Cost and Rents to Logging in the Brazilian Amazon

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Thesis submitted to the faculty of the
Virginia Polytechnic Institute and State University
College of Natural Resources
Department of Forestry
In partial fulfillment of the requirement for the degree of

MASTER OF SCIENCE
IN
FORESTRY

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May 26th, 2004
Blacksburg, VA

Keywords: cost functions, rents, logging industry, Amazon

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Abstract

The logging industry of the Amazon is a topic that has received little attention in the literature, beyond specific single firm case studies. This has not allowed estimation of cost and production functions that can be used to predict changes in the industry in response to external market factors or government policies. Cost functions and rents are very important to characterize the dynamics of industry behavior, as well as providing important information for future policies. This study relies on a survey of 527 firms to estimate harvest, transportation, and milling cost functions for the logging industry in the Brazilian Amazon, finding variables such as labor cost, distance from the forest to the sawmill, equipment and frontier type to significantly affect the total and marginal cost of each activity. Rents are also estimated for different sampled milling centers, and a cost minimizing mathematical programming model is presented that explains the advance of the logging frontier in Brazil.

Acknowledgements:

I would like to thank my advisor, Dr. Gregory Amacher for all his guidance and support, not only when I first got here but also along the way: for giving me the opportunity to pursue my degree here, for relying on my work, and also for his contagious enthusiasm for the field of economics, which influenced my decision to pursue a Ph.D.

I would also like thank Dr. Dan Taylor, for his incentive and interest in this thesis, and Dr. Frank Merry, for the first contact with this project and helping me with doubts.

Funding for my Masters program and research was graciously provided by the Amazon Institute of Environmental Research (IPAM) through projects from: United States Agency for International Development; Banco da Amazonia, Gordon and Betty Moore Foundation; and the Hewlett foundation.

Coming from Brazil was a big decision, but friends here made it easier. I'd like to thank my friends: Michael, Olyssa, Nathan, José, Heike, Ingmar, Stefan, Sujana, Mathias, and my fellow graduate student, Melinda, for helping through all my troubles.
Friends that I left behind were also as important: the girls at BAO, Montro, Stábulo, Gibão, Juliano, Carmen, Eduardo, Dalva, Jimmy, Açauto, Koala, Vegetal, Limonada, Piru, and others; not to mention all the support from my advisors
Dr. Luiz Carlos Rodriguez and Dr. Fernando Seixas.

Finally, but also most importantly, I'd like to thank my family: my parents and brothers. For all their support, incentive and cheering, despite distance. If it wasn't for their guidance I would not be here now.

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I. Introduction

The development of the Amazon region and its accompanying deforestation are growing concerns that are intrinsically related and, some argue, unavoidable. One factor related to this problem is the region's historical extraction of forest resources, and current position as one of the main potential World suppliers of tropical wood. The Amazon region comprises 5.5 million square kilometers, of which 60% is located in Brazil with an estimated stock of more than 60 billion cubic meters (WWF, 2004). Annual log production in Brazil alone is over 28 million cubic meters, although currently only 14% of this amount is exported (Smeraldi & Veríssimo, 1999). It is clear that potential timber production is large, especially when considering declining timber production from other sources, such as Southeast Asia (Brown & Durst, 2003).

Another factor in deforestation and logging expansion has been infrastructure improvement resulting in development of new logging frontiers. A key determinant of frontier expansion is the rent (i.e., profits) captured by the logging industry. When transportation becomes possible through road development, logging expands to the point where rents to harvesting dissipate (Hyde and Sedjo, 1992; Stone, 1998a). Yet little work has focused on understanding the components of rent at the microeconomic level for logging firms. For example, information on the cost of basic forest operations (such as harvest, transportation and processing) and their variations across different frontiers is unknown. Thus we have little information on how costs and rents respond to infrastructure changes, or how they compare for different stages of logging and processing. This information is clearly needed if we are to understand the patterns of deforestation on the Amazon landscape.

The purpose of this study is to link local features, such as forest stock and frontier characteristics, to industry costs and to markets through the estimation of cost functions for three different stages of the timber production: logging, transportation and milling. Given that costs are the main components of rents, estimation of cost functions will provide policy makers with a means to predict the industry's behavior in response to future policies such as government subsidies, infrastructure improvements, macroeconomic shocks and other market influences. By estimating processing firms' (i.e., suppliers) costs, decision makers will also have important information regarding how changes in input prices or output demands influence industry costs and behavior; this will allow a more reliable prediction of the effects of any given public policy. The use of regression models explaining a sample of the regional industry also allows predictions of costs for non-sampled firms, making it possible to analyze the responses of the industry across a broad region. Estimating a different function for three logging related activities recognizes that greater variability that can exist within firms, and it also allows use of more specific variables for each stage of processing. This is very important in the sense that aggregating variables can dismiss certain firm characteristics and therefore constrain future analysis.

To approach the problem above, cost functions for three different stages of logging activities: harvest, transportation and processing are estimated in this thesis, with both Cobb Douglas and Translog functional forms being estimated and tested. Marginal costs are then estimated and compared to identify important variables affecting these costs. Variables in our model and data will be chosen according to their importance in production or as policy targets. Statistically significant variables are the most important targets if the goal is to affect costs and rents and therefore industry behavior or logging frontier expansion patterns. The marginal effects of the significant variables are used to estimate rents to the logging industry, and a math programming model is constructed using the cost function coefficient estimates to study the incentive to open new frontiers by allocating firms in areas with minimum production costs.

The work in this thesis also differs from previous literature on general cost function estimation. For example, few studies have actually estimated cost and rent functions for the logging industry. There are some examples of functions estimated for the forestry sector in the U.S. such as Cubbage et al (1989) who estimated cost functions to characterize the logging industry based on a 1979 census of southern pulpwood producers, concluding that exponential functions had the best behavior. Carter and Cubbage (1994) modeled an econometric frontier production function for southern U.S. pulpwood harvesting and tested Cobb-Douglas and translog functional forms, finding that these functions yielded very similar results. Finally, Stier and Bengston (1992) present a literature review on different approaches to estimating technical change in the North American forestry sector, of which a significant part is composed by studies that estimated production and cost functions. Most of the latter are based on translog functional form models applied to specific empirical cases.

However, very few studies have attempted to estimate cost and rent functions in the tropics. An exception is Vincent (1990), in which the author estimates a rent function for the logging industry based on government revenue data to analyze the efficiency of tropical timber royalty systems as indicators of the potential financial return to forest management. He concludes that royalties are too low and should be increased. This conclusion is refuted by Hyde and Sedjo (1992), who point out that the change in government revenue for an increase in royalty depends on the marginal cost elasticity of firms, highlighting the importance of estimating firm-specific marginal costs. Another study related to rents to forestry is Stone (1998b), who undertakes a financial analysis for an old developed frontier based on comparing results from interviews in 1990 and 1995. He illustrates a decrease in profits for the forest industry and therefore a transition from the extraction of spatial Von Thünen rents to infinite Faustmann rotations based on rents of plantations. However, his results are particularly sensitive to underlying assumptions not tested in the analysis that could possibly reverse the results. Examples are the interest rate considered in both surveys (4% in 1990 and 20% in 1995), and the conversion rate from logs to sawn wood obtained from other literature (47% used for the analysis of 1990 and 34% in 1995, with no technological change to justify it).

The remaining literature related to forest rents focuses on analyzing the financial aspects of one particular firm. This has not allowed a generalization of industry or firm costs outside of local conditions, much less regional conditions. These studies calculate the financial results for reduced impact logging projects comparing them to returns from conventional logging practices. All of these studies (except one reviewed by Pearce, 1999) conclude that reduced impact logging has higher returns than conventional logging practices in the long-term. Examples of these types of studies in Brazil include Holmes et al (2002), Barreto et al (1998), Uhl et al (1991), Veríssimo et al (1992, 1995), Johns et al (1996), Oliveira et al

(1999) and Costa Filho & Ferreira (1993). For a current literature review on other studies outside of Brazil see Pearce et al (1999).

