Economic Valuation of Changes in the Amazon Forest Area

Value maps for Timber Forest Products

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Value map for Timber Forest Products

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Abstract

Despite large efforts undertaken in Brazil to reduce deforestation, Amazon forests are still overlooked when it comes to the Ecosystem Services (ES) they can provide at regional, national, and global levels. As part of the project "Economic Valuation of Changes in Amazon Forest Area", this report assesses the local and regional-scale economic values of one key ES from native forests in the Brazilian Amazon: Sustainable Timber. We developed a simulation model of the tropical timber industry (SimMadeira+) that allows us to estimate the commercial volume and examine the profitability of sustainable timber harvest. Results indicate that the Brazilian Amazon forest contains about of 5.3 billion m^3 of commercial roundwood at an average of 15 m^3ha^{-1}. Only a small fraction of the forest, however, is profitable given land use zoning constraints—*i.e.* logging is not allowed in indigenous lands and strictly protected areas—and the current and foreseeable investments in infrastructure and milling capacity. Our results show that the Equivalent Annual Annuity (EAA) for Sustainable Timber averages US$ 20±2.8 $ha^{-1}year^{-1}$ but can reach up to US$ 47±17 $ha^{-1}year^{-1}$ near milling centers. Our results also show that roughly 11% of the volume and 19% of the gross revenues stem from hardwood and the remainder from softwood timber types (*i.e.* classification according to timber response to fire). These results allow us to explore possible policy contexts for enhancing the value of sustainable timber in the Brazilian Amazon and ensuring a long lasting economic benefit from this ecosystem service.

1. Introduction

Forests managed for timber production are extensive, functionally diverse and important for the provision of many ecosystem services [1]. One of which is timber. Indeed, more than 20% of the world's tropical forests have been selectively logged, and large areas are allocated for future timber extraction. With the increasing attention to the negative impact and collateral damage done by poorly planned selective harvest, Reduced Impact Logging (RIL) is being promoted as a best practice forestry that increases sustainability and lowers CO_2 emissions. RIL is also thought to minimize the impacts of selective logging on biodiversity [1].

The forestry sector in Brazil supports 7 million jobs and in 2007 was responsible for 3.5% of the Brazil's GDP of US$ 37.3 billion as well as 7.3% of the total of the Brazilian exports [2]. In 2010, the forestry sector was worth US$ 8.37 billion. Plantation silviculture contributed 72% (US$ 6.09 billion) of the total income, while native timber harvest accounted for 28.2% (US$ 975 million) of the total [2] (Figure 1.1).

Contributing to the sectoral dynamics are the multiple forestry production chains, which comprise the many stages by which timber is transformed from standing tree through processing and on to delivery to the final consumer [2]. Indeed, forestry product chains in Brazil are diversified and include both energy and industrial products. And the industry ranges from vertically integrated processors of high-quality tropical timber products from natural forests in the Amazon to pulp and paper makers, whose supply comes exclusively from plantations.

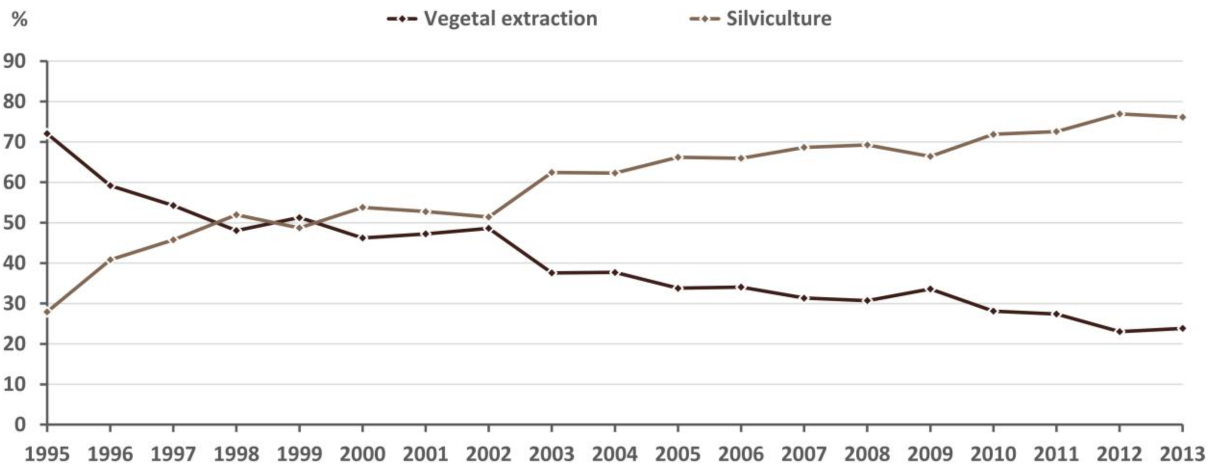


Figure 1.1 - Percentage of participation in the value of primary production in Brazil (from 1995 to 2013): silviculture (including timber) versus vegetal extractivism (including NTFP).

The forestry or timber industry is a major component of the financial success and stability of Brazil. By June 2012, Brazil had 7.74 million hectares of certified forest (according to FSC and CERFLOR standards)[1]. Notwithstanding the importance of the forestry sector, logging has

[1] http://www.brazil.org.za/the-forestry-industry.html. Accessed in March 2017.

been seen as a negative feature of frontier development in the Amazon. However, most discussions ignore the fact that logging can be part of a renewable, environmentally benign, and broadly equitable economic activity in the Amazonian remote places if carried out according to sustainable timber standards.

A successful forestry sector in the Brazilian Amazon would integrate timber harvesting from private lands with harvesting from timber concessions and undesignated anual government lands that could become timber concessions. 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 forest concessions. However, designating forest concessions also requires adequate and sensible investments in governance outside of their borders. Logging on private lands or other government lands outside protected areas can provide a much-needed source of sustainable income on the forest frontier but it has to be based on sustainable timber management as described in the section below.

2. Sustainable timber in the Brazilian Amazon

The Brazilian Amazon, encompassing two thirds (64.7%) of the entire basin, contains about 11.2 thousand tree species [3]. From this diversity of tree species, however, only a small share can be legally logged. Table S1 in the Supplementary Material lists the tree species that can be legally logged as well as their average timber price in selected locations.

From late eighties to the nineties (particularly from 1985 to 1997) there was a major boom in tropical timber harvest in the Amazon. Throughout this period timber harvest was above 20 million m^3 per year and reached peaks of approximately 40 to 50 million m^3 [4]. During the boom period logging became directly associated with deforestation, when in fact it was initially somewhat of a by-product. Since then, harvest volumes have been substantially lower at around 15 million m^3 per year in the period 1997-2013 [5, 6] and are nowadays likely below 10 million m^3 per year; this still requires logging of 1 million ha per year at 10 m^3 of volume per ha. Even though logging has been decreasing, timber harvest still remains a significant actor on the Amazon landscape as it is estimated to have had a gross value of approximately US$ 1.98 billion in 2012 [7, 8]. There are many intermediaries in the supply chain with complex patterns of timber harvesting and supply (Figure 2.1) originating from private management areas as well as from illegal logging and deforestation.

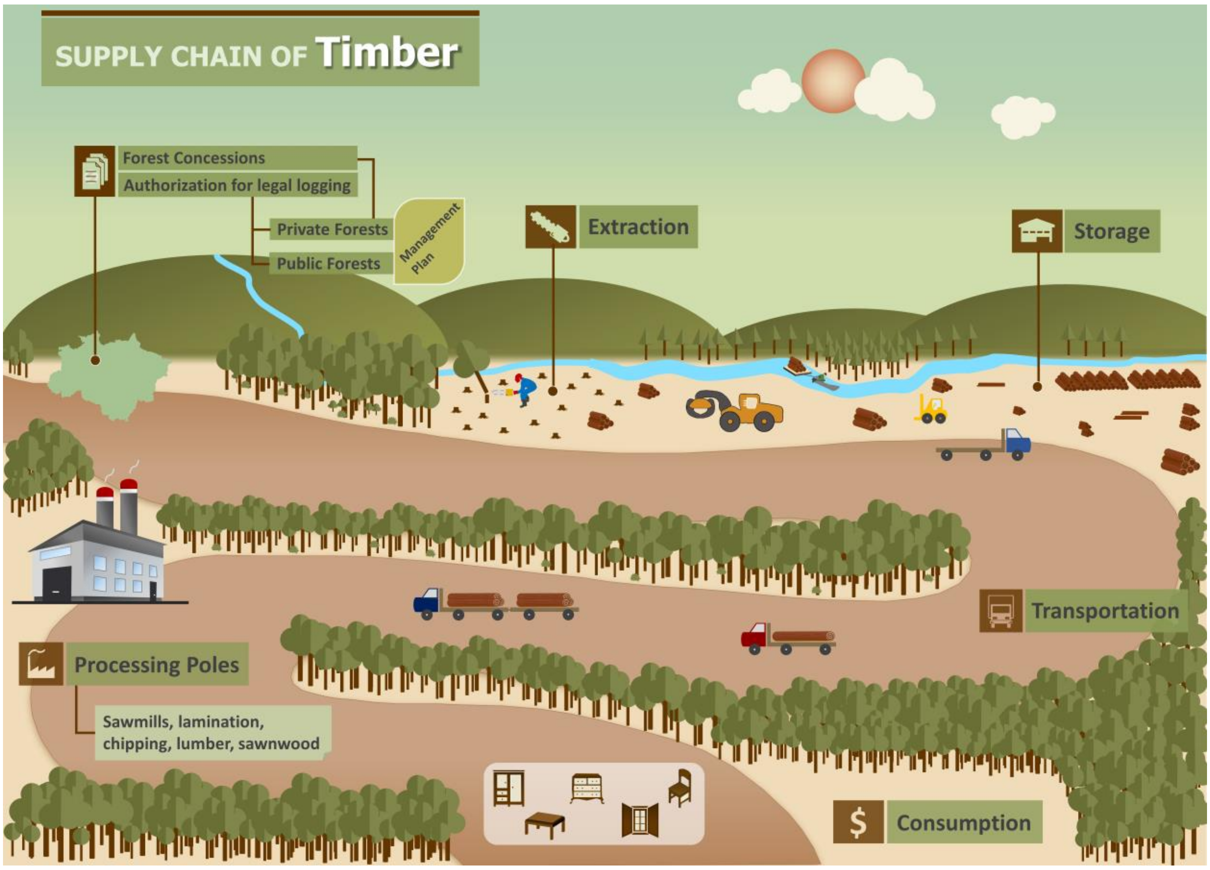


Figure 2.1 - Sustainable timber chain: major phases and actors.

A key policy change, approved in 2006, was the granting of timber harvest concessions on public forests. This policy intended to catalyze the development of a legal timber sector by providing a positive legal source. The first concessions were granted in 2010 with three forest management units in Jamari National Forest and then one in Saracá-Taquera National Forest. Within these limited concessions only 160,000 m^3 were harvested between 2010 and 2013, with total value of US$ 6.9 million. With new concessions in three other national forests awarded as of June 2014 there are currently 513,000 ha in federal concessions [7, 8]. Eight additional national forests and one undesignated land now have been identified in 2015 as suitable for establishing new concessions, bringin the total up to around 3.4 million ha [7-9]. Indeed, large scale forest concessions have been implemented in several South American countries, and their reforms have received some international attention but comparative studies between the nations are still largely lacking [10].

In order to model the potential economic returns in forest concessions of Brazilian Amazon, we developed the SimMadeira+ [11] simulation model, which incorporates a new set of algorithms that allow us to examine the profitability of legal sustainable logging [4]. Legal logging, also known as Reduced Impact Logging (RIL), is more akin to the holistic concept of forest management and includes a significant component of planning to maximize efficiency while minimizing impact [12].

2.1. SimMadeira+ Model

The SimMadeira+ model estimates economic returns to timber harvest for any location in the Brazilian Amazon. This model builds on earlier work developed to assess the expansion of the timber industry in the Amazon that has been used in several economic analyses of land use and land use change [4, 13-15]. SimMadeira+ consists of a partial equilibrium dynamic spatial simulation model of the Amazon timber industry, which calculates a residual stumpage value of forested land, annual harvest volume and value, potential tax revenues, and also forecasts primary industrial capacity (Figure 2.2).

SimMadeira+ was conceived to simulate both sustainable and conventional (including illegal) logging (Figure 2.2), but in this simulation we configure the model platform to estimate the value of sustainable timber across the Brazilian Amazon. In doing so, we set the SimMadeira+ parameters to the specifics of Reduced Impact Logging, which are represented through rules of maximum harvest intensity, adoption of forest management units, annual cutting areas, protection of areas against re-entry during the harvest cycle, and exclusion of harvesting in indigenous lands and other protected areas others than national and state forests [12].

