Contributions of fallow lands in the Brazilian Amazon to CO$_2$ balance, deforestation and the agrarian economy: Inequalities among competing land use trajectories

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Abstract

Development of regulations limiting greenhouse gas emissions is creating demands and new markets for land-based carbon sinks. Expectations of development of clean technologies and new sources of clean energy are affecting the supply side, creating opportunities for remuneration for sustainable development of natural resources. This paper presents a model developed to gain a realistic understanding of the heterogeneous roles of capoeira (fallow agricultural land) in land use dynamics and CO$_2$ balance in the Brazilian Amazon. The model estimates the areas and CO$_2$ balance of different types of capoeira in association with different farming activities and also monitors carbon intensity over time in the context of technological trajectories (distinct farming systems). Modeling with agricultural census data compared six different, competing technological trajectories of capoeira for changes in major land use variables and impacts on CO$_2$ balance from 1990 to 2011. Results revealed that: a) technological trajectories contribute differently to net emissions of CO$_2$, with livestock for meat enterprises being the highest net emitters and peasant agroforestry and plantation enterprises the lower emitters; b) carbon intensity tends to diminish over time because of increased weight of trajectories with lower carbon intensity, in combination with reduced carbon intensity of trajectories with higher carbon intensity; and c) for most trajectories, reuse of “old land” becomes increasingly more important for explaining the essence of agricultural dynamics, including CO$_2$ balance, than is deforestation for opening up new agricultural land. These results draw attention to the role of capoeiras in modernization and intensification of the agricultural sector through renovation of deforested land. The model allows evaluation of deforestation and CO$_2$ emissions as functions of the evolution of markets for agricultural products and of deforestation dynamics decoupled from those market fluctuations. The model points to the land market as a possible hypothetical determinant of deforestation; and has possible applications to development policies targeting the Brazilian Amazon.

1. Introduction

The advent of regulations limiting greenhouse gas emissions is creating demands for environmental assets, forming new markets for these assets. Expectations of development of clean technologies and new sources of clean energy and of decreases in costs of production of clean technologies are affecting the supply side,
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creating opportunities for remuneration for sustainable development of natural resources (Perez, 2012a, 2012b). These mutually dependent forces underlie the development concepts of a “green economy” and “green growth”, envisioning growth with lower carbon intensity and greater social equity (GCP, 2008; MI, 2009a; UNEP, 2011; World Bank, 2012).

This conceptual and timely context consolidates recognition of the importance of native forest biomes, especially tropical biomes, capable of both sequestering carbon (CO₂ sinks) and maintaining biodiversity (GCP, 2008; MI, 2009b). At the same time, agricultural systems are gaining recognition as carbon sources and sinks. These systems, formerly seen almost exclusively as CO₂ emitters and tending to reduce biodiversity, are now being reconsidered for their potential to sequester carbon and replenish biological complexity, due to the demand created by new markets for environmental assets. Agricultural systems that include perennial crops and agroforestry were first highlighted by the Stern Review (Stern, 2007: 603–621) and then in the REDD perspective (Nepstad et al., 2011, 2013; Moutinho et al., 2012) as potentially consistent with forest conservation aiming to reduce emissions. Perennial crop and agro–forestry systems offer potential to reduce pressures on forests, create mechanisms to absorb carbon, and increase the supply and thus decrease the costs of environmental assets, either stabilizing or reversing greenhouse gas emissions from agricultural land uses. Overall, this package of potential benefits could make mitigation strategies more cost effective.

This paper addresses two objectives related to climate change, economic dynamics and sustainable development of the Brazilian Amazon. First, this paper addresses the quantitative variables of land use dynamics by describing supply and demand of the emerging market for CO₂ net emissions, and documenting trends in carbon intensity of the rural economy and the underlying mechanisms of deforestation and land restoration. Second, it presents economic modelling to analyze the interaction between economic and natural resources, to distinguish the heterogeneity of economic agents and structures, and to evaluate inequalities in the existing economy in relation to the development of new markets.

Natural resources in the Brazilian Amazon are fundamental elements of its economy, and their transformation and use are entropic processes and should be understood and treated as such. An entropic conception of the economy allows for appropriate treatment of negentropic (i.e., negative entropic) dynamics and the anti–entropic property of living systems created by human endeavors, open to energy entry, as is the case explored here (Georgescu–Roegen, 1971: 193; Guha and Martinez–Alier, 1997).

Structural heterogeneity arises from asymmetrical access to both natural and social resources, mirroring the specific forms of environmental disturbance demonstrated in CO₂ emission balances. This matter has been discussed by Georgescu–Roegen in a lesser known work (1960) and emphatically by Guha and Martinez–Alier (1997) in a wider context. The matter has been discussed more recently in the Brazilian Amazon context (Costa, 2005, 2009a, 2009b, 2009c).

Finally, existing literature shows that the use of key natural resources often promotes social (Altvater, 1993) and regional (Bunker, 1985) inequalities. It is important to assess these processes in the Amazon while considering structural heterogeneity and the potential new markets.

The purpose of the four sections below is as follows: Section 2 discusses different forms of rural development in the Brazilian Amazon associated with different land use dynamics. Section 3 presents the fundamentals of a structural approach to the dynamics of rural economies and associated land use. Section 4 develops a methodology connecting these structures to emissions of CO₂, presenting an historical perspective (1990 to 2011) of this relationship. Section 5 discusses results, concluding by suggesting strategic paths for policy development.

2. From production systems to technological trajectories: The role of capoeiras

Forested areas can be incorporated into productive agricultural systems through logging activities or through extraction of non–timber forest products. Alternatively, forest can be transformed into agricultural lands and pasturelands, these subject to formation of capoeiras. Capoeiras are areas with secondary vegetation that are either temporarily or permanently removed from agricultural production. Agriculture can be based either on annual or perennial crops, with differing environmental impacts, particularly in regards to net CO₂ balance. Understanding the relationships between different land uses in forested areas, their co–existence and future trends is important for understanding the dynamics of the rural sector and entropic and negentropic processes.

Capoeiras are land areas in different stages of natural regeneration after having been radically altered by human activity. Capoeiras are an important component of the rural landscape in the Brazilian Amazon. The current official accounting of Amazon deforestation calculated by Monitoramento da Floresta Amazônica Brasileira por Satélite (PRODES), expressed as the gross deforestation rate, is the amount of area clear–cut in the Amazon[2]. This rate increases each year, expanding environmental liabilities. Because this measurement does not account for capoeiras, they constitute an invisible environmental asset.
Calculation of the net deforestation rate should consider capoeiras because areas that are either restored or undergoing regeneration have significant value. According to the census carried out in 1995, capoeiras in the northern region comprised an area of 4.5 million hectares. This corresponds to 8% of the entire Brazilian Amazon region and to 17% of the area in use either as natural or planted pasturelands, as permanent or temporary crops or as planted forests. Unfortunately, the latest Agricultural Census in 2006 does not present variables relating to all of these lands uses. Instead, the census treated land uses either as inseparable aggregates for the production of seasonal crops or, if old enough, as indivisible aggregates of forests (IBGE, 2006:35).

2.1 Different notions of capoeira and what they mean in rural development

At the core of the environmental debate about the Brazilian Amazon are two distinct views of capoeiras. The first one states that capoeiras are important only as an expression of the destruction of the forest by agriculture and as an indicator of the failure of agricultural activities. The second notion emphasizes the importance of capoeiras as a reforestation mechanism, restoring ecological properties of tropical forests. The first viewpoint presents capoeiras as a liability, while the second one views them as an asset.

One argument used to support the liability viewpoint is that capoeiras are associated with practices such as shifting cultivation. These practices are economically inefficient, leading to unsustainable use of natural resources. The use of capoeiras could only be justified by agents who are somehow excluded from other endeavors that have lower opportunity costs. These agents tend to move to the “speculative frontier” of the Brazilian Amazon. This is the position defended by Schneider (1995:15–32), followed by Margulis (2003).

Margulis further argues that the “speculative frontier” would generate a “consolidated frontier” economically sustainable only in areas with intermediate rainfall, suitable for large scale entrepreneurial ranching activities. According to Margulis, in areas of high humidity, where efficient ranching activities would fail, the only thing left after the inexorable failure of shifting cultivation would be abandoned lands and subsequent “capoeiras”. The Bragantina region located in northeastern Pará is a perfect example of this effect. In this region, Margulis, in agreement with Chomitz and Thomas (2000) and Schneider et al. (2000), notes: “the irrefutable evidence that few economical activities can withstand an intense rainfall and only logging activities make sense in these areas.” (Margulis, 2003:65). In summary, the new capoeiras are transitory elements of the landscape, since they are bound to an inefficient economy, whereas the old ones represent abandoned lands, the culmination of predicted inefficiency, thus being indicators of deterioration and incapacity.

The second notion, which highlights the importance of capoeiras associated with shifting cultivation as an asset, evolved from botanical, biological and agronomic research developed in the Bragantina region. Research shows that capoeiras have species diversity, complex root systems, and dense biomass, properties that are more apparent with less intensive and shorter periods of agriculture activity, and longer time elapsed since cessation of use (Vieira et al., 1996; Pereira and Vieira, 2001; Vielhauer et al., 1997; Sá et al., 2004; Davidson et al., 2004; Vieira and Gardner, 2012).

Economic research on the land use dynamics of the Bragantina region showed that there was no statistically significant loss of productivity in shifting cultivation. There was a drastic reduction in production during the 1930s and 1940s, followed by a period of productivity stabilization in the region, so that the cyclical profitability crisis observed from the 1950s onward was caused by socio–economic factors rather than by ecological ones (Hurtienne, 2001).

