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Analysis

Is It Possible to Make Rubber Extraction Ecologically and Economically Viable in the Amazon? The Southern Acre and Chico Mendes Reserve Case Study

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ABSTRACT

Rubber extraction in the Amazon faces enormous ecological and economic challenges. We modeled the ecology (tree density and forest yields) and the production chain, including rents of the three major rubber products: Pressed Virgin Rubber (PVR), Liquid Latex (LL), and Liquid Smoked Sheet (LSS) from native forests and from plantations in Southern Acre, including the emblematic Chico Mendes Reserve. Our estimates show that, in native forests, tree density ranges from 0 to 4 trees/ha (average = 1.67 trees/ha), while productivity varies from 1 to 3 l/tree/year (average = 2.26 l/tree/year) with yields between 1 and 6 l/ha/year. Our model estimates a potential annual production of 890 tons of dry rubber in the 2.5 million ha of forests of Southern Acre (average = 0.36 kg/ha/year). Rubber extraction in native forests is not economically viable without government subsidies. Mean Equivalent Annual Annuity (EAA) for LL is US$ 3.24 ha/year in a scenario with subsidies and of 75% of potential annual harvest. LSS from plantations reaches an EAA of US$ 270 ha/year if costs of formation are subsidized. Public subsidies or Payments for Ecosystem Services are essential to sustain, at least temporally, rubber tapper identity – an important Cultural Ecosystem Service of the Amazon.

1. Introduction

The Amazon is well-known for its diversity of living organisms (Lewinson and Prado, 2004; Hubbell et al., 2008; ter Steege et al., 2013; Fauset et al., 2015) as well as for the variety of livelihoods and cultures of its traditional communities that live in or by the forest (Gonçalves, 2005; McMichael, 2015). Despite Brazil's success in reducing deforestation (Nepstad et al., 2009), challenges to secure further reductions remain (Soares et al., 2014). In this respect, one key component for forest conservation policies continues to be the need to promote sustainable development, especially for traditional livelihoods (Arima et al., 2014). To meet this goal, the upgrading of sustainable production chains of timber and non-timber forest products (NTFPs) has been suggested as central (Delang, 2006; Schroth et al., 2004; WWF, 2014).

The consumption and trade of NTFP mirror well the Amazonian diversity. NTFPs encompass a variety of raw materials, such as food, fibers, resins, and animal products used and traded by local communities. NTFPs are also famed for their potential genetic pool for the future (Elisabetsky and Shanley, 1994; Coelho-Ferreira, 2009) and often linked to traditional knowledge and folk culture, hence regarded as "non-material" cultural ecosystem services (Gomes et al., 2012).

Yet, despite their reported potential to protect biodiversity and support traditional livelihoods, NTFPs market values are not sufficient to sustain economically viable, large-scale exploitation (Schroth et al., 2004; Shone and Caviglia-Harris, 2006; Gomes et al., 2012; Albers and Robinson, 2013). As a result, four decades of attempts to harness NTFPs production chains to further conservation goals and support traditional livelihoods have had mixed outcomes. While critics have questioned the limited potential of natural resource management of timber and NTFPs for reconciling

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conservation goals with local livelihoods (Shone and Caviglia-Harris, 2006), others have identified factors that could improve those production chains (MMA, 2009; Nunes et al., 2012; WWF, 2014).

Among the vast number of NTFPs from the Amazon, rubber is of particular importance due to its tie to the Amazon history and high potential for application in industry. It is the presence of the rubber tree (*Hevea* spp) that geographically defines the Amazon biome (Gonçalves, 2005). Rubber is one of the hyperdominant trees in the Amazon (ter Steege et al., 2013) with its ecology related to the long history of human occupation in the region. The rubber cycles in the late XIX century and from 1942 to 1965 boosted the Amazon economy, projecting it onto the world market (Hecht, 2013). Particularly, the early rubber boom was crucial for Brazil's scramble for the Amazon (Hecht, 2013). Rubber tappers' identity is still strong in some areas of the Amazon (Gomes et al., 2012). In addition, natural rubber has numerous applications with uses that go beyond 50 thousand objects (FNP, 2014) with high industrial applicability (Embrapa, 2015). Yet Brazil is not self-sufficient in rubber. As of 2011, rubber consumption in Brazil amounted to 400 thousand tons, of which 235 thousand tons, totaling US$ 1.1 billion, were imported mostly from Asian countries (FNP, 2014).

Despite its importance, rubber tapping from native forests in the Amazon has steadily declined due to its low profitability (Embrapa, 2015). In face of the threats posed to this traditional extractive system (Gomes, 2009; Gomes et al., 2012; Hecht, 2013), there are but few studies that address in an integrated way the ecological, economic and cultural aspects of rubber tapping. A particular challenge of such studies is to overcome the shortage of geographically distributed data on productivity (forest yields) and profitability (prices and costs) of NTFPs. In this regard, spatially-explicit assessments are key to help design and put in place policies aimed at valuing the multiple services provided by the Amazon forests, as these policies need reliable estimates of current and expected forest yields and rents under a set of ecological and socioeconomic conditions (Maes et al., 2012; Maes et al., 2013).

As rubber is a raw material traded in markets, conventional economic approaches use market prices to value this product (Turner et al., 2015). There are two major ways whereby rubber enters the market. One is through community industry partnerships (Morsello, 2006) and the other is through NTFPs product market chains (MMA, 2009). While the former occurs through scattered initiatives, *e.g.* The Body Shop Foundation initiative (BodyShop, 2015), the latter is a mainstream practice. However, Ecosystem Services (ES) from standing rubber trees (*e.g.* biodiversity, carbon storage, and rubber tapper's identity) are seldom incorporated in market values. Knowledge of the production chain, including environmental, socio-institutional and economic aspects, is therefore key for orienting policy interventions and investment programs, such as Payment for Ecosystem Services (PES) projects that could ensue sustained and equitable benefits to all those involved (MMA, 2009).

Here, we combine spatially-explicit ecological modeling with economic valuation of three rubber products – Pressed Virgin Rubber (PVR), Liquid Latex (LL), and Liquid Smoked Sheet (LSS) – from native forests as well as from plantations to inform policies aimed at safeguarding the tradition of rubber tapping that has had so much meaning to the ecology and history of the Amazon. To this end, our study focuses on the rubber production chain in Southern Acre including the emblematic Chico Mendes Reserve (CMR).

2. Case Study Area

In Acre, one of the nine states of the Brazilian Amazon, the traditional NTFPs are rubber (*Hevea* spp.) and Brazil nut (*Excelsa bertholletia*). These NTFPs have well-established production chains involving cooperatives that receive support from various government agencies and non-governmental associations (MMA, 2009; WWF, 2014). Southern Acre was included in the national plan for socio-biodiversity (MMA, 2009) as the target region for promoting the rubber chain. The consolidation of rubber chain in the state is moving forward based on three major rubber products, namely PVR, LL, and LSS. LL is produced in Acre since 2005 when the state government set up a condom factory in Xapurí, named Natex Condoms. This was the first factory in the world to produce condoms from LL extracted from native rubber trees (Tollefson, 2015). LSS technology was developed by the department of chemistry of the Federal University of Brasilia to generate thin sheets of pure rubber. Since 2006, various municipal initiatives have supported different associations to produce LSS used, for example, as shoe soles (WWF, 2014).

Rubber extraction in the state is supported by a government agency named System of Incentives for Environmental Services (SISA), which advances market consolidation strategies and provides subsidies to rubber tappers through PES programs (CIFOR, 2014). These subsidies are paid to rubber tappers which receive per kilo of dry rubber (paid at an affiliated institution), in addition to the market price, a share of subsidy to reach a minimum price. These subsidies from SISA are welcomed by pro-rubber tapping movements that emerged after the murder of Chico Mendes – a celebrated rubber tapper leader. In 2012, the subsidies amounted to US$ 1.75 per kg for PVR, and US$ 3.90 and 3.75 for LL and LSS, respectively (Table 1).

Moreover, as a means to become self-sufficient in rubber production and to reduce deforestation, rubber plantations in agroforestry systems have been proposed as a an economic alternative to cattle raising as in the case of Brazilian Extractive Reserves (Schroth et al., 2004). To this end, the state government has supported since 2010 reforestation on degraded pastures with different native trees, such as *Hevea* spp. In addition to restoring degraded lands, rubber plantations are envisaged as a way to improve efficiencies of scale (Line Carpentier et al., 2000; Schroth et al., 2004). In native forests, one person may extract 500 to 600 kg of latex a year, whereas in rubber plantations the same workforce may extract as much as 20 tons a year (SEAPROF, 2014).