Another related approach in the literature is one that tries to explain what drives deforestation in a certain region. This approach relies on the assumption that deforestation is linked to logging, thus these studies estimate the impact of distance and other variables on the probability of land clearing. Examples of this approach are Cropper et al (2001), who used econometric models to explain the impact of the location roads and protected areas on deforestation in North Thailand, Pfaff (1996), who built econometric models with GIS data to explain deforestation in the Brazilian Amazon, and Stone (1998a), who built a GIS model to describe logging industry growth in the State of Pará, Brazil. The first study concluded that population density and market access have statistically significant effects on land clearing, but the greatest impact is due to the presence of roads, especially at the forest fringe. Pfaff (1996) concluded that paved distance is significant in determining deforestation, while overall distance is not. Population-associated variables were also shown to be significant only when considered as quadratic variables, having a negative impact on the probability of deforestation, but this is not expected. Stone (1998a), using costs from previous literature and GIS data, concluded that logging industry will grow by 11 to 19% per year over the next ten years in Pará, Brazil, and that policies could affect area and volume produced. He found that lowering interest rates increased the logged area, while enforcing park boundaries did not affect the expansion of the industry but its location. Finally, enforcing forest management regulations reduced the volume of timber harvested but actually increased the harvested area by encouraging the extraction of high value species.

Chomitz and Gray (1995) describe deforestation as a function of rents to different types of land use. They use a spatial model to predict rents across the landscape based primarily on road access, distance to market, and inherent productivity of the land. They conclude that these factors are highly related to deforestation and that intensification of the current road network would offer higher economic returns and less environmental damage than the extension of roads into new areas. Finally, Albers (1996) builds a model to describe landowner decision making under different levels of uncertainty, irreversibility of land uses, and spatial interdependence. She concludes that these factors encourage reversible land uses, instead of development and, due to the inclusion of positive values for preserving an area, the impact of choosing different discount rates on optimal land use patterns was reduced.

The reader should be cautioned that the focus of this thesis is to develop an understanding of the logging industry in the Brazilian Amazon, specifically, to understand how the industry responds to external policies or resources. The work here is related to deforestation, as we will discuss later, but understanding deforestation is not a primary goal of the thesis. Rather, this study is a necessary precursor to predicting patterns of deforestation, because how the logging industry organizes around frontiers that develop is important to the dynamics of deforestation.

The remainder of this thesis is organized as follows. First a short section on the background of timber extraction in Brazil is provided. Second a specification of the cost function models used in the analysis is discussed. Third, a section on the data and its descriptive statistics is used to provide an initial outline of the data collection and composition of the dataset. Fourth, econometric results are presented for each operation: harvest, transportation and processing. Fifth, a section with the results of a linear programming model is presented along with the estimation of rent functions. Finally, conclusions, policy implications, and suggestions for further research are offered in the last section.

II. Background

Logging in Brazil started in the 1500's when Portuguese settlers began to export logs from the forest on the Atlantic coast. The range of forest harvesting expanded rapidly to the South, but only much later to the Amazon region due to the distance from demand centers. The first products from the Amazon were spices, collected from trees, shrubs, and other plants in the forest, such as pepper and cacao. Markets for these products flourished for some time due to their higher aggregate values and facility to transport (less volume). Later natural rubber became the main cash crop, bringing a boom of development to the region. However, rubber seeds were taken to Asia and plantations in this new area began competing with natural stands in the Amazon. This competition led the Amazon producers to bankruptcy, driving the regional economy into deep depression. As the national and worldwide demand for wood rose, the region became a significant lumber producer, supplying most of the domestic market and satisfying some export demand.

Logging and wood processing have grown to become a major part of the region's economy, accounting for 15 to 20% of the GDP in the states of Pará, Rondonia, and Mato Grosso and second only to mineral extraction (WWF, 2004). This has increased pressure on the remaining primary Amazon forest, as well as causing policy makers to focus increasingly on ways of achieving a sustainable wood production flow while protecting future stocks. In 1998, the Amazon timber production amounted to 28.25 million cubic meters (Veríssimo et al, 2002), of which 82 percent was argued to be illegal[1]. Considering that most of this harvesting has not followed reduced impact logging prescriptions, and given that much of it has involved transformation of primary forests into other non-forest land uses, shows that deforestation is clearly an important continuing problem for the region.

Deforestation depends on the existence of economic incentives to log (positive profits or producer surplus) as well as the development of public infrastructure, such as the opening of new roads. As public incentives and infrastructure are developed, labor-intensive logging activities move further into the primary forest, expanding the frontier. Old milling centers become characterized by having access by paved roads but a greater distance to the forest. New frontiers are closer to the forest but are served only by dirt roads. This causes a trade off between the distance to log and the distance to transport the output (usually sawn boards), technology available in each area, quality of the forest, size of the enterprise, cost of inputs, as well as the enforcement of regulations in each area. The rising costs of inputs in old frontiers result in the relocation of many firms towards newer frontiers or an increase in the size of the remaining enterprises to capture increasing returns to scale. This results in a "boom collapse" cycle that has characterized most logging frontiers (Schneider et al, 2000).

[1] This percentage was calculated based on the official information on allowed wood extraction in 2000 by the Brazilian environmental agency when compared to the estimates in Sobral et al. (2002).

III. Econometrics

The econometric analysis in this study is used to explain logging, transportation, and processing costs for firms in the Brazilian Amazon. To achieve this, regressions were run to fit the data with different functional forms, and hypothesis tests were then used to determine the functional form that best fit the data. Heteroskedasticity was corrected, when needed, based on results from Breusch Pagan Chi Square tests. In these cases White's method was used to correct the estimates for heteroskedasticity (for a discussion about this method, refer to Greene, 1997, pp. 505).

The Cobb Douglas functional form is defined as (for a discussion about this functional form and its properties refer to Chung, 1994, pp. 93):

$$y = Ax_1^{\alpha} x_2^{\beta} \ldots x_n^{\eta}$$

where y is the cost of production, x_i is the price of input i (in our case some variables used as proxy for these prices were also included, as we discuss later), and $A>0$ is a constant. To be able to estimate this function using linear regression, a logarithmic transformation was made. As a result of this transformation, the estimated coefficients are the actual elasticities of cost with respect to each variable (percentage change in cost for a percentage change in the analyzed variable).

The estimated harvest cost model was given by:

$$C_{har} = f(V, Mhar, W, Al, Ch, Sk, B, Lo, e_{har})$$

where C_{har} is the cost of harvest per cubic meter, V is the total volume of logs processed in 2002, $Mhar$ is the number of months with logging activities per year, W is the total monthly cost of labor in the Summer, Al is the average age of the logging equipment, Ch is the number of chainsaws, Sk is the number of skidders, B is the number of bulldozers, Lo is the number of loaders, and e_{har} is the error term. The age of capital items was used as instrumental variables for capital unit costs. This was needed because these costs either had no variation in the data or were not available for enough firms in the data.

The output volume measure used in the cost function estimation was the total volume processed in 2002 by each firm. The latter should equal the first for firms that do not buy logs from other harvesters, while it can be higher for firms that buy logs besides having their own harvesting. The fact that total volume was a better predictor can be explained by more firms answering the questions in our survey (discussed later) for total volume processed in 2002. A reason for this is that under Brazilian environmental law each firm is responsible for the amount of wood harvested, but not for the origin of the processed wood. Therefore, it is in the interest of the entrepreneur to avoid answering any question about the amount of wood harvested and instead give only total processed volume. From all the companies with harvesting activities, 18.2% did not answer about volume harvested in 2002, but only 8% did not answer the question related to the volume processed in 2002.

The number of months with harvesting activities per year was determined by accessibility conditions to the harvest sites. Locations with poor roads are not accessible during months with more rainfall, usually December through May. That is also the reason that total monthly costs of labor refer to the Summer (production intensive) months.

The transportation cost model was estimated as follows:

$$C_{transportation} = f(Dist, Pdist, T, At, W, V, Tf, e_{transp})$$

where $C_{transportation}$ is the transportation cost per cubic meter, *Dist* is the distance from the forest (origin of logs) to the sawmill (processing unit), *Pdist* is the paved distance from the forest to the sawmill, *T* is the number of trucks, the variable *At* is the average age of the trucks, *W* is the total cost of labor per month in the Summer, *V* is the total volume of logs processed in 2002, *Tf* is a dummy variable to represent if a firm owns its transportation fleet or not, and e_{transp} is the error term.