The Hurtienne study indicates that capoeiras linked to shifting cultivation are technologically consistent with agriculture because they were able to maintain their physical function in the agricultural systems. Capoeiras have great capacity for deterring leaching of soil nutrients and allowing agricultural production to continue in the same area over the long term. Following this reasoning, capoeiras could provide environmental services through carbon sequestration, biodiversity maintenance, and maintenance of the rainfall regime in addition to their role in traditional agricultural production. Thus, capoeiras show potential to address growing environmental and climate change concerns.

2.2 Towards a structural view of capoeira: Technological trajectories in the rural sector of the northern region

However, things are not that simple. If one looks closer at different sub–regions within a limited timeframe, one sees that shifting cultivation is actually dynamic. Various paths of agricultural intensification evolve out of shifting cultivation, either as adaptive solutions to crisis situations, or as induced changes produced by public policies and agricultural incentives (Costa, 2000). There is not one single, steady type of shifting cultivation. Land use dynamics often lead to dominant solutions characterized by diversified systems, where perennial and semi–perennial crops (orange, black pepper, passion fruit, etc.) tend to replace shifting cultivation (Costa, 1996, 1997). But, outcomes towards more simplified systems also occur, as do situations of failure and deterioration. In other regions of Pará, for example, as in southeastern Pará, small–scale beef cattle production
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evolved in association with shifting cultivation (Michelotti and Rodrigues, 2002; Solyno Sobrinho, 2002, 2013). Similar production systems have been verified empirically in other Brazilian Amazon sub-regions (Maciel, 2004; Costa and Inhetvin, 2013).

Even areas with high rainfall in northeastern Pará revealed efficient production systems based on botanical species specifically favored by this kind of microclimate. This is the case with different palm tree production systems. The açaí economy, for example, hitherto associated exclusively with peasant ancestral forms of agriculture in the region, expanded beyond local niche status to grow in importance nationally and even internationally. A series of studies conducted in the 1990s testified to this shift, clarifying many characteristics that are technological (Bovi, 2004), economic and social (Nascimento, 2004; Mourão, 2004; Costa, 2004; Lopes et al., 2005; Santana, 2004; Santana and Gomes, 2005) and ecological (Ohashi and Kageyama, 2004; Nogueira et al., 2004; Silva and Almeida, 2004). Another case involves large-scale entrepreneurial agriculture, specifically the advance of oil palm production (Costa, 2000).

Costa (2009a) pointed out that agricultural dynamics in the region actually followed different technological trajectories(3), depending on types of economic agents, whether peasants or enterprises(4), and available natural and institutional resources. Costa (2009a) highlighted the different conditions regarding access to financial capital resources and considers both tacit technical knowledge associated with institutions embodied in the culture – in family and social rules – and tested technological knowledge supported by science and technology organizations. Costa (2009a) analyzed data of the 1995 Agricultural Census(5), to identify six technological trajectories, three conducted by peasants and three by enterprises, and then characterize economic attributes of each trajectory (Costa, 2009a). Results of this analysis (Table 1) led to the following considerations: 1) intensification of peasant agriculture in northeastern of Pará was part of a pattern of technological solutions present in many sub-regions of the Brazilian Amazon – several production systems converging into technological trajectory T1, involving intensive agriculture of perennial crops and dairy production; 2) peasant producers of extractive açaí in northeastern Pará show many similarities with a wide range of peasants in other sub-regions of the North – indeed, as a whole they make up the technological trajectory T2, which guides technological convergence with agroforestry; 3) enterprises planting oil palm in northeastern Pará presented a similar technological pattern to those developing plantations elsewhere in a T5 trajectory, based on plantation of perennial crops; 4) cattle ranching on an enterprise basis is a unique trajectory, the T4, and the hypothesis that it is dominated by highly profitable and professional livestock production remains to be tested (see below, Section 6); 5) technological trajectory T4 is almost always adjacent to a T3 trajectory, the trajectory of peasants that also depends on meat production; and 6) some companies were also investing in reforestation in a T6 trajectory.

These findings indicate that an increase in both land area and duration of capoeiras may involve economic development. Therefore, old capoeiras, instead of being failed agricultural systems, may be associated with agricultural intensification, and hence with the adaptive dynamics of more efficient agricultural practices, which, because they require less land area, would displace more extensive systems.

These findings also indicate that capoeiras can be either a constituent part of shifting cultivation or a product of the denial of shifting cultivation. Thus, capoeiras can represent distinct ways of creating new vegetative cover which, in either case, is relevant to the way capoeiras contribute to CO₂ balance in the Brazilian Amazon.

Table 1. Features of technological trajectories in the rural sector, northern region, 1995

<table>
<thead>
<tr>
<th>Trajectory Characteristics</th>
<th>Trajectory</th>
<th>Total in 1995 Value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peasant production systems converging to:</td>
<td>Enterprise production systems converging to:</td>
</tr>
<tr>
<td></td>
<td>Intensive agriculture (perennial crops and/or dairy) (T1)</td>
<td>Agro-forestry (T2)</td>
</tr>
<tr>
<td>Production Units (N)</td>
<td>Number 171,292</td>
<td>130,593</td>
</tr>
<tr>
<td>%</td>
<td>39%</td>
<td>29%</td>
</tr>
<tr>
<td>Owned Land (L.)</td>
<td>Ha 9,314,347</td>
<td>3,011,825</td>
</tr>
<tr>
<td>%</td>
<td>17%</td>
<td>5%</td>
</tr>
<tr>
<td>Property Size Average (L/N)</td>
<td>N/L 54.47</td>
<td>23.04</td>
</tr>
<tr>
<td>Gross Production Value, price indexed to 2012</td>
<td>R$ 1,000.00</td>
<td>2,675,727</td>
</tr>
<tr>
<td>%</td>
<td>29%</td>
<td>18%</td>
</tr>
<tr>
<td>Workplaces</td>
<td>Number 717,449</td>
<td>498,280</td>
</tr>
<tr>
<td>%</td>
<td>38%</td>
<td>27%</td>
</tr>
</tbody>
</table>

*Source: Costa, 2009a
doi:10.12952/journal.elementa.000133.e001
2.3 Towards a structural view of capoeira

Dynamic economic settings form *capoeiras* in the Brazilian Amazon (Costa, 2009b). These settings are characterized by the diversity of economic agents, production means, and technological capabilities characterizing the trajectories presented above. The 1995 Agricultural Census presents two categories of secondary vegetation. They are: "Terras em Descanso" (fallow land), areas that are not used for up to four years, and "Terras Produtivas não Utilizadas" (unused agricultural lands), referring to areas not used for more than four years. These two kinds of land areas totaled 4.5 million hectares: 1.1 million hectares of land fallow for up to four years and 3.4 million hectares of land not used for more than four years.

2.3.1. *Capoeira*: Time and space

In establishing such a rigid limit for classifying lands – either a maximum of four years for the category of "fallow lands in agricultural use" or more than four years without use classified as "suitable but not used areas" – the Census induces several errors when one wishes to evaluate productions systems with *capoeiras*. Chomitz and Thomas (2000), for example, assumed that lands classified as "unused" by IBGE are in fact what this designation suggests: lands without utilization or function or abandoned lands. Thus, the extreme thesis of Chomitz and Thomas is that these lands, in total and generically, are indicators of both economically and ecologically non-sustainable production systems (Schneider et al., 2000). There is a good reason to question these conclusions, as presented below.

The land’s resting time is a variable that depends on external conditions. Ponte and Van Dyle (2000) proposed the time–space relation in fallow agricultural systems as:

\[
\frac{A}{A_a} = \frac{t}{u}
\]

The total area required to make the system work, represented by (A), is to the planted Area (Aa) as the complete cycle of fallow and use (t) is to the time that is possible to plant in the same area (u). If we consider that the system’s total need of land can be represented as the planted area (Aa) plus the falllow area (Ac), and the total time as the number of years that it is possible to plant in the same area (u) plus the number of years of development of *capoeira* until it is ready to accomplish its active function (n), then we could re-write the equation (1) as follows:

\[
\frac{A_a + A_c}{A_a} = \frac{u + n}{u} \Rightarrow \frac{A_a}{A_a} + \frac{A_c}{A_a} = \frac{n}{u} + 1
\]

And then,

\[
\frac{n}{u} = \frac{A_c}{A_a}
\]

If we assume additionally that

\[
A_c = \frac{P_c}{n \cdot P_c}
\]

as we understand that the area kept as *capoeira* is a result of the *capoeira’s* own production, Pc, this production can be a volume of biomass or a set of functions such as producing logs for fire, logs for mills, for construction, or more importantly to sequester carbon and to maintain biodiversity. The total P represents the availability of the *capoeira* to deliver any of the required functions in the production system, which is gradually achieved by annual incremental productivity per hectare with the average \( p_c \) during time \( n \), already defined.

Furthermore, we might consider that

\[
A_c = \frac{P_a}{u \cdot P_a}
\]

because this biomass volume or set of functions of the *capoeira* is required for agricultural production, Pa, derived from an average agricultural productivity hectare/year of \( p_a \) for a rotation cycle, also defined above, u.