Our study area, the southeast part of Acre state, comprises 3.88 million hectares (ha) of which 2.5 million ha consist of forests and 0.9 million ha of pasture and croplands. The study area encompasses the 11 largest municipalities of Acre on a population basis, including the Chico Mendes Extractive Reserve situated alongside the BR-317 highway that connects Brazil to the Pacific Ocean *via* Peru (Fig. 1).

CMR is emblematic for many reasons. It was one of the first protected areas in Brazil designated as an extractive reserve (RESEX) category, which allows sustainable human occupation inside. Its designation was pressed by popular movements (*i.e.* rubber tappers and nut gatherers) resisting the appropriation of forest areas by large farmers (Salisbury and Schmink, 2007). Rubber tapping has been the main economic activity in CMR guided by its Management Plan and Advisory Council Utilization Plan (MMA, 2009).

Table 1
Total production costs and sale prices (US$/kg) for Pressed Virgin Rubber (PVR), Liquid Latex (LL) and Liquid Smoked Sheet (LSS) in scenarios of full (FC) and partial (PC) cycles and with (PS) and without subsidies (AS).

Economic variables	Presence of subsidies			Absence of subsidies		
Products	PVR	LL	LSS	PVR	LL	LSS
Total cost in full cycle	2.58	3.08	3.35	2.82	3.80	5.32
Total cost in partial cycle	1.66	1.97	2.27	1.98	2.94	4.78
Sale price	1.75	3.90	3.75	0.81	1.89	2.49

Conversion factor (*Fn*): 1 kg of latex extracted: 0.9 kg LSS, for other products *Fn* = 1. US$ 1 = R$ 2.

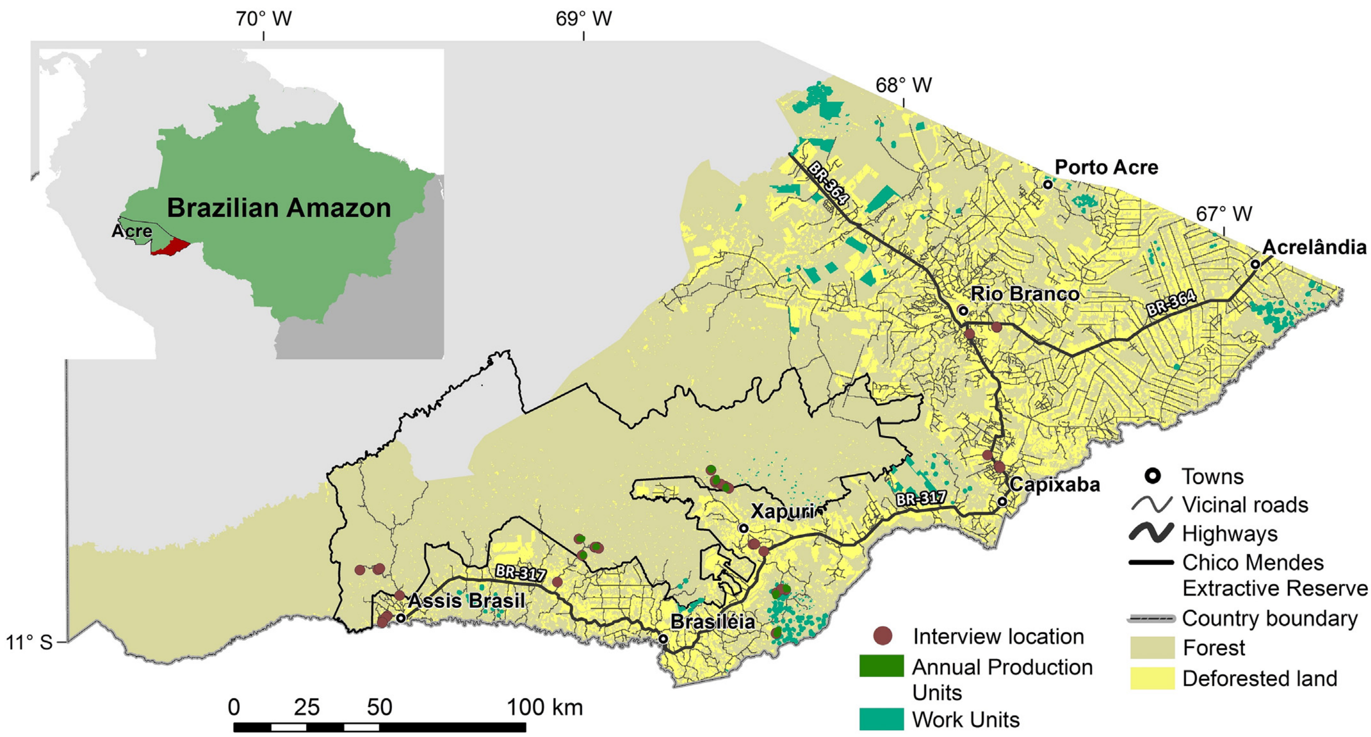

Fig. 1. Case study area.

Despite strong commitment by governmental bodies to promoting the rubber chain,[3] several issues have hampered the progress of rubber tapping in Southern Acre. These include the low profitability of tapping in native forests, little research in disease control, namely the rubber leaf blight (South American Leaf Blight) that ruined plantations in the Amazon (*e.g.* Fordlandia), lack of special market niches aimed at adding value to forest-friendly products, and diminishing international rubber prices. This has been further aggravated as a result of the world economic crises, given that rubber products such as PVR are used as raw material for Brazilian Dark Granulate (in Portuguese GEB, Granulado Escuro Brasileiro) used in the automobile industry. All of this has brought the rubber chain near bankruptcy, encouraging the conversion of forest to pasture for cattle raising, which is more profitable in the short term (Bowman et al., 2012), but both ecologically and culturally less sustainable in the long run (Embrapa, 2015).

3. Methods

3.1. General Approach

We developed and applied a spatially-explicit model to evaluate the rubber production chain from both native trees and plantations in Southern Acre. The model encompasses two components: the first simulates the spatial distribution and productivity of native rubber trees (tree density and forest yields) based on field plot data, and ecological and biophysical variables; the second integrates selling prices, costs of production and transport per product (PVR, LL, and LSS) in order to calculate annual net rents per hectare (Fig. 2). The annual net rents were transformed into Net Present Value (NPV) and then converted to Equivalent Annual Annuity (EAA). In the case of plantations, we also included the costs of plantation formation and maintenance (thereafter called formation costs C*form*) (Fig. 3). Model spatial resolution is of 6.25 ha (250 × 250 m); all components were developed using Dinamica EGO platform http://csr.ufmg.br/dinamica/ (Soares Filho et al., 2009; Soares Filho et al., 2013).

For the case of native trees, two scenarios of annual production were assessed. The full cycle (FC) collects rubber yields as of 2009 from 100% of annual production cycle (from May to October) and the partial cycle (PC) from 75% of annual production cycle, concentrating production in the more productive months (Fig. S1, Supplementary material). These two production scenarios are combined with a scenario of subsidies (Presence of Subsidies, PS) and another without subsidies (Absence of Subsidies, AS). The subsidy scenario includes complementary payment (to reach the minimum price), initial supply of inputs and collection tools, and transportation assistance by the establishment of 30 points of sales located within the forest (Table 1, Table S2).

3.2. Input Data

The components for modeling tree density and forest yields include 27 input maps of biophysical variables and ecological and economic data from fieldwork and secondary sources (Table S1). Data on tree density and productivity of native rubber come from forest management plans by Technology and Forest Management (Tecman, 2009) and from annual production units (APU) of Associação de Moradores de Xapuri (Amoprex, 2009). Tecman data contain geographic coordinates of rubber trees in Southern Acre, including 35,051 trees (27,010 trees records of DBH, Diameter at Breast Height) (Figs. 1 and S2) that we used to estimate the spatial pattern of trees and tree density. Nine APU, also known as rubber trails (*estradas de seringueiras*) within the ecological register of 867 live trees by Amoprex, were used to estimate tree productivity. Amoprex data included morphological differences between *Hevea* spp. (*i.e. Real*, *Vermelha*, *and Branca*), their geographic coordinates, DBH, and records of liters collected per week during six months of 2009 (Fig. S1).

