# Property and household life cycles, markets, and land use/cover change in the Brazilian Amazon

**Gilvan R. Guedes**
Associate Professor – Department of Demography
Universidade Federal de Minas Gerais (UFMG)
Email: grguedes@cedeplar.ufmg.br

**Bernardo L. Queiroz**
Associate Professor – Department of Demography
Universidade Federal de Minas Gerais (UFMG)

**Alisson F. Barbieri**
Associate Professor – Department of Demography
Universidade Federal de Minas Gerais (UFMG)

**Leah K. VanWey**
Full Professor – Department of Sociology
Brown University

## Abstract

Initial stages of frontier settlement in the Brazilian Amazon were characterized by high migration inflows, intense deforestation, and property turnover. Forty years later, rural households are more market oriented and have developed strategies to adapt to the local environment. Building on theories of household demography and bid-rent, this paper proposes a conceptual framework for land use/cover change in agricultural frontiers that considers an interactive relation between property and household life cycles, regardless of the history of property use. Based on longitudinal survey data for Altamira, Brazil, we find that older households (household life cycle) and properties closer to urban centers (market integration) are associated with higher levels of deforestation, but we find no evidence that experience with the farm environment (on the property life cycle) reduces pressure on the remaining forest. For commercial land use, on-site capital and distance to markets dominate demographic markers, suggesting that Altamira is in later stages of development.

**Keywords:** Household Life Cycle; Property Life Cycle; Market Integration; Brazilian Amazon; Land Use/Cover Change

**Introduction**

The recent colonization of the Brazilian Amazon was marked by the inflow of migrants from different parts of Brazil (Bilsborrow and Hogan 1999) and a steady growth in deforestation rates (Skole et al. 1994). The combination of colonization and other human land uses has raised concerns about the economic and environmental sustainability of human occupation and its impact on biodiversity loss, degradation of water systems, and carbon emissions.

To understand how the process of environmental change in the Amazon has occurred, and to identify likely commonalities in other frontiers elsewhere in the region, studies usually divide frontier change into phases. Almeida and Campari (1995), for instance, argue that the first stage of frontier development in the Brazilian Amazon was characterized by high rates of deforestation and property turnover. A combination of contextual factors motivated the initial deforestation, such as the need to secure land (Binswanger 1991), land abundance (Moran 1981), lack of knowledge about the biophysical characteristics of the frontier (Moran et al. 2006), and settlers' response to the perceived return to their capitals (McCusker and Carr 2006).

This first phase was marked by a dramatic change in frontier demography, inducing rural-rural migration flows, followed by a growing rural-urban migration and circulation in several Amazonian countries. The intense migration flows within the Amazonian frontier forced farmers to adjust their new household structure to laborsaving land use systems (Barbieri et al. 2009). Different from the Ecuadorian Amazon, where fragmentation predominates, the Brazilian Amazon experienced intense conversion of clear fields and forested areas into pasture, producing a farm structure where consolidation and laborsaving practices predominate (VanWey et al., 2012a).

This evolving scenario results from complex forces acting at different scales and pace over frontier development: (1) from household demographic dynamics affecting land use choices and farm structure in initial stages of development, as predicted by household life cycle theories (Ellis 1993, De Sherbinin et al. 2008); (2) from a growing connectivity of rural-urban areas through migration of selected family members, dual-residency, and growing market-oriented land use systems, as predicted by bid-rent models (Andersen et al. 2002), and (3) from institutional changes affecting farmers' perceived returns to their capital stocks, as predicted by the political economy perspective (Guedes et al. 2012, VanWey et al. 2012b)[1]. The growing integration of local farmers into markets, boosted by new infrastructure developments, have produced consequences for land cover change in the Amazon, posing a new challenge for governance schemes (Brondizio and Moran 2008).