In this model, as in the previous one, the variable used to define output volume also refers to the total volume processed and not volume harvested in 2002. The milling cost model applies to sawmills, since few firms (37) in our sample produced plywood or veneer products only. Therefore, due to technological differences in processing, plywood and veneer mills were discarded from the sample. The milling cost model was defined as follows:

$$C_{milling} = f(Vs, W, O, Bs, Cs, Mb, S, Am, Mmill, L, F, e_{mill})$$

where $C_{milling}$ is the cost of processing a cubic meter, *Vs* is the volume of sawn wood produced in 2002, *W* is the total cost of labor per month in the Summer, *O* is other aggregate costs per cubic meter, *Bs* is the number of band saws, *Cs* is the number of circular saws, *Mb* is the number of multi-blade edgers, *S* is the number of sanders, *Am* is the average age of the milling equipment, M_{mill} is the number of months per year with milling activities, *L* is a dummy variable to characterize if the firm owns logging operations, *F* is a dummy variable to characterize if a firm is located in a new/intermediate frontier or not, and e_{mill} is the error term. A model without the frontier dummy variable will also be estimated, and a hypothesis test was carried out to verify if the models were statistically different.

The other aggregate cost variable, included in the model above, was calculated as follows:

$$Oc = C_{milling} - \frac{W}{V/Mmill}$$

Where $C_{milling}$ is the cost of processing a cubic meter, *Oc* is the variable for the other aggregate costs, *W* is the monthly labor cost in the summer, M_{mill} is the number of months of milling activities per year, and *V* is the processed volume per year. Basically, it is a proxy for all other costs combined, or milling cost minus labor cost per cubic meter.

Besides the Cobb Douglas functional form, the Translog form was also used here. The Translog function is a variation of the Cobb Douglas function in the sense that it adds interaction variables between the variables to the original variables in the Cobb Douglas specification (for a discussion about this functional form and its properties refer to Chung, 1994, pp. 139). The Translog functional form is written as:

$$\ln y = \ln a_0 + \sum_{i=1}^{n} a_i \ln x_i + \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n} b_{ij} \ln x_i \ln x_j$$

$$(i \neq j; i, j = 1, \ldots, n)$$

where y is the cost of processing a cubic meter and x_i is the price of each input i or proxy for input price. In our model, we used as interaction terms only the significant variables in the estimated Cobb Douglas model.

A hypothesis test was carried out to verify if the translog function was statistically superior to the Cobb Douglas function by calculating the standard F statistic for model selection:

$$F = \frac{(SSR_r - SSR_{ur})/q}{SSRur/(n-k-1)}$$

Where SSR_r and SSR_{ur} are the sum of squared residuals for the restricted and unrestricted models, respectively, q is the numerator degrees of freedom (df_r - df_{ur}); n is the number of observations, k is the number of independent variables in the unrestricted model. After these regressions and tests, the marginal effects (change in cost for a unit change in the studied variable) were also estimated and compared to identify key variables to these costs. As we will discuss later, these marginal effects are important in identifying potential and important targets for policy makers.

IV. Rent estimation

Rents are very important to determine the location of firms along frontiers. By calculating rents, we can estimate the returns to logging for firms that earn positive profits, or firms that operate on the margin with cost below price. This is important information for policy makers since it allows them to quantitatively analyze how policy instruments affect profitability of logging, and thus deforestation and frontier expansion. For example, the distance from the sawmill it is economically profitable to log can be calculated.

Rents were estimated for the logging industry described by the transportation cost functions above to be able to describe the distribution of rents according to distance from forest to sawmill. Rent is defined according to the formula below:

$$R_{dj} = \int_{dj} (P_j - MC_j) dd_j$$

Where R_{dj} is the rent at distance j, P_j is the price of sawn wood in milling center j, and MC_j is the marginal cost (change in cost for a change in the significant variable analyzed at the time) recovered from the transportation cost function estimates. The prices (Pj) were obtained from a weighted average for each milling center according to the percent destination of the final products (exports, domestic market, and residue). The rent for each milling center with respect to distance was calculated using the average marginal cost, distance and price for each milling center.

To allow regional data analysis, milling centers were obtained by grouping sampled municipalities according to geographical proximity and then classifying them into three different definitions according to access infrastructure:

- Old frontiers: municipalities served by paved roads or river ports
- Intermediate frontiers: municipalities accessed by unpaved roads but within 40km of paved roads or river ports
- New frontiers: municipalities further than 40km from paved roads or river ports.

This resulted in 12 different milling centers, for which weighted prices and rents were calculated. These milling centers were also the base for the math programming model discussed below.

Later, rents were calculated for each frontier type by simplifying the equation above, and each frontier was assumed to be a point on this rent function. Therefore price, marginal cost and distance were considered constant within a frontier (calculated as the average for all observations in each frontier type).

V. Math Programming

After obtaining the logging, transportation and milling cost functions the estimated significant coefficients were used in a cost-minimizing math programming model (see Hillier & Lieberman, 1995 pp. 25). The purpose of this model was to identify mill location given the estimated cost and rent functions. Considering that the logging industry is competitive, the cost minimizing problem is identical to one of rent maximization.

The data were divided into 12 different milling centers according to their location. These were then classified as new, old and intermediate frontier areas and predicted costs were estimated using the estimated functions evaluated at the averages of variables for observations in each milling center. The objective function for the cost minimization problem was then constructed as:

$$\min z = \sum_{i=1}^{n} (F + C_{har} + C_{trnsp} + C_{milling}) v_i$$

Where z is production cost per cubic meter, F is the stumpage price paid to the forest owner, C_{har} is the harvesting cost, C_{transp} is the transportation cost, and $C_{milling}$ is the milling cost per cubic meter, v_i is the volume processed in each milling center i, n is the number of frontiers under consideration. This resulted in a linear programming model with 49 constraints.

The constraints were defined as (for the actual model, refer to Appendix B):

Transformation rows: $S_i = H_i = T_i = c_f \times M_i$, where S_i is volume for which stumpage price was paid, H_i is volume harvested, T_i is transported volume, M_i is volume processed (all of them for each milling center *i*), and c_f is the conversion rate from logs into sawn wood for each frontier type (*f*). The conversion rate was calculated as the volume of sawn wood produced divided by the volume of logs consumed. Since some milling centers had conversion rates higher than those cited in the literature (e.g., see Gerwing and Uhl, 1995; Veríssimo et al, 1992), all conversion rates above 50% were discarded and replaced by the average conversion rate for each corresponding frontier type.

Maximum production constraints: $M_i \leq V_i$,

where M_i is the processed volume chosen by the math programming model and V_i is the actual volume of sawn wood produced in milling center *i*.

Minimum production constraint: $\sum_{i=1}^{n} M_i \geq \sum_{s=1}^{q} V_s$

where *n* is the number of frontiers under consideration, and V_s is the volume of sawn wood produced by all sampled firms (*q*).

After running the model the shadow prices (measures of the marginal value) for the maximum production constraints were ranked to identify the sequence of lowest to highest cost production locations. This is valid because shadow prices show how the objective function value would change for a unit change in the constraint. The algorithm chooses the location with the lowest cost first, then the second and so on, until the last location that completes the total volume constraint is at the highest cost. Therefore, this last location will have a zero shadow price, and the lowest cost location will have the highest shadow price.

VI. Data and Descriptive Statistics

The data for this study was collected between June and November, 2003. Interviews were randomly conducted with owners and managers of 527 sawmills in the Brazilian Amazon. The sampled areas include 27 municipalities in the State of Pará, 9 municipalities in the state of Rondonia, 6 municipalities in the state of Mato Grosso and 3 in the state of Acre. A questionnaire (appendix A) was applied to collect information regarding the characteristics of each firm, as well as its costs. The questions were designed to characterize the logging, transport and processing activities of each operation, as well as equipment, forest stock (specie value group, volume harvested per hectare), labor costs, output, and other costs.

Answering the questionnaire was voluntary and therefore not all sampled sawmills participated in the survey, and there were some missing answers. Despite this, there is no reason to believe this is a biased sample since only 5.57% of the sampled mills refused to answer the questionnaire (computation based on the first 300 observations), which is small given the difficulties of collecting data in the region and the total size of our sample. It is also known that operations are fairly labor intensive, and thus operations are similar across firms. There are no technological differences that would make us suppose otherwise and firms are fairly uniform within the frontiers sampled.

Of the 527 observations, 315 were located in old frontier areas, 118 in intermediate frontiers and 94 in new frontiers. This is expected considering that old frontiers are characterized by having more sawmills, and there were more municipalities in old frontiers (25) when compared to new (11) and intermediate (9) frontier municipalities. Therefore, old frontiers had on average a greater number of sawmills per municipality than intermediate frontiers, and this was greater than new frontiers.