We gathered economic data on the production chain of rubber from native trees (Table S2) through 44 interviews with rubber tappers,

[3] The Brazilian government is promoting its NTPF programs through a series of initiatives (Utilização Sustentável dos Componentes da Política Nacional da Biodiversidade PNB -Decreto 4.339 de 22/08/2002 Política Nacional de Desenvolvimento Sustentável dos Povos e Comunidades Tradicionais, Decreto no. 6.040 de 07/02/2007, Programa Nacional de Fortalecimento da Agricultura Familiar - PRONAF, Decreto no.1.946 de 28/06/96, Pronaf Florestal, Agroecologia, Eco, Programa de Aquisição de Alimentos da Agricultura Familiar – PAA). In addition, Brazil has a legislation (MP 2.186-16/2001) that governs access to genetic resources and local traditional knowledge. The law incorporates aspects of benefit sharing to local communities.

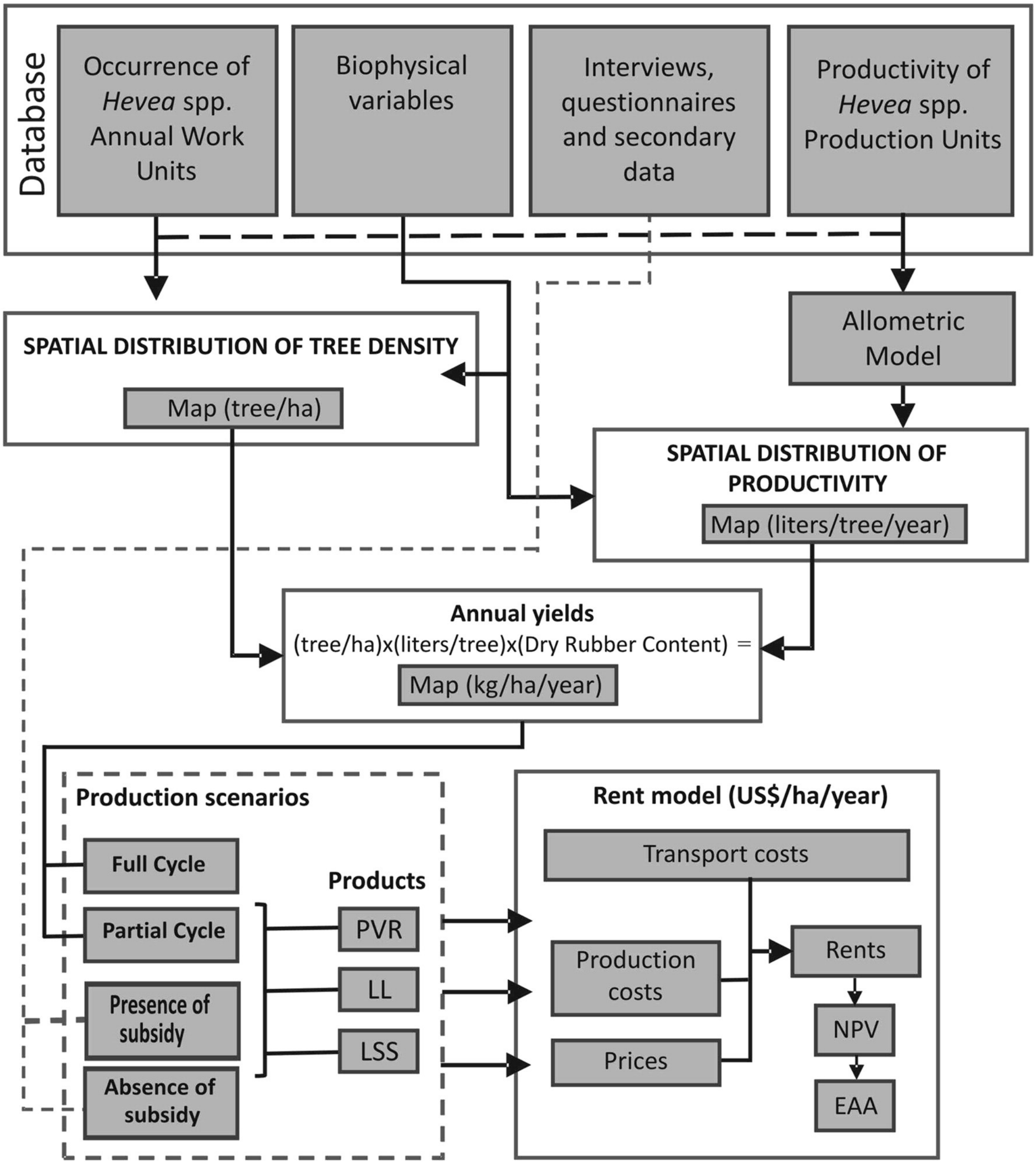

Fig. 2. Model flowchart for rubber yields and rents from native trees. The model first simulates the spatial distribution and productivity of native rubber trees (tree density and yields) based on field plot data (production units) and ecological and biophysical variables (Table S1). The model then integrates selling prices, costs of production and transport per product (Tables S2, S3) to calculate annual net rents per hectare for PVR, LL, and LSS under different production scenarios.

cooperatives, and latex industry representatives in 2010 and 2012 throughout the study area (Fig. 1). The transport costs from native forests (Table S3) and production and formation costs and yields of rubber plantations (Tables S4, S5) were derived from the Brazilian Yearbook of Agriculture (FNP, 2013) and Secretaria de Planejamento, SEPLAN (Gonçalves et al., 2013).

3.3. Model Development

3.3.1. Rubber Tree Spatial Pattern and Density

In native forests, we started by assessing whether rubber trees are clustered or randomly distributed. We applied the Ripley's K function on the dataset of tree locations. The test of significance was determined by comparing our results with the statistical distribution from a Complete Spatial Randomness model (Baddeley and Turner, 2005; Itoh et al., 2003) (Fig. S3).

Next, we applied the Continuous Weights of Evidence method (Soares Filho et al., 2009) for modeling tree density and tree productivity in native forests. Of the 27 initial variables (Table S1), the method selected 11 variables, namely Mean Diurnal Temperature Range, Annual precipitation, Isothermality, Precipitation of Wettest Quarter, Precipitation of Driest Quarter, Mean Temperature of Driest Quarter, Mean Temperature of Wettest Quarter, Distance to rivers, Elevation, Soil, and Vegetation Classes (Fig. S4). The method calculates the influences (W^+) of these variables to determine the spatial probability of tree occurrence and thus density (Eq. (1)).

$$P\left\{Treedensity_{x,y}|V_1 \cap V_2 \cap V_3 \cdots \cap \cdots \cap \cdots V_j\right\} = e^{\sum W^+ V_n}/1 + e^{\sum W^+ V_n} \quad (1)$$