In view of this, relation (2) could be rewritten as

\[
n = u \left( \frac{P_c}{n \cdot P_c} \right) \left( \frac{P_a}{u \cdot P_a} \right)^{1/2}
\]

and therefore as:

\[
n = u \left( \frac{P_a}{P_c} \cdot \frac{P_c}{P_a} \right)^{1/2} = u \left( \frac{P_a}{P_c} \right)^{1/2}
\]
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This relation (5) shows that for the same proportionality $P_c/P_a$, the age of the capoeira ($n$) varies directly with the productivity per unit of agricultural land and with the duration of planting in the same area. By the age of capoeira, we mean the time necessary for the capoeira to fulfill its potential. In addition, the proportion above is inversely related to the capoeira productivity. Thus, the duration “$n$” of the capoeira, as a dependent variable, can grow either as a result of incremental technological changes in agriculture (growth of $p_a$ and increase in $u$) or as a result of limitations to the productive capacity of the capoeira (decrease in $p_a$). These two drivers create a multiplicity of possible situations not captured by the categories of IBGE, so that, hypothetically, the “fallow lands” category could cover both productive capoeiras and capoeiras derived from agricultural systems in the process of intensification. Therefore, the different categories of capoeiras should be better understood and weighed before judging the resulting systems, be it in the economic or the ecological sense. To the extent that the environmental goods market becomes a reality, the need to better understand these different categories of capoeiras becomes more important.

2.3.2. Capoeira: Functions in production systems

Three types of decisions lead to the existence of capoeira. The first type is the use of a farming technique that requires fallow or resting time – in this case the capoeira is part of the production system within a technological trajectory. The function of the capoeira is to form biomass to be used in agriculture. In this case, capoeira is considered to be a production tool, as if it were a machine producing nitrogen, phosphorus, and other elements needed in agriculture. For this reason, we will call this capoeira, “capital–capoeira”. The fallow or resting time in this case is the processing time for the capital–capoeira. Nature and its laws governing ecosystem function determine the value of $P$ in formula (5). On the other hand, agricultural variables ($P/P_a, p_a$, and $u$) resultant from capoeira development as part of economic activities through market forces, determine the fallow time. In a sense, capoeira constitutes secondary vegetation with its duration determined by the logic of productive processes. Giving capoeiras the time they need, the extension of the capital–capoeira is endogenously contained, regulated by the extension of agricultural needs (refer to formula (2)). There is no limitation to repeating slash–and–burn or eventually slash–and–mulch operations for, in such a context, there is no structural limitation to forest regrowth, as in the cases evidenced by Johnson et al. (2001), Vieira (1996), Uhl (1987) and Uhl and Jordan (1984).

The second type of decision involves those that lead to the abandonment of areas that are unproductive (productivity approaches zero), in which agents use the same technological procedures throughout the trajectory and therefore, capoeiras result from this technology. A broader concept of technological trajectory is underscored here as composed of procedures that mediate labor and nature, also conditioned by intangible institutional factors. In this case, technology presupposes socially determined ownership relationships, which allows for continuous discard of land rendered unable to produce the usual goods of the technological trajectory. Thus, a capoeira is a result of the deterioration of soil–plant–climate relationships of a given area, as a result of technological impacts on soil, water, or air. Capoeiras can then be considered by economic agents as depreciated products, or scrap. We call these capoeiras either scrap–capoeiras or waste–capoeiras. In this case, as a result of the type of use that created the capoeiras, the $p_a$ and $P$ can be very small; therefore, time “$n$” in formula (5) can be correspondently very high, regardless of other conditions. The extent of “$n$” is inversely related to decrease in regrowth rates of secondary forest associated with previous land use procedures as those described by Zarin et al. (2005), Fearnside and Guimarães (1996), Uhl, Buschbacher, and Serrão (1988) and also by Nepstad, Uhl, and Serrão (1991). In these terms, capoeiras would not be endogenously contained. It is important to note however that the scrap–capoeiras are not always symptoms of economic failures of the activities that generate them. Scrap–capoeiras can be conditions to maintain and even increase profitability in the view of economic agents. As we will show in Section 4, this may be a major problem for development of policy measures that target sustainability.

The third type of decision is to use technologies that render the land in operation more productive, reducing the area needed to produce the same output. In this case, capoeiras are the result of innovation. This condition is observed when better technology is used, reducing the amount of land needed to produce the same output, for example, when cultivation of annual and semi–annual crops or plantation forests substitute shifting cultivation or extensive ranching (Costa, 1996, 1997). This capoeira is the result of use of new techniques that constitute capital–capoeira, as described above, making it obsolete, that is, without function in the production system. Even keeping its operational capability, capital–capoeira can be seen as an idle asset, constituting a mere stock. We designate this capoeira as reserve–capoeira. Due to conditions that form the reserve–capoeira, $P_c$ (production that depends on capoeira) in formula (5) is very small, approaching zero. Therefore, as is the case with the above–mentioned scrap–capoeiras, reserve–capoeira is not constrained by time to be transformed into agricultural elements. Nevertheless, there is a significant difference between these two kinds of capoeiras. For scrap–capoeiras, the fact that $p_a$ tends to zero makes $P_c$ (that is, the objective maturity of the capoeira) tend to zero as well. This indicates that this kind of capoeira can represent degradation of the environment and, ultimately, a first step towards desertification (refer to (3)). Conversely, the mechanism that creates reserve–capoeiras allows a $p_a$ different from zero, leading over time to correspondent levels of maturity and complexity and therefore, creating botanical areas similar to the original biome, the tropical forest.
3. Technological trajectories, land use and \textit{capoeira} formation

The structural view of capoeira presented above lead to two questions: what can be said about the proportions of the three types of capoeiras in the distinct technological trajectories? What can be said about their respective positions and functions, considering the specific rationale of the diverse technological trajectories in land use? To answer these questions we need to evaluate how each production system relates to capoeiras, how resources are allocated and what are the results of these interactions. In turn, this requires analyzing to what extent these relationships apply to each type of capoeira.

We consider, just like Arthur (1994: 13–32), that economic agents will make path–efficient decisions. That is, they will consider two technologies: \( z_j \), expressed as variable \( m \) (and whose outcome will be scrap–capoeira, for example), and \( z_k \), expressed as variable \( k \leq m \) (whose outcome will be reserve–capoeira, for example). At any instant \( t, z_j \) will be chosen with payoff \( \Pi \) if \( \Pi z_j (m) \geq \max \{ \Pi z_{j'} (m) \} \) for \( k \leq j \leq m \).

The economic agent’s decision is as consistent as the degree of the agent’s adherence to the postulate above. This means that, for any given agent, the amount of reserve–capoeira that is theoretically justifiable is the share of all types of capoeiras he possesses (his share \( A_c \)), which can be explained by using a calculation compatible with the path–efficient decision. Even though the decision is made beforehand, results are reflected in the year when the Census takes place, favoring activities and procedures that generate reserve–capoeira. The same happens with scrap–capoeira or capital–capoeira.

3.1 Types of capoeira and systems associated with them: Exploring the 1995 Census

This logic allows us to calculate all forms of capoeiras discussed herein. We start by discussing reserve–capoeiras. There are those originating from the transition from extensive agricultural systems to intensive agricultural systems and those originated from the transition from extensive cattle ranching activities to intensive cattle ranching activities. For the first group, let’s consider that areas used for temporary crops or ranching activities in a sub–area \( A \) are converted into areas for permanent crops or silviculture in a sub–area \( A^p \) and into capoeiras in another sub–area \( A^r \), so that

\[ A = A^r + A^p \]

(6)

Considering the path–efficient condition of one agent, within a context of constant income, the conversion will happen when

\[ A \cdot p \leq A^r \cdot p^r + A^p \cdot p^p \]

(7)

That is, the total area used in its prior function, multiplied by its profitability per unit area (\( p = \) proxy of payoff of shifting cultivation), is less than or equal to the yield of the area with permanent crops, multiplied by its profitability per unit area (\( p^r = \) proxy of payoff of systems with permanent crops), plus the area with capoeiras multiplied by the profitability of capoeira (\( p^c \)). Substituting \( A \) in (7) for its value in (6), considering further that the capoeira value is instantly irrelevant (\( p^c = 0 \)) and that the process will convert up to the limit, when both sides of the equation are equal, then:

\[
\frac{A^r + A^p}{A^p} = \frac{p^p}{p} \\
A^p + 1 = \frac{p^p}{p} \\
A^r = \frac{p^p}{p - 1} \cdot A^p
\]

(8)

We have the values for this variable in the Data1995Trajectories\textsuperscript{(9)}, so we can find the area of reserve–capoeira for each case. The caveat though, is that we cannot differentiate extensive cattle ranching from intensive cattle ranching. Therefore, we cannot specify formula (6) and we will not know the amount of reserve capoeira originating from intensification of cattle ranching activities (more about this point in Section 4.4).

The scrap–capoeiras (\( A^s \)) also have two components: the first derives from cattle ranching and the second from shifting cultivation. Those that derive from cattle ranching are determined by the amount of land required for stock breeding activities (\( A^s_{\text{poc}} \)) in the set of activities that generate capoeiras – ranching (\( A^s_{\text{poc}} \)) and temporary crops (\( A^s_{\text{tmp}} \)). This proportion is projected to areas with capoeiras that cannot be explained by the origin of reserve–capoeiras (\( A_c - A^r \)). Then,

\[ A^s = \frac{A^s_{\text{poc}} + A^s_{\text{tmp}}}{A^s_{\text{poc}} + A^s_{\text{tmp}}} \left( A_c - A^r \right) \]

(9)
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Based on the Data1995Trajectories, we can easily calculate the areas for each case. However, we will not be able to calculate the scrap–capoeiras generated by shifting cultivation.

Finally, we can obtain the capital–capoeiras \( (A_c^x) \) as the difference shown below:

\[
A_c^x = A_c - A_c^e - A_c^r
\]  

(10)

When we apply each of the relations above to Data1995Trajectories, we create new variables representing the three types of capoeiras in association with other variables defined by the technological trajectories. The results for the northern region are shown in Table 2 below.

The reserve–capoeiras lands associated with 0.73 million hectares of permanent crops expand to 1.4 million ha, of which 0.9 million hectares correspond to peasant trajectories (64%), mostly, as expected, to the T1 (more than one–third of total) and the remaining 0.5 million hectares (36%) to corporate trajectories, principally to the T4 (about 25% of total).