Table 1 shows the sampled municipalities, number of observations in each municipality as well as their frontier classification. Table 2 presents descriptive statistics from the sample used in the econometric modeling. Most of the interviews (66%) were conducted in the state of Pará, which is the main producer of tropical timber in the region, being responsible for 40% of the production (Veríssimo et al, 2002).

The size of firms was characterized by the volume of sawn wood produced in 2002. The data in Table 2 shows an average of 4,034 m^3 per year was produced, but the standard deviation of 14,269 m^3 is high. This is due to the fact that there is a considerable variance in the size, and thus production, of different firms. In terms of size, the number of production lines used characterizes the firms, which is measured by the number of band saws, circular saws, multi-blade edgers and sanders. On average, the sampled mills had 1 band saw, 1.7 circular saws, 0.4 multi-blade edgers, 2.1 trimmers, and 0.8 sanders. This is typical for small firms with only one production line. The average age of this equipment was 11.6 years with a standard deviation of 7 years. The average total milling cost was R$71.22 (US$1=R$0.34) per cubic meter with a standard deviation of R$81.37. This large variance is interesting in the sample since it shows that there are variations in cost that should be explained by different factors, such as frontier position, labor cost, and other site-specific characteristics. We return to this later in our econometric estimation.

The average for the other aggregate cost variable was negative R$5.02 standard deviation of R$107.41. This variable may assume negative sign if the monthly labor cost or the volume processed per year were underestimated due to its calculation (shown previously). Average monthly labor cost in the Summer (production intensive months) was R$25,270.38 with a standard deviation of R$69,604.90. On average the firms had 45.5 employees, and dividing the monthly labor cost by the number of employees results in an average monthly wage of R$555.39 per employee. The sampled firms averaged 10.62 months of milling activities per year, standard deviation of 1.9 months. The average number of months with logging activities was 7.02 months per year, standard deviation of 2.38 months. This could be due to the rainy season (or winter) in which access to the forest is more difficult mainly due to precarious road conditions resulting from intense rain. There were 35.5% of sampled firms that had their own logging operations, and therefore harvested at least some of the total processed wood. The average total harvest cost was R$45.37 per cubic meter, standard deviation of R$31.05 per cubic meter. The average volume harvested by the firms with their own logging operations in 2002 was 11,130 m^3 with a standard deviation of 20,451 m^3; this suggests that the larger sawmills tended to have their own logging operations. Average volume harvested per hectare was 27 cubic meters, standard deviation of 16.68 cubic meters. There are differences in forest quality and also of the number of species harvested according to the frontier area. This is also consistent with the total forest cost variable (payment for harvest of the forest, without the land), which had an average of R$528.51 per hectare and a standard deviation of R$773.44. The average logging operation owned 3.3 chainsaws, 0.6 skidders, 1.3 bulldozers, 1.3 loaders, with an average age for this equipment of 10.9 years.

There were 72% of firms having their own logging operations that also had their own transportation fleet. The average transportation cost was R$30.57 per cubic meter, standard deviation of R$14.19. The average transported distance from the forest to the sawmill was 90.90km, standard deviation of 59.1km. From this total, the paved average distance was 13.6km standard deviation of 28.1km. The average number of logging trucks per firm was 1.9, standard deviation of 2.0 and these trucks were, on average, 6.2 years old (standard deviation of 4.3).

Our statistics are consistent with previous studies although their purpose and data collection procedures were different. Veríssimo et at (2002) describe data for the state of Pará and state that the annual consumption of logs for a micro sized enterprise is between 1,300 and 3,800 cubic meters per year. For small firms this ranged from 5,400 to 7,700 cubic meters, medium sized firms from 12,000 to 14,500, and large processing industries consume between 28,000 and 78,000 cubic meters per year. The authors also point out that 56% of the firms have their own extraction, while 44% buy logs from independent harvesters. While 43% of the harvest is done with the help of bulldozers, 29% is harvested by skidders. Thirty six percent of the harvest takes place on the logger's own land, and at the extreme 91% of the wood comes from private land. They find that 6% of the roads are paved, and paved distance decreases cost. While they did not estimate formal cost functions, they estimated that total production cost (to harvest, transport and process a cubic meter of sawn wood) was between US$119/m^3 and US$90/m^3 varying according to the geographical location of the firm (i.e. type of frontier).

Stone (1998b) in his analysis of sawmills in Paragominas, Pará, stated that that the average harvest cost for a small firm in 1995 was US$17.60 per cubic meter, while large firms had an average cost of US$15.34 per cubic meter. The average transportation cost was US$20.09 per cubic meter for a small firm and US$18.08 per cubic meters for large firms. These results show economies of scale captured by larger firms, since his entire sample was for one municipality. However, as an important town in the region, many firms only maintain offices there while the actual processing facility is located closer to the log source and therefore the results could have considered the location of the mill.

VII. Estimation results

In the case of the logging and transport cost functions, only the Cobb Douglas function was estimated (it was not possible to estimate a translog form due to lack of degrees of freedom). For the milling cost function, three different models were estimated: a Cobb Douglas specification, a Cobb Douglas specification with a dummy variable for firms in intermediate and new frontiers, and a Translog function specification.

VII.1. Harvest cost

The Cobb Douglas harvest cost function parameter estimates are shown in Table 3. The variables used in the model and their estimated parameters reflect their expected effect on total harvest cost. The data was corrected for heteroskedasticity, because the Breusch Pagan Chi Squared test statistic value equaled 10.65 in an initial regression. Heteroskedasticity was expected due to the large standard deviation in mill size documented earlier. The estimated model's R squared was .15, while the adjusted R squared was .08%. The Durbin Watson Statistic for autocorrelation was 1.93 and the F statistic for the model regression was 2.05.

There were four significant variables. The first was the volume of wood consumed by the firm in 2002, significant at the 5% significance level, which had a coefficient of R$-0.20 (standard deviation of R$0.10). This sign reflects lower costs for larger firms, indicating economy of scale effects captured by the industry. Another significant variable (at the 5% significance level) was the total cost of labor per month in the Summer, which increased costs with a coefficient of R$0.24 and a standard deviation of R$9.82E-2. This effect shows the importance of this input for the industry, indicating a labor-intensive activity.

The number of loaders used in the logging operation was significant at the 5% significance level, with a coefficient of R$ 4.68E-4 and a standard deviation of R$1.59E-4. This result is explained by the fact that having a loader is similar to a technological improvement, since very small firms load their trucks without using loaders, and this is less efficient. The sign and importance of the loaders variable also reflects economies of scale to be captured by larger firms. Finally the number of months with logging activities per year was significant at the 15% level with a coefficient of R$-0.50 and a standard deviation of R$0.23. This negative effect shows that as the firm logs in areas with better access, allowing harvesting for longer time periods during the year, cost decreases accordingly. A longer harvest season allows the firm's fixed costs to be spread over a longer period of time.

Finally, the average age of the harvesting equipment was not significant in this model, which can be explained by the fact that there are at least two factors countervailing: as the age of the harvesting equipment increases, depreciation is not included in the logging cost but there are higher variable costs.

Table 4 shows the marginal effects of the significant variables in the model described above. An additional dollar spent in labor in the Summer increases cost by R$3.83E-4, standard deviation of R$2.70E-4. An additional cubic meter in the total volume of logs consumed in a year decreases cost by R$1.48E-3 (standard deviation of R$2.26E-3). An additional loader in the harvesting activities decreases cost by R$1.31E-2 with a standard deviation of R$5.73E-3. Finally, the possibility of logging a site for an additional month during the year decreases cost by R$3.47 (standard deviation of R$1.62).

VII.2. Transportation cost

The transportation cost function was estimated using the Cobb Douglas functional form. Table 5 shows the parameter estimates for the function. The model's R squared was .42, while the adjusted R squared was .35. The model was significant with an F statistic value of 5.78. The Durbin Watson statistic was 1.89.

The results are as expected, showing that the distance from the forest to the sawmill is highly correlated with transportation cost (significant at less than the 1% significance level). The coefficient for this variable was R$0.50 (standard deviation of R$9.63E-2), showing that costs increase as distance increases. The paved distance between the harvesting location and the milling center was also significant (at the 10% significance level) with coefficient of R$-2.06E-4 and a standard deviation of R$1.23E-4. This implies that improvement in current infrastructure affects logging, since costs decrease, firms have incentives to move into new areas. Comparing these results to Pfaff (1996), in which only the paved distance was significant, our results show the importance of the distance to the sawmill on costs and, therefore, on the chance that land will be deforested.