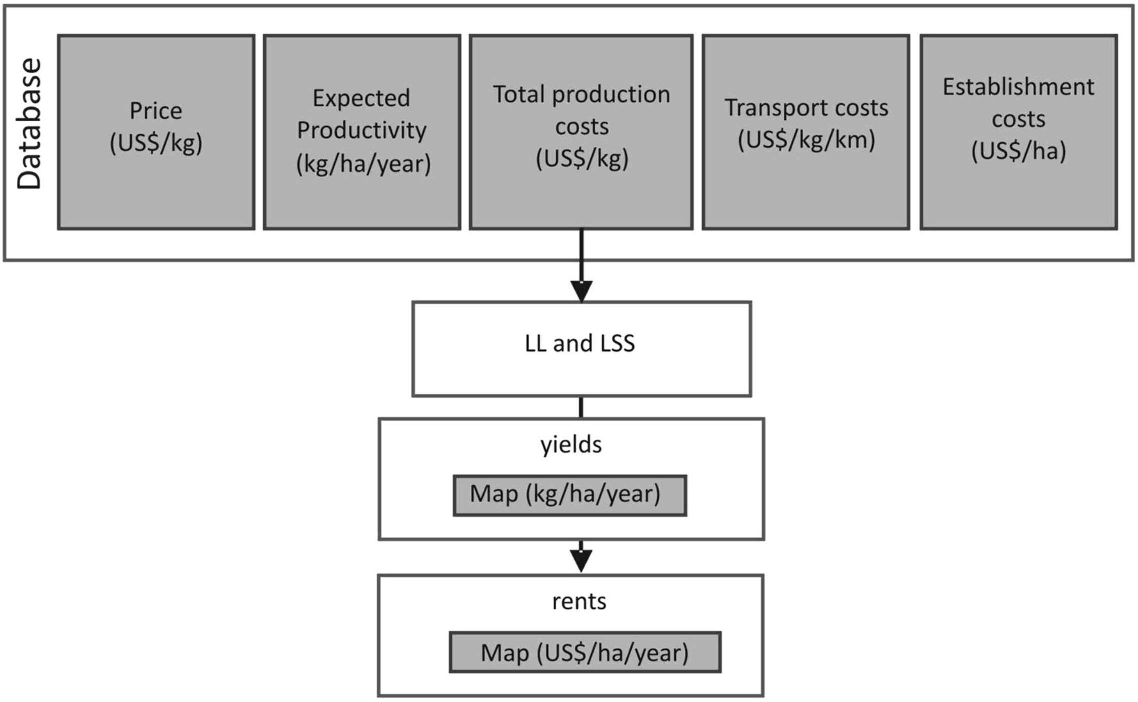

Fig. 3. Model flowchart for rubber yields and rents from plantations. Model includes selling price for LL and LSS, costs of plantation formation and maintenance, and transportation costs. Productivity of latex varies as a function of plantation age.

where P is the probability of tree density at location x,y given a series of spatial variables and $W^{+}{}_{Vjn}$ is the weight of evidence of category n of variable V_j (Bonham-Carter, 1994).

The model then simulates tree density by stochastically drawing numbers from two probability distribution functions (PDF) and comparing these numbers with cell values of the resulting probability map. For $P \leq 0.8$ we used the Weibull PDF and for $P > 0.8$ the LogNormal PDF. These PDFs were derived from tree occurrences in the sampled area (Fig. S5).

3.3.2. Tree Productivity

First, we related productivity (l/tree) with DBH of 867 individuals from the nine production units of Amoprex to derive a statistical alometric model Eq. (2), (RSME is statistically significant for $P \leq 0.05$). We then assigned estimated productivity to 27,010 trees in the Tecman's data that had a DBH record.

$$Productivity = -0.4264DBH + 0.04511 \quad (2)$$

After the spatial randomness test (Fig. S6) confirmed random distributions ($P \leq 0.05$) for all productivity classes (low 0–1.1; median 1–2.6; high >2.6 l/year) up to 500 m of tree distance, we applied again the Weights of Evidence method to derive a probability map of tree productivity (l/year) by integrating the influence (W^{+}) of a set of 13 spatial determinants. Variables selected were Mean Diurnal Temperature Range; Temperature Seasonality; Mean Temperature of Wettest Quarter; Mean Temperature of Driest Quarter; Annual precipitation; Precipitation of Wettest Quarter; Precipitation of Driest Quarter; Precipitation of Warmest Quarter; Slope, Distance to rivers; Elevation, Vegetation, and Soil classes (Fig. S7). Next, we ran stochastic simulations of tree productivity using two PDFs, LogNormal for $P \leq 0.6$ and Weibull for $P > 0.6$ (Fig. S8). Finally, we multiplied the resulting two maps (tree density in trees/ha and productivity in l/tree/year) to obtain a map of rubber yield (kg/ha/year). We used a coefficient of 53% to transform liquid latex into Dry Rubber Content (DRC).

Because productivity of rubber in the native forest declines over the harvest period – from March to October (Fig. S1) –, we simulated two scenarios of annual productivity. The full cycle (FC) collects rubber yields as of 2009 from 100% of annual production cycle and the partial cycle (PC) from 75% of annual production cycle, concentrating production in the more productive months. Thus, the major difference between scenarios is the use of labor force, resulting in production costs for FC greater than those for PC.

3.3.3. Rent Model

The main latex products are differentiated in terms of production costs and prices (CONAB, 2012). Prices for each product with and without subsidies as of 2012 come from CONAB (2012) (Table 1). We gathered costs of utensils, time required for cleaning trails, removing tree barks (extraction panels), collecting, and transporting latex to storage points, post processing according to each product, and storage and transportation to sale points. Next, we transformed working hours into fixed and variable costs for each rubber product by using the average minimum wage of 2012 (US$ 311 per month) for the different PC and FC scenarios (Table S2). Although, in reality, rubber tappers may earn less, the minimum wage is mandatory in Brazil, and thus a common basis for monetizing rural labor.

We applied a land-use map of navigable rivers and roads to calculate a map of accumulated transportation costs (Table S3). Transportation always assumes the least cost pathway between source and destination using a mix of transport modes (motorcycle, mule, boat, and truck) and associated costs. In the PS scenario, transportation costs are calculated from storage points to points of sales. In turn, for the AS scenario, transportation costs are calculated from the storage points to the nearest town. The potential rent of rubber extraction (US$/ha/year) for a location (xy) in the native forest is denoted as follows:

$$Rent\ from\ Native\ forest = Q_{xy} * Fn^{*}(P_n - Cpr_n - Ctr_{n,xy,z,m}) \quad (3)$$

where Q_{xy} is the total or partial annual rubber yield (kg/ha/year) at location x,y. For a product type n (PVR, LSS or LL), F_n, P_n, Cpr_n, $Ctr_{n,xy,z,m}$ are, respectively, the conversion factor, price, cost of production, and transportation cost from xy to z per transport mode m: motorcycle, mule, boat, and truck.

Table 2
Population and productivity characteristics of *Hevea* spp. observed in nine annual production units of Amoprex.

APU	Number of trees	Number of dead trees	Abundance			Annual productivity (liters/tree)			DBH (m)		
			Real	*Real Branca*	*Verme-lha*	*Real*	*Real Branca*	*Verme-lha*	*Real*	*Real Branca*	*Verme-lha*
1	73	3	11	62	0	2.01	1.73	–	0.57	0.49	–
2	98	13	26	71	1	3.62	2.40	1.37	0.54	0.44	0.41
3	74	3	29	45	0	3.07	2.82	–	0.68	0.51	–
4	105	1	64	41	0	2.86	2.06	–	0.51	0.42	–
5	94	11	23	71	0	4.68	1.75	–	0.56	0.49	–
6	108	7	26	82	0	2.02	2.09	–	0.60	0.57	–
7	101	4	22	77	2	1.26	1.16	0.53	0.57	0.54	0.35
8	104	12	27	66	11	1.97	1.83	1.445	0.54	0.48	0.54
9	110	5	26	57	27	2.43	1.56	1.21	0.58	0.47	0.43
Total/average	867	59	254	572	41	2.72	1.89	2.88	0.57	0.49	0.43

In the case of plantations, we assumed a density of 476 trees per ha. In this case, costs also include investments in formation and maintenance ($Cform_{xy}$) before plantations begin producing – administrative costs were not included (Table S4). Production cycle of plantations is assumed to be 30 years with costs and yields varying as a function of plantations age (t) up to the 16th year (Table S5), so that:

$$Rent\_plantations = Q_{xyt} * Fn * (P_n - Cpr_n - Ctr_{n,xy,z,m}) - Cform_{xy} \quad (4)$$

For both native forests and plantation, rents from rubber products were simulated for a 30-year period to calculate Net Present Values (NPV) using a discount rate of 6% and transformed into Equivalent Annual Annuity (EAA) to facilitate comparison.

3.4. Verification and Sensitivity Analysis

Verification of the model was performed by comparing the simulated mean tree density (trees/ha) and productivity (l/tree/year) with the observed density and productivity in the nine units of production of Amoprex. The simulated potential annual production (in tons per year) for the study area was compared with the historical records from SEPLAN (Gonçalves et al., 2013) and records of rubber production in Acre from IBGE (IBGE, 2011). Sensitivity analysis for rents were performed varying by 25% production and transport costs, prices, and productivity

4. Results

4.1. Ecology of Rubber Trees

We find in Amoprex APU three rubber species (*Hevea* spp), namely *Real* (31%), *Real Branca* (66%) and *Vermelha* (5%). Average annual productivity is 2.18 l/tree declining over time (Fig. S1); 86% of rubber trees had DBH between 0.13 and 0.8 m while the DBH of the remainder 14% ranged from 0.8 to 1.26 m. The *Real* variety had the largest DBH, and the *Vermelha* the greatest annual productivity, on average. Average tree density observed in the nine APUs was 1.71 trees/ha (Table 2).