Lands that are in fact abandoned, probably useless, herein treated as scrap–capoeiras or waste–capoeiras, would be equivalent to 2.2 million hectares, associated with 24.4 million hectares of pasture. Of these, 30% are associated with peasant and 70% with enterprise trajectories. The T4 trajectory alone represents 64% of the total.

Capital–capoeiras that are active components of production systems based on 1.2 million hectares of temporary crops comprise 771,562 hectares, of which 80% are from peasant trajectories, principally T1 and T2.

### Table 2. Different types of land uses and capoeiras in the northern region by technological trajectory, 1995 (ha)*

<table>
<thead>
<tr>
<th>Trajectory</th>
<th>Areas with Annual Crops (A&lt;sub&gt;e&lt;/sub&gt;)</th>
<th>Capital–Capoeira (A&lt;sub&gt;c&lt;/sub&gt;)&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Areas with Perennial Crops (A&lt;sub&gt;r&lt;/sub&gt;)&lt;sup&gt;2&lt;/sup&gt;</th>
<th>Reserve–Capoeira (A&lt;sub&gt;x&lt;/sub&gt;)&lt;sup&gt;3&lt;/sup&gt;</th>
<th>Areas for ranching (A&lt;sub&gt;c&lt;/sub&gt;)&lt;sup&gt;4&lt;/sup&gt;</th>
<th>Scrap–capoeira (A&lt;sub&gt;c&lt;/sub&gt;)&lt;sup&gt;5&lt;/sup&gt;</th>
<th>Forests (A&lt;sub&gt;]&lt;sup&gt;6&lt;/sup&gt;)</th>
<th>Total (E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1 Peasant Intensive</td>
<td>409,682</td>
<td>256,504</td>
<td>365,053</td>
<td>543,337</td>
<td>2,552,542</td>
<td>224,141</td>
<td>4,978,505</td>
<td>9,329,764</td>
</tr>
<tr>
<td>T2 Peasant Agroforestry</td>
<td>195,131</td>
<td>254,831</td>
<td>110,835</td>
<td>146,607</td>
<td>371,445</td>
<td>77,517</td>
<td>1,853,055</td>
<td>3,009,421</td>
</tr>
<tr>
<td>T3 Peasant Pasture</td>
<td>286,703</td>
<td>99,906</td>
<td>66,704</td>
<td>205,485</td>
<td>2,895,682</td>
<td>315,611</td>
<td>6,808,168</td>
<td>9,329,764</td>
</tr>
<tr>
<td>T4 Enterprise Castle</td>
<td>242,510</td>
<td>-</td>
<td>86,246</td>
<td>376,092</td>
<td>16,665,541</td>
<td>1,421,081</td>
<td>12,100,528</td>
<td>20,391,998</td>
</tr>
<tr>
<td>T7 Enterprise Grains</td>
<td>75,362</td>
<td>-</td>
<td>30,884</td>
<td>21,880</td>
<td>1,183,597</td>
<td>125,961</td>
<td>2,203,670</td>
<td>2,203,670</td>
</tr>
<tr>
<td>T5 Enterprise Plantation</td>
<td>24,837</td>
<td>-</td>
<td>68,115</td>
<td>149,785</td>
<td>716,551</td>
<td>39,359</td>
<td>1,183,097</td>
<td>2,339,640</td>
</tr>
<tr>
<td>Total</td>
<td>1,234,225</td>
<td>611,241</td>
<td>727,837</td>
<td>1,443,186</td>
<td>24,385,319</td>
<td>2,038,670</td>
<td>23,928,034</td>
<td>54,533,512</td>
</tr>
</tbody>
</table>


<sup>1</sup>Using relationship (8) with the following restrictions: a) if \( A_e > A_c \) then \( A_c^e = A_c \); b) if \( A_e < 0 \) than \( A_c^e = 0 \); c) considering \( p \) as total net income per unit of area applied to ranching and to temporary crops, including capoeiras for a fallow period of six years and utilization of annual crops in the same area for two years.

<sup>2</sup>Using relationship (9) with the following restrictions: \( A_c^e > (A_c - A_e) \) then \( A_c^e = A_c - A_e \).

<sup>3</sup>Using relationship (10). All lands classified as used in the Census. This total is different from the property total that includes swamps and other unusable lands.

<sup>4</sup>This enterprise trajectory based on annual crops (soybeans and corn) was not significant in 1995, hence it does not appear in Table 1.

3.2 Digression on errors I: What underestimation means

There are three reasons why the calculations above are underestimated: first, we cannot calculate the effects of intensification of ranching activities – only the effects of agriculture and silviculture intensification. Therefore, the amount of reserve–capoeiras is lower than it should be considering intensification of ranching activities. Secondly, we cannot calculate the formation of scrap–capoeiras that originate from shifting–cultivation; again, the amount of scrap–capoeiras is lower than the actual. Thirdly, the amounts of underestimation presented above correspond to overestimation of the amounts of capital–capoeiras that are impossible to demonstrate.

What do these errors mean? The immediate answer is that the importance of these errors is bigger when intensification of ranching and reduction of rotation of capoeiras in shifting–cultivation is more relevant. On this topic, we have to consider the issues addressed below.

3.2.1 About intensification of ranching and importance of error in the reserve–capoeira

First, Figure 1 shows that cattle ranching does not intensify production if it has less than 4,300 animals. Only beyond that point, at a scale of 12,500 animals, is intensification observed. Secondly, the segment that is intensified at this scale represents only 1% of the activity.

In 1995, 48% of the herd originated from establishments with herds of up to 200 animals and an average of nineteen animals. This group of establishments manages cattle ranching as part of complex and diversified systems, dominantly managed by peasants. These workers are not specialized and stockbreeding represents only 24% of their total production. In addition, 76% of this amount comes from dairy products. These peasant–managed establishments have an intensification rate measured at 0.9 animals/ha – the highest of all classes of cattle ranching.
For the next four categories: 201 to 1,000 animals, on average, 392 animals; 1,001 to 3,000, on average 1,455 animals; 3,001 to 8,000, on average 4,318 animals; and over 8,000 animals with an average of 12,849 animals – the level of specialization increases, representing 80%, 89%, 94%, and 97% of total production of the establishments. The level of intensification of the establishments falls to 0.6 animals/ha and is almost constant in the next two categories: 0.59 and 0.56 animals/hectare. It is only in establishments with herds greater than 8,000 animals that this parameter increases significantly to 0.78 animals/hectare (Figure 1).

Profitability increases with the level of production, even though at decreasing rates: it jumps from R$1,509 to 2,503 from the first to the second levels of production; from the second to the third it increases to R$2,929 and at the last level it is R$2,995. For all ranching activities, profitability correlates positively with the level of production but it is indifferent to the intensity of land use. Therefore, the error in the formation of reserve–capoeira is irrelevant.

3.2.2. About formation of scrap–capoeira in shifting cultivation

It seems impossible to use the Census data for evaluating the necessary period for capoeira rotation associated with capoeiras originated from shifting–cultivation in the peasant trajectories and, therefore, for evaluating how they determine scrap–capoeira. However, the amount of scrap–capoeira originated from cattle ranching can be estimated. That is, fallow agricultural land is the first step in a trajectory that bifurcates into two systems: one of permanent crops that can be associated with production of dairy products[9] and one of cattle ranching. Many analysts call this bifurcation of trajectory, the “capoeira crisis”.

The formation of scrap–capoeiras resulting from ranching activities was captured by the model estimate, therefore the error associated with this underestimation is irrelevant.

4. Evolution of land use by trajectories: The model

Given the 1995 stocks of all types of capoeiras for each case in Data1995Trajectories, the evolution of land use as a whole under delimited technological trajectories was modeled before and after this date. The modeling approach considered the following:

a. The technical coefficients of the relations among all types of capoeiras and their bases are constant for each case. This means that technology remains the same at this level. For each trajectory as a whole in a defined geographical boundary, however, changes occur, resulting from the composition effects of changing weights of different production systems.

b. The IBGE estimates[10] for annual evolution of planted areas with permanent and temporary crops and the expansion of cattle ranching for the northern region are robust indexes for the evolution of the rise of capoeiras. The different rate of these indexes for different geographical delimitations determines changes in the weights mentioned above, giving the model its complex feature.

Thus:

\[ F'_{01} = A'_{01} + A'_{02} = A'_{0195} \cdot I_{01} \left( 1 + \frac{A^C_{1995}}{A^T_{1995}} \right) \]  \hspace{1cm} (11)

\[ F'_{01} = A'_{01} + A'_{02} = A'_{0195} \cdot I_{01} \left( 1 + \frac{A^R_{1995}}{A^T_{1995}} \right) \]  \hspace{1cm} (12)
Agrarian dynamic, CO₂ balance and deforestation in Amazon

\[
F_{\text{rec}}\left(t_{0}\right) = A_{\text{rec}}\left(t_{0}\right) + A_{\text{rec}}^S = A_{\text{rec}}\left(t_{0}\right) + 1 + \frac{A_{1998}^T}{A_{1998}^0}
\]

(13)

\(F\) is the dominant productive basis, \(I\) the index of the dominant basis – notation \((T)\) meaning temporary crops (index composed of areas planted to pineapple, cotton, peanuts, rice, sweet potato, sugar cane, beans, tobacco, jute, mallow, cassava, watermelon, melon, corn, soybeans, sorghum, and tomato); \((P)\) permanent crops (areas planted to avocado, banana, rubber, cacao, coffee, cashew nut, coconut, Africa oil palm, guava, guarana, orange, lime, papaya, mango, passion fruit, palm, black pepper, tangerine, urucum \((Bixa orellana)\) – sources for \(T\) and \(P\) (IBGE, PAM, several years; see footnote 10) and \((Pec)\) cattle ranching (size of cattle herd – source IBGE, PPM several years; see footnote 10) – expressed as indexes for any year \((t)\) between 1989 and 2011.