The total volume of logs processed in 2002 was significant at the 5% level with a coefficient of R$-0.26 and a standard deviation of R$0.10, showing that economies of scale might play an important role in this activity. Finally, the dummy variable for owning a transportation fleet was significant at the 5% level with a coefficient of R$0.56 and a standard deviation of R$0.22. However, the age of trucks was not significant. This can be explained by the fact that older fleets do not have depreciation included in the transportation cost calculation, moreover, variable costs increase as maintenance costs increase.

Table 6 presents the marginal effects for the significant parameters. It can be seen that each kilometer of distance between harvest site and the sawmill increases cost by R$8.93E-2 (standard deviation of R$4.09E-2). However, each kilometer of paved distance decreases cost by R$2.06E-4 (standard deviation of R$2.88E-4). Each additional cubic meter of logs processed in 2002 reduced cost by R$2.02E-3 (standard deviation of R$5.95E-3), again showing the importance of the economy of scale to timber production in the Brazilian Amazon.

VII.3. Milling cost

Two different functional forms performed well for the milling cost estimation. These were the Cobb Douglas function and the Translog function with interaction terms for the significant variables. Two models were obtained for the Cobb Douglas functional form, one of which included a dummy variable for firms in the new/intermediate frontier. The results are described below:

VII.3.A. Cobb Douglas

Table 7 presents the Cobb Douglas milling cost estimates. The R squared for this model was .33, while the adjusted R squared was .31. The overall significance for this model resulted in an F value of 17.31, and the Durbin Watson Test Statistic for autocorrelation was 1.71. This model was corrected for heteroskedasticity following a Breusch Pagan Chi Squared test that resulted in a critical value of 55.48 during preliminary estimation.

Six variables were significant up to the 15% significance level. First, the volume of sawn wood produced in 2002 was significant at the 1% significance level with a coefficient of R$-6.67E-4 and a standard deviation of 0.52. This shows that, as in logging and transportation, economy of scale influences total cost. The cost of labor per month in the Summer was also significant at the 1% significance level, with a coefficient of R$0.27 and a standard deviation of R$5.04E-2, this again shows the importance of this input for the logging industry and it continues to support the assertion that logging and processing in the Amazon is indeed labor intensive. The variable representing other aggregate costs was significant at the 1% significance level, with a coefficient of R$6.44E-4 and a standard deviation of R$8.66E-5, as expected.

Equipment used in wood processing also affected the cost since the number of band saws and the number of sanders was both significant at the 5% significance level. The number of band saws had a coefficient of R$-6.16E-4 and a standard deviation of R$2.18E-4, while the number of sanders had a coefficient of R$2.83 and a standard deviation of R$6.99E-5. The number of band saws is a clear indication of the size of the firm, since each band saw is associated with one production line; this shows that larger firms have lower costs, confirming the conclusion drawn from the sign of the coefficient for the volume processed. The number of sanders increased the cost - sanded boards have a higher cost due to the additional processing phase. However, this increase in cost should be compensated for by an increase in the output price. The number of multi-blade edgers was not significant in the model, which can be explained by the fact that it is considered a technological improvement when compared to the simple circular saw, but it has a higher cost. Therefore, the gain from increasing production is offset by the higher acquisition cost of this machinery.

Finally the number of months with milling activities per year was significant at the 10% significance level with a coefficient of R$-0.29 and a standard deviation of R$0.17, which shows that if the firm can obtain logs during a longer period the processing costs decrease, because fixed costs are spread out over a longer period of time.

Table 8 presents the marginal effects for the significant variables in the model above. As shown in this table, an additional cubic meter produced decreases cost by R$3.61E-6 (standard deviation of R$6.61E-6). A unit increase in monthly labor cost in the Summer increases cost by R$4.48E-4, standard deviation of R$7.65E-4, while an increase in other aggregate costs increases the total milling cost by R$1.73E-3 (standard deviation of R$3.96E-3). An additional band saw decreases cost by RS1.33E-2 per cubic meter (standard deviation of R$2.08E-2) while an additional sander increases cost by R$5.28E-3 (standard deviation of R$8.74E-3). Finally processing logs for an additional month per year decreases cost by R$0.75 per cubic meter (standard deviation of R$1.26).

VII.3.B. Cobb Douglas with frontier dummy

Table 9 presents Cobb Douglas milling cost estimates for a model containing a dummy variable for the location of each firm in a new/intermediate frontier and Table 10 shows the descriptive statistics of the marginal effects for the significant variables. The R squared for this model was .33, while the adjusted R squared was .31. The overall significance for this model resulted in an F value of 15.89, and the Durbin Watson Test Statistic for autocorrelation was 1.71. This model was corrected for heteroskedasticity following a Breusch Pagan Chi Squared test that resulted in a critical value of 58.12 during preliminary estimation.

Comparing this model to the previous one, without the dummy variable for firms located in new and intermediate frontiers we can see that the inclusion of this variable increased the R squared by .03 without much change in the estimated coefficients. The significant variables for this model were the same as in the model without the frontier dummy, monthly cost of labor, other aggregate costs, and the number of sanders increased the milling cost, being significant at the 1% significance level. Volume of sawn wood produced in 2002, number of band saws, and number of months with milling activities per year decreased cost, as did the dummy variable for firms located in new and intermediate frontiers. This dummy, significant at the 6% significance level, had a negative coefficient of R$0.23 and a standard deviation of R$0.06, showing that new and intermediate frontiers have lower milling costs than old frontiers (this result will be discussed further in our math programming model).

VII.3.C. Translog

In estimating the translog cost function for the milling activities, the interaction terms for all significant variables in the Cobb Douglas model were included (except the dummy variable for firms in the new and intermediate frontiers). The model's R squared was .76, while the adjusted R squared was .74. The overall significance of the model resulted in an F value of 42.71 and the Durbin Watson Statistic for autocorrelation was 1.86. This model was corrected for heteroskedasticity due to a previous Breusch Pagan Chi Squared test of 118.35.

The estimated coefficients for this function are shown in table 11. As a result, 10 variables were significant up to the 15% significance level. The volume of sawn wood produced in 2002 was significant at the 1% significance level with a coefficient of R$4.08E-3 and a standard error of R$3.55E-4. The total cost of labor per month in the Summer was significant at the 10% significance level with a coefficient of R$0.66 and a standard error of R$0.36. Other aggregate costs were significant at the 5% significance level with a coefficient of R$-2.49E-4 and a standard deviation of R$1.14E-4, showing that there might be the effect of economy of scale from other costs beside the labor cost. Since total volume of sawn wood actually increased the milling cost, we can say that the labor effect was larger than the economy of scale effect for this model.

The coefficient for number of band saws was significant and negative at the 10% significance level. This variable had a coefficient of R$-2.70E-4 and a standard deviation of R$1.49E-4.

The number of sanders was also significant (at the 10% significance level) with a coefficient of R$7.01E-5 and a standard deviation of R$4.36E-5, showing that sanded boards have a higher production cost than non-sanded boards. The average age of the milling equipment was significant at the 5% significance level, and decreased milling cost by R$1.65E-4 (standard deviation of R$7.48E-5). This shows that in this model maintenance cost was not as important as the lack of depreciation in total milling cost. Finally, the number of months with milling activities was significant at the 5% significance level, with a coefficient of R$3.02 and a standard deviation of R$1.34.

Three interaction variables were also significant. The number of months with milling activity times the volume of sawn wood produced was significant at the 1% significance level with a coefficient of R$-0.239 and a standard deviation of R$7.30E-2. Another significant interaction term was months with milling activity times the number of band saws which was significant at the 1% significance level with a coefficient of R$0.55 and a standard deviation of R$0.21. Finally the interaction variable of other aggregate costs times the number of band saws was significant at the 10% significance level, with a coefficient of R$-3.61 and a standard deviation of R$1.92E-2.