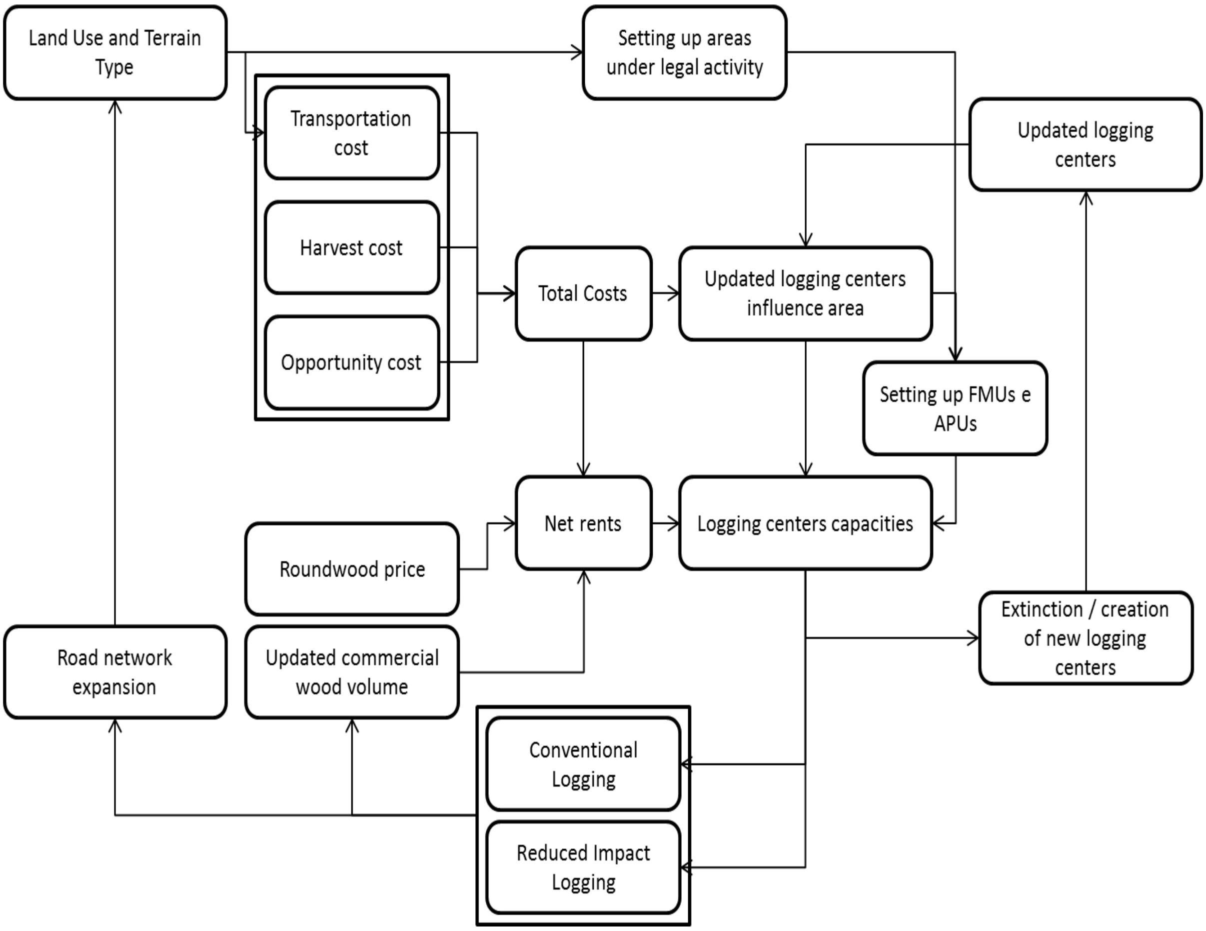


Figure 2.2 - SimMadeira+ conceptual framework.

2.1.1. Timber prices

In the original logging model 20%, 40%, and 40% of the volume is estimated as high, medium, and low value timber, and the respective roundwood price was calculated based on the mix of domestic and export percentages for prices at any given proccesing center. These prices reflect the common mix of commercial timber species on logging frontiers.

In this simulation, we redesigned timber distribution and pricing components in SimMadeira+ (Figures 2.3 and 2.4), dividing commercial timber in soft and hardwood[2] based on a list of the 40 most common commercial timber identified originally by IMAZON [16] (Table S1 in the (Supplementary Material). The list provided by IMAZON contains both genera such as *Aspidosperma sp* with many tree species that go under the common name of “Peroba” or tree species such as *Mezilurus itauba* (Itaúba) that corresponds to one species.

After classifying the commercial timber types as soft and hardwood, the second step was to develop a tree-species distribution model for the Brazilian Amazon. This procedure relied on

[2] The species are classified as soft and hardwood according to fire response and are integral to the report detailing the interaction between logging and fire. Interviews with loggers were conduct to determine species descriptions. Note that these designations have nothing to do with coniferous vs broadleaf seeding that are used in temperate forestry.

the database of tree species provided by the Global Biodiversity Information Facility (GBIF) [17] and Reference Center on Environmental Information (CRIA) [18]. GBIF and CRIA list the geographical coordinates of 106,975 occurrences of tree species encompassing 40 timber types selected for this analysis. Even though this is one of the most comprehensive sources for the presence of tree species in the Amazon, this dataset has substantial sampling errors and geographic bias that need to be corrected in order to obtain a reliable spatially explicit estimate.

For example, the geographic coordinates of single observations of tree species are sometimes inaccurate, some locations in the Amazon are more intensely sampled than others, and the quality of data collection varies. Furthermore, many of the samples were taken in areas that had undergone years of illegal timber extraction, leading to the local disappearance of some hardwood species with higher commercial value. To reduce sampling bias, each tree species record was checked in relation to its geographical accuracy based on Brazilian municipalities georeferenced database. In the absence of actual coordinates, samples located at a municipality's seat were removed from the dataset. This was necessary due to the sensitivity of the spatial distribution model and the large area of some municipalities in the Amazon. Since the predictive ability of the model is affected by the sample size, we used only species with more than 15 occurrences (Figure 2.3). Together these restrictions eliminated 61% of the samples from the final dataset. Nevertheless, all commercial tree genus, as identified by IMAZON 237 species (40,938 records), could still be found in the dataset.

To create the occurrence maps for each of the 40 timber types, the data from CRIA and GBIF were analyzed in relation to 19 predictive bioclimatic variables obtained from WorldClim [19] plus elevation data for South America region. First, the bioclimatic and elevation data were preprocessed to avoid data collinearity. Then, a principal component analysis (PCA) identified that only the first four axes were statistically significant, representing 89.4% of the variance of the predictive variables. These variables were then transformed into raster maps and analyzed in relation to the tree species dataset using species distribution models: Bioclim; Domain; Mahalanobis distance; Maxent, Garp; and SVM [20, 21]. We used the model to build maps of presence/absence of each tree species based on minimum value of suitability observed in the samples. The subsequent maps were then multiplied by the species suitability maps, so that within the area predicted as having species presence there would be variation of suitability values. This was done to estimate the spatial variation in the map of species abundance. The distribution models underlying the maps obtained were cross-validated with a sub-sample of 30% of the dataset. To exclude models with a low degree of confidence, only models with area under curve (AUC) (a metric that indicates the relation between true and false positives) above 0.80 were adopted (Figure 2.3).

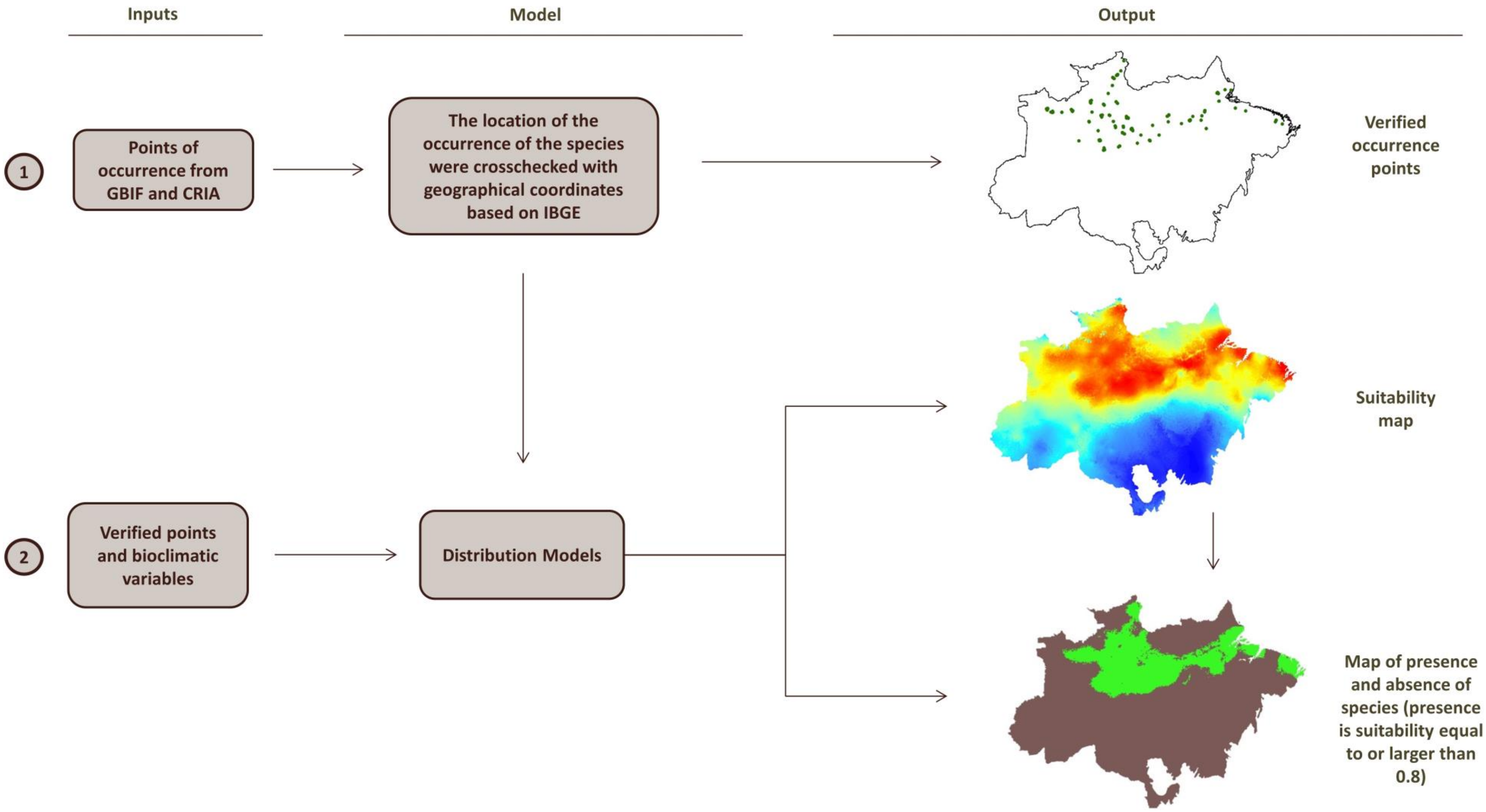


Figure 2.3 - Species distribution modeling.

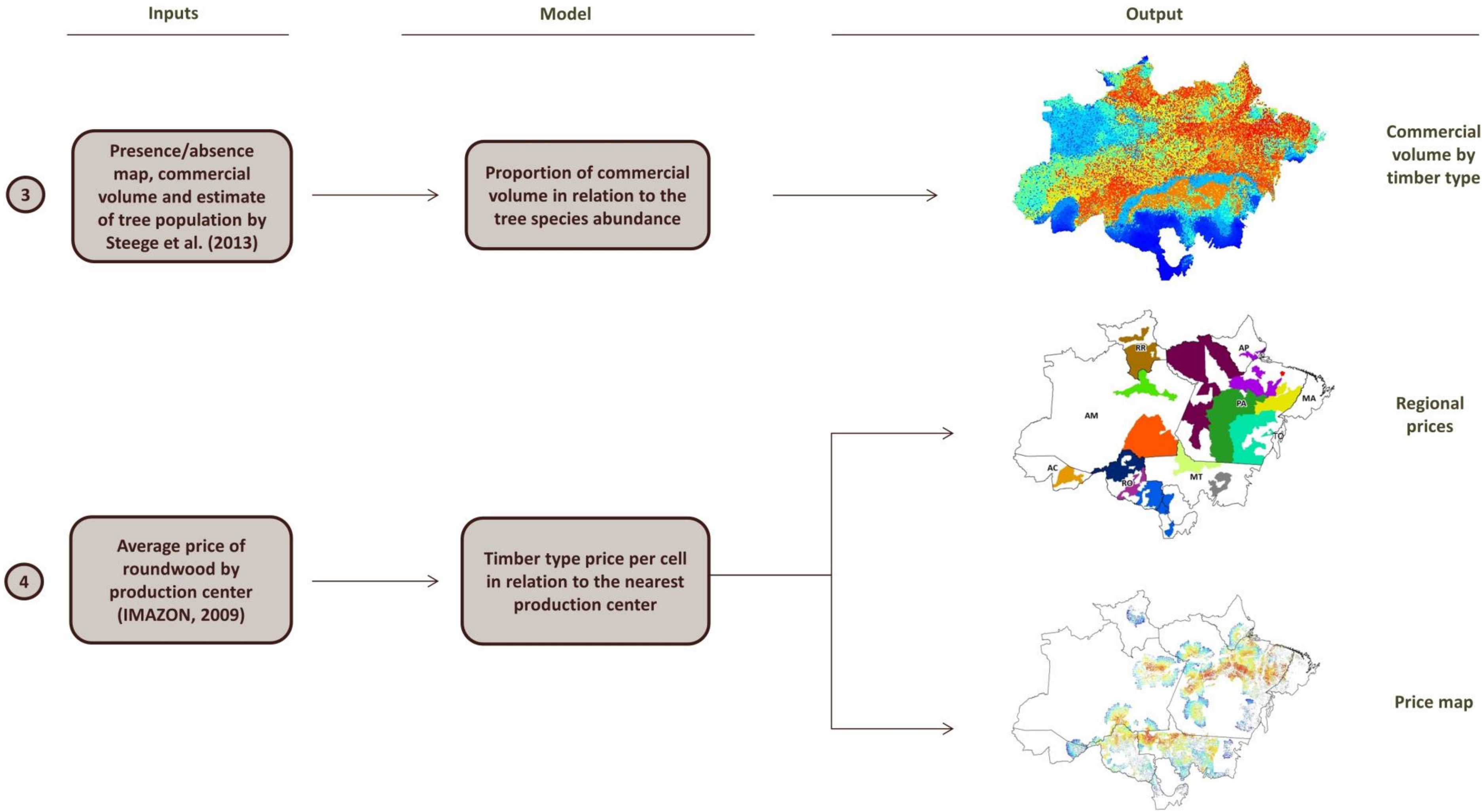


Figure 2.4 - Steps of SimMadeira+ to calculate timber volume and prices.

To create a consensus between the models, a weighted average of the AUC value of the model results was generated per species. To obtain the models of each timber type, we combined the models of each species corresponding to each timber type. The consensus models for the timber types were standardized by rescaling them to values between 0 and 1. This procedure generated a single map, at resolution of 1 km^2, for each of the 237 tree species whose data points were deemed reliable. The tree species and genera corresponding to the list of commercial timber type were combined to total 40 maps; 27 of them corresponding to softwood and 13 to hardwood. These maps were again combined to create a map of the presence/absence of softwood and hardwood (Figures 2.5a & 2.5b). Results show the number of softwood genera per location ranging between 7 and 27 types, while the number of hardwood genera ranges between 2 and 13.