Assuming that all agrarian development was based on the same structure of ownership – that is, all areas appropriated in 1995 were already part of the assets of the agents since the beginning of the 1990s, and continued being the land base on which they operated up to 2011 – making \(E\) a constant, we have:

\[A_{\text{rec}}\left(t_{0}\right) = F_{1998} - F_{t_{0}} - F_{t_{0}} - F_{t_{0}}
\]

(14)

With this, the evolution of the principal elements of land-use areas are reconstructed, as presented in Table S1.

A comparison between the estimated values of key variables with the 2006 Census results shows the accuracy of the model (see Table 3; the last column shows the degree of over or underestimation). For agricultural production, the model estimate for the year 2006 for temporary and perennial crops corresponds to, respectively, 98% and 87% of what was found in the Census for the same variable that year. Associated with these crops, the model found 1.04 million hectares of capital-capoeiras and 2.3 million hectares of reserve-capoeiras. As already explained, these variables are not in the 2006 census. For the total area of pasture in use the estimated value exceeds only 1% of the value found in the Census. On the other hand, the 2006 Census raised the area of “degraded pastures”, which is equivalent to the variable scrap-capoeiras estimated by the model: the value of the latter corresponds to 88% of the former. Finally, the estimated value of forests exceeds by only 2% the value found in the Census. In turn, the 2006 Census measured the area of “agroforestry systems” including managed forests for the production of non-timber products. The model does not calculate these areas separately, including them in the estimated value of “forests”.

Table 3. Comparison of values estimated by the model and 2006 Census figures of the main land use variables

<table>
<thead>
<tr>
<th>Land Use</th>
<th>2006 Census (ha) (A)</th>
<th>2006 Estimate (ha) (B)</th>
<th>Estimate/Census Value (B)/(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Crops</td>
<td>1,993,725</td>
<td>1,947,761</td>
<td>0.98</td>
</tr>
<tr>
<td>Capital-Capoeiras</td>
<td>-</td>
<td>1,040,606</td>
<td>-</td>
</tr>
<tr>
<td>Perennial Crops</td>
<td>1,863,160</td>
<td>1,629,230</td>
<td>0.87</td>
</tr>
<tr>
<td>Reserve-Capoeiras</td>
<td>-</td>
<td>2,345,675</td>
<td>-</td>
</tr>
<tr>
<td>Pastures</td>
<td>25,078,328</td>
<td>25,264,571</td>
<td>1.01</td>
</tr>
<tr>
<td>Scrap-Capoeiras (Degraded Pastures)</td>
<td>2,295,351</td>
<td>2,028,478</td>
<td>0.88</td>
</tr>
<tr>
<td>Agroforestry Systems</td>
<td>1,283,287</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Forest</td>
<td>21,057,761</td>
<td>21,518,196</td>
<td>1.02</td>
</tr>
<tr>
<td>Other Uses</td>
<td>1,964,152</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>55,535,764</td>
<td>55,774,517</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Sources: IBGE Census 2006. Table S1.

doi:10.12952/journal.elementa.000133.t003

4.1 Production systems, deforestation and restoration

Two important concepts for the analysis that follows can be established here. The concept of deforestation associated with agricultural activity and derivable from its statistics is expressed by a variable named Deforested Area Required by the Level of Economic Activity \((D_{1998}^N)\), as follow:

\[D_{1998}^N = F_{1998} + F_{1998}^P + F_{1998}^\text{rec}
\]

(15)

Agricultural uses, pastures and capoeiras compose this variable, from which annual deforestation rates can be derived, comparable to PRODES deforestation rates.
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Indeed, \( d_{u(t+1)}^{A} - d_{u(t)}^{A} \) is additional deforested area required by economic activity in year \( t+1 \). As economic activity fluctuates depending on circumstances, the variable can eventually be negative. This, of course, does not mean that past deforestation was physically reduced, though it means certainly that the rate of deforestation driven by economic activity should tend to zero: i.e. economic activity should not require additional deforested area that year. It means as well that given the situation, some sort of capoeira may be formed, that will be captured by the model in the proper manner.

The other important concept worth introducing here is Successional Area with Permanent Cover \((S_{l(t)}^{A})\), which amounts to:

\[
S_{l(t)}^{A} = A_{l(t)}^{C} + A_{l(t)}^{P} + A_{l(t)}^{O} + A_{l(t)}^{E} \tag{16}
\]

### 4.2 Production systems and CO₂ sequestration

The parameters of emission and carbon sequestration based on Fearnside (2000) and Nepstad et al. (1999) are applied, as follows:\(^{(11)}\):

\[
F_{t}^{e} = C \cdot (A_{u(t)}^{e} - A_{u(t-1)}^{e}) + \left[ \frac{C}{15} \cdot \frac{\partial A_{u(t)}^{e}}{\partial t} \right] = C \cdot (A_{u(t)}^{e} - A_{u(t-1)}^{e}) + \frac{C}{15} \cdot A_{l(t)}^{C} \tag{17}
\]

\[
F_{t}^{T} = 9 \cdot A_{u(t)}^{e} + \frac{C}{15} \cdot A_{l(t)}^{C} \tag{18}
\]

\[
F_{t}^{T} = 0 \tag{19}
\]

\[
F_{t}^{P} = \frac{C}{20} \cdot A_{u(t)}^{P} + \frac{C}{15} \cdot A_{l(t)}^{C} \tag{20}
\]

\[
F_{t}^{P} = C \cdot (A_{u(t)}^{P} - A_{u(t-1)}^{P}) + 6 \cdot A_{l(t)}^{P} \tag{21}
\]

\[
F_{t}^{P} = 6 \cdot A_{u(t)}^{P} + \frac{C}{60} \cdot A_{l(t)}^{C} \tag{22}
\]

\[
F_{t}^{Mata} = 0.45 \cdot A_{l(t)}^{Mata} \tag{23}
\]

\[
E_{t}^{T} = (F_{t}^{T} - F_{t}^{T}) + (F_{t}^{P} - F_{t}^{P}) + (F_{t}^{P} - F_{t}^{P}) - (F_{t}^{P} - F_{t}^{P}) \tag{24}
\]

In equations (17) to (24), \( C \) represents the average stock of carbon in one hectare of the Amazon forest (200 t/ha, according to the sources represented here), \( F \) is the terms of net balance of emission (+)/sequestration (−) in carbon in different activities and \( E \) is the final balance of the analyzed structure (production unit, technological trajectory or sector) in each year \( t \).

The denominators of \( C \) are the number of years required by vegetation of the variable in question to achieve the forest level of carbon reserve. The results will be absorption/release levels in tons of carbon/ha/year. The denominator of \( capital\ capoeira \) is the fallow period. The results are the volume of \( capoeira \) initiated in year \( t \). The other parameters (9 in equation (18), 6 in equations (21) and (22), and 0.45 in equation (23)) derive from the two mentioned sources of emission/sequestration in t/ha/year relative to the parametric variable.

The emission balances by year, from 1990 to 2011, and their emission and sequestration components by technological trajectories are presented in Table S2. In the next section, these results will be discussed in terms of the question posed initially. For now, it is worth recalling that the balance value for 1990, of 0.206 Gt of CO₂ equivalent (see Table S2, balance from year 1991, 4,359,067,632 t, minus the balance from 1990, 4,153,041,395 t of CO₂ divided by \( 10^9 \)), is very different from, though compatible with Fearnside’s balance of 0.324–0.328 Gt of CO₂ equivalent. This difference is due to the size of the region described. Our calculation accounts for the northern region, while Fearnside’s accounts for the Legal Amazon (Fearnside, 2000, Table 6) that includes Mato Grosso and parts of Maranhão State in addition to the seven states of the northern region. The other factor that can explain the difference, even though on a smaller scale, is that the model does not account for logging activities as does Fearnside.

### 4.3 Production systems and gross production value

The Gross Production Value (GPV) of the production systems in year \( t \) \((Y)\) is calculated by the following equation:

\[
Y_{t} = \bar{r}_{t} \cdot l_{t} \cdot p_{t} \cdot A_{u(t)}^{e} + \bar{r}_{t} \cdot l_{t} \cdot p_{t} \cdot A_{u(t)}^{P} + \bar{r}_{t} \cdot l_{t} \cdot p_{t} \cdot A_{u(t)}^{O} + \bar{r}_{t} \cdot l_{t} \cdot p_{t} \cdot A_{u(t)}^{E} + \bar{r}_{t} \cdot l_{t} \cdot p_{t} \cdot p_{Pec} \cdot A_{u(t)}^{P} + \bar{r}_{t} \cdot l_{t} \cdot p_{t} \cdot p_{Mata} \cdot A_{u(t)}^{Mata} \tag{28}
\]

In equation (28), \( \bar{r} \) is the monetary value of production per unit area of the designated activity in the year of the Census (IBGE, 1995 Agricultural Census), for a pertinent geographical area. If \( \bar{r} \) is marked by \( T \), it refers to the overall value of the production of temporary crops, vegetables and other horticulture products, chickens and small and medium-sized animals; if it is marked by \( P \), it results in the production value of
permanent crops; if by Pec, it refers to the value of livestock products; if by Mata, it refers to extractive production from the forest. The terms \( i \) and \( p \), in turn, are annual variation indices of, respectively, physical productivity and prices of each set of products mentioned above (source IBGE: PAM, PEM, PPM, PHM; also FNP: Agrianual and Anualpec; and IPEADATA; see footnote 10). Results are given in Table S3.