Table 12 shows the marginal effects of the significant variables in the translog model. As depicted in this table, one more cubic meter of sawn wood produced per year decreased cost by R$3.68E-6 per cubic meter, with a standard deviation of R$6.75E-6. Another R$1.00 spent on labor increased cost by R$4.58E-4 (standard deviation of R$7.81E-4), while another R$1.00 spent on other costs increases cost by RR1.77E-3 (standard deviation of R$4.06E-3). In terms of equipment, an additional band saw decreased cost by R$1.35E-2 (standard deviation of R$2.11E-2), while an additional sander increased milling cost by R$5.28E-3 (standard deviation of R$8.75E-3). If milling equipment were, on average, a year older, milling cost would decrease by R$4.14E-4 (standard deviation of R$1.19E-3). Finally, if a firm could process wood for an additional month per year, milling cost per cubic meter would decrease by R$0.80 (standard deviation of R$1.35).

VIII. Extensions

VIII.1. Hypothesis testing

The significance of the translog model over the Cobb Douglas model was tested using an F statistic, where the translog was assumed to be the unrestricted model, and the Cobb Douglas was assumed to be the restricted model. The null hypothesis in which all the coefficients for the interaction terms are zero was rejected at the 1% significance level, due to an F statistic value of 42.91.

VIII.2. Rents

Estimated rents are shown in Tables 13 and 14. Table 13 shows the rent per kilometer of distance from the logging site to the sawmill estimated for each frontier type. We can see that the new frontier has a higher rent (R$6.36) per kilometer than the other types. This is another reason we can expect harvesting to relocate to new frontiers, instead of expanding on older frontiers. It can also be seen that the rents per kilometer in intermediate and old frontiers are very similar (R$4.13 for the first and R$4.27 for the latter), which shows that better roads do not influence marginal costs to a large degree. However, partially paved roads decrease costs, as can be seen by the rents in old frontiers being higher than in intermediate frontiers. Finally, Table 14 shows the results to rent estimation in each milling center. These results establish that old frontiers usually have lower rents per kilometer than newer frontiers. Intermediate frontiers usually have higher rents per kilometer, and new frontiers are somewhere in between.

VIII.3. Math programming

The results for the math programming model are shown in table 15. In this model we minimized production cost subject to production constraints (see Appendix B). By sorting the resulting dual prices, we can see that the new frontiers were the best locations for firms opting to minimize costs, due to their higher dual prices. The next lowest cost/highest rent locations were the intermediate frontiers, followed by the old frontiers. These results show why frontiers keep expanding. It is due to the fact that these areas are located closer to forests and lack enforcement of regulations and taxes, resulting in lower costs.

IX. Conclusion

The purpose of this thesis was to estimate cost functions for three different stages of the logging industry in the Brazilian Amazon: harvest, transportation and milling, we also estimated rents to firms with respect to distance from logging sites. Finally, a cost minimizing mathematical programming model was used to explain expansion of logging and the location of firms in new areas. The analysis was based on data from interviews with 527 logging firms in the Brazilian States of Pará, Mato Grosso, Rondonia and Acre. The interviews were conducted during July through December, 2003.

This study allows cost determination of different activities using related variables, and thus the results are important for future policy instruments directed toward the logging industry in the Amazon. The cost functions were estimated using variables such as volume produced and consumed, distance from mill to logging site, labor cost, equipment and its age. Rent was estimated using the cost function estimates and regional prices of wood. The math programming objective function was also constructed using the estimated coefficients of the cost functions.

This thesis addresses the economic implications of logging in one of the greatest remaining tropical forests of the world. The results will allow decision makers to understand logging industry behavior and its reactions to changes in market parameters and government policies. This data will allow predictions of future policy scenarios on the spread of deforestation. The use of regression models explaining a very large sample of the logging industry in the Brazilian Amazon also affords a method for predicting costs for firms outside of the sample. Further, estimating different cost functions for each stage of logging and processing allows for greater variation within firms and use of stage-specific variables for each function. We are not aware of a similar microeconomic study conducted for Amazon firms.

The estimated functions show an array of significant variables that have considerable impact on each stage's cost. In the harvest cost function, labor wage was a significant variable that increased cost, mainly due to the fact that this is a labor-intensive activity in the Amazon.

This is important in that if wages were higher, or enforcement of labor laws was greater; cost would increase and logging would decrease. Volume of logs, number of loaders and months with milling activities per year also significantly reduced harvest cost. The decreasing marginal cost as volume increases indicates that there are economies of scale to be captured by firms. We also found that government subsidies and credit lines for machinery should be used cautiously, since by subsidizing loaders the government would indirectly reduce costs of logging, as harvest costs clearly decrease with use of this equipment. Other factors that might influence this variable are macroeconomic changes, such as fluctuations in interest rate, which change a firm's financial constraints and access to credit. Access to logging areas is also a major factor influencing harvest cost. This was established through the relation of the number of months a site could be logged per year and total harvest cost. Improved infrastructure would allow logging over a longer period of time and therefore decrease costs significantly.

The estimated transportation cost function had four significant variables, of which two increased cost. Distance from the forest to the sawmill was highly significant and increased cost, showing that there is a maximum economic distance for logging in spite of paved distance actually decreasing cost. This also shows that road improvement can be a major factor that affects deforestation and should receive special attention among decision makers, at least according to the results here. Finally, owning a transportation fleet increased cost, while the volume of wood transported decreased cost, once again showing economies of scale.

Three different models had good results for the milling cost function; two Cobb Douglas models (one including a dummy variable for firm located in new and intermediate frontier areas), and a translog model with interaction terms for the significant variables in the Cobb Douglas model. Volume of sawn wood produced in 2002, total monthly cost of labor in the Summer, other aggregate costs, number of band saws, number of sanders, and number of months with milling activities per year were all significant variables in the three models. In the Cobb Douglas models, the volume of sawn wood decreased milling cost, showing the existence of economies of scale, however, in the translog model the volume actually increased cost. Since the F test for these models showed that the translog model was a better fit than the Cobb Douglas model, the result that the volume of processed wood increases milling cost is more reasonable to expect. Interestingly, the models are fairly robust, as the calculated marginal effects from the Cobb Douglas function were the same as the marginal effects from the Translog function. This shows that, despite having some estimated coefficients with different signs in the two functional forms, the inclusion of the interaction terms in the calculation of the marginal effects for the translog function correct for any seeming differences.

Another indication of firm size is the number of band saws, which account for separate production lines. This variable decreased cost in all three milling cost models. The monthly cost of labor increased milling cost in all models, which shows that, like harvesting, milling is a labor intensive activity and very dependent on the cost of labor. Other aggregate costs increased milling cost in the Cobb Douglas models but actually decreased it in the translog model. The number of sanders was also significant in all models and increased cost. This has interesting policy implications, since encouraging further processing of sawn wood could increase milling cost but also allow firms to obtain a higher market price. Finally the number of months with milling activities per year decreased costs in the Cobb Douglas models but increased it in the Translog model.

The estimated rents per kilometer from the mill show that rents are higher in new frontier areas when compared to intermediate and old frontiers. The latter are very similar, although old frontiers have higher rents than intermediate frontiers, which can be explained by better road conditions. When comparing different milling centers, the results are mixed, although there is a tendency of lower rents in old frontiers and higher rents in new frontier areas. The difference between these two analyses is due to the large differences in rent across milling centers in the same type of frontier. This contrasts with other work that has not examined wood processing at all stages in Amazonia, or has not relied on firm-specific microeconomic data.

In analyzing the location of cost minimizing firms, the mathematical programming model provided had a very good prediction ability, by perfectly classifying new frontiers as the lowest production cost areas, followed by intermediate frontiers, and finally by old frontiers. This is an explicit demonstration of why firms relocate to new areas, where the distance to the forest is smaller, the forest has a lower stumpage value, and enforcement of taxes and regulations is less strict. Therefore it shows that economic reasons are strong incentives for firms to move into new frontiers and thus expand the area under logging pressure.

Future research should focus on estimating rents according to other important variables, as well as building scenarios to estimate the response of firms to policies over time. Another important contribution would be to include GIS data to add geographic characteristics to the estimated functions and thus allow a quantitative estimation of economic distance, for example. This would be an important complement to the analysis in this study, and it would inform decision makers about outcomes of policy choices. As a result, better policies could be designed with the goal of encouraging regional development without increasing deforestation or associated environmental externalities. Policy instruments could then be used to minimize the difference between the private and social costs of firms in the Amazon.

Table 1: Sampled municipalities along with the State, type of logging frontier and number of observations.