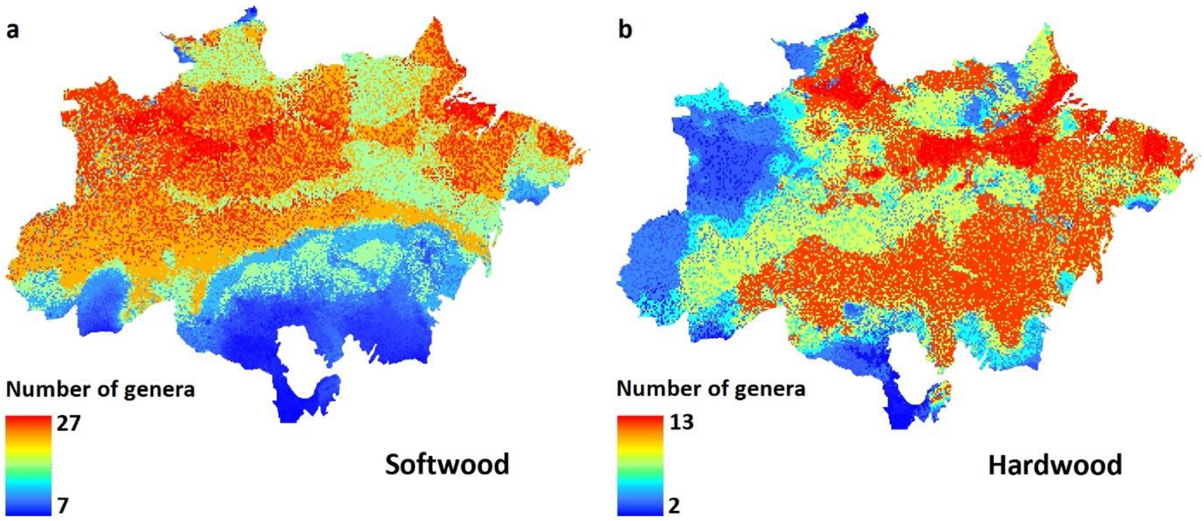


Figure 2.5 - Number of tree genera of softwood (a) and hardwood (b) in cell location of 100 ha.

In a fourth step, we estimated the commercial volume for each timber type. We expanded on Merry et al. [4] to differentiate the total commercial timber volume by timber type based on the genus distribution maps. To account for the relative abundance of tree species, we used the Amazon-wide distribution for the population of 4,962 species estimated by Steege et al. [22]. Hence, the total commercial timber volume was divided among different tree genus found in each map cell based on the relative abundance of tree species in the Amazon (Figure 2.6).

In a fifth step, the maps of commercial timber volume, separated by timber genus, were combined with roundwood prices to calculate the gross timber production revenue for each 100 ha cell. IMAZON [16] provides the average prices for the 40 tree genus for the states of Pará, Mato Grosso and Rondônia (Table S1). This study also provides the average prices of high, medium, and low value timber for each of the 15 main timber production centers in the Brazilian Amazon. The price datasets were combined in order to obtain an estimate of the price of the 40 tree genus for each of the 15 timber production centers in the Amazon. The output consisted of timber price maps based on the prices from the nearest production centers and reflect local market conditions, including transport costs between production centers and the final consumers in the national and international markets. For example, higher selling prices can be found in the production centers of Belém and Belém-Brasília due to the proximity to the ports. Prices are also high in Sinop and Alta Floresta thanks to the highway BR-163 that enables the transportation of timber to domestic markets in the Southeast of Brazil. In contrast, prices are lower in northwestern Amazon (Figure 2.7).

Finally, the potential timber gross revenue (R_j) at a cell j is calculated by multiplying the estimated timber volume by the price of each timber genus, so that:

$$R_j = \frac{\sum_g P_g * occ * Per_g * V_g}{\sum_g occ * Per_g} \quad \text{eq. (1)}$$

Where P_g is the location-specific price of the timber type g in the cell j, V is the commercial volume of the genus type g and *occ* is binary occurrence modeled by the distribution model, and Per_g is the percentage of *genus g* in relation to the total tree population in the Amazon according to Steege et al. [22]. The gross revenue of the individual timber genus are aggregated by soft and hardwood.

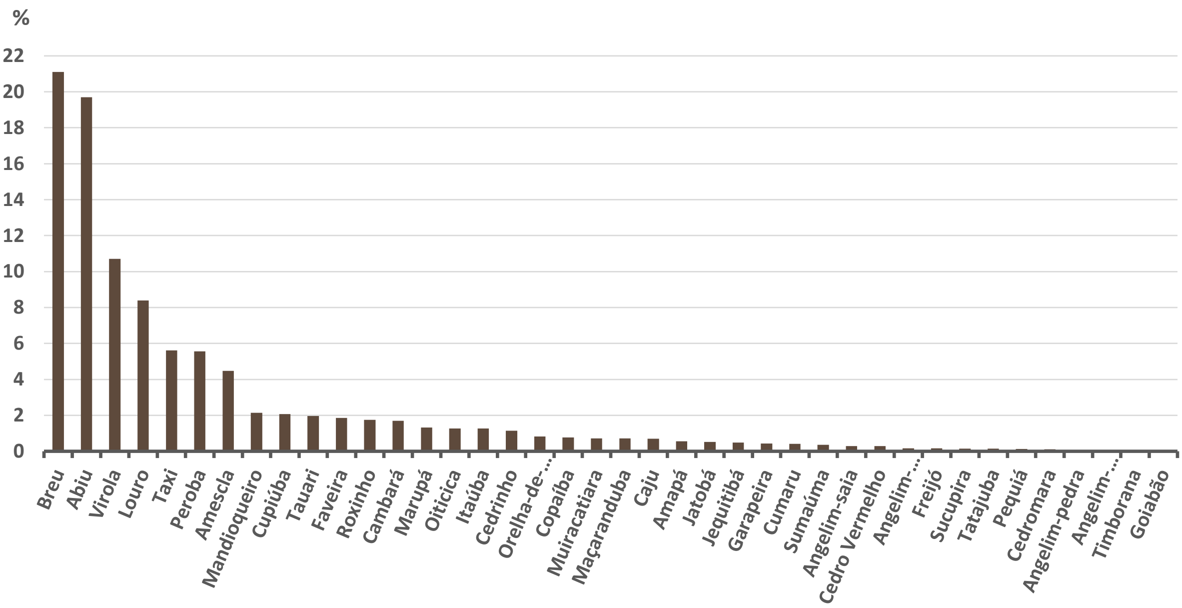


Figure 2.6 - Share of commercial timber genus in relation to the total tree population in the Amazon. Source: [22]

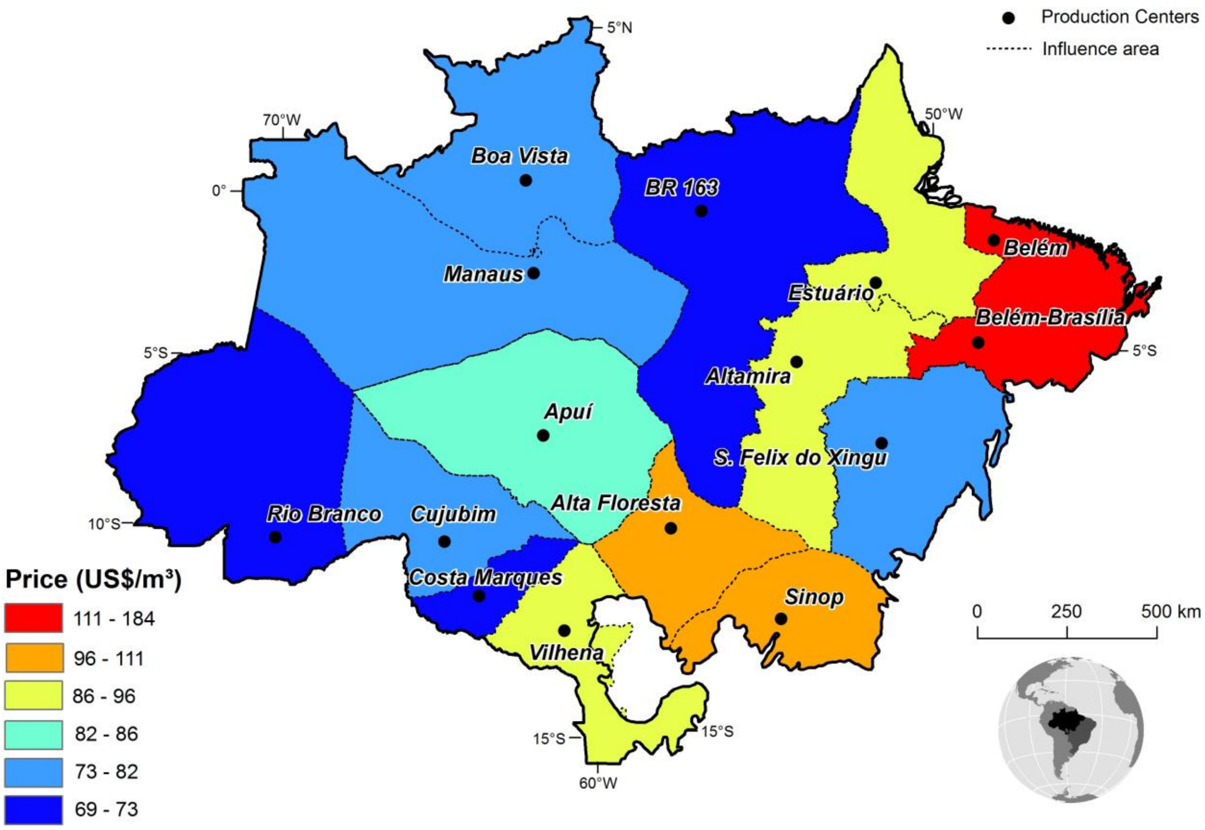


Figure 2.7 - Areas of influence of the main timber production centers and associated average price for roundwood timber for a mix of 40 selected timber genus.

2.1.2. Commercial volume map

The second step of the modeling approach is to calculate the volume of timber in any specified area—in this case in cells of 1 km^2. An initial commercial wood volume map comes from Merry et al. [4] which converted biomass into roundwood volume by using wood density coefficients (in ton/ha) as well as a biomass expansion factor [23, 24]. Both wood density coefficients and biomass expansion factors have been widely used in the scientific literature for estimating wood volume [23-25]. Merry et al. [4] calculated those coefficients for 3,700 locations of the RADAM project[3]. These coefficients were spatially differentiated using Thiessen polygons and then multiplied (cell by cell) by the biomass map (Figure 2.8). To account for deforestation, we removed commercial wood volume from cells where deforestation had occurred up to 2012 using a land cover map from PRODES (Amazon Monitoring System by Satellite) [26]. Results showed that although there are locations in the Brazilian Amazon where the maximum commercial volume is 47 m^3, in the vast majority of areas (99% of its area), the maximum volume of timber is 35 m^3 (Figure 2.9).

[3] In October of 1970, the RADAM (Radar in the Amazon) Project was created with a focus on prioritizing the collection of data on mineral, soil, vegetation resources, and land-use in the Amazon.

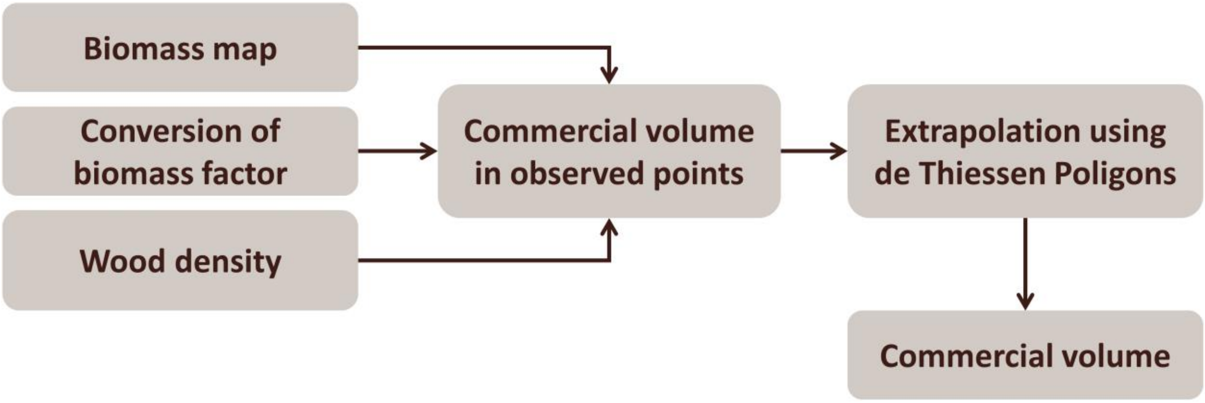


Figure 2.8 - Steps of the calculation of the commercial volume map.

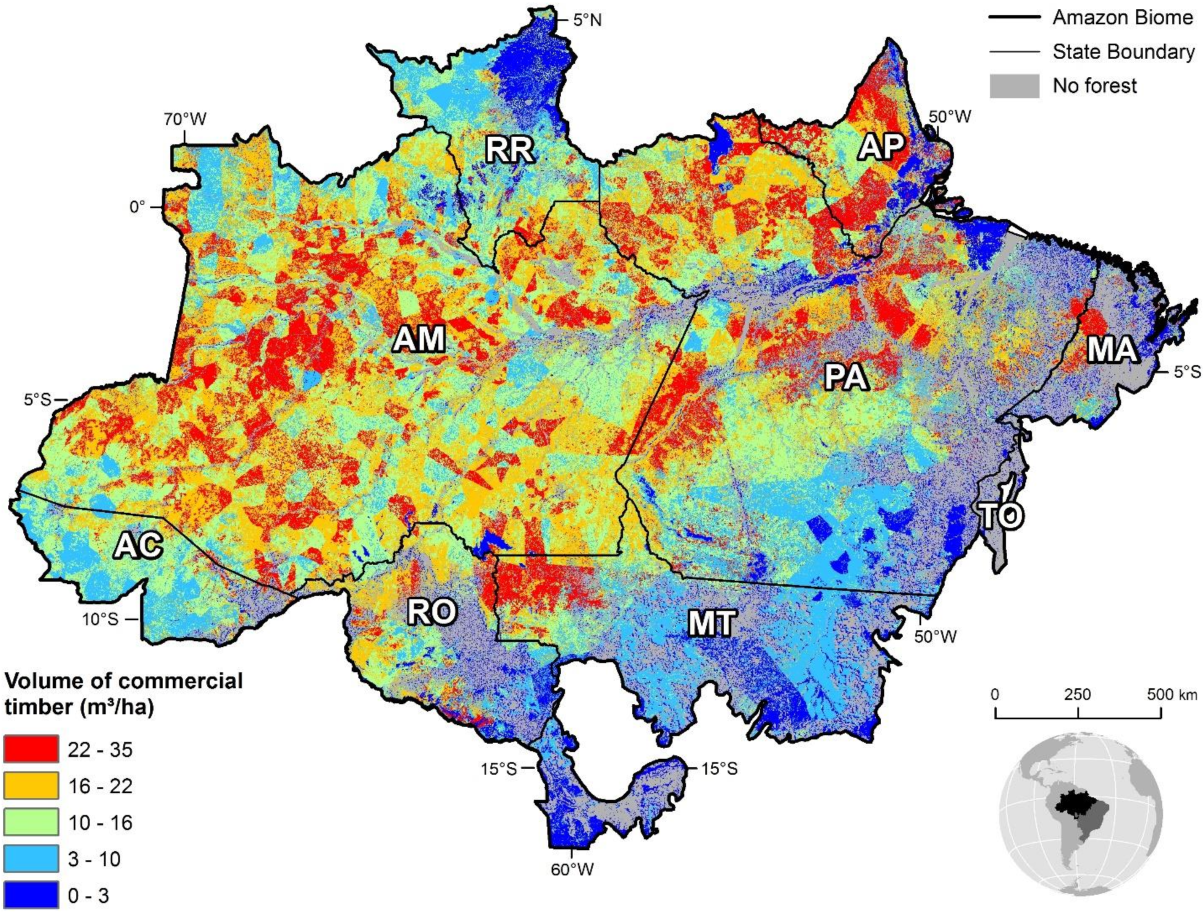


Figure 2.9 - Commercial timber volume across the Amazon.