This paper proposes a revised version of the relationship between household and property life cycles, integration into markets, and land use/cover change. As in VanWey et al. (2007), we define household life cycle as the change in household structure due to the aging of household members and the generational transition that follows. Property life cycle is defined as the evolution of the property itself, reflected in adaptation of land use to the biophysical characteristics of the soil and the growing place-specific knowledge of the frontier environment. We expand the concept of property life cycle in this paper, distinguishing two different components: *property* (history of

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[1] New findings about small-farmers' behavior in agricultural frontiers suggest that rural smallholders respond to the perceived opportunities and barriers, adopting livelihood strategies in tandem with the new challenges offered by an evolving institutional context (McCusker and Carr 2006). For instance, as market forces penetrate into the frontier, commercial land use systems tend to prevail (VanWey et al. 2012a, 2012b). At the same time, increasing road and family networks reduce the cost of education and increase the return to more qualified labor in the urban areas of the region (Barbieri and Pan 2013). Finally, as families age in the frontier, place-specific capital increases, promoting efficiency over extensification in the use of land (Guedes et al. 2014). This learning-by-doing process is argued to reduce pressure on the remaining forest and relax constraints imposed on household labor supply, allowing households to diversify across economic sectors and specialize in more profitable land use systems (Barbieri and Pan 2013, VanWey et al. 2012a).

property use since first occupation) and *on the property* (length of time the household lives in the property) life cycles.

Based on our proposed framework, we hypothesize that: (H1) the influence of *household demography* on land use/cover declines as individual farmers integrate into markets; (H2) the influence of *household composition* on landscape dynamics declines as farmers' time on the property increases, and (H3) farmers, therefore, develop new livelihood strategies, taking advantage of the new institutions entering to and emerging within the frontier space. The dynamic nature of livelihood strategies reflects the shifting portfolio of capitals as perceived returns to capitals change over frontier development, creating incentives for diversification over space and across economic sectors (McCusker and Carr 2006, VanWey et al. 2012b).

In order to test our framework, we examine how the different cycles (household and property) and the proximity and accessibility to urban areas (integration into markets) affect deforestation and land use in the TransAmazon Highway. In addition, we analyze the influence of regional institutions, such as remittances and local associations, on land use/cover change, since they provide insights about diversification of household livelihood strategies, with important implications for the regional landscape dynamics. Using longitudinal survey data from rural properties and households, first interviewed in 1997/1998 and followed-up in 2005 in Altamira, Pará, Brazil, we find empirical evidence that the association between household life cycle and deforestation weakens as time on the property increases. Furthermore, as implied in our framework, the weakening in the association between household composition and land use is more evident in areas deforested for commercial than for subsistence land use.

Our analysis suggests that older households as well as properties closer to the urban centers have higher levels of deforestation, but we find no evidence that experience with the property environment independently reduces pressure on the remaining forest - yet it explains differences in land use. Lastly, our results support the differentiation between *on the property* and *property* life cycles, suggesting that on-site knowledge is key for developing land use systems, *regardless of* the history of property use.

**Land Use/Cover Change in the Amazon**

Conventional approaches[2] on the relationship between household demography and land use emphasize that change in the household size and composition represents variation in the labor pool and consumption needs of the household over its life cycle (Thorner et al. 1986, Hammel 2005). These approaches predict that property deforestation is high upon arrival to meet immediate consumption needs of the recently established farm, followed by a phase of low deforestation rates as households age and consolidate their land use strategies. When households reach later stages in the life cycle, children leave home to establish their own farms within the original property boundaries (*generational shift*) or migrate to urban or other rural areas (*empty nest*). Land use shifts from annuals to pasture or perennials production, followed by forest regrowth if the empty nest scenario holds (Perz 2001).