Estimated Ripley's K envelopes (Baddeley et al., 2006) and their theoretical confidence intervals for randomness over a distance of 500 m (Complete Spatial Randomness) at a 95% confidence level indicate a random spatial pattern for the adult population of rubber trees as well as their productivities in the forests of southeastern Acre (Figs. S3 and S6). Opposed to the clustered spatial pattern of Brazil nut trees (Nunes et al., 2012), randomness may indicate a natural (not influenced

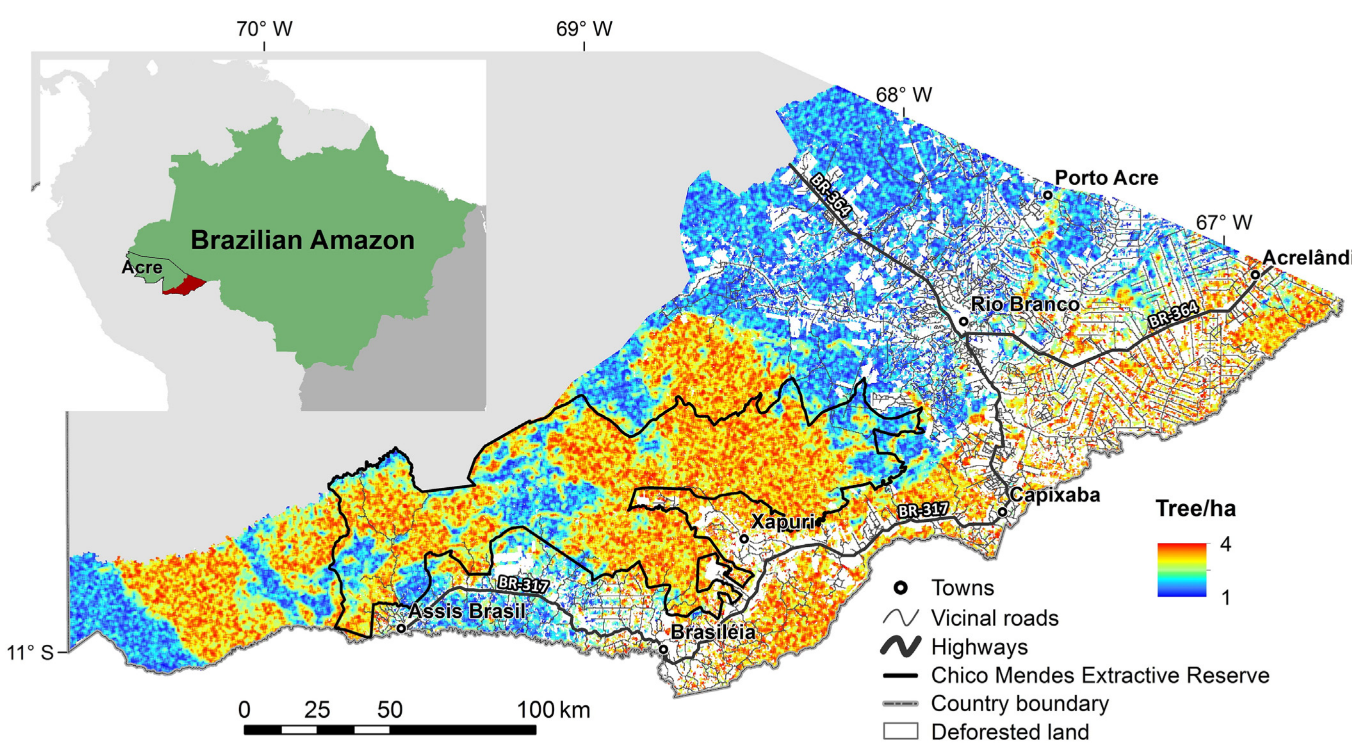

Fig. 4. Simulated tree density in the study area. Areas with higher tree density concentrate in the central south of the region, especially within CMR.

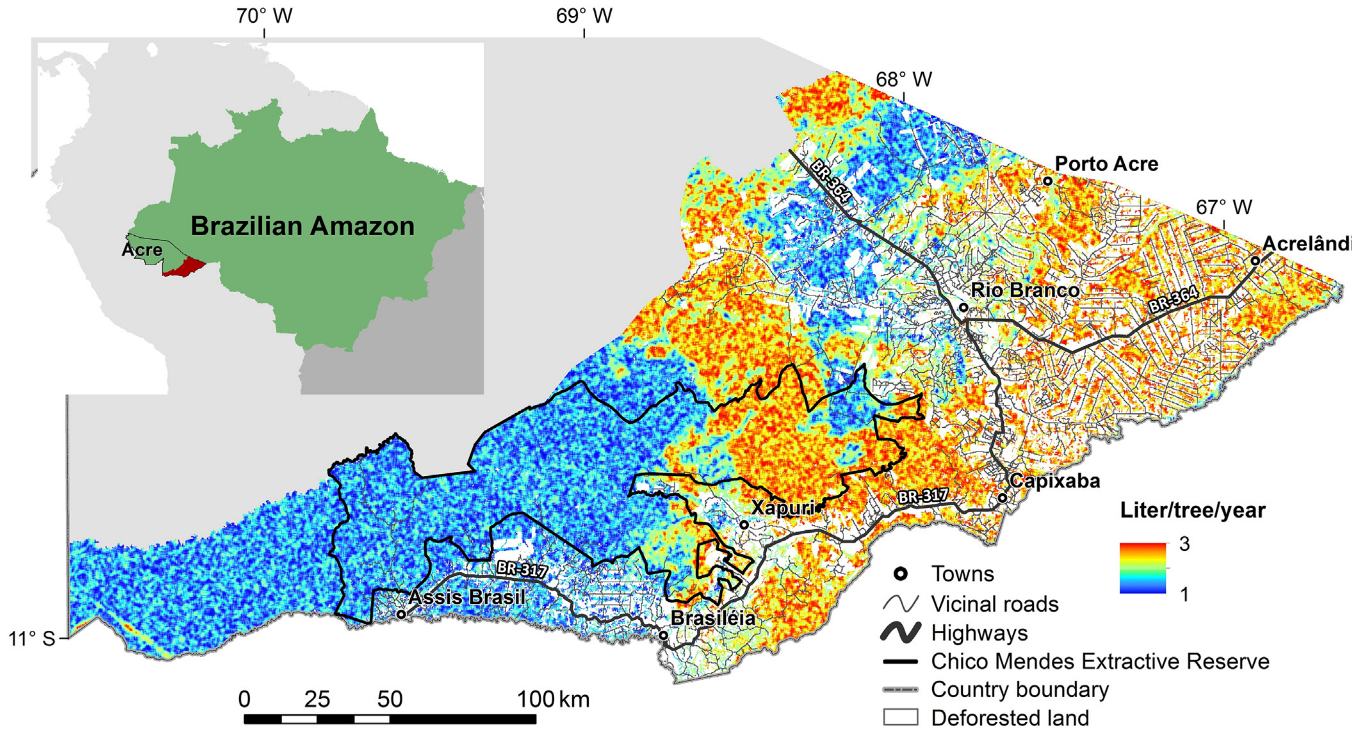

Fig. 5. Simulated tree productivity in the study area. Higher productivity areas locate across the central part of the region.

by humans) geographic dispersion of *Hevea* spp., such as *H. brasiliensis* and *H. guianensis*, which are pervasive throughout the Amazon biome (Priyadarshan and Goncalves, 2003).

Simulation results of tree density are within the range of 0 to 4 trees/ha with average density of 1.67 trees/ha (Fig. 4). In turn, simulated tree productivity ranges between 1 and 3 l/tree with average productivity of 2.26 l/tree/year (Fig. 5). The average simulated tree density and productivity within the nine APUs exceeded the observed values by 22% and 25%, respectively. Nonetheless, the average simulated values for the entire study region (tree density of 1.67 trees/ha and annual productivity of 2.26 l/tree) approximate to those observed in the nine APUs: tree density of 1.71 trees/ha and annual productivity of 2.18 l/tree. Table 3 compares our results with previous studies; note that there is a scarcity of studies on productivity of native rubber trees (Homma, 2008; Peters et al., 1989, Embrapa, 2015).

The combination of both maps resulted in yields varying from 0 to 6 kg/ha/year across the study area with more productive areas located in southern and central parts of the region (Fig. 6). As a result, the model estimated a potential annual production of 890 tons of dry rubber in the 2.5 million ha of forests of the study region (0.36 kg/ha/year) and 300 tons in the 0.77 million ha of forests of CMR (0.39 kg/ha/year).