Municipality	State	Frontier	Number of obervations
Analândia do Norte	Mato Grosso	New	10
Marcelândia	Mato Grosso	New	25
Paranaíta	Mato Grosso	New	9
Brasil Novo	Para	New	2
Medicilandia	Para	New	4
Novo Progresso	Para	New	13
Pacaja	Para	New	5
Placas	Para	New	4
Ruropolis	Para	New	3
Trairão	Para	New	6
Uruara	Para	New	13
Acre	Acre	Intermediate	17
Rio Branco	Acre	Intermediate	1
Xapure	Acre	Intermediate	2
Guarantã do Norte	Mato Grosso	Intermediate	17
Breu Branco	Para	Intermediate	23
Maracaja	Para	Intermediate	17
Novo Repartimento	Para	Intermediate	6
Tucurui	Para	Intermediate	24
São Miguel do Guaporé	Rondonia	Intermediate	11
Alta Floresta	Mato Grosso	Old	22
Sinop	Mato Grosso	Old	4
Altamira	Para	Old	13
Belem	Para	Old	1
Breves	Para	Old	10
Dom Eliseu	Para	Old	24
Goianesia	Para	Old	29
Itaituba	Para	Old	22
Jacunda	Para	Old	26
Maraba	Para	Old	4
Paragominas	Para	Old	5
Portel	Para	Old	7
Rondon do Para	Para	Old	17
Santarem	Para	Old	7
Tailandia	Para	Old	26
Tome Acu	Para	Old	19
Ulianopolis	Para	Old	16
Ariquemes	Rondonia	Old	16
Cacoal	Rondonia	Old	5
Espigão do Oeste	Rondonia	Old	11
Jaru	Rondonia	Old	6
Ji-Paraná	Rondonia	Old	11
Pimenta Bueno	Rondonia	Old	1
Rolim de Moura	Rondonia	Old	9
Vilhena	Rondonia	Old	4

Table 2: Descriptive statistics and units of measurement for the selected variables.

Variable	Mean	Standard deviation
Volume of sawn wood produced in 2002 (m^3)	4,034.615	14,269.216
Owns logging operations	0.355	0.479
Forest cost (R$/ha)	528.508	773.444
Total harvest cost (R$/$m^3$)	45.366	31.053
Volume of logs processed in 2002 (m^3)	8,974.800	12,281.798
Volume harvested in 2002 (m^3)	11,129.792	20,451.038
Volume harvested per hectare (m^3)	27.015	16.683
Months with logging activities per year	7.024	2.380
Months with milling activities per year	10.621	1.901
Owns transportation fleet	0.722	0.449
Total transportation cost (R$/$m^3$)	30.568	14.195
Distance from forest to sawmill (km)	90.90	59.10
Paved Distance (km)	13.580	28.071
Total milling cost (R$/$m^3$)	71.227	81.372
Total cost of labor per month in Summer (R$)	25,270.381	69,604.903
Number of chainsaws	3.325	2.446
Number of skidders	0.640	0.752
Number of bulldozers	1.326	0.930
Number of loaders	1.277	1.109
Average age of logging equipment (years)	10.873	5.842
Number of trucks	1.901	2.022
Age of trucks (years)	6.246	4.327
Number of band saws	1.076	0.708
Number of circular saws	1.666	1.306
Number of multi-blade edgers	0.395	0.840
Number of trimmers	2.098	1.796
Number of sanders	0.781	1.120
Average age of milling equipment (years)	11.603	7.010
Other aggregate costs (R$/$m^3$)	-5.016	107.410

(US$1=R$0.34)

Table 3: Estimates for the harvest cost using a Cobb Douglas function. * = significance at 0.15; ** = significance at 0.10; *** = significance at 0.05

Variable	Coefficient n=98	Standard error
Constant	3.915	0.677
Total cost of labor per month in Summer	0.240*** (0.016)	9.815E-02
Volume of logs consumed in 2002	-0.199*** (0.051)	0.100
Average age of logging equipment	-8.313E-02	0.128
Number of chainsaws	1.122E-04	2.736E-04
Number of skidders	-1.125E-04	1.171E-04
Number of bulldozers	-6.251E-05	1.183E-04
Number of loaders	-4.675E-04*** (0.004)	1.591E-04
Months with logging activities per year	-0.502*** (0.035)	0.234

Table 4: Descriptive statistics for the marginal effects of significant variables in the Cobb Douglas harvest cost model.

Variable	Mean	Std.Dev.
Total cost of labor per month in Summer	3.828E-04	2.697E-04
Volume of logs consumed in 2002	-1.484E-03	2.255E-03
Number of loaders	-1.310E-02	5.726E-03
Months with logging activities per year	-3.470	1.619

Table 5: Estimates for the transportation cost using a Cobb Douglas function. * = significance at 0.15; ** = significance at 0.10; *** = significance at 0.05

Variable	Coefficient n=63	Standard error
Constant	3.172	0.841
Distance from forest to sawmill	0.501*** (0.000)	9.632E-02
Paved Distance	-2.058E-04** (0.100)	1.229E-04
Number of trucks	0.151	0.105
Age of trucks	-1.902E-04	4.336E-04
Total cost of labor per month in Summer	-5.087E-02	9.211E-02
Volume of logs processed in 2002 (m^3)	-0.256*** (0.014)	0.100
Owns transportation fleet	0.563*** (0.013)	0.220

Table 6: Descriptive statistics for the marginal effects of significant variables in the Cobb Douglas transportation cost model.

Variable	Mean	Std.Dev.
Distance from forest to sawmill	8.933E-02	4.092E-02
Paved Distance	-2.058E-04	2.876E-04
Volume of logs processed in 2002	-2.017E-03	5.950E-03

Table 7: Estimates for the milling cost using a Cobb Douglas function. * = significance at 0.15; ** = significance at 0.10; *** = significance at 0.05

Variable	Coefficient n=363	Standard error
Constant	2.461	0.524
Volume of sawn wood produced in 2002	-6.669E-04*** (0.001)	2.016E-04
Total cost of labor per month in Summer	0.267*** (0.000)	5.039E-02
Other aggregate costs	6.437E-04*** (0.000)	6.856E-05
Number of band saws	-6.156E-04*** (0.005)	2.178E-04
Number of circular saws	3.372E-05	1.490E-04
Number of multi-blade edgers	-1.141E-04	8.451E-05
Number of sanders	2.832E-04*** (0.000)	6.989E-05
Average age of milling equipment	-6.513E-05	1.481E-04
Months with milling activities per year	-0.294** (0.084)	0.170
Owns logging operations	-5.647E-02	7.070E-02

Table 8: Descriptive statistics for the marginal effects of significant variables in the Cobb Douglas milling cost model.

Variable	Mean	Std.Dev.
Volume of sawn wood produced in 2002	-3.612E-06	6.608E-06
Total cost of labor per month in Summer	4.479E-04	7.648E-04
Other aggregate costs	1.730E-03	3.964E-03
Number of band saws	-1.334E-02	2.080E-02
Number of sanders	5.278E-03	8.738E-03
Months with milling activities per year	-0.750	1.264

Table 9: Estimates for the milling cost using a Cobb Douglas function with a binary variable for intermediate frontier. * = significance at 0.15; ** = significance at 0.10; *** = significance at 0.05

Variable	Coefficient n=363	Standard error
Constant	2.498	0.526
Volume of sawn wood produced in 2002	-6.675E-04*** (0.001)	2.013E-04
Total cost of labor per month in Summer	0.269*** (0.000)	5.034E-02
Other aggregate costs	6.454E-04*** (0.000)	6.830E-05
Number of band saws	-6.127E-04*** (0.005)	2.174E-04
Number of circular saws	4.060E-05	1.500E-04
Number of multi-blade edgers	-1.024E-04	8.547E-05
Number of sanders	2.787E-04*** (0.000)	6.980E-05
Average age of milling equipment	-5.690E-05	1.482E-04
Months with milling activities per year	-0.308** (0.072)	0.171
Owns logging operations	-6.016E-02	7.070E-02
New frontier	-0.231*** (0.056)	0.121

Table 10: Descriptive statistics for the marginal effects of significant variables in the Cobb Douglas milling cost model with a frontier dummy.

