30 years (Soares-Filho and others 2006).

The first scenario (S1), in which there is full access to all land independent of current land use designation, shows that production from the timber industry would drop during the first decade but then increase to a peak in year 28, at approximately 36 million m^3 of production (Fig. 2). The total area harvested during the 30 years would be approximately 51.5 million ha. While this scenario is unfeasible because of established land use designations, it serves as a benchmark by which to estimate the opportunity cost, in terms of forgone potential logging income, incurred by establishing protected areas. In this scenario we estimate that logging would generate \$7.1 billion dollars over the next 30 years in discounted sustainable rents to landowners. As default landowners in areas with no current designation or as owners in protected areas, the government would be eligible to earn some of this income. In other areas, however, the government has little option to tax this revenue, because logging is considered an unproductive use of the land. The Brazilian rural land tax (ITR) is based on land holding size and percentage productive (cleared). The bigger the land holding, the higher the tax, and the higher percentage cleared, the lower the tax. Therefore there is an incentive to clear forest. The tax ranges from

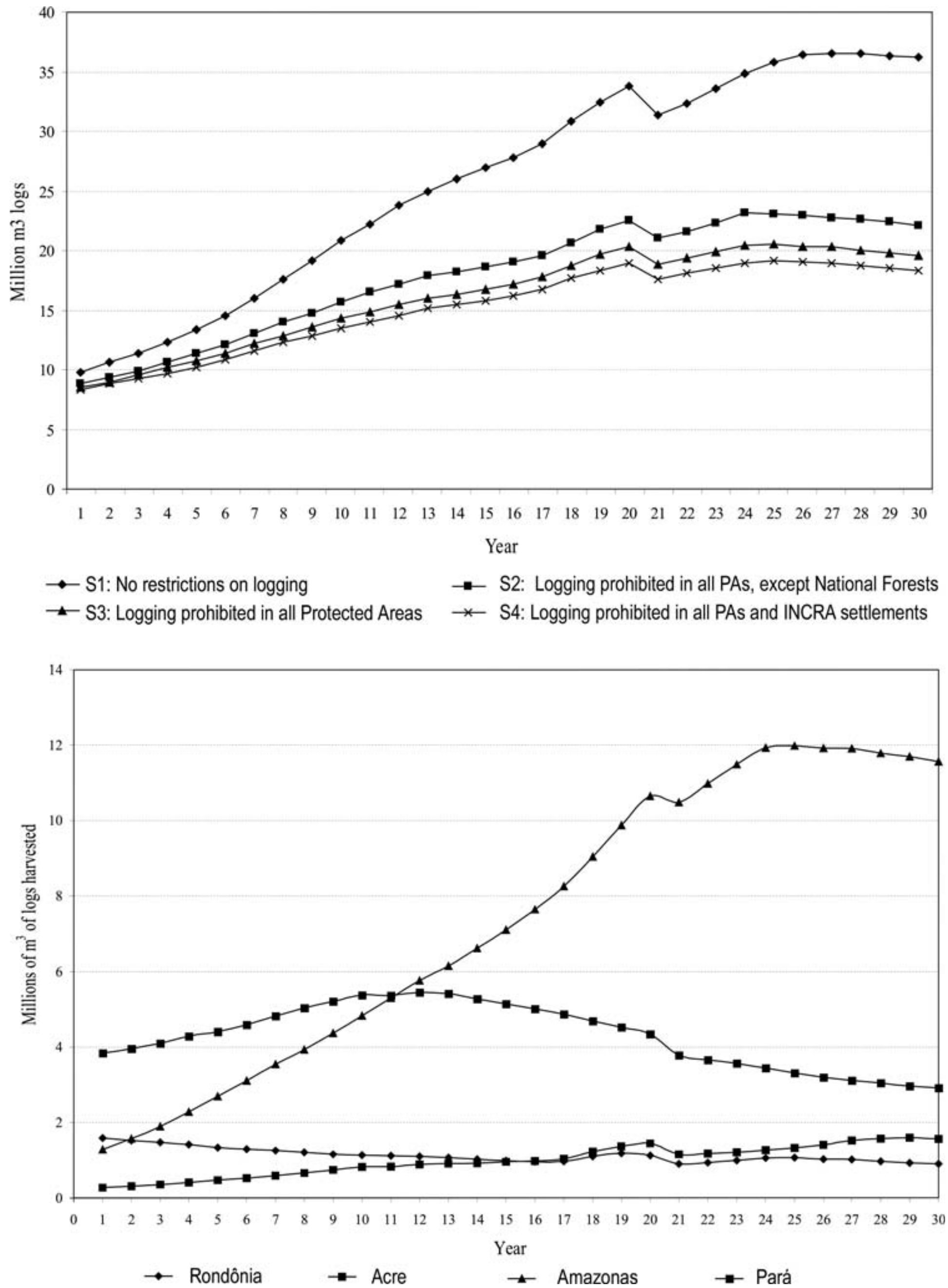

Fig. 2 *Top* Annual harvest volume showing maximum potential growth under a full access scenario (S1) (i.e., logging no protected areas), with 22 million ha available for logging in timber concessions on national forests (S2), a full protection scenario (S3) (no logging on protected areas), and, finally, a scenario examining the role of smallholders in the logging economy (S4). *Bottom* Forecast harvest production for four states in the Amazon: Rondônia, Acre, Amazonas, and Pará. The production trajectory for Mato Grosso closely matches that for Rondônia and so, for clarity, is not shown here