4.4 Digression on errors II: Is it possible to assume that cattle ranching did not intensify over time?

In estimates presented above, it is assumed that technological parameters are constant. This is a fact widely accepted for both temporary and permanent crops in the northern region. However, we have to discuss whether this assumption is valid for cattle ranching. Margulis’ (2003, op. cit.) work shows a tendency to form a “consolidated frontier” in the Amazon, based on professional and profitable cattle ranching activities that exist in this region. Such an assertion suggests that cattle ranching activities evolve by intensifying the use of land. Nevertheless, what it shows is that ranching in the Amazon is a business activity, in the sense that it is profitable. However, it does not indicate that the use of land is intensified. On the contrary, it seems that extensive use of the land is a condition for profitability of the activity. This was demonstrated in section 4.4 for the year 1995. Based on the above assumptions, what happens in more recent years, including the most recent Census, can be evaluated.

In the period from 2002 to 2007, FNP Consultants researched annual cost and profitability of cattle ranching activities. The research encompassed several ranches in five regions of the North region: two in Pará, one in Rondônia, and two in Tocantins, distinguishing three levels of technological intensity (extensive, semi-intensive and intensive) and two levels of production – 500 and 5,000 animals. The study presented two indicators of profitability: payback expressed as profitability divided by total assets and profitability per unit area. Figure 2 below shows the average values obtained for the Brazilian Amazon for the period. Based on information in this figure, the following conclusions can be reached:

- **Level 500 animals** – Profitability in a more extensive level (0.73 animals/ha) is highest for the production units with an average of 500 animals;
- **Level 500 animals** – Based on both indicators, as the technology level increases to 0.98 animals/ha, the smaller production units (average of 500 animals) are less efficient, reaching negative profitability at a higher technological level (1.06 animals/ha).
- **Level 5,000 animals** – The profitability of the lower technological level (0.71 animals/ha) on a larger scale of production (average of 5,000 animals) is five times higher than that of a lower scale of production (average of 5,000 animals) with the same technological level.
- **Level 5,000 animals** – As technological level increases, profitability per unit area also increases. This is true despite the fact that higher technological intensity does not imply higher support capacity per unit area: from 0.71 animals/ha at the extensive level, to 1.1 animals/ha at the semi-intensive level and to 0.91 animals/ha at the highest level of technological intensity.

These results, compatible with those of the Census, indicate that intensification of cattle ranching for the meat market is not path-efficient at a low scale. Intensification does not produce a consistent trajectory. If the establishments with an average herd of 500 animals switched to more intensive technology their profitability would be reduced. If they intensified further, the profitability would decrease at higher rates.

However, for a lower intensity of 0.7 animals/ha, profitability increases with level of production. As shown in Figure 2, considering point A where the profitability per unit area is R$13.10 for a scale of 500 animals and intensity of 0.7 animals/ha; and considering point B where profitability is R$68.10, for a scale of 5,000 animals, and the same intensity of 0.7 animals/ha, the angular coefficient of a line that goes from A to B against the scale axis would be 0.012. This means that for every additional 100 animals, the profitability increases R$1.20 – a 9.1% increase in profitability.

In summary, cattle ranching activities in the Brazilian Amazon combine technological solutions with the extensive use of land that generates *scrap*–*capoeiras*, and the profitability grows with the scale of business operations.

Technological developments in this area are focused on the herds rather than on pastureland conditions. The technological advances internalize institutionalized credit, especially credits from FNO that are vital for the scale of production. This situation increases tension that leads to the acquisition of new lands.
5. Discussion of results

5.1 Agricultural economy and CO$_2$ balance

The agricultural economy of the Brazilian Amazon constitutes both a physical and a social system, in other words, a social system that is part of a broader system regulated by physical and natural laws. The social system reproduces itself through entropic processes transforming highly structured forest material into production means, like agricultural and cattle ranching systems, and waste (CO$_2$, energy dissipated and part of scrap—capoeiras when the land eventually becomes degraded). In the agricultural systems and in the capoeiras, the processes of CO$_2$ absorption are negative entropic factors due to their potential ability to neutralize damaging effects of emissions. Emissions that are not neutralized are an indicator of produced entropy and, thus, an objective measure of the need for sustainability. This need, that is a condition for permanence of society, can be considered the foundation of the market for environmental assets.

The Gross Production Value (GPV: total physical production times current prices indexed to constant 2012 prices) is a proxy for measurement of the northern region agricultural economy, which increased from 1990 to 2011 at a rate of 4.6% pa, reaching the amount of R$ 28.1 billion at the end of the period (Figure 3). In turn, the net measure of carbon stored (accumulated annual difference emission–sequestration) by the agricultural economy in the northern region is an indicator of its contribution to global entropy. Figure 3 shows the evolution of the orders of magnitude for the total (considering the status quo of the sector in 1990) and the analyzed period. The figure shows that the accumulated amount of CO$_2$ emissions increased about 1.5 times, from 4.2 to 6.3 Gt in 21 years, while increasing ten fold, from 0.206 Gt in the first year to 2.125 Gt in the last year (about 34% of total), if one considers just the accumulated amount for the period.
5.2 The structural foundation of the agricultural economy and its CO$_2$ balance

The impressive growth of net balance of CO$_2$ shown above at 2.1% pa (Figure 3), is determined mainly by the emissions vector, which underwent growth at a rate of 2.0% per year. However, it is important to note that the sequestration vector also evolves rapidly at an average rate of 1.6% pa (Table S2).

Technological trajectories contribute differently to the agricultural economy of the North region and to its CO$_2$ net balance (emissions minus sequestration). The differences should be considered a proxy for social inequalities in using key natural resources. Over time, with a share higher than 50% of all CO$_2$ net emissions, the technological trajectory T4 (enterprise – livestock for meat), for example, is the largest net emitter of CO$_2$. To the extent that its share in the agricultural economy constitutes approximately 22% of the total, its weight as a user of environmental assets is about two times its social contribution (for these and following results see Figures 4 and 5). In turn, at the other extreme, T2 (peasant – agroforestry) contributes to approximately 5% of CO$_2$ net balance and to about 22% of the agricultural economy: its contribution as a CO$_2$ emitter is 25% of its economic and social importance. The T1 trajectory (peasant – intensive) contributes more than 20% of the CO$_2$ net balance, but contributes with not less than 30% to the economy. The increasingly significant T7 (enterprise – annual crops), constituting 9% of the economy, participates nonetheless with about 15% of the net CO$_2$ balance. This is essentially the same share as the T3 trajectory (peasant – livestock for meat), which however, contributes to the economy with 17%. The T5 trajectory (enterprise – plantation) exhibits on average a very low level of about 5% of net CO$_2$ balance – basically the same level as its economic importance.
5.3 CO\textsubscript{2} balance – fundamentals of emission and sequestration

It is important to underline the specific ways that both the positive and negative effects of net CO\textsubscript{2} balances evolve for the technological trajectories. Figure 6 shows the ratio of CO\textsubscript{2} sequestration and emission (S/E) over time for each trajectory. This ratio provides a measure of the respective potential of the given trajectories to supply carbon sinks, an environmental service. If regarding a specific trajectory S/E happens to be greater than 1, it means that that the trajectory’s relative contribution to the reduction in CO\textsubscript{2} balance is S/E times greater than its relative contribution to CO\textsubscript{2} emission increase. If it is less than 1, it contributes relatively to reducing only the fraction S/E of its relative contribution to increasing the CO\textsubscript{2} balance. If approximately equal to 1, its contribution to both sides of the balance is equivalent. The trajectories that presented values of S/E greater than 1 were T2 (peasant – agroforestry), whose relative participation in sequestration is 2.5 times its participation in emissions, with a slight downward trend (at 0.3% pa); the T5 (enterprise – plantation) and the T1 (peasant – intensive agriculture) trajectories, both with a declining trend, the latter much more than the first. S/E values less than 1 were presented by T4 (enterprise – livestock for meat) and T7 (enterprise – annual crops), the first trajectory with a declining trend, the latter with an increasing trend.

5.4 The agricultural economy and its cycles

Examination of growth rates of accumulated net CO\textsubscript{2} emissions from the agricultural economy identified, four very well defined phases (Figure 7): in the first phase emissions decrease up to 1995 and stay level for several years; in the second emissions rise from this point up to 2004 when they reach the highest all time level; from there emissions go down in a third phase up to 2007 and from there increase in a fourth and final phase. The variations correspond to fluctuations in the agricultural economy in the region (Figure 8), which shows consistent negative growth rates in the first phase, positive growth in the second phase, consistent decline in the third phase, and rise in gross production value in the fourth phase.

Figure 5

Shares of technological trajectory in Gross Production Value (GPV), 1990 to 2011.

Different technological trajectories contribute differently to the agricultural economy of the North region. The share of the T4 trajectory (enterprise – livestock for meat) in the agricultural economy (y-axis; GPV) constitutes approximately 22% of the total, and its weight as a user of environmental assets is about two times its social contribution. At the other extreme, T2 (peasant – agroforestry) contributes to about 22% of the rural economy, about four times its contribution as a CO\textsubscript{2} emitter. The T1 trajectory (peasant – intensive agriculture) contributes 30% of the agricultural economy, 1.5 times its participation as a CO\textsubscript{2} emitter. In turn, the T7 trajectory (enterprise – annual crops), constituting 9% of the economy, is 1.7 times greater as a CO\textsubscript{2} emitter. The T3 trajectory (peasant – livestock for meat) contributes to 17% of the economy, 1.2 times its participation in net CO\textsubscript{2} balance. The participation of the T5 trajectory (enterprise – plantation) in the economy, about 5%, is basically the same level as its contribution to CO\textsubscript{2} emissions. Source: Table S2 and Table S3.

doi: 10.12952/journal.elementa.000133

Figure 6

Ratios of CO\textsubscript{2} Sequestration/ Emission (S/E) by technological trajectory, 1990 to 2005.