2.1.3. Economic returns, profitability and expansion

The demand for timber is set as equal to the processing capacity in the nearest municipal logging center (a pre-established milling capacity at the nearest processing hub). The initial estimates take into account the historical production records (2007-2012) as well as the regional markets with specific roundwood prices and production costs (Figure 2.10) [27, 28].

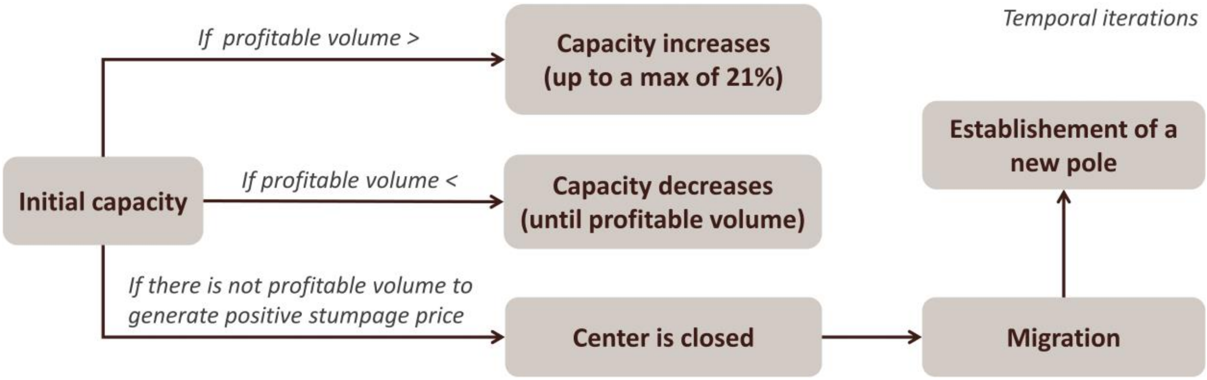


Figure 2.10 - Production capacity of processing centers.

If there is sufficient volume to supply the current demand, the model simulates the harvest and then increases local capacity, and thus the quantity demanded. In this manner available commercial wood volume dynamically changes over time as the harvest is simulated. No tree recovery is taken into account since the model is set to run for one harvest cycle only (in this case 30 years). The model continues to harvest annually until available profitable timber is less than the demand (processing capacity), at which time the logging center declines at a rate commensurate with available profitable timber. Once a logging center shuts down, the model starts a new center thus mimicking the migration of production centers further into the rainforest. During the annual harvest process, logging roads are built and the costs of access to and transport of logs further into the forest continually decline. This has been described as a friction surface, where as roads are built or improved the friction (or cost) of traversing them lowers. In this way, the model accounts for the dynamics of the milling centers (emergence, expansion, shutdown, and migration) depending on commercial volume that can be profitably harvested.

The profitability of sustainable timber is calculated from the mill gate to the forest by subtracting production and opportunity costs from the log price. The resulting value is the potential net rent from sustainably harvesting a particular forest unit in a given location at a given point in time. This is often described as a residual or stumpage price (Figure 2.11). The stumpage price is multiplied by commercial volume at each land unit to arrive at an estimate of forest rent (also described as residual value or stumpage value) for the land unit (US$ ha^{-1}). The stumpage value π_j, for a cell *j* is calculated as follows:

$$\pi j, = [V_j * (P_j * -(TC_j + HC)] * (1 + I) \quad \text{eq. (2)}$$

Where V*j* is the available commercial volume, P_j is the price of roundwood at the milling gate, TC_j is the transportation cost of roundwood from a specific cell *j* to the location of the nearest milling center, *HC* is the harvest cost, and *I* is the rate of interest (the model assumed an interest rate of 5%).

Figure 2.11 - Profitable timber extraction.

Transportation costs (expressed in US$ m^3km^{-1}) reflect the effort of crossing each type of terrain (or land use). For example, on roads and other transportation routes, it represents the cost of transporting a cubic meter of round wood per kilometer (set according to available literature [29], and on other types of terrain (*e.g.,* deforested area, indigenous land) the value represents the costs of building or clearing a means of traverse. Transportation costs range from US$ 0.04 to 2,167 m^3km^{-1} according to: land-use types (*e.g.* deforested area, public forest without designation); road paving conditions (*e.g.* paved, unpaved, four-lane road); or waterway conditions (*e.g.* navigable waterway, inexpressive navigability, navigability only in rainy season). Total transportation cost of each cell—the least cost pathway—represents the distance from a point to the nearest logging center (assigned according to the area of influence) multiplied by the transportation cost by type of terrain of each cell (*e.g.* Figure S4). Table 2.1 presents the variation in transportation costs for the different forest types, road paving conditions and waterways. SimMadeira+ also simulates improved access by expanding logging roads and skid trails. The model simulates the building of logging roads based on the expected locations of major logging tracks to new units entering production (Figure S6 in the Supplementary Material). As forest parcels are logged and roads are built, the transportation cost changes and the cost surface is updated (Figure 2.12).

RIL in SimMaderia+ represents, in a simplified manner, the norms and practices adopted by the Brazilian government for timber concessions [30] through rules of maximum harvest intensity, adoption of forest management units, annual cutting areas and protection of areas against re-entry during the harvest cycle [11]. In order to comply with the definition of sustainable logging found in CONAMA resolution n. 406/2009 [31], the maximum yearly extraction is set at 0.86 m^3ha^{-1}, which multiplied by a 30 years harvest cycle yields 25.8 m^3ha^{-1}. Thus, cells where the commercial timber volume was above this threshold had the value truncated. In the model, the areas under “Sustainable Forestry Management” are divided into forest management units (FMU), which are then divided into annual production units (APU) (Figures S2 and S3). The number of APUs inside a FMU equals to the number of years of the harvest cycle (Figure S1). For each FMU, one APU area is harvested per year while the rest are left alone. Each APU will be harvested just once per cycle, allowing the area to recover (Figure S1).

Table 2.1 - Transportation costs used in SimMadeira+.

Category Name	Transportation cost (US$ m^3km^{-1})*
Sustainable use protected area	0.35
Public forest without designation	0.35
Strictly protected area	2,167
Military lands	2,167
Indigenous lands	2,167
Deforested area and Cerrado biome	0.30
Paved road	0.13
Unpaved road	0.21
Duplicate Road	0.08
Navigable waterway	0.04
Inexpressive navigability	0.43
Navigability only in rainy season	0.43

*1 US$ = R$ 2.36.

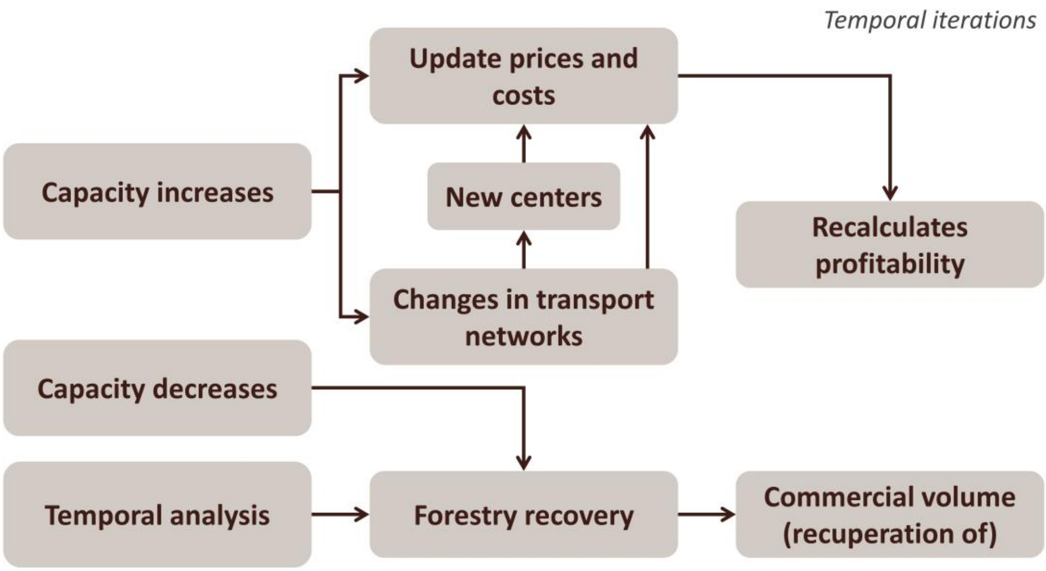


Figure 2.12 - Calculation of rents in SimMadeira+.

To account for uncertainty in future timber prices, we conducted a sensitivity analysis using a range of prices in relation to input costs. SimMadeira+ was developed using Dinamica EGO [14].

2.1.4. Value map for sustainable timber

Our results show that Amazon forests contain about of 5.3 billion m^3 of commercial roundwood at an average of 15 m^3ha^{-1}. Roughly 11% of the volume and 19% of the gross revenues stem from hardwood and the remainder from softwood timber types (Figures 2.13 and 2.14). Although gross revenues can potentially average US$ 373 ha^{-1}, only a small fraction of the forest is profitable due to land use zoning constraints—logging is not allowed in indigenous lands nor strictly protected areas—as well as the limits imposed by current and foreseeable investments in infrastructure and milling capacity. Simulation of timber harvest over the next 30 years show that annual net revenues and production volumes increase, respectively, from US$ 432±91 million and 10.3±0.16 million m^3 in 2012 to a maximum of US$ 1.15±0.3 billion and 41±5 million m^3, after 15 (in 2027) and 23 years of harvest, respectively (Figures 2.15 and 2.16). During the complete 30-year cycle, accumulated net revenue and production amount to a net present value of US$ 14.3±2 billion and a harvested volume of 964±131 million m^3.

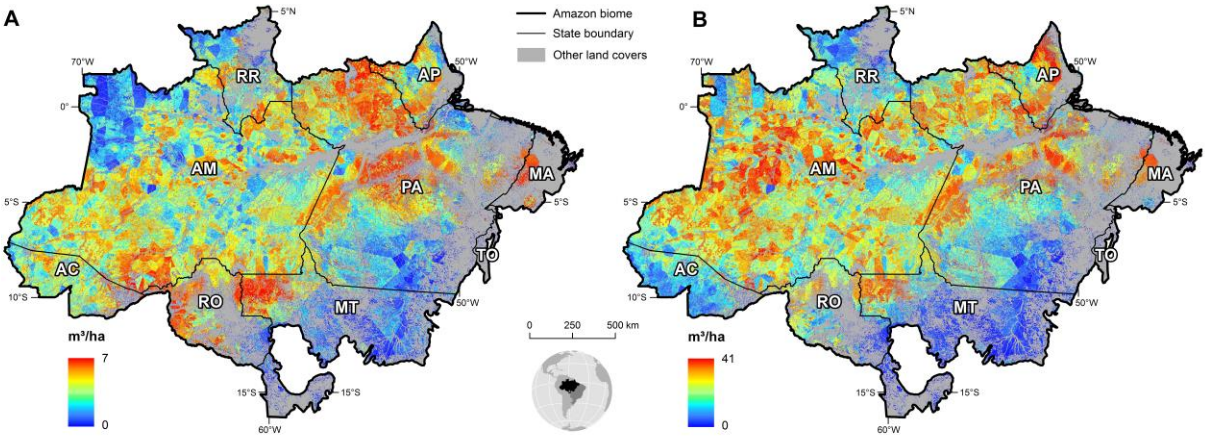


Figure 2.13 - Commercial volumes for hard (A) and softwoods (B).

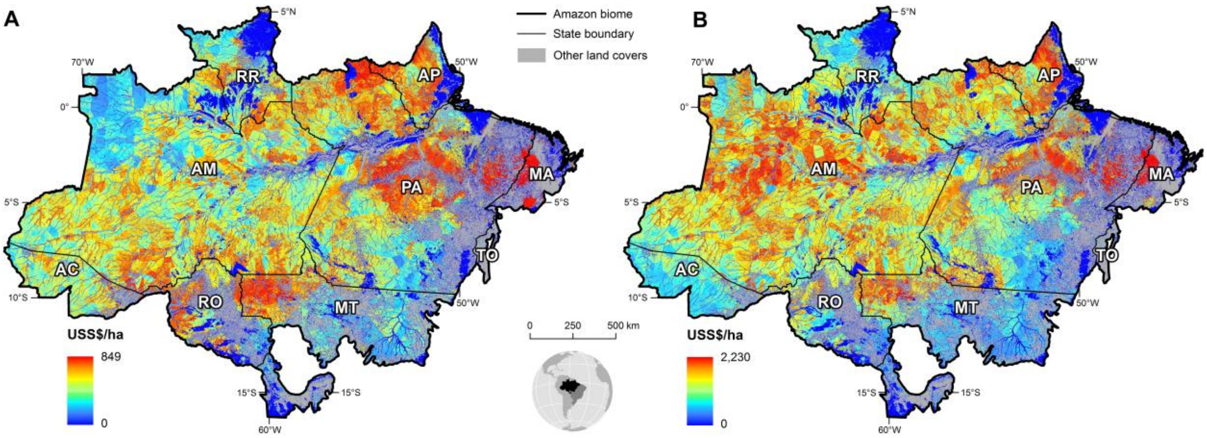


Figure 2.14 - Commercial values for hard (A) and softwoods (B).