0.3% to 20%. Assuming that forest rents are equivalent to land values (probably a slight underestimate since there is the possibility of a second rotation), even at the lowest available rate this would generate an additional $215 million in government revenue through a land tax. This production volume would generate a total discounted gross product value of $26 billion—with an annual gross product ranging between $667 million and $2.4 billion to the industry, depending on respective production volumes. Sales taxes on sawnwood would generate some $ 2.7 billion in discounted government revenue over the 30-year period.

In the second scenario (S2), in which there is logging allowed in national forests and outside of protected areas only, we see a drastic reduction in production due to the exclusion of all protected areas except 22 million ha of national forests. We begin the simulation with only 8.8 million m^3 of production, but this steadily increases to a plateau of around 22 million m^3 of annual log harvests—recall that current estimates for logging are between 20 million and 25 million m^3. The total area harvested during the 30 years would be approximately 36 million ha. In this scenario, we estimate that logging would generate $5.3 billion dollars over the next 30 years in discounted sustainable rents to landowners. The value added on this volume, in terms of sawnwood only, would lead to a total discounted gross product value of $16.5 billion—with annual estimates at $600 to $1.5 billion per year, depending on respective production volumes. Sales tax on sawnwood production only would generate some $2 billion in discounted government revenue over the 30-year period. This represents a decrease in potential government revenue from imposing a sales tax of $0.7 billion compared to S1 (government revenue in S1 minus government revenue in S2).

Although each millshed—defined as the least transportation cost area around a processing center—in this simulation model has different stumpage prices, the average stumpage price for year 1 in the simulation is almost $20 per m^3. The timing of concession production is shown in the final curve in Fig. 2; by examining the difference between S2 and S3 the results suggest that concessions should be phased in gradually, while eventually reaching no more than 10% of total production to maximize sector revenues. For example in year 1 the optimal spatial distribution of logging would include no more than 2% from concessions (or approximately 170,000 m^3), increasing over time to approximately 11% (2.48 million m^3). Thus, national forests can play an increasing role in production as the harvest in other regions is accomplished. This is an intuitively attractive scenario, in which harvest on private lands, and the returns to private landholders, is done first, with public lands coming into play to maintain the growth of the industry over the longer term. Although the exact distribution of logging is difficult to assess, it is clear that national forests can play an important and increasing role in the industry, but it is inefficient to bring them into production before harvest on private lands has been accomplished.

As we continue to restrict access to land for harvesting we see a shrinking of the forest economy. For example, in the third scenario (S3), where logging is no longer allowed on the 22 million ha of national forests, we see an additional decrease in logging volumes. In this case no logging is permitted on any protected areas, and the industry begins with a production volume of 8.5 million m^3 in year 1, increasing to a maximum of 20.5 million m^3 in year 25 and declining to year 30. The total area harvested during this period would be about 32 million ha, with a maximum annual harvest area of 1.36 million ha. Logging entirely outside of current protected areas will still generate an estimated $4.8 billion to landowners over 30 years, a reduction of $0.5 billion from the scenario where logging is also allowed on national forests. With an estimated total gross product of just over $15 billion, this scenario would generate approximately $1.8 billion in revenues to the government through sales tax revenues on sawnwood. This difference shows that by allowing logging on national forests, the government could potentially earn the revenues associated with "land ownership" of approximately $0.5 billion over 30 years through royalties on concessions. This scenario shows, however, that there is a sustainable future for logging outside of the 43% of protected areas in the Amazon that could complement, and partially offset, the costs of, a protected area program: we do not, however, recommend directed taxes; rather the revenue generated through government taxes on sawnwood should go where it would produce the highest returns to society. We only note here that they are some portion of the costs of protection. In effect, this type of tax has a double dividend, by reducing logging where needed but raising revenues for other parts of the economy.

Our fourth scenario (S4) examines the role played by smallholder settlement communities in the logging sector, in a situation where no logging is allowed in protected areas (i.e., S2). As reported in Table 3, there is considerable commercial and profitable volume located within areas formal INCRA (National Institute of Colonization and Agrarian Reform) settlements (referred to as 'formal settlements' from here on). In this case the area under consideration is only 283,024 km^2, which would hold approximately the same number of families. In fact, estimates of the number of families located in the Brazilian Amazon are much higher, at approximately 500,000, and informal settlement may double the area controlled by smallholders (Lima and others 2006). Therefore, these estimates are very conservative.