Regarding a specific trajectory, the relationship between its relative shares of CO\textsubscript{2} sequestration and emissions is a ratio S/E. If S/E is greater than 1, it means that the trajectory’s relative contribution to the reduction in net CO\textsubscript{2} balance is S/E times greater than its relative contribution to CO\textsubscript{2} emission increase. If the ratio is less than 1, it means that it contributes to reducing only the fraction S/E of its relative contribution to increasing the net CO\textsubscript{2} balance. If the ratio is approximately equal to 1, the contribution to both sides of the balance is equivalent. The trajectories that showed values of S/E greater than 1 were notably T2 (peasant – agroforestry), with a slight downward trend, T5 (enterprise – plantation) and T1 (peasant – intensive agriculture), trajectories with declining trends. S/E values less than 1 are seen in T4 (enterprise – livestock for meat) and T7 (enterprise – annual crops), the first trajectory with a declining trend and the latter with an increasing trend. Source: Table S2.

doi: 10.12952/journal.elementa.000133.006
5.5 Carbon intensity of the agricultural economy and trajectory concurrence

The ratio of net CO₂ emissions to gross value of total production expresses the carbon intensity of the agricultural economy in question, meaning how much carbon it requires to generate a unit of value. From another perspective, it is a cost indicator of entropy, or what society pays for each unit of currency generated by the productive activities in the sector. Figure 9 shows the evolution of this relationship during the period studied. It highlights different carbon intensity evolution regimes associated with the phases previously presented: in the first stage there is a regime of high carbon, in which the CI almost tripled; from there it shows a low intensity regime, leading to a sharply falling trend in the second phase; the third phase appears...
as a strong fluctuation in the direction of another high–carbon regime, altered with the start of the fourth phase, when it seems to reconfirm the downward trend of the second period. Each phase follows its own track, in which technological trajectories play a specific role, representing different periods of time and contexts of markets, policies and institutions.

In the first phase, the overall picture is one of crisis: as a whole, the GPV of the economy falls at an average rate of 12.6% per annum (for this and following results see Figure 10). The GPV of all trajectories decrease, except for T4 (enterprise – livestock for meat), which grows at a high rate of 4.5% pa. However, the technical basis of its expansion was such that it led to growth in net emissions of CO$_2$ at an even higher average rate of about 6.7% per year. The various defense mechanisms of the other technological trajectories confronting the crisis in the period produced positive rates of net CO$_2$ emissions, however, with the exception of T1 (peasant – intensive agriculture), lower than that of T4. The economic driving force of T4 seems to have been the favorable cycle of live cattle prices – an internalized factor in the model in variable $r$ in the relation (28). It should be noted, however, that institutional aspects favored the T4 trajectory since this period was an FNO phase characterized by marked orientation in favor of cattle ranchers in the Amazon (see Costa, 2005). The fact is that the T4 trajectory, in its most traditional form, indelibly characterized this phase as one in which the carbon intensity of the agricultural economy in the Amazon grew 2.5 times.

In the second phase, the agricultural economy grew at 10% per year and the net emission of CO$_2$ at a much lower rate of 1.7% pa. In this stage, all trajectories expand, with net emission rates of CO$_2$ increasing less than their GVP; global growth is driven mainly by peasant trajectories T1 (peasant – intensive agriculture) and T2 (peasant – agroforestry) with high weights in the sector and also with high S/E; but the not yet relevant enterprise trajectories T5 (enterprise – plantation) and T7 (enterprise – annual crops) boosted growth as well. Purely economic reasons can be raised to clarify this situation: key–products of peasant trajectories had increased prices, such as black pepper, milk and açai. The first of these products, black pepper, no longer a traditional commodity in the region, was driven by an increase in international prices. The latter, açai, was driven by higher prices formed in the wake of a new industrialization process associated with the build–up of national and international product markets (Costa et al., 2006). The expansion of T7 has to do with stimuli associated with soybean price growth and that of other grains. However, it is also associated with T4 (enterprise – livestock for meat) resource shifts, following tension in the relative prices of products accounted for by two paths: T4 product prices stagnating or in decline and product prices of T7 on the rise. Despite the clear influence of these purely economic factors, here too one must remember the importance of institutional changes in FNO, since precisely at this stage peasant trajectories, particularly T1 (peasant – intensive agriculture) and T3 (peasant – livestock for meat), but also the enterprise trajectory T5 (enterprise – plantation), gained expression in development policies, and credit resources shifted from T4 to T7. It is important to note, finally, that the carbon intensity of agricultural production at end of the period represented just 70% of what it was at the beginning.
The third phase is characterized by reduction in the economy to ~5% per year, the result of substantial reductions in the GPV of the T7, T1 and T4 trajectories, in all cases with positive increments in the net balance of CO2. This movement could be explained by falling prices for key products of different trajectories. One should not ignore, however, the institutional moment marked by redefining FNO credit policies, against a default crisis plaguing many farmers, particularly those allocated to the T1 trajectory. This also highlights the economic growth of T3, a trajectory with low carbon content in net CO2 balance. Yet, as result of these economic conditions, the agricultural economy returned to high levels of carbon intensity.

The fourth phase seems to resume the downward trend in carbon intensity shown in the second phase. One difference, however, is crucial: the average growth rate of 12.5% pa in this current phase is far superior compared to the second phase rate of 10% per year. The growth rates of net CO2 emissions, in turn, are equivalent (1.8% to 1.7% pa), which results in a more marked downward trend of CI of 7.1% pa compared to ~5.9% pa in the second phase. Here again there are economic considerations in key product prices such as soybeans, beef, açai and milk. But there were also important changes in the institutional framework brought about by PPCDAM (Action Plan for Prevention and Control of Deforestation in the Legal Amazon), as steps were taken to form forest reserves, constraints were placed on credit based on environment–friendly criteria and monitoring and enforcement of environmental offenses was carried out, with a high degree of effectiveness (IPEA, GIZ, CEPAL, 2011).

5.6 Explaining carbon intensity evolution: Deforestation and actual land use

The model developed above considers that the fundamental determinants of net CO2 balance are the ways in which land use relates to production processes: whether as new, reused or unused land. The model obeys an operating assumption: lands are “produced” in order to leave the status of “pristine forest” to another condition set by the rationale of a technological trajectory, with an initial action of deforestation, that is, an operation that involves the one–time release of the carbon stock previously stored in vegetative cover. This occurs when additional lands are required by establishments evolving within a technological trajectory and decisions become factual by accessing existing forests in establishments recognized by the Census. This is the meaning of the category Deforested Area Required by the Level of Economic Activity (D_{t1}^{T}), presented in 4.1, relation (15). In turn, reused lands are accounted for in the variable Successional Area with Permanent Cover (S_{t1}^{D}).

In this case, the CO2 balance is regulated by the ecology of the various systems present on these land areas. Deforestation expressed by D_{t1}^{T} is, for the model, the main source of emission estimates, and the presence of different systems in S_{t1}^{D} determines CO2 sequestration amounts. Ratio S_{t1}^{D}/D_{t1}^{T}, therefore, is a substrate of net CO2 balance and the higher the former, the lesser the latter. Taking the above established phases as references, the second phase was a passage from the value of this ratio of 7% to 27%. In the following phases, variations are observed around this latter value, with a slight trend upward, despite the decline in the past few years (see Figure 11).

Differences between the trajectories are also remarkable here. The second phase exhibited a T2 ratio S_{t1}^{T}/D_{t1}^{T} from less than 40% to over 70%; T3 (peasant – livestock for meat) and T5 (enterprise – plantation) ratios increased from 10% to about 50%; the T1 (peasant – intensive agriculture) ratio increased from 10% to slightly below 30%; finally the T4 (enterprise – livestock for meat) ratio held at around 10%, a level which converges with the T7 (enterprise – annual crops) ratio (see Figure 12).

![Figure 11: Deforested and reused land required by the agricultural economy, 1990 to 2011.](http://example.com/figure11.png)

The model considers that the fundamental determinants of CO2 balance are the ways in which land use relates to production processes, whether as new, reused or unused land. Deforested Area Required by the Level of Economic Activity (D_{t1}^{T}) refers to additional lands required by establishments evolving within a technological trajectory implying an initial action of deforestation, that is, an operation that involves the one-time release of the carbon stock previously stored in vegetative cover. In turn, reused lands are accounted for in the variable Successional Area with Permanent Cover (S_{t1}^{D}). In this case, the CO2 balance is regulated by the ecology of the various systems present on these land areas. Ratio S_{t1}^{D}/D_{t1}^{T} is therefore a substrate of net CO2 balance and the greater the former, the lesser the latter. Taking the above phases as references, the second phase represented an increase in ratio from 7% to 27%. In subsequent phases, variations are observed around this 27% value, with a slight upward trend. Source: Table S1.

doi: 10.12952/journal.elementa.000133.011
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5.7 Explaining carbon intensity evolution: Actual deforestation explained by agricultural dynamics

To what extent can it be expected that modeled deforestation matches the actual physical deforestation as measured by PRODES? The answer is, modeled deforestation matches actual deforestation to the extent that the process of “land production” (Costa, 2012) continues in balance with the need for new land by the agrarian economy. It was noted earlier that the model considers “production” of land endogenous to establishments, so it is as if establishments were putting into operation lands acquired at another time. However it turns out that the land market, despite the close relationship with the agricultural economy in the region (Costa, 2010), reacts to determinations of other planes, spheres and scales of economy, including urban and rural speculation (Reydon et al., 2006; Reydon and Souza, 2012), so that actual deforestation may be associated with the immediate process of “land production”, and not necessarily with the needs of “rural production”.