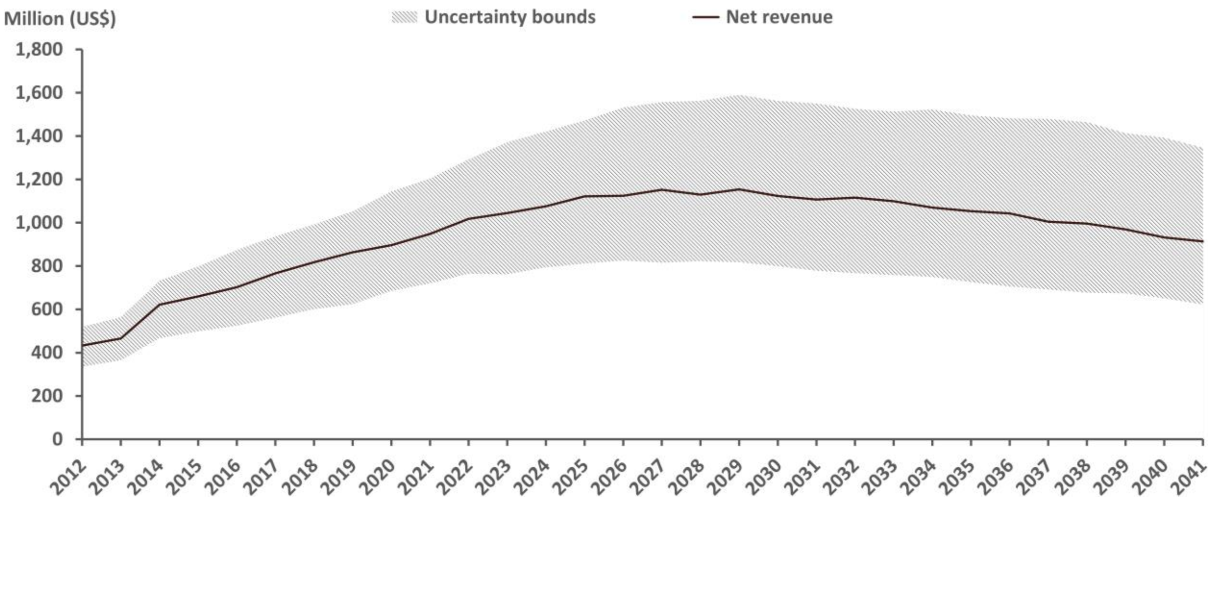


Figure 2.15 - Total net revenue per year (uncertainty bounds correspond to ±15% variation in timber price).

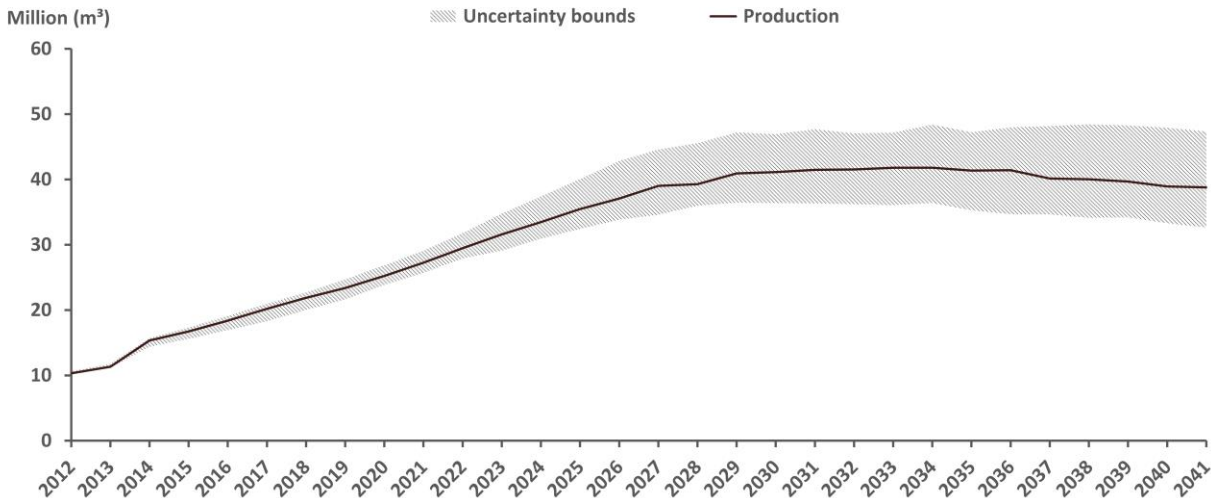


Figure 2.16 - Timber production per year (uncertainty bounds correspond to ±15% variation in timber price).

Figure 2.17 shows the location of the forest concessions (outlined in black), as well as the sustainable timber harvested in and out selected concessions. In each concession, there are areas that have not been logged due to competition with external areas.

Since timber realizes its value only in the year in which it is harvested, we calculate the net present value (NPV) taking a 30 years harvest cycle into consideration, so that:

$$NPVj = \sum_{i=1}^{30} \frac{\beta \mathrm{ij}}{(1+\sigma)^{i}} \qquad \text{eq. (3)}$$

Where β_{IJ} represents the annual rent and $\boldsymbol{\sigma}$ a social discount rate of 5%.

The annual rents of sustainable timber are presented as the Equivalent Annual Annuity (EAA). Based on the NPV, the model calculates the Equivalent Annual Annuity (EAA) by deriving a dollar value of the project/activity that is equally spread over the lifespan of the project. Thus, the EAA derives a dollar value of the project/activity that represents the same financial value of the Net Present Value (NPV), except that the dollar value of the EAA is for payments or benefits that are equally spread over the life of the project (an annuity). This procedure is necessary to render the value of timber production comparable to activities, such as rubber and Brazil nut collection, which consist of annual rents.

There are few locations where EAA reaches values equal or greater than US\$ 47±17 $ha^{-1}year^{-1}$. However, in the vast majority of harvested areas (48±7 million ha of forests), EAA averages US\$ 20±2.8 $ha^{-1}year^{-1}$ as depicted in Figure 2.18. Higher EAA for sustainable timber is generated in Amapá, eastern and central Pará, central and south of Amazonas, southeast of Acre, northern Rondônia, and Mato Grosso.

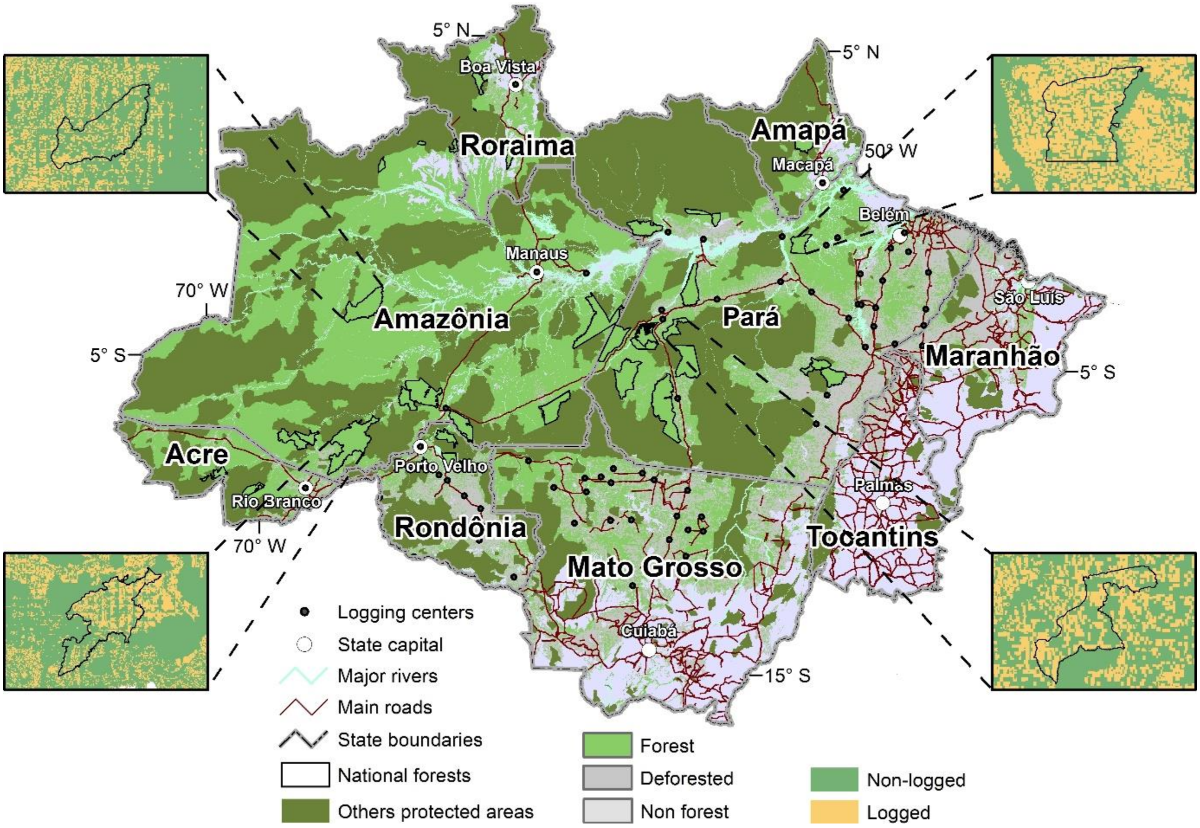


Figure 2.17 - Sustainable timber harvested in and out selected concessions.

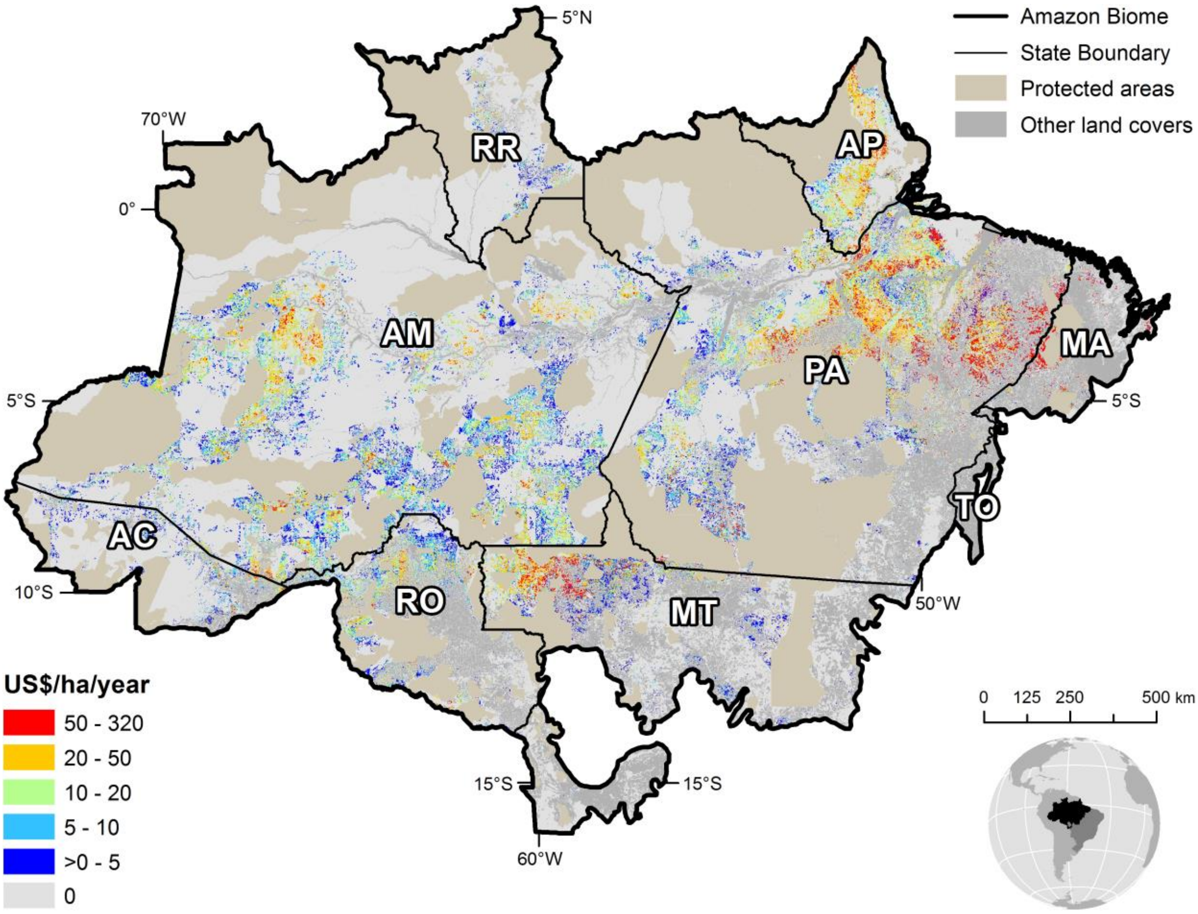


Figure 2.18 - Potential equivalent annual annuity (EAA) of sustainable logging rents.

3. Discussion and Final Remarks

Most Amazonian countries face problems in their timber supply chains and many have undergone forest regime reforms during the last 20 years [1]. In both Brazil and Bolivia, for example, large-scale forest concessions have been implemented in an effort to update the sector and catpture potential economic and social benefits associated with a well-managed forest estate.