While this approach focuses on household dynamics, the literature on the political economy of frontier settlement in the Amazon focuses on the structural constraints that shape individual and household livelihoods in frontier settlements. This literature helps unveiling the role of institutional macro-level dynamics and rural-urban connections on shaping micro-level dynamics. The political

[2] This literature is related to the pioneer theoretical and empirical studies about household demography and land use in agricultural frontiers. These studies assume a typical household that ages in predictable life cycle stages, thus not explicitly discussing how household and property life cycles differ in their influence on land use dynamics.

economy theory of frontier development argues that the growing influence of market forces in rural areas has disrupted traditional agricultural forms of production, inducing smallholders to compete with large capitalist farmers in an asymmetric away (Little 2001). This perspective predicts a non-linear trajectory of frontier change, with varying consequences for landscape dynamics. During boom cycles, deforestation may increase in response to economic stimulus, but in areas where economic activities shrink, we may see an inverted U-shape curve of deforestation activity (Rodrigues et al. 2009). Post-frontiers therefore are characterized by the exhaustion of natural resources and the out-migration of small farmers unable to cope with the decline in soil fertility and experiencing limited access to subsidized credit. This mobile population fosters new streams of internal migration, providing cheap labor to other frontiers, or feeding migration and circulation streams to the urban centers of the region in search of urban employment (Barbieri et al. 2009).

These approaches emphasize the importance of contextual or macro-level factors related to market dynamics and institutional settings, which foster market penetration in frontier areas. For example, existing and evolving road networks reduce the transportation cost for small-scale agricultural production, allowing smallholders to consolidate market-oriented land use systems and to focus on local and regional markets (Pfaff et al. 2009). In addition, the expansion of these urban regional markets represents risk mitigation opportunities, as they create alternatives for farmers to weather labor or credit scarcity (VanWey et al. 2012b). Some studies argue that out-migration, especially temporary and short-term migration of family members, may work as a livelihood option in the origin household when family labor exceeds labor required in agricultural management (Robson and Nayak 2010, VanWey et al. 2012a). Local associations and unions are also key in helping farmers to overcome obstacles through the provision of subsidized credit, technical information, seeds, and tools (Coomes 1996, Helfand 2001). These social and quasi-economic institutions that develop within the frontier space, combined with the growing influence of market institutions at different levels of aggregation, set the stage for our revised household life cycle framework in agricultural frontiers.

Our framework departs from a traditional household life cycle model of land use in different ways. We explicitly address (1) how exogenous factors to the rural household mediate its ability to send away young adults to reduce labor if they do not need it, and (2) how *on the property life cycle* modifies the ability of households at specific life cycle stages to predict land use trajectories. As in many other conceptual frameworks, ours assume that agriculture frontiers evolve in phases. However, we assume that the growing influence of macro and meso level factors[3] on land use decisions at the household level takes place asymmetrically in different frontiers, creating a unique dynamic in each frontier (Rodrigues et al. 2009).

Therefore, in each phase (for the same frontier), or in each frontier (at different stages), the connection of the household with each of the hierarchical levels (local, regional, national, and global markets) may change, allowing them to articulate their connections to certain hierarchical scales while disarticulated from others[4] (Guedes et al. 2009). This non-linear dynamics of frontier development and, to a certain extent, of the property, implies that contextual factors, such as the

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[3] Following VanWey et al. (2012b), we define meso level institutions as those that are not fully endogenous to the local context, such as family structure and local kinship, but also not exogenous to the household decision maker, such as public policies at the national level, international agreements on land use and conversion, and international commodity markets. Examples of these meso level institutions are local associations that can provide for agricultural equipment and subsidized credit, local associations that can provide an arena for exchange of agricultural techniques, and family remittances - which use kinship as a channel for filtering the opportunities provided by international markets in terms of flows of cash and knowledge.

[4] For instance, as suggested by Brondizio (2008), small-scale açaí berry producers in the Amazon are increasingly involved in trade negotiation with buyers from New York and London, without going through local trade mediators.

social profile of farmers, their settlement history and the connection networks of the frontier with other frontiers and markets, determine the characteristics and the pace of change in each phase (Summers 2008). Although some frontiers may experience boom-and-bust cycles ranging from intense deforestation to land abandonment, a general trend of change from subsistence to an increasing articulation with markets is expected (Caldas et al. 2007).