Variable	Mean	Std.Dev.
Volume of sawn wood produced in 2002	-3.680E-06	6.747E-06
Total cost of labor per month in Summer	4.575E-04	7.814E-04
Other aggregate costs	1.766E-03	4.058E-03
Number of band saws	-1.350E-02	2.106E-02
Number of sanders	5.284E-03	8.752E-03
Months with milling activities per year	-0.800	1.352

Table 11: Estimates for the milling cost using a Translog function with interaction terms for significant variables. * = significance at 0.15; ** = significance at 0.10; *** = significance at 0.05

Variable	Coefficient n=363	Standard error
Constant	-3.744	3.027
Volume of sawn wood produced in 2002	4.075E-03*** (0.000)	3.548E-04
Total cost of labor per month in Summer	0.657** (0.071)	0.362
Other aggregate costs	-2.487E-04*** (0.030)	1.140E-04
Number of band saws	-2.703E-04** (0.071)	1.491E-04
Number of circular saws	8.153E-05	1.291E-04
Number of multi-blade edgers	2.218E-05	4.982E-05
Number of sanders	7.006E-05** (0.109)	4.365E-05
Average age of milling equipment	-1.651E-04*** (0.028)	7.485E-05
Months with milling activities per year	3.022*** (0.025)	1.344
Owns logging operations	-3.546E-02	4.500E-02
New frontier	-6.931E-02	8.447E-02
Months with milling activities per year x volume of sawn wood produced in 2002	-0.239*** (0.001)	7.295E-02
Months with milling activities per year x total cost of labor per month in Summer	-0.132	0.144
Months with milling activities per year x other aggregate costs	4.115E-02	6.356E-02
Months with milling activities per year x number of band saws	0.554*** (0.007)	0.206
Months with milling activities per year x number of sanders	0.262	0.417
Volume of sawn wood produced in 2002 x total cost of labor per month in Summer	1.370E-02	1.617E-02
Volume of sawn wood produced in 2002 x other aggregate costs	2.212E-02	3.116E-02
Volume of sawn wood produced in 2002 x number of band saws	-0.115	0.198
Volume of sawn wood produced in 2002 x number of sanders	5.413E-02	4.582E-02
Total cost of labor per month in Summer x other aggregate costs	1.250E-02	2.099E-02
Total cost of labor per month in Summer x number of band saws	-1.647E-02	0.162
Total cost of labor per month in Summer x number of sanders	-0.102	9.138E-02
Other aggregate costs x number of band saws	-3.611E-02** (0.061)	1.922E-02
Other aggregate costs x number of sanders	-4.363E-02	0.156

Table 12: Descriptive statistics for the marginal effects of significant variables in the Cobb Douglas milling cost model with a frontier dummy.

Variable	Mean	Std.Dev.
Volume of sawn wood produced in 2002	-3.680E-06	6.747E-06
Total cost of labor per month in summer	4.575E-04	7.814E-04
Other aggregate costs	1.766E-03	4.058E-03
Number of band saws	-1.350E-02	2.106E-02
Number of sanders	5.284E-03	8.752E-03
Average age of milling equipment	-4.144E-04	1.186E-03
Months with milling activities per year	-0.800	1.352

Table 13: Estimated rent per kilometer for each frontier type.

Frontier	Rent
intermediate	4.13
old	4.65
new	5.84

Table 14: Estimated rent per kilometer for each sampled milling center

Frontier	Rent	Frontier type
G	2.03	Old
F	3.58	Old
I	3.46	Old
A	4.09	Old
K	4.35	Intermediate
B	4.70	Old
E	5.72	Intermediate
C	5.87	Old
J	6.24	New
D	8.37	New
H	7.09	New
L	7.54	Intermediate
TOTAL	7.49	

Table 15: Math programming model results: dual prices according to frontier.

Milling center	Frontier	Dual price
J	New	144.411
H	New	104.162
D	New	95.834
K	Intermediate	72.887
E	Intermediate	71.006
L	Intermediate	60.379
A	Old	54.039
G	Old	47.710
F	Old	33.890
C	Old	19.356
B	Old	19.276
I	Old	0.000

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Appendix A: Questionnaire applied to sawmills

Questionnaire **Date: ______**

1 Company's name:
2 Address:

3. Contact information:
Name:
Phone:
Fax:
E-mail:

4 How long has this firm been operating? ____________ years

5 What are the firm's main outputs?

Product	Annual volume	Per day (m3)
Logs		
Sawn wood		
Veneer		
Laminado		

6. Days worked per month: _________

7 Do you harvest? Yes / No
If you do not have harvest activities, go on to question 16:

8 Who owns the area you harvest? Yourself / Others

Cost of land in case of owning forest: R$____________ per ha or alqueire

Payment to the land owner in case of not owning forest: R$_____________
(circle one) per ha/ alq/ m3/ log or tree

9 What is your harvest cost? R$ ______________/m3

10 What was the volume of wood harvested in 2002? ___________ m3

11 What was the volume harvested per hectare? ___________m3

12 Do you tranport your logs or not? Custo (por m3): R$____________

13 What is the distance from the logging site to the sawmill? ___________km
14 What is the paved distance? _________________km
15 What is the distance from the sawmill to the nearest town? ___________km

16 Do you buy logs from others? Yes / No Cost/m3 Noble: ___________________
Red: ___________________
White: ___________________

17 If you buy logs and have your own harvest, what is the percentage bought from others? _______

18 What was the volume of logs used in the sawmill in 2002? ____________ m3

19 What is the processing cost in your sawmill (per m3)? R$______________

20 Months with harvesting activities per year: ____________ months/year
21 Months with milling activities per year: ____________ months/year

22 How many employees do you have in the summer? ________
23 Total monthly labor cost: R$ ____________

24 How many employees do you have in the winter? ________
25 Total monthly labor cost: R$ ____________

26 Technology in the forest:

Equipment	Quantity	Average age
Chainsaw		
Skidder		
Bulldozer		
Tractor		
Loader		
Truck		

27 Technology at the sawmill

Equipment	Quantity	Average age
Chainsaw		
Loader		
Band saw		
Circular saw		
Multi blade edger		
Trimmer		
Sander		
Lathe		
Trimmer for veneer		

Revenue:
28 What is the percentage of your production that is exported? ____________

29 What percentage of your production is residue? ____________

30 What is the price of wood by type?

Type	Price (R$/m3)		
	Noble	Red	White
Export			
Domestic market			
Residue			

31 What is the total investment in your firm? R$______________

Appendix B: Linear programming model

The linear programming model is described below:

Notation: Milling centers A through L
F: Stumpage price
H: Harvest cost
T: Transportation cost
M: Milling cost

Min z = 25.59AF + 30.78AH + 25.88AT + 80.99AM + 25.59BF + 35.16BH + 25.80BT + 103.29BM + 25.59CF + 39.35CH + 20.04CT + 107.76CM + 13.46DF + 39.47DH + 28.31DT + 88.23DM + 20.91EF + 32.10EH + 23.17ET + 78.37EM + 25.59FF + 40.63FH + 22.44FT + 82.56FM + 25.59GF + 35.93GH + 17.48GT + 96.74GM + 13.46HF + 48.38HH + 18.56HT + 81.86HM + 25.59IF + 40.74IH + 35.05IT + 79.58IM + 13.46JF + 32.86JH + 17.92JT + 79.28JM + 20.91KF + 34.55KH + 23.79KT + 67.46KM + 20.91LF + 42.06LH + 19.37LT + 70.88LM

SUBJECT TO:
Transfer rows:
stumpage volume = volume harvested = volume transported = conversion rate x volume sawn

AF-AH=0
AH-AT=0
.345AT-AM=0

BF-BH=0
BH-BT=0
.345BT-BM=0

CF-CH=0
CH-CT=0
.345CT-CM=0

DF-DH=0
DH-DT=0
.429DT-DM=0

EF-EH=0
EH-ET=0
.340ET-EM=0

FF-FH=0
FH-FT=0
.345FT-FM=0

GF-GH=0
GH-GT=0
.345GT-GM=0

HF-HH=0
HH-HT=0
.429HT-HM=0

IF-IH=0
IH-IT=0
.345IT-IM=0

JF-JH=0
JH-JT=0
.429JT-JM=0

KF-KH=0
KH-KT=0
.340KT-KM=0

LF-LH=0
LH-LT=0
.340LT-LM=0

Maximum production constraints: maximum volume was the sum of the volume for all firms interviewed in each milling center
AM<=414238
BM<=298598.153
CM<=220656.548
DM<=77928.249
EM<=239832.258
FM<=71251.50
GM<=412486.00
HM<=22366.5
IM<=37433.5
JM<=121482.00
KM<=41411.75
LM<=27346.304

Minimum production constraint: total volume of sawn wood for all interviewed firms
AM+BM+CM+DM+EM+FM+GM+HM+IM+JM+KM+LM>=1985030.762

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