Despite large efforts carried out in Brazil to reduce deforestation, Amazon forests are still overlooked in terms of the Ecosystem Services they provide at regional, national, and global levels [2, 6, 12]. In this work we used spatially-explicit models to identify how timber values are distributed geographically across the Brazilian Amazon [4, 13]. The SimMadeira+ model allows us to examine the commercial volumes and profits of sustainable logging. Our results show that Amazon forests contain about of 5.3 billion m^3 of commercial roundwood at an average of 15 m^3ha^{-1}. Roughly 11% of the volume and 19% of the gross revenues stem from hardwood and the remainder from softwood timber types (Figures 2.13 and 2.14). Although gross revenues can potentially average US$ 373 ha^{-1}, only a small fraction of the forest is profitable given land use zoning constraints—logging is not allowed in indigenous lands and strictly protected areas—as well as the current and foreseeable investments in infrastructure and milling capacity. Our simulation of timber harvest over the next 30 years shows that annual net revenues and production volumes increase from US$ 432±91 million and 10.3±0.16 million m^3 to a maximum of US$ 1.15±0.3 billion and 41±5 million m^3, after 15 and 23 years of harvest respectively, (Figures 2.15 and 2.16). During the 30-year cycle, accumulated net revenue and production amount to US$ 28.4±9 billion (US$ 14.3±2 billion NPV) and 964±131 million m^3, respectively. There are few locations where EAA can reach values equal or greater than US$ 47±17 $ha^{-1}year^{-1}$. However, in the vast majority of harvested areas (48±7 million ha of forests), EAA averages approximately US$ 20±2.8 $ha^{-1}year^{-1}$.

In sum, there is a need for promoting the sustainable timber harvest on public and private forested lands to attain a balance between economic development and environmental conservation in the Amazon. Policies that encourage such a joint outcome are therefore crucial. Nevertheless, for those policies to succeed information on the economics of timber sector in the Amazon, incentives to encourage the widespread adoption of reduced impact logging, and improved monitoring and enforcement are all required, none of which are trivial barriers [4, 9, 28].

4. Supplementary Material

The model divides the sustainable forestry management areas into blocks (Unidades de Manejo Florestal - UMFs) within which are located plots or annual production units (Unidades de Produção Anual - UPAs). Figure S1 demonstrates this spatial pattern for a production cycle of 25 years.

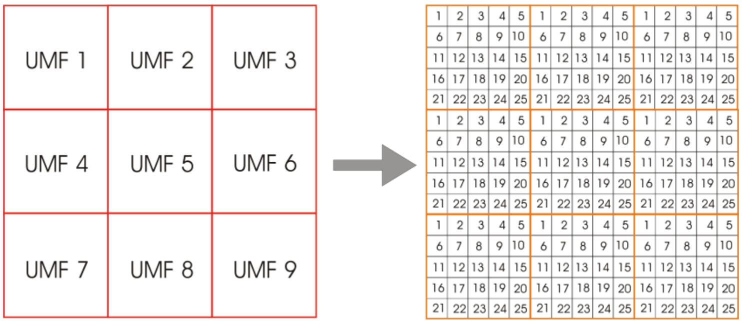


Figure S1 - Division of UMF into 25 annual production units (UPAs).

In this work, we assumed that sustainable forestry management has a harvest cycle of 30 years therefore, unlike Figure S1, each UMF is divided into 30 (UPAs). Although the model uses, for simplification, square plots we acknowledge that in reality some UFMs might have complex shapes if constrained by topography or infrastructure, such as rivers and roads.

The model starts by selecting the most profitable plots (UPAs) within each block (UFM) by calculating the average net rent by UPA considering the net rent of each individual cell (Figure S2 and S3). In order to calculate net rents, the model starts by computing total costs. Total cost of roundwood (in US$ per m^3) includes 3 components as follows: (1) harvest costs (2) transport costs and (3) investment costs. Harvest costs include the costs of cutting down the trees, displacing it to the truck and transporting round wood to the mill gate. Transport costs are listed in Table 2.1 in the main report. Broadly, investment (opportunity) costs capture the money that can be earned if applied in other activity. Investment costs are represented by an interest rate of 5% multiplied to the sum of harvest and transport costs.

$$\text{Total costs} = (\text{ECcenter}+TC_{ij})*(1+\text{interest rate}) \qquad \text{eq. (4)}$$

EC_{center} is the harvest costs in the TC_{ij} – transport costs from the cell with the coordinates (i, j) to its respective processing center.

After calculating the total cost, the commercial volume (m^3ha^{-1}) is multiplied by the area of the cell (ha) in order to get the volume in cubic meters by cell. This is in turn multiplied by the roundwood price (m^3) in order to obtain the gross revenue.

Table S1 - Tree genera/species and respective mean prices for roundwood.

Name (in Portuguese)	Scientific name	Mean prices (US$/$m^3$)				Category
		Mato Grosso	Pará	Rondônia	Mean	
High Economic value tree species		**148**	**159**	**132**	**152**	
Ipê-amarelo	*Tabebuia serratifolia*	137	173	131	160	Hard
Ipê-roxo	*Tabebuia impetiginosa*	142	164	131	156	Hard
Cedro Vermelho	*Cedrela odorata*	137	137	156	140	Hard
Itaúba	*Mezilaurus itauba*	155	103	97	139	Hard
Freijó	*Cordia goeldiana*	126	120	140	125	Hard
Medium economic value tree species		**101**	**102**	**74**	**94**	
Amescla	*Protium heptaphyllum*	73	74	60	70	Soft
Angelim-pedra	*Hymenolobium petraeum*	110	106	78	99	Hard
Angelim-vermelho	*Dinizia excelsa*	111	113	81	108	Soft
Breu	*Protium sp.*	68	89	62	73	Soft
Cambará	*Vochysia sp.*	86	117	64	79	Hard
Cedrinho	*Erisma uncinatum*	110	83	62	97	Hard
Cedromara	*Cedrela sp.*	84	105	65	73	Soft
Cerejeira	*Torresea acreana*	113	-	94	97	Hard
Cumaru	*Dipteryx odorata*	115	111	87	105	Hard
Cupiúba	*Goupia glabra*	98	96	68	90	Hard
Garapeira	*Apuleia molaris*	105	83	78	89	Hard
Goiabão	*Pouteria pachycarpa*	87	86	59	83	Soft
Jatobá	*Hymenaea courbaril*	101	100	77	95	Hard
Jequitibá	*Cariniana sp.*	144	84	71	81	Hard
Louro	*Ocotea sp.*	84	83	62	79	Soft
Maçaranduba	*Manilkara huberi*	90	114	83	107	Soft
Muiracatiara	*Astronium sp.*	81	100	76	92	Soft
Oiticica	*Clarisia racemosa*	85	100	67	71	Soft
Pequiá	*Caryocar villosum*	72	91	64	86	Soft
Peroba	*Aspidosperma sp.*	116	156	82	108	Hard
Roxinho	*Peltogyne sp.*	91	109	65	78	Soft
Sucupira	*Bowdichia sp.*	104	96	68	85	Hard
Tatajuba	*Bagassa guianensis*	72	99	64	92	Soft
Timborana	*Piptadenia sp.*	84	89	72	89	Soft
Low economic value tree species		**77**	**73**	**61**	**69**	
Abiu	*Pouteria sp.*	84	83	64	78	Soft
Amapá	*Brosimum parinarioides*	134	71	51	71	Soft
Amesclão	*Trattinnickia burseraefolia*	72	69	42	67	Soft
Angelim-amargoso	*Vataireopsis speciosa*	87	67	70	70	Soft
Angelim-saia	*Parkia pendula*	67	101	57	67	Soft
Caju	*Anacardium sp.*	55	64	56	62	Soft
Marupá	*Simarouba amara.*	71	70	62	67	Soft
Copaíba	*Copaifera sp.*	72	72	56	67	Soft
Faveira	*Parkia sp.*	66	67	73	69	Soft

Mandioqueiro	*Qualea sp.*	78	84	42	83	Soft
Orelha-de-macaco	*Enterolobium schomburgkii*	59	81	55	68	Soft
Paricá	*Schizolobium amazonicum*	64	64	56	61	Soft
Sumaúma	*Ceiba pentandra*	71	66	57	64	Soft
Tauari	*Couratari sp.*	78	83	61	72	Soft
Taxi	*Tachigali sp.*	78	73	58	72	Soft
Virola	*Virola sp.*	84	65	36	62	Soft

Source: [16].

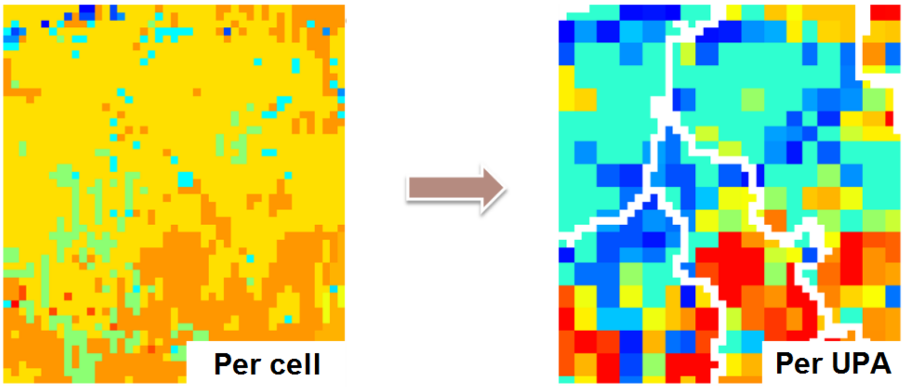


Figure S2 - Converting net rent by cell (left) to net rent by UPA (right).

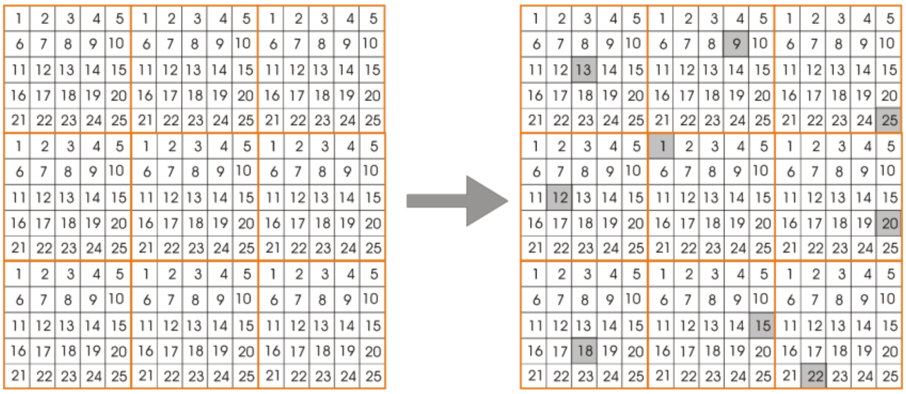


Figure S3 - Selection of the most profitable plots (UPS) in each block (UMF).

The selected plots will be the ones delivering the sustainable timber volume available to the processing center. We calculate the processing harvest "shed", or area of influence, using the location of processing centers, the land cover types, as well as transportation costs (road and river networks). The area of influence of each center can change annually due to road access). Figure S4 shows the processing centers (in yellow) and their area of influence (shaded in grey to blue around processing centers).

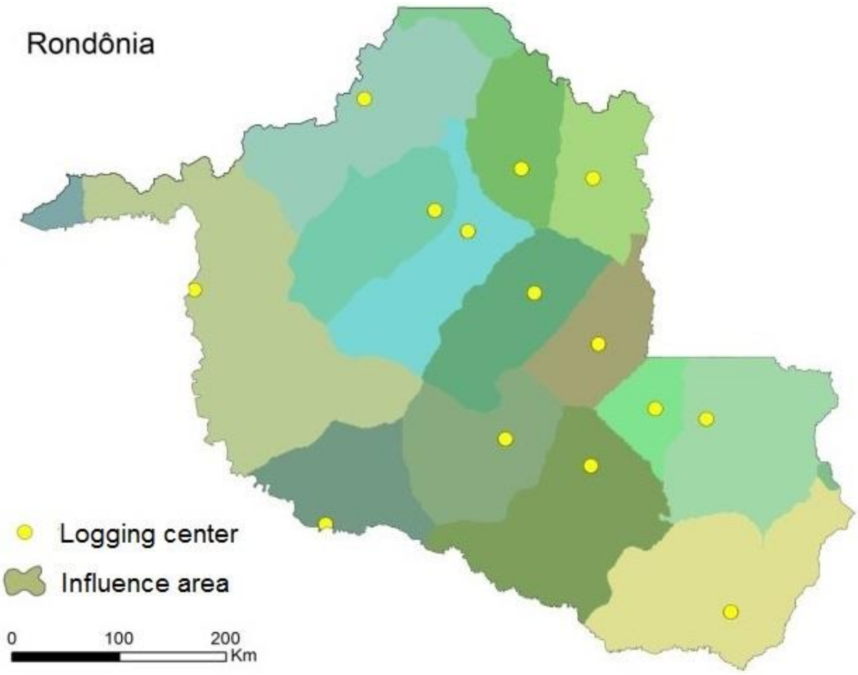


Figure S4 - Example of areas of influence of processing poles (shaded in grey to blue) and processing poles (yellow circles) in Rondônia.

Each processing center (located in the municipality seat) has an initial capacity set based on its past processing records from 2007-2009. The volume available to process in the future (though yearly iterations) will change based on the available timber produced in the most profitable plots (UPA) within each block (UFM) (Figure S3).

The model allows either expansion of the center (up to a maximum of 20% of the previous year capacity[4]) or the shutting down of the center (no profitable timber to be extracted). The model also allows new centers to be created (as one center is shut down other can be created to replace this in an area where there is profitable timber available).

Total costs include felling, transportation and processing costs, as well as capital and opportunity costs (Figure S5). These costs vary in time and space. For example as a processing center is created new roads are built changing the transport costs. It was assumed that the costs of building the roads is included into the harvest costs thus it is not accounted as km of road built, but as cubic meters of wood harvested. The logging road is always based on the previous year infrastructure and its connection to main roads is assumed (Figure S6). Similar to the NTFP models, SimMadeira assumes that the main infrastructure network remains unchanged.

[4] The 20% estimate was given in Fatos florestais IMAZON.