Simulated potential production for the study area exceeded by 16% the state production in 2009 as informed by SEPLAN (Gonçalves et al., 2013). However, verification is uncertain because other sources (*e.g.* IBGE, 2011 and FNP, 2013) published different numbers compared with those of SEPLAN (Fig. S10). Furthermore, none of these sources specify if the production is coming from native forests within Acre or from neighboring states or from the 1146 ha of rubber plantations in the region (IBGE, 2009). Finally, we need to take into account that potential production from the region's forests has steadily declined due to continued forest disturbance, such as fragmentation and fires (Aragao et al., 2007), not to mention the recent economic slump of the sector across the Amazon (Schroth et al., 2004).

4.2. Economics of Rubber Production Chain

Although it is practice to extract rubber in CMR during the full season of collection, this strategy does not compensate, considering as the opportunity cost of labor the minimum wage. Nevertheless, this common situation ensues from the limited number of activities that can generate income in CMR (Homma, 2008). Thus, our results point out that the partial production cycle would be more efficient, should CMR offer more diversified economic activities.

In the PC scenario including subsidies (PS), only two latex products deliver positive returns, on average. LL showed the highest rent followed by LSS and PVR with value near zero (Fig. 7). This result illustrates that although PVR is the most common product, there is no net return in transforming latex into PVR. Moreover, it is only economically viable to produce any of these three products in the presence of government subsidies (PS).

The maximum values for LL (US$ 6 ha/year) are observed near Natex, in the municipality of Xapurí due to easier access (Fig. 8). In

Table 3
Rubber tree density and productivity from previous studies together with mean observed and simulated values in the APUs and for the entire study area.

Study	Schroth et al. (2004)	Kageyama et al. (2004)	Souza et al. (2011)	This study, observed	This study, simulated in APUs	This study, simulated for the entire region
Density (trees/ha)	–	<5	0.007–3	1.71	2.08	1.67
Annual Productivity (liters/tree)	2.4*	–	4.5	2.18	2.73	2.26

* 0.05 kg per tree/week in agroforests.

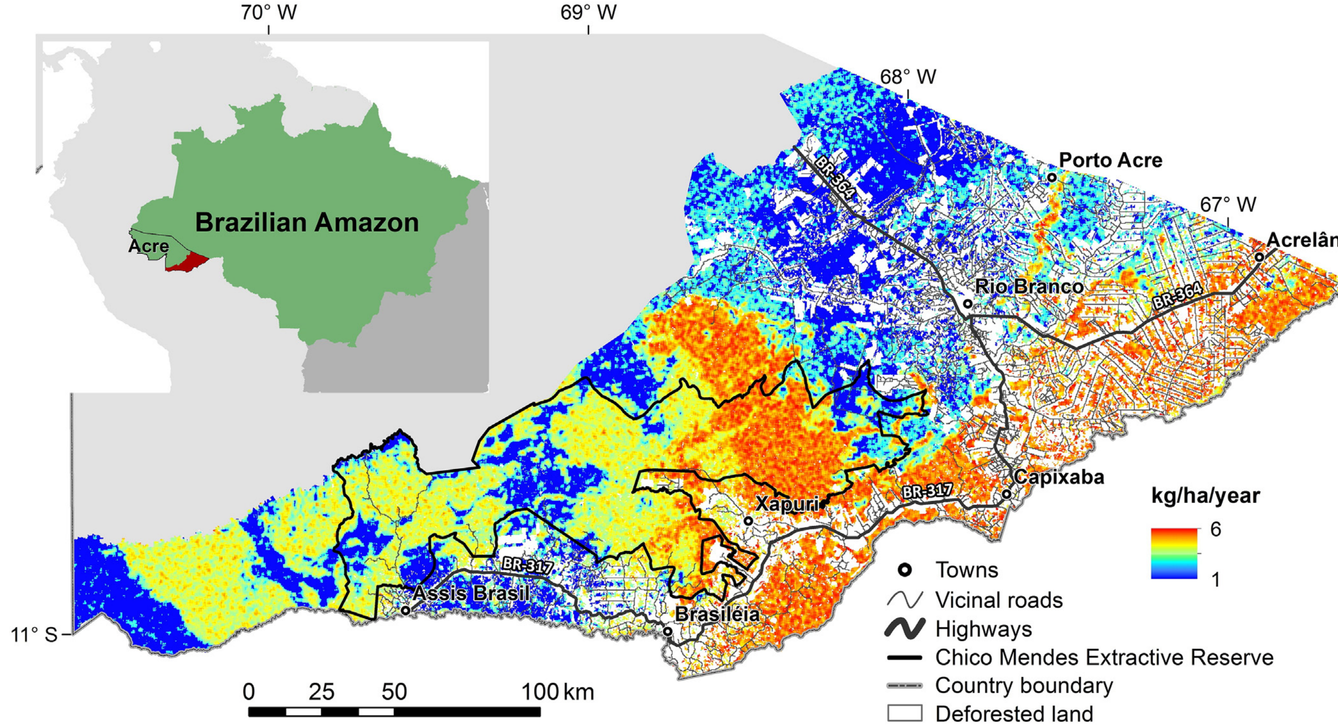

Fig. 6. Simulated rubber yields in the study area. Higher yields occur where both tree density and tree productivity are high, particularly across the east of CMR.

areas away from Xapurí, LL is not economically viable since the maximum distance the company collects LL is 100 km. LL production, even with modest rents, benefits from the presence of Natex, which generates about 150 direct manufacturing jobs and income for 700 families of rubber tappers (out of the 2000 in the CMR). However, even subsidized, rubber-tapping rents are not sufficient to outdo the ones from traditional agriculture, such as extensive cattle ranching that makes, on average, US$ 50 ha/year in the region (Bowman et al., 2012).

On the other hand, our results show that LSS could be promising especially in remote areas (*e.g.* Assis Brasil, Bujari, Porto Acre, Brasiléia) where latex cannot be delivered to Natex on a weekly basis (Fig. 9). Nevertheless, LL needs upfront investments to install small processing plants along with the guarantee of a stable minimum price, given that there have been disagreements between buyers and rubber tappers over prices (SEAPROF, 2008).

Sensitivity analyses demonstrated that price and productivity are the major factors influencing rents (Table S6, Fig. S9). In a context in which prices are mainly determined by the market, increasing productivity through developing rubber plantations on deforested lands is therefore the most plausible strategy to secure rubber production chain in Acre. In order to so, it is mandatory to use and improve clones already tolerant to diseases caused by the fungus *Microcyclus ulei* (Camargo et al., 2003). Even so, we recommend the development of plantations only in small groves adjacent to the forest or in association with agroforestry systems.

Another remaining issue is the cost of plantation formation and maintenance (C*form*). The costs of rubber plantations throughout the establishment stage can reach US$ 7.5 thousand per ha (Tables S4 and S5) with revenues exceeding expenses only during the stabilization phase. This is an upfront investment that a rubber tapper or small landowner could seldom afford. Therefore, even plantations will require government subsidies in order to expand throughout Southern Acre. Furthermore, EAA from plantations was positive only for LSS due to its higher market price compared with others products (Table 4).

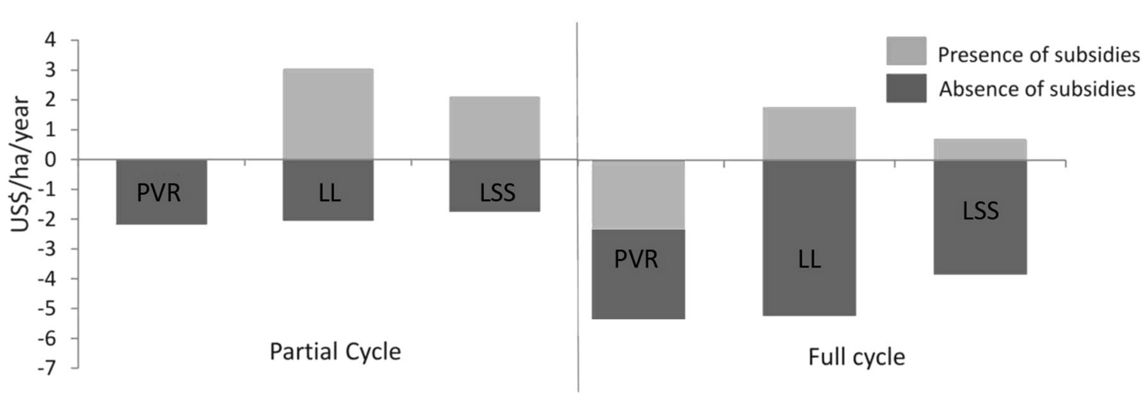

Fig. 7. Mean annual rents for Pressed Virgin Rubber (PVR), Liquid Latex (LL) and Liquid Smoked Sheet (LSS) in full cycle (FC) and partial cycles with (PS) and without subsidies (AS). If subsidized, LL and LSS deliver positive returns.