Our framework highlights the importance of regional institutions (meso level) that develop within the frontier to mediate the household decision-making process. The main factors operating at the meso level are the rural-urban connections, the social networks, labor markets and local produce, local governance, and environmental regulations (de Sherbinin et al. 2008). In this paper, we highlight the importance of the rural-urban connections and social networks only because these are the most relevant for our study area (VanWey et al. 2012b).

Rural-urban connections are more than a simple spatial concept, as it represents the space where social relations operate facilitating flows of information, technology, work, and money. Therefore, the way the relation between the rural and the urban develops is key to understanding how local farmers interact with the environment beyond the frontier boundaries (Summers 2008). Social networks, already in existence at the time of frontier establishment, evolve in their complexity over time. They shift from a predominantly *bonding social capital* to an expanded network, extending its outreach by adding *bridging social capital* resources. Bonding social capital is the bonding agreements to provide mutual help between family or small farmers. They operate through kinship or friendship, resembling Granovetter's (1973) definition of strong ties. Bridging social capital represents the weak ties connecting individuals from one network to another network that can source new capitals to the origin network.

Following Wegener (1991), we argue that the opportunities that emerge with frontier development produce a complex interaction between bonding and bridging social capital. These more complex social networks are not only an expanded version of the networks based on bonding, but it rather widens the decision-making space of rural farmers by buffering their land use decisions with improved knowledge and larger funds for investment at a cheaper cost[5] (Wouterse and Taylor 2008). We argue that out-migration of selected family members allows the use of its inherent bonding capital (strong ties) to reach out other networks in the destination places (weak ties), providing financial and non-local educational opportunities as new informational input to the rural households in the origin areas (Haan and Zoomers 2005).

The second important aspect of our revised framework is how the household life cycle and property life cycles interact in their influence on landscape change. From a temporal perspective (Figure 1 – Panel A), the influence of household and property life cycles is indistinguishable in initial stages of frontier development because site-specific knowledge is scarce. Therefore, landscape transformation is dictated by changes in household demography. As the frontier develops and endogenous institutions consolidate, the arrival of new cohorts of settlers and the exit of older cohorts increase population heterogeneity. This growing heterogeneity of settlement cohorts, in a context of local institutional development, produces a gradient of knowledge about the biophysical characteristics of the property, favoring older cohorts to make good decisions about livelihood choices. At very later stages, when land use systems consolidate, the influence of property and household life cycles on landscape change is dominated by the factors beyond property boundaries.

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5 Although in some contexts a widen social network may translate into net costs to the individual, resulting from larger "giving" than "receiving" flows of resources.

The previous discussion of cycles interaction on a time scale implies that *property* life cycle can be divided into *on the property* life cycle – place-specific human capital, and *property* life cycle – soil chemistry/texture cycles. They render independent influences on the relation between household life cycle and land use/cover change[6]. The "property life cycle" may limit the household life cycle's ability to influence land use and land cover change (LULCC) if technological stagnation predominates. The "on the property life cycle", on the other hand, acts as a technological improvement-like impact on household strategies. Thus, while *property* life cycle may reduce households' latitude over frontier development (unless technological change may come into play), *on the property* life cycle improves households' ability to make informed decisions on land use choices.

From a spatial standpoint (Figure 1 – Panel B), household life cycle's impact on LULCC declines as the analysis is taken at higher spatial scales at any given point of frontier development. The interactive effect of life cycles (*household* and *on the property*) on land use change predominates at the household or property level and vanishes at higher scales. At the regional and national scales, other factors such as road networks and economic growth predominates, yielding indistinguishable and very marginal impacts of household and property cycles on land use dynamics.