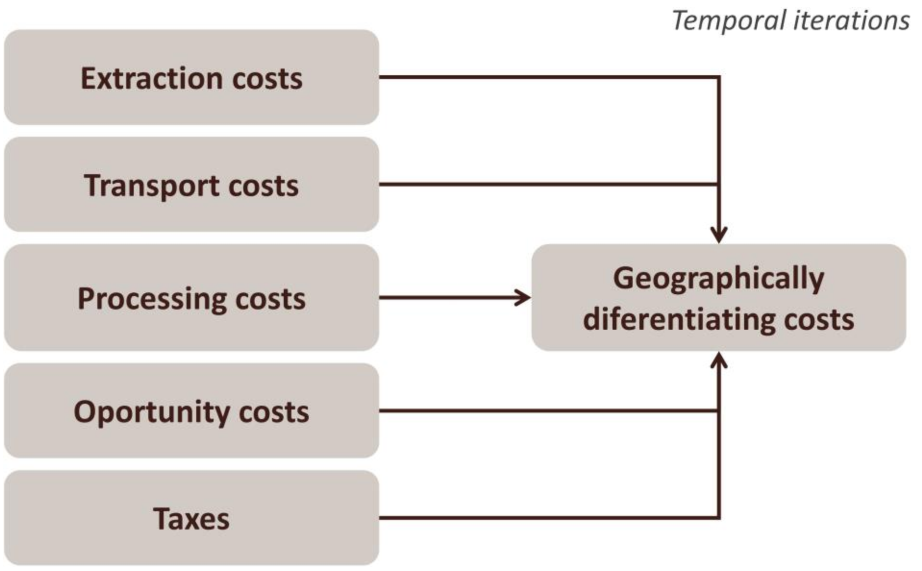


Figure S5 - Geographically differentiating costs.

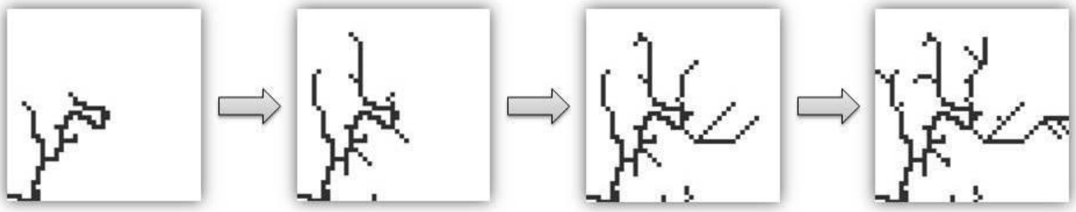


Figure S6 - Logging road creation.

Reference System specifications

Coordinate system for all the input maps is SIRGAS 2000 (The geocentric system for Americas).

Map formats

Format: GeoTIFF; cell size: 0.009° (approx. 1 km^2); number of rows: 2601; number of columns: 3612; Upper left corner coordinate: (Y = 5.309; X = -74); bottom right coordinate: (Y = -41.492; X = -18.1).

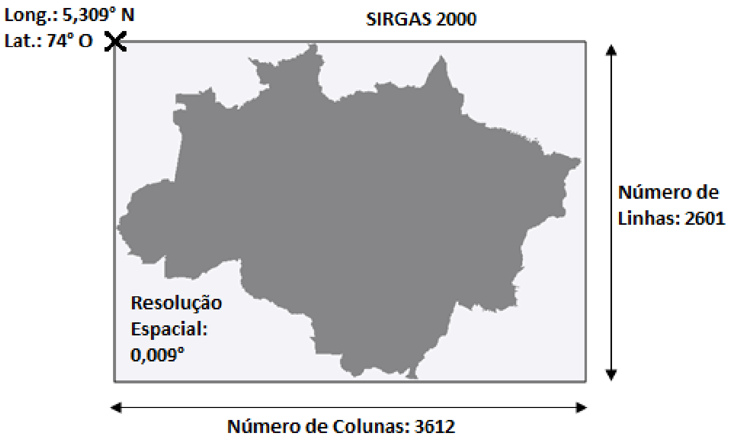


Table S2 - Inputs.

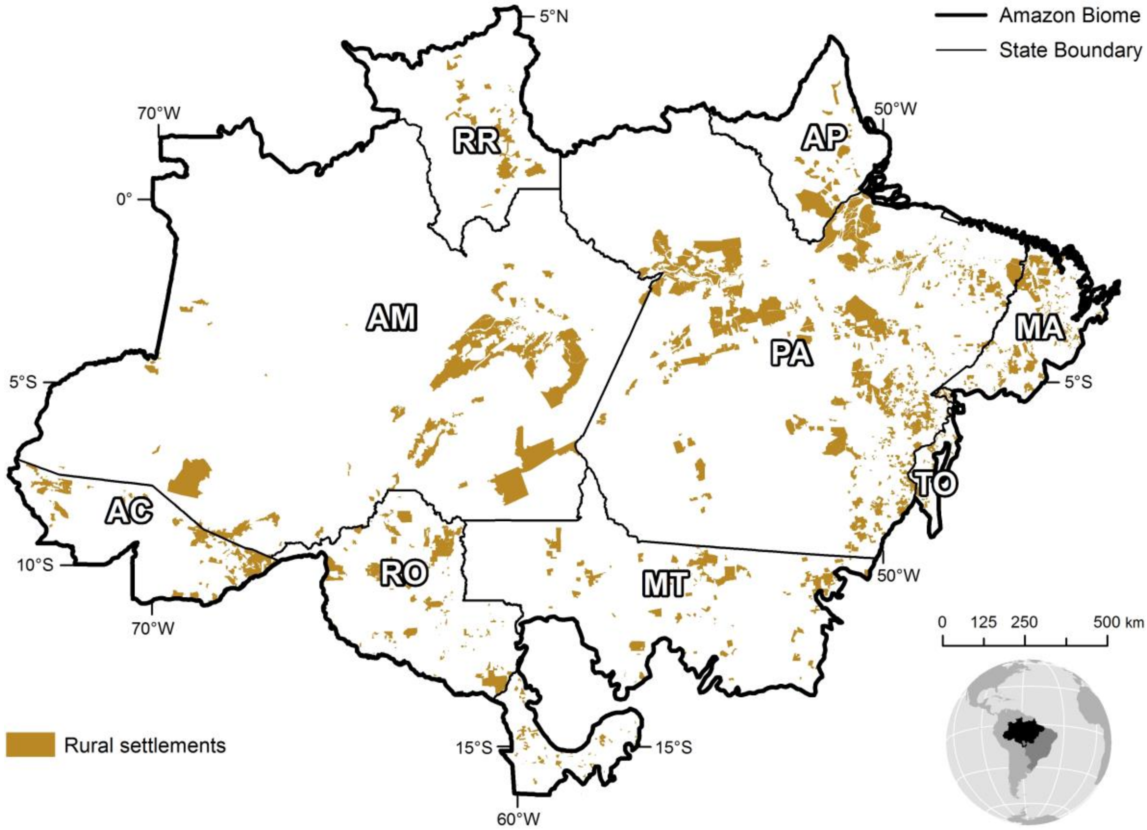
Model / Variables	Source
1.1 Environmetal	
Land Cover	INPE - Instituto Nacional de Pesquisas Espaciais. Monitoring Tropical Forest form Space: the PRODES digital project. Resolution: 60 m. Date 2010. Available in: Instituto Nacional de Pesquisas Espaciais (INPE). Projeto PRODES - Sistema de monitoramento da Amazônia por imagem de satélite. <http://www.obt.inpe.br/prodes/index.php>
Hydrography (distance to)	ANA - Agência Nacional de Águas. 2012. Available in: http://www.ana.gov.br/bibliotecavirtual/solicitacaoBaseDados.asp Ottobacias ANA
1.2 Geopolitical	
Study area	Own elaboration (CSR/UFMG)
Municipalities	IBGE - Instituto Brasileiro de Geografia e Estatística. Date: 2013. Available in: http://www.ibge.gov.br
Setlements	INCRA - Instituto Nacional de Colonização e Reforma Agrária. 2010. Available in: http://acervofundiario.incra.gov.br/i3geo/interface/incra.html?j4ttaav61mm659aevb65gvr5f6
Public forests (per protection type)	SFB - Serviço Florestal Brasileiro. CNFP - Cadastro Nacional de Florestas Públicas; ICMBio - Instituto Chico Mendes de Conservação da Biodiversidade; Funai - Fundação Nacional do Índio. 2012
1.3 Infrastructures	
Wood volume map	(Merry et al. 2009).
Transport network	Vicinal: CSR/UFMG - Centro de Sensoriamento Remoto de Minas Gerais (2004). Major roads: MT/PNLT - Ministério dos Transportes/Plano Nacional de Logística e Transportes (2014).
Transportation cost	Transport costs [R$/($m^3$ or kg)/km] reflect the friction: of the different transport means. For each transport type (boat, donkey, truck).
Max/Min distance to new (logging) centers	Own elaboration (CSR/UFMG)
FMU/APU size/format	Own elaboration (CSR/UFMG)
Capacity expansion factor	Own elaboration (CSR/UFMG)
Opportunity cost	Own elaboration (CSR/UFMG)

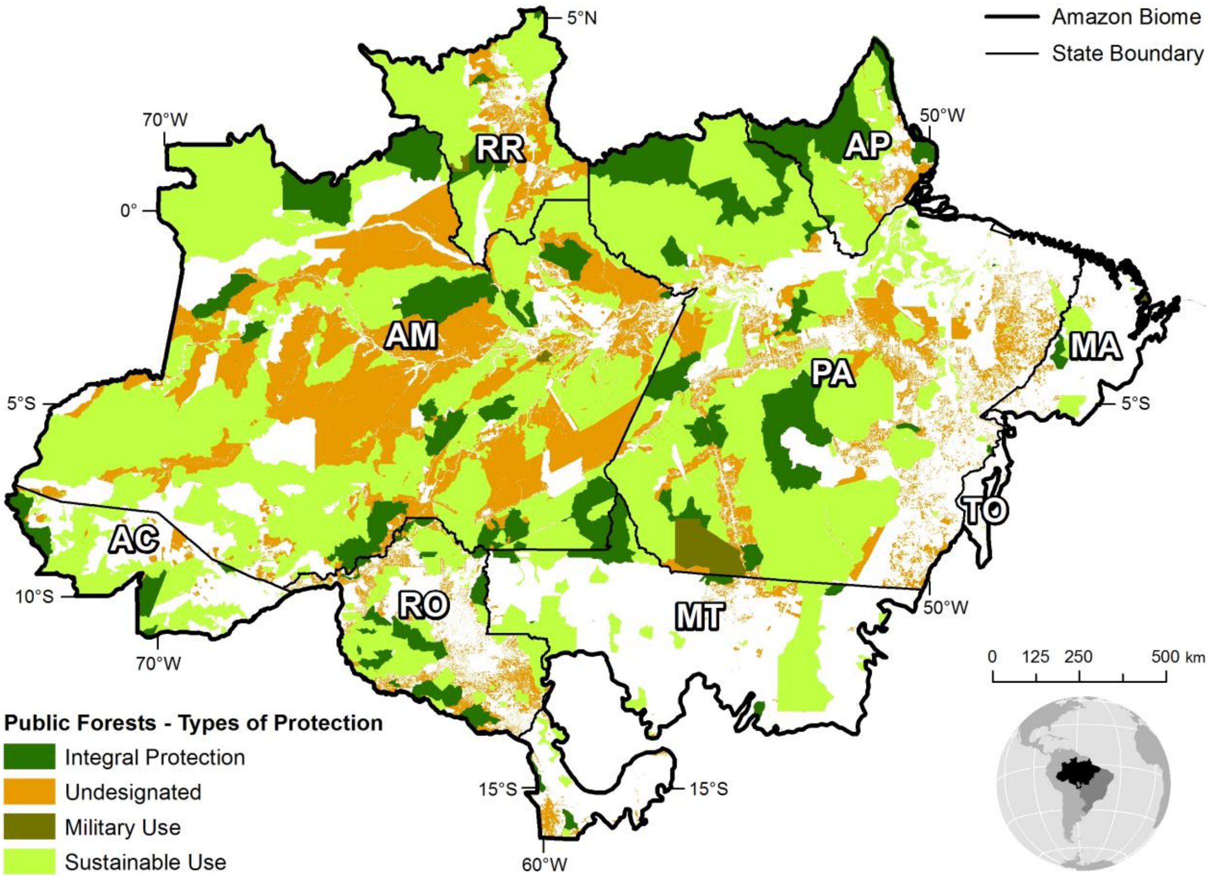
Table S3 - Conversion of real to dollar.

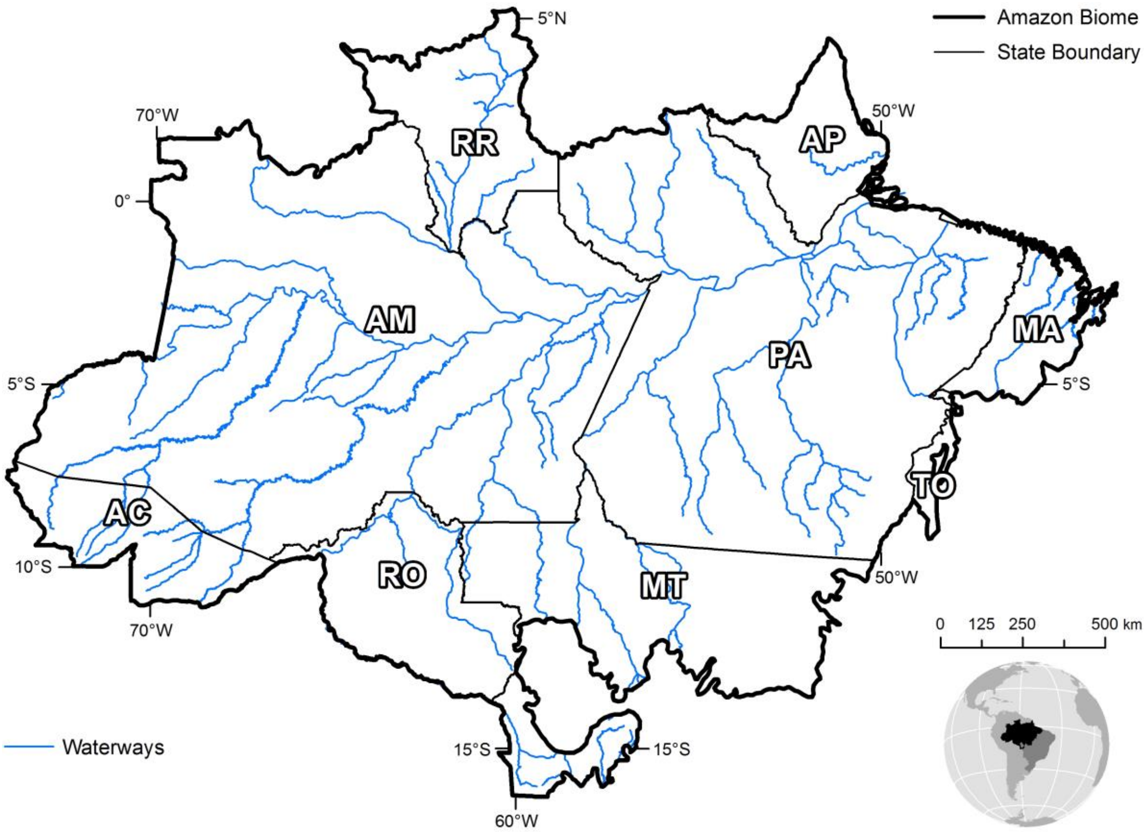
Year	Conversion factor
1994*	0.87
1995	0.92
1996	1.01
1997	1.08
1998	1.16
1999	1.81
2000	1.83
2001	2.36
2002	2.93
2003	3.06
2004	2.93
2005	2.44
2006	2.17
2007	1.95
2008	1.83
2009	2.00
2010	1.76
2011	1.67
2012	1.95
2013	2.15
2014**	2.36

*Only considers 6 months - July to December - until June 1994 Brazilian currency was Cruzeiros Reais.
**We used the conversion factor of 2.36.