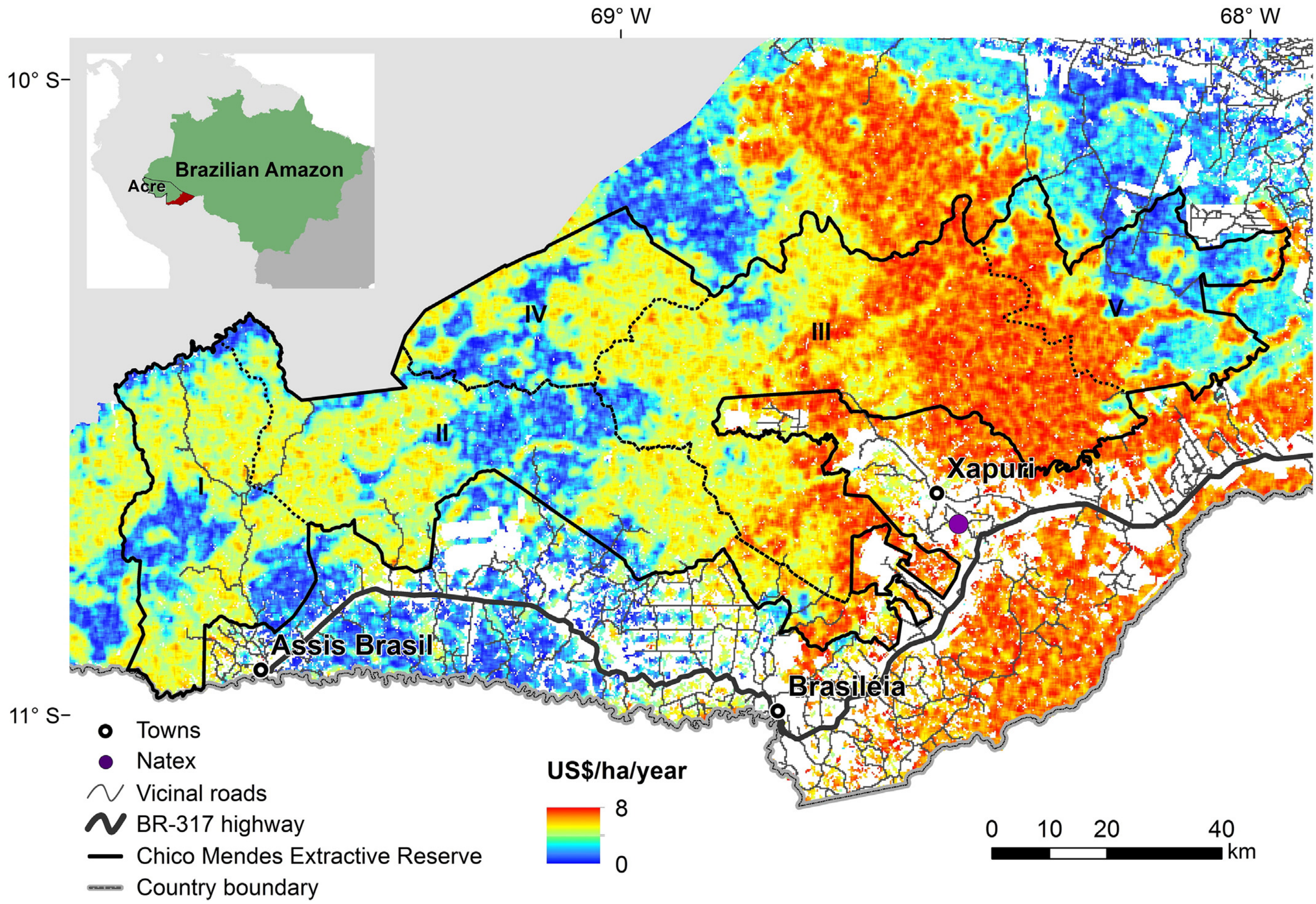

Fig. 8. EAA of Liquid Latex (LL) product from native forest. Local associations in the CMR are AMOPREAB (Zone I), AMOPREBE (Zone II), AMOPREX (Zone III), AMOPRESEMA (Zone IV), and AMOPRECARB (V Zone). Higher rents concentrate around Xapuri town where yields are higher and transportation costs lower.

In summary, latex if transformed into PVR, though the most common product, is not profitable in the current market circumstances (Fig. 8). On the other hand, LSS might be a viable alternative if extracted from rubber plantations (the EAA for LSS may reach US$ 270 ha/year (Fig. 10), but considerable investments are needed to attain these rents.

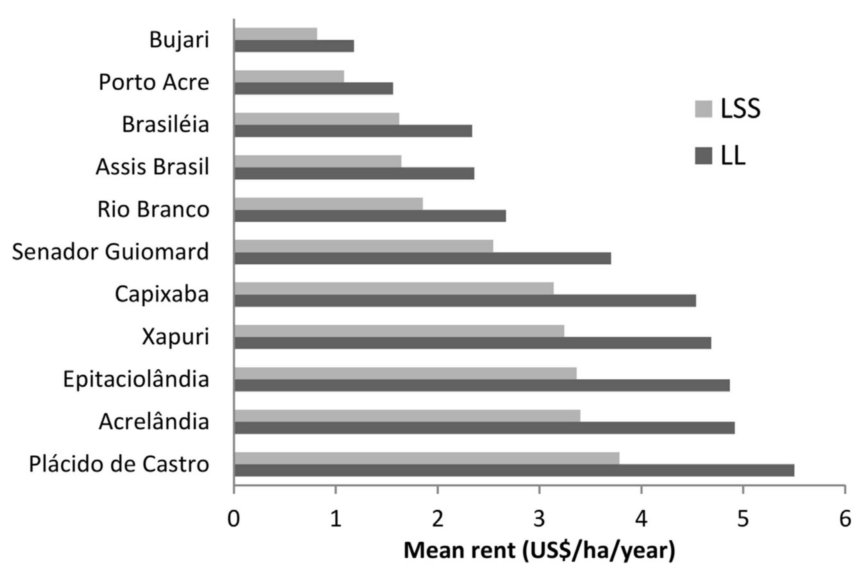

Fig. 9. Mean annual rents in PC-PS scenarios for (LL) and LSS from native rubber tree in municipalities of southeastern Acre. Municipalities near Natex factory present higher average rents, especially for LL.

Table 4
Mean EAA in US$/ha/year for Pressed Virgin Rubber (PVR), Liquid Latex (LL), and Liquid Smoked Sheet (LSS) from native rubber trees and plantations.

	Products		
	PVR	LL	LSS
Native forest	0.015	3.24	2.25
Rubber plantations*	−748	−124	270

* Excluding costs of plantation formation.

5. Discussion and Conclusions

Studies have suggested that the hyperdominance of rubber trees might relate to widespread forest management in pre-Columbian times, especially in southwestern Amazon (Hecht, 2013). Nevertheless, our results indicate a random distribution of *Hevea* spp. trees, rather than in highly concentrated groves such as the ones of Brazil nut trees (Nunes et al., 2012). Our estimates of mean density of 1.67 trees/ha is within the range of two previous studies (Table 3), though our yield of 2.26 l/ha is about half of that reported by Souza et al. (2011). Of the few studies on *Hevea* spp. trees density and yields published, ours has the largest number of sampled trees. In view of this fact, we suggest the use of the identified bioclimatic and environmental determinants of tree density and productivity to pinpoint other productive areas throughout the Amazon forests.