In all, our revised framework yields three important predictions:

a) In Amazonian agricultural frontiers dominated by smallholders, market influences predominate at later stages, although land use decisions at the household level continue to

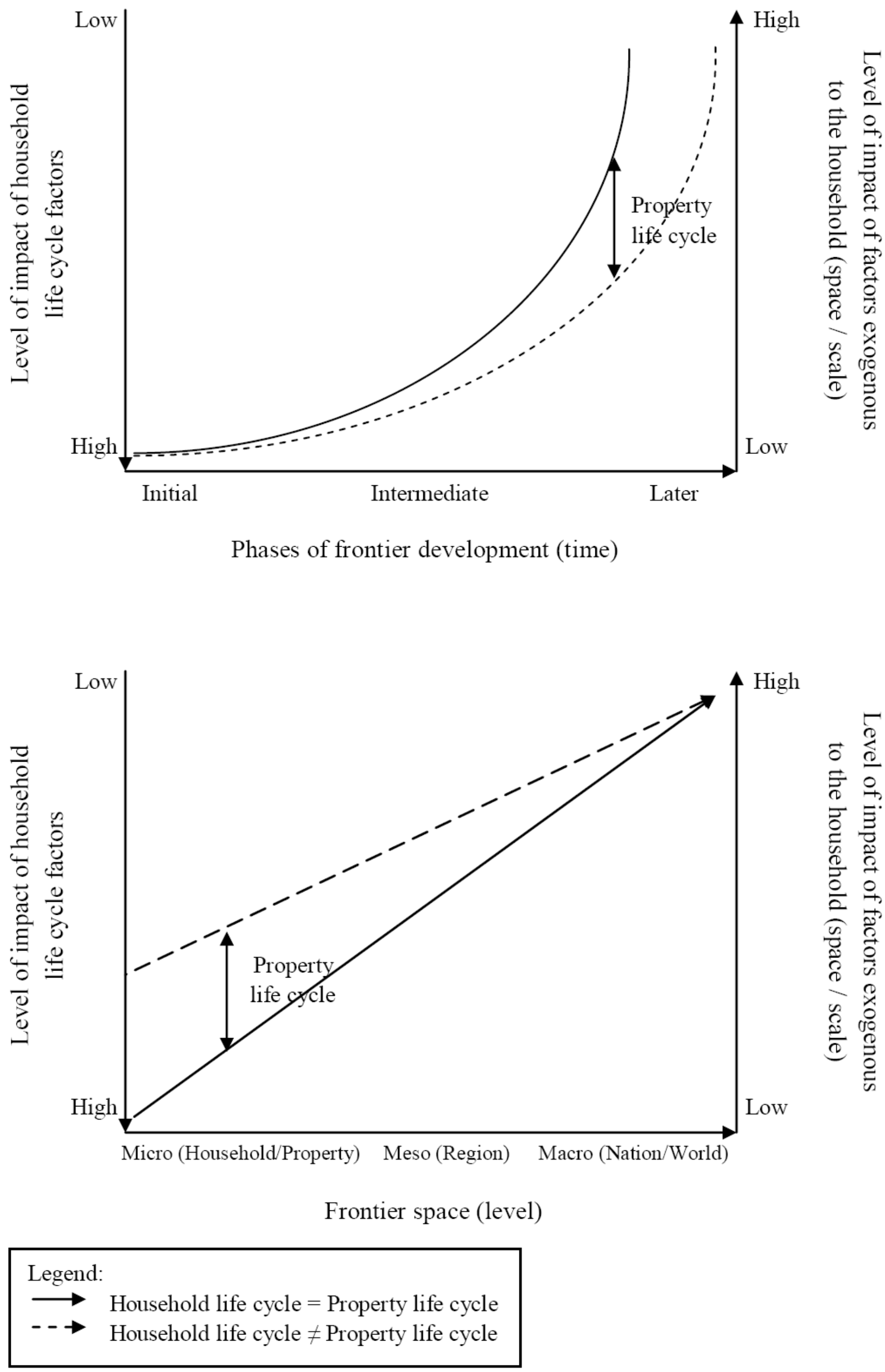
[6] In order to simplify visual representation, Figure 1 ignores this distinction.