The influence of formal settlements can be examined by removing them from possible production, much like we did with protected areas. Again, this adjustment then takes into account "leakage," because production can be accomplished elsewhere. In this scenario, the total reduction in harvest volume over the 30-year run is approximately 79 million m^3, or 15%. The logging income lost over the 30 years by excluding smallholders is approximately $800 million. This shows a significant potential contribution of smallholders to logging industry profits. Forest policies designed to maximize returns to a sustainable industry must therefore include an analysis of these settlers.

Discussion

With the advances in logging technology and increasing interest in governance of the forest industry, timber harvesting in neotropical forests could play some role in the development of sustainable economics returns on the Amazon forest frontier. Protected areas are also a necessary component of effective frontier governance, but the influence of these areas on how the forest sector develops must be considered when evaluating their effectiveness. There is a considerable forest estate outside of protected areas that could be managed to generate income and partially offset the costs of protected areas.

This is particularly true of the logging industry in the Brazilian Amazon. Within our model and assumptions made in this article, we show that there are positive and significant logging rents to be captured in protected areas. These rents have historically been captured illegally, and this will continue unless there is adequate concomitant investment in enforcement—the current Brazilian forest policy with effort in concession management effectively addresses this concern. There is another side to the story, however. There can be profitable sustainable logging outside of protected areas. In fact, we show that over a 30-year period it is economically possible for the industry to expand production almost threefold while leaving protected areas untouched. We also show, however, that there would be an opportunity cost to this action from logging rents lost by not harvesting in protected areas where our model finds it is profitable to log. Therefore, a mix of private and public harvesting is most attractive. If a legal, productive, timber industry can be established outside of protected areas, then society can capture the environmental benefits from both actions.

The current Brazilian forest policy emphasizes timber concessions in national forests. This is not incompatible with the mixed benefit scenario we find to be optimal; in fact, we show that production in national forests should increase over time up to a maximum of 12% of total harvest volume in an optimal distribution. But this needs to be carefully managed in light of the limited investment available for frontier governance; IBAMA (the Brazilian Institute of the Environment and Natural Resources), the newly created Brazilian Forest Service (SFB), and State forestry agencies are all severely underfunded, and any action in protected areas must be considered with respect to lost opportunities to supervise logging on private lands or monitor illegal logging on other government lands. Furthermore, the government must carefully consider the impacts of setting artificially low royalties in logging concessions—this has been historically problematic in managing national forests in both developed and developing countries. Royalties that are below market rates will provide incentives for logging in concessions at the expense of logging on private lands.

Furthermore, the significant logging rents to be captured on lands outside of protected areas that could make the mandatory 80% legal forest reserve (on private landholdings in the Amazon forest biome) more attainable, help logging compete with other land uses, and generate substantial government tax revenue (see Barros 2002; Morton and others 2006). To date, logging rents in the Brazilian Amazon have been considered a transient element in the progression of native forests to another (clearing-based) land use. Our results, however, suggest that this need not remain the rule. We demonstrate that, even with no logging in protected areas, there is tremendous potential for logging to be an integral part of sustainable economic returns on the frontier. Logs from both timber concessions and private lands, however, will continue to compete in the market against illegal logs harvested from unsettled and unenforced government lands. Therefore, poor enforcement of timber legislation outside of protected areas will continue to devalue rents to land left in forests.

Our results also demonstrate very clearly that the balance between conservation and development is delicate. Protected areas certainly play a vital role, but designating protected areas requires adequate and sensible investments in governance outside of their borders. Here we show that logging on private lands or other government lands outside protected areas can provide a much-needed source of sustainable income on the forest frontier. Furthermore, while some logging on public lands (i.e., national forests) will provide additional sources of revenue, a focus on concessions cannot be the only forest policy implemented in the Amazon. The current forest policy and creation of the Brazilian Forest Service is a step in the right direction, but good governance coupled with a focus on developing forestry on private lands will be necessary to maximize potential rents to both land users and the government. State governments, now responsible for managing private forest production, must be strengthened and able to deliver forest extension and training as well as encouraging forest management by reducing the transaction costs of inefficient bureaucracy. We show that a sustainable future for the Amazon timber industry is possible and is an important partner to protected areas in the effort to halt deforestation. In fact, sustainable timber production is an important component of a high-carbon rural development pathway for the Amazon that could help maintain higher carbon stocks, biodiversity, and regional climate stability, while providing income and employment for Amazon society.

The analysis in this article could be extended in a number of ways. First, we have not modeled the effects of harvesting on domestic and international markets, reasoning that most logging expansion occurs on export-based older frontiers where firms are price takers. Second, it would be useful to investigate the pattern of how deforestation and logging spreads over time in each of our scenarios. Finally, more complicated opportunity cost computations could also be made that incorporate future changes in agricultural production on cleared land, which are missing in our current analysis.

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