The cultural-ecological interlinks of the Amazon forest are fragile. Rubber trees – one of the hyperdominant trees species in the Amazon (ter Steege et al., 2013) – provide multiple environmental and cultural services: latex, carbon storage, soil and water retention, and rubber tapper (*seringueiro*) identity (Souza et al., 2011). In spite of this importance, the economically sustained management of *Hevea* spp. has proven challenging (Schroth et al., 2004). All of the three products derived from latex (PVR, LSS, LL) showed only marginal economic viability despite the policy of minimum price.

Production of rubber in the Amazon has steadily declined over the last twenty years (FNP, 2014; Embrapa, 2015). Today traditional rubber tappers' livelihoods are at risk of extinction. Narrow and highly hierarchical rubber market chains do not therefore work, even if subsidized and politically nurtured as a highly appraised “socio-biodiverse” asset (MMA, 2009). Hence, associations of the rubber tappers alongside current policy programs, though strong in Acre, cannot safeguard traditional livelihoods and cultural values of rubber tappers “*seringueiros*” *via* rubber extraction only (Gomes et al., 2012; Salisbury and Schmink, 2007).

So far, Amazon forests are producing undifferentiated raw rubber material mostly used in the pneumatic industry. As it is, the market has been unable to forge a virtuous circle for transforming latex in products with high aggregate value. Thus, answering the question of our study—“Is it possible to make rubber extraction ecologically and economically viable in the Amazon?”—, we provide evidence that it is indeed possible, but there is a need to reframe current policy options by including other approaches (Shone and Caviglia-Harris, 2006), such as technological niche innovations. Current knowledge indicates a variety of industrial applications for products from rubber trees. For example, *Hevea* spp. seeds are identified as having lubricant properties (Aravind et al., 2015). Additionally, leftovers from the pneumatic industry could

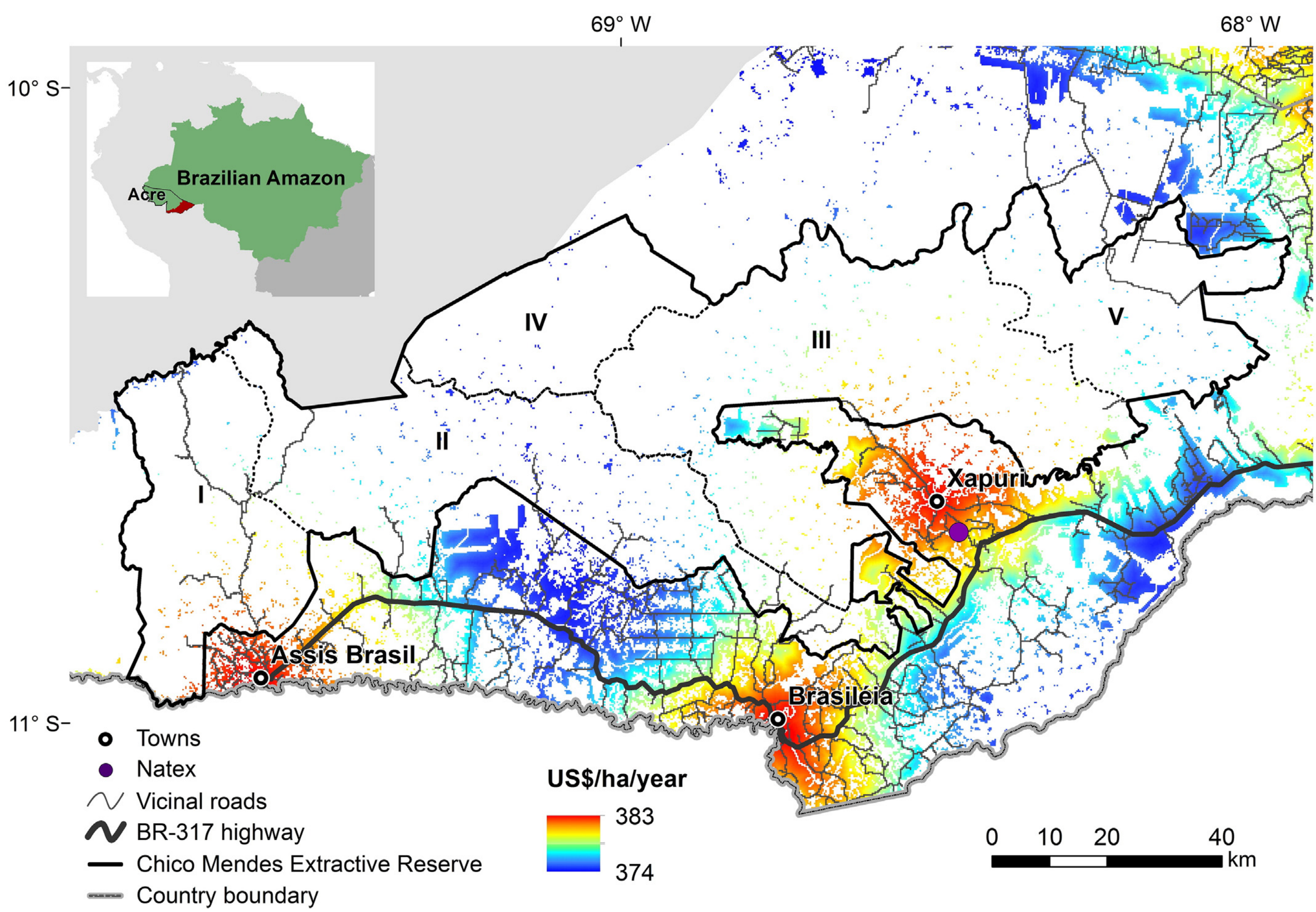

Fig. 10. Rents of LSS from plantations. Higher rents concentrate around towns where transportation costs are lower.

become an important resource for concrete paving (da Silva et al., 2015). In this vein, we argue that investments in technological developments could foster market niches, especially if prices are differentiated for native rubber products in the light of its environmental co-benefits. And this does not cost much, for example, to produce vulcanized rubber products with aggregate value, the equipment needed is relatively simple (a horizontal cylinder for incorporating new components into natural rubber together with a press machine). Even though relatively simple, those means for aggregating value to rubber are not disseminated in the Amazon.

Another issue is whether the "traditional rubber production chain", even if improved, will be able to promote such niche innovations considering that these new market arrangements will need to go well beyond the local partnerships already in place (Morsello, 2006; Morsello et al., 2014). This will demand engagement of international players, such as the Green Fund, the Amazon Fund, and resources from grant-making foundations. These private and public funds should not solely attempt to promote rubber extraction from native forests in Amazon through conventional market strategies. They should also target novel market niches that would demand higher quality rubber products, increasing as a result the price of native rubber (WWF, 2014). Higher taxation for rubber imports would be another strategy to increase prices of native rubber from the Amazon. Aside from being an artificial measure, this would be problematic because internal production does not meet the national demand. To this end, it is essential to promote agroforestry systems enriched with rubber trees in order to increase rubber yields and profitability. Agroforestry plantations have been promoted since 2007 in the Amazon (in Acre only from 2010). The trees planted by then are starting to produce latex in 2016. At the same time, disease-resistant clones have been developed (EMBRAPA, 2015) that promise to deliver more productivity.

Our study shows that an initial investment of US$ 2 million, plus the costs of a system for monitoring diseases including technical assistance (Tables S4 and S5), would be needed to develop rubber tree plantations on 30% of the deforested land (0.3 million ha) of the study region. Payments for ecosystem services from national and international funds raised by SISA could cover the costs for establishing rubber plantations, hence enabling the economic viability of the rubber chain in Acre (Bauch et al., 2014). In the current situation, PES schemes promoted *via* SISA are essential to secure rubber extraction in the Amazon while other market arrangements are not in place.

Another possibility directed to private agents is to bridge the interest of automobile industry giants for buying tires made from rubber collected from the native forests. Whereas rubber tapping in the Amazon is an ally of forest conservation, rubber from Asian plantations poses a threat both to Asian environment due to extensive conversion of native forests to homogenous plantations and to the Amazon region because of unfair competition. To this end, campaigns are needed to press the automobile industry about their reputational risk in promoting deforestation.

Although local PES projects are emerging in the Amazon, careful economic valuation of ecosystem services and willingness to accept payments are still rare. Spatially-explicit ecological modeling integrated with economic valuation (Rounsevell et al., 2012), such as the approach developed here, is therefore, of paramount importance not only to assess potential rents to beneficiaries (Schroth et al., 2004), but also to explore policy options that could harness sustainable development to conservation in the Amazon.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ecolecon.2016.12.035.

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