be influenced by risk-aversion behavior, since part of the livelihoods still derives from subsistence agriculture.

b) Household life cycle and *on the property* life cycle follow different paths over frontier development due to the site-specific knowledge derived from long-term experimentation with the property environment, regardless of the *property* life cycle. The longer a smallholder stays on the property, the less important household demographic composition is in explaining landscape change at the property level once historical property use is considered. This cross-cycle influence is stronger for commercial than subsistence land use systems.

c) Given that part of the deforestation occurs due to experimentation with the property environment, the influence of household life cycle on deforestation predominates over the effect of *on the property* life cycle. The opposite is true for land use systems.

**Figure 1: Conceptual framework for the influence of household life cycle, property life cycle and integration into markets on land use/cover change in agricultural frontiers**

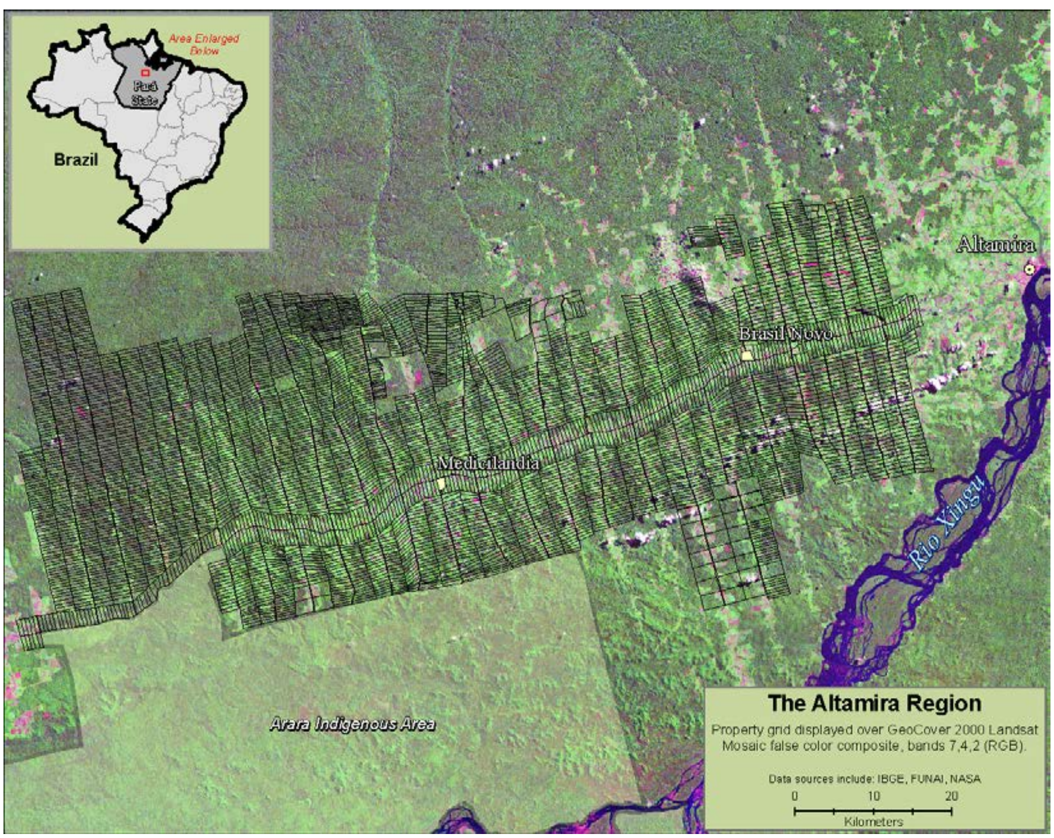



Source: Author's elaboration.

**Study Area**

Our study area is part of an original settlement program established with the construction of the TransAmazon Highway in 1971, intended to crosscut the Amazonian states from east to west. The government-sponsored settlement was one among other initiatives to occupy the Amazon as part of a territorial integration plan. Its settlement scheme followed the traditional fishbone structure seen in other parts of the Amazon (Figure 2). The planned area was divided into lots of approximately 100 hectares, with 500 meters front wise and 2000 meters sidewise. For each settler household was assigned one lot.