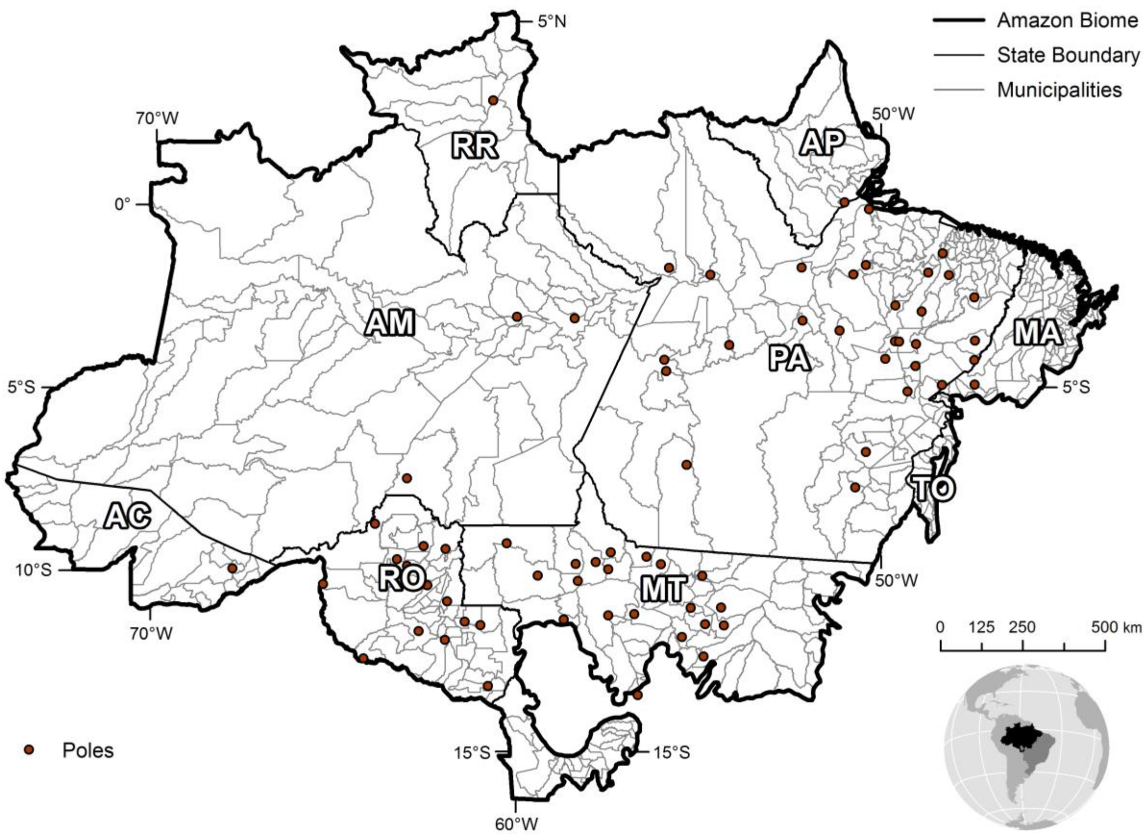
Inputs maps


Amazon Biome
State Boundary
5°N
70°W
50°W
0°
5°S
10°S
15°S
60°W
RR
AP
AM
PA
MA
TO
AC
RO
MT
0 125 250 500 km
Rural settlements


Amazon Biome
State Boundary
5°N
70°W
50°W
0°
5°S
10°S
15°S
60°W
RR
AP
AM
PA
MA
TO
AC
RO
MT
0 125 250 500 km
Public Forests - Types of Protection
Integral Protection
Undesignated
Military Use
Sustainable Use

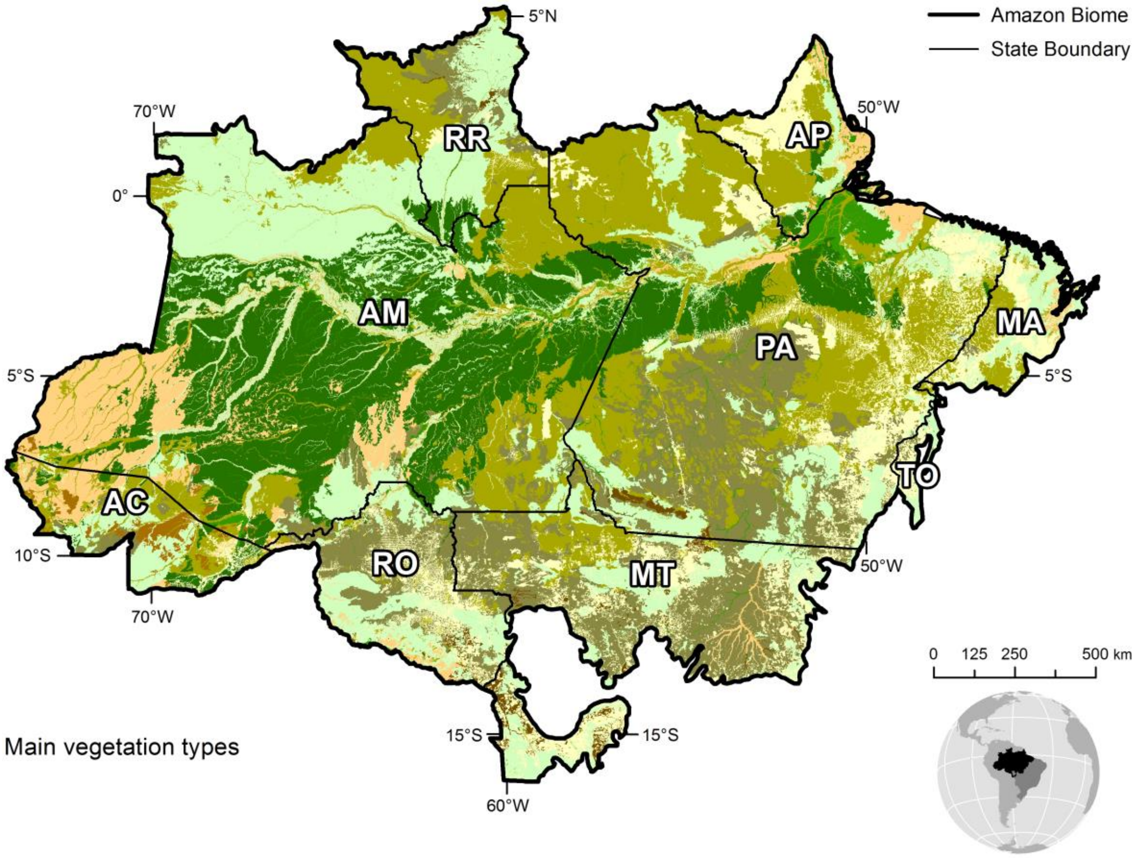


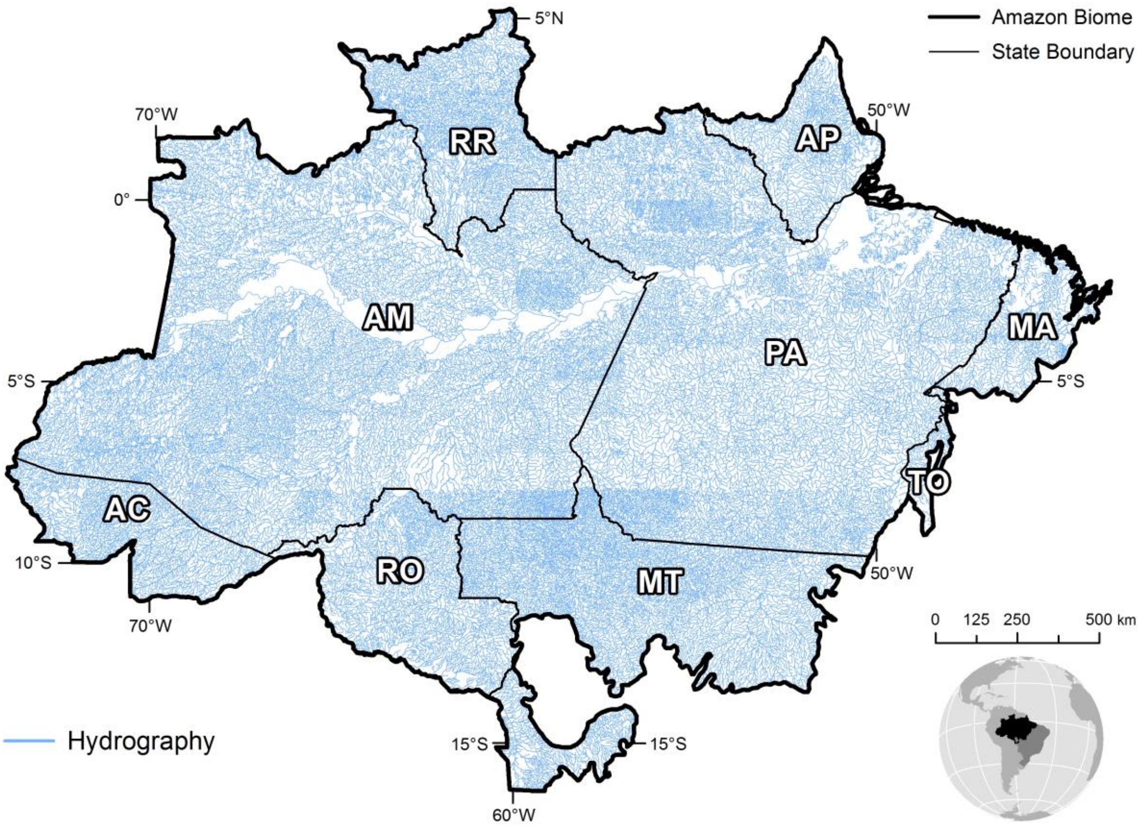
Amazon Biome
State Boundary
Waterways
5°N
70°W
0°
5°S
10°S
15°S
60°W
50°W
RR
AP
AM
PA
MA
TO
AC
RO
MT
0 125 250 500 km



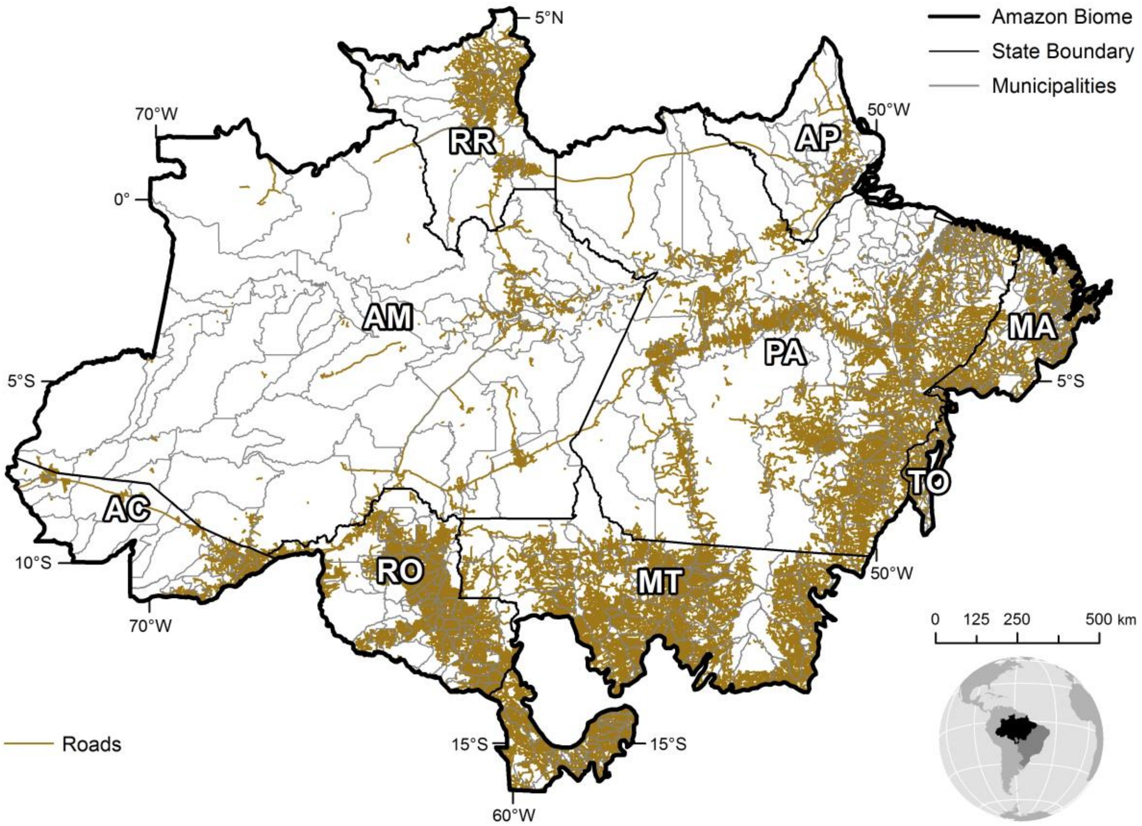
Amazon Biome
State Boundary
Municipalities
Poles
5°N
70°W
0°
5°S
10°S
15°S
60°W
50°W
RR
AP
AM
PA
MA
TO
AC
RO
MT
0 125 250 500 km

Environmental





Infrastructures



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CSR

CENTRO DE SENSORIAMENTO REMOTO

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