If the process of “land production” has relative autonomy in relation to the absorption of new lands for the agrarian economy and, on the other hand, deforestation modeled here refers exclusively to the latter process, then the deforestation amounts measured by PRODES (Prodes) include Dₙ but are not limited to it. Modeled deforestation also incorporates an amount derived from the commodity status which lands acquire. A comparison between Prodes and Dₙ along the phases already defined reveals the following: in the first phase Prodes moves according to the needs of the agricultural economy, so that its total over time corresponds to total Dₙ for the period; in the second phase, a stock of land of 5.2 million hectares was formed up to 2002, of which around 400,000 hectares were required by the strong dynamics of the agrarian economy in following years; the third phase starts from 4.8 million hectares and even with Prodes numbers falling, adds around 2 million hectares of land not explained by the needs of the rural economy, which tends to zero in the period. In the fourth phase, Prodes numbers continue to decline, resulting in reduction in the stock of land, since Dₙ grows systematically (see Figures 13 and 14).
6. Conclusion

The model developed here estimates that in two decades, development of the agricultural economy in the northern region of Brazil delivered a total of 2.1 Gt of CO₂ to the atmosphere, almost one third of all CO₂ accumulated by evolution of the rural sector in the region under current conditions. The model is able to explain the structural heterogeneity of the rural sector in the region, showing that recent acceleration in CO₂ emissions was caused by different contributions from different production structures, treated here as technological trajectories. The results discussed show how six of these trajectories impact net CO₂ emissions, highlighting the main emitter (technological trajectory T4: enterprise – livestock for meat), while drawing attention to the trajectories of very low impact (T2: peasant – agroforestry and T5: enterprise – plantation) and to trends in trajectories with intermediate impact, either increasing, such as T1 (peasant – intensive agriculture) and T7 (enterprise – annual crops), or decreasing slightly, as T3 (peasant – livestock for meat).

The exercise allows consideration of the attributes of these structures in addressing the role of the rural sector in the Brazilian Amazon in shaping the demand for environmental services that is expanding given the threat of climate change. It also allows observation of the values in a perspective that focuses on the supply side of environmental services accumulating in the region, considering the potential of the rural sector to sequester carbon. A point that is highlighted is that sequestration capacity is growing almost as fast as emissions. In this regard, the study emphasizes the importance of all peasant trajectories, with particular emphasis on T2 (peasant – agroforestry). Enterprise trajectory T5 should also be highlighted in this respect.

The ratio of net CO₂ emissions and the values that represent the underlying agricultural economy indicate that carbon intensity tends to fall over time as a result of the growing importance of trajectories with smaller CI in combination with the reduction in CI of trajectories with higher carbon intensity. The model makes it clear in this regard, that the viability of a low carbon economy as a development basis for the Brazilian Amazon depends, on one hand, upon competition of trajectories, in relation to their market fundamentals, while on the other hand it is dependent on the role of development policies in this competition. Availability of technological capabilities and access to credit adjusted by trajectory are examples of policies that could reduce the carbon intensity of farming systems.

Broad policies to reduce carbon intensity should take into account both courses of action. First, policies need to tackle the foundation of the main emission vectors, cattle ranching ranking at the top, assembling institutional resources to contain these emissions. This article presents evidence that cattle ranching is vulnerable because the payoff is easily contestable, representing low opportunity costs. However, promotion of systems that sequester carbon also need to be considered, such as forestry and agricultural systems based on perennial crops. Forestry could replace existing or evolving _capoeira_ on large ranching operations. In turn, diverse perennial cropping systems could replace shifting cultivations on family farms, withdrawing land from the _capital–capoeira_ function, freeing these lands as _reserva–capoeira_, to become diversified forests once again.

Current trajectories showing endogenous ability in this regard will depend on certain factors, including development of an environmental goods market. Carbon balances of given agricultural development trajectories contribute to calculation of virtual social gains and losses for the country and region, associated with a possible worldwide carbon market.

In addition, the model highlights the role of carbon balance of deforestation in contrast to renewed use of deforested areas. An obvious result is that, except for T4 and T7, for all trajectories reuse of “old land” is becoming increasingly more important in explaining the essence of agricultural dynamics than deforestation for the production of “new lands”. Among the uses of renovated deforested land, the article draws attention to the role of _capoeiras_ and their existence as part of modernization and intensification of the sector through strategies observed in various technological trajectories. As such, _capoeiras_ may not be environmental liabilities, as some allege.
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In regards to deforestation, the methodology developed here allows for evaluation of economic dynamics determined by evolution of the market for products, in comparison with deforestation which seems largely to be independent of these fluctuations. The results point to issues which should motivate further studies: the land market is the determinant of this relative autonomy of the "production of land" in relation to the actual needs of rural production, stocks of land which might in part be destined to urban uses and in part to speculative assets. The existence of this excess amount of land could explain the situation like the one observed since 2007 when rapid growth of the agricultural economy was accompanied by decreasing deforestation.

References


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Acknowledgments

I thank the editors and anonymous reviewers for the time and effort they invested in reading and critiquing the original manuscript and for their insightful and constructive feedback. I thank also the Amazonian Environmental Research Institute (IPAM) and the Nucleus of Higher Amazon Studies of the Federal University of Para (NAEA–UFPa) for suport.

Funding information

Text written as part of a research productivity project granted by Brazilian National Counsel of Technological and Scientific Development (CNPq) “Trajetórias tecnológicas, arranjos produtivos e regimes de crescimento de economias locais: explorando as possibilidades atuais da heterodoxia econômica para o estudo e o planejamento de alternativas do desenvolvimento sustentável em sub-regiões paradigmáticas da Amazônia”.

Competing interests

The author has no competing interests to declare.

Data accessibility statement


Supplemental material

- Table S1. Evolution of areas used in the agricultural economy of the North region by trajectory (model estimates in ha)
- Table S2. Evolution of components of the annual balance of carbon emissions (t) in the northern region by technological trajectory
- Table S3. Evolution of Gross Production Value in the northern region by technological trajectory (in constant R$ from 2012, corrected by IGP–FGV)

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Notes

1. Presented at the IV Econtro de Economia Política da Amazônia, held in Belém, NAEA, 23 a 27 November 2015.

2. “Any material process consists of the transformation of some materials into others (the flow elements) by some agents (the fund elements)...’and...’ there is no substitution between flow and fund factors.” (Georgescu–Roegen, 1979:98, 1983:23 and 28).

3. Deforestation calculations measured by PRODES, from the Brazilian Space Research Institute (INPE). For additional information on calculation methods, see Krug (2001: 92–93).

4. Unless otherwise noted, the statistics presented are for the North region – Pará, Amazonas, Roraima, Rondônia, Acre, Amapá, and Tocantins. This paper also refers to this region as the Brazilian Amazon Region or just the Amazon. The Legal Amazon also includes the states of Mato Grosso and northeastern Maranhão state.

5. Technology, in this context, means the set of techniques and procedures that mediate labor and nature, made of both tangible and intangible factors, inherited on the one hand, from past labor processes, which, therefore, constitute “...organs of the human brain, created by the human hand; the power of knowledge, objectified.” (conf. Marx 1953:706); inherited, on the other hand, as a paradigm, i.e., as cognitive structures, “...as a ‘model’ or a ‘pattern’ for solution of selected technological problems (Dosi, 2006: 22 and 23).

6. The peasant production form, where the family is the basic structure, providing work and absorbing the results of the applied efforts, relies on relatively small plots of land. The corporate or enterprise form is characterized by major use of wage labor and usually large parcels of land (conf. Costa, 2000 and 2006).

7. The Agricultural Census of Brazil represents a detailed structural data set on the agricultural sector, comprising statistics on the number of establishments, land use, number of tractors, implements, machinery and vehicles, characteristics of the establishment and of the producer, employed persons, head of livestock, crop and animal production, among other aspects. Costa (2009a) developed a methodology to differentiate, based on the Census data, technological trajectories in the rural sector considering social relations of production (whether family or wage work force), the fundamental technical
relations (proportion between land, work and capital), the structure of the production (composition between cattle, milk, annual crops, perennial crops, forest non-timber and timber products, forestry) and the presence of institutions (credit and technical assistance).

8. Dataset of the 1995 Agricultural Census (see footnote 8), each case marked with the attributes of respective technological trajectory.

9. For further details on the “capoeira crisis”, see Hurtienne (2001). See also Costa (2006) for an extensive analysis of technological trajectories of the rural sector in the Amazon.

10. In addition to the Census, the IBGE also publishes annual data at the municipal level of agricultural production (production, productivity, price, planted area, harvested area) for all products compiled by the Census. It proceeds in the same way with extractive crops (production, price) and for different types of livestock (cattle, dairy, poultry, goats). For agriculture, the annual estimates are given in the Produção Agrícola Municipal (PAM), for extractive production, the annual estimates are given in the Produção Extrativa Municipal (PEM) and for livestock, the annual estimates are given in the Produção Pecuária Municipal (PPM).

11. These references are used because they represent the state-of-the-art knowledge in this region. Fearnside (2000), a well-known researcher on forest ecology in the Amazon publishes data on important variables in environmental matters in the Amazon. He updated his 1997 work and presents detailed data for shifting cultivation, original forest, etc. Nepstad is also a renowned specialist in forest ecology in the Amazon. His work is less technical, but both his evaluation and choice of parameters are qualified corroboration of sources. We are aware of the risks of using average values to represent such a large region. However, the methodology presented and the strategic discussion of results reveal it to be more important here than the margin of error inherent in these calculations.