**Figure 2: Altamira Study Area**




Source: ACT/Indiana University (unpublished material).

At the project inception, the Brazilian Forest Code established that half of each lot had its forest cover preserved, and that the deforested area was used primarily for subsistence (Moran 1981). To speed up the occupation, the Brazilian Institute for Colonization and Agrarian Reform (INCRA) prioritized larger families that could provide larger family labor pools (INCRA 1978). This demographic selection of households produced a demographic composition of settlers' households slightly older than other settlement projects elsewhere in the Amazon. Different from other experiences of spontaneous frontiers – where individual migration at the frontier inception predominates, the migration profile in our study area was characterized by family migration (McCracken et al. 1999).

Most settlers arrived during the 1970s and the first half of the 1980s, leading to a fast growth of local cities in the region (Perz 2002). Over the frontier development, many original settlers left their properties and migrated to other rural areas or to the nearby cities. The intensive turnover in the initial stage of Altamira frontier was driven by lack of governmental support, production loss due to lack of technical assistance and climate shocks, as well as high rates of malaria infection. As a result, only 34% of the 402 settlers interviewed in 1997/98 in our study area were still there in 2005 (Ludewigs et al. 2009).

While the rural population in the region was shrinking, the emerging urban centers quickly developed. The growth of local cities gave rise to incipient local production and job markets, opening new opportunities for individuals from the rural areas seeking higher returns to labor (Guedes et al. 2009). With the consolidation of Altamira frontier, market expansion seems to increasingly influence land use preferences among farmers, with a significant decline in subsistence crops and increase in commercial crops (Guedes 2010).

## Analytical Strategy

### *Analytical Sample*

We use longitudinal survey data collected in the Altamira Study Area in 1997/98 and 2005, combined with aerial photography and remote sensing data of property land cover from 1970 to 1996. In 1997/98, a group of researchers from Indiana University and the University of Campinas interviewed small farmers in 402 properties representative of the entire INCRA settlement grid (Figure 2). Since in 1997/98 almost all the properties had just one household, household and property levels matched for that year. The original questionnaires collected detailed information on sociodemographic characteristics of the household members, along with questions about land use and land cover as well as physical characteristics of the property. In 2005, researchers returned to the field to follow up the households, applying the survey instruments covering the same set of topics in the instruments used in 1997/98. Due to the establishment of new households on the original property, some property fragmentation and selling and moving out of some families, the number of households in 2005 is higher than in 1997/98 (VanWey et al. 2012a).

To preserve comparability over time, we restricted our sample to the household/property owner, originally interviewed in 1997/98, which held the same property in 2005. This way, we reduced our longitudinal sample to 315 households/properties. Additional cases were lost due to missing information for the dependent (14 observations) and independent variables (additional 43 observations). Our final survey sample was restricted to 258 households/properties[7].

The remote sensing information was based on the following data: Landsat MSS (1973, 1975, 1976, and 1979) analogic images (scales 1:250,000 and 1:500,000) from the archives of

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[7] In the regression analysis, we tested for the influence of selection bias using a two-stage Heckman selection model with panel data, but the inverse of Mills ratio was not significant in the models.

SUDAM (*Superintendência do Desenvolvimento da Amazônia*), Landsat TM images for 1995, 1996, and 1997, and Landsat 7 ETM+ for 2004, 2005, and 2006. For more recent data, we used three years for each point in time to find the pixels with the smallest cloud/shadow cover for 1996 and 2005 (Lu et al. 2008). Remote sensing data was used to identify the year when the first 5% of the original lot identified in the colonization property grid was visible. Each property was assigned a year of first settlement, and then aggregated into settlement cohorts. We use this variable as our proxy for "property life cycle", differentiating it from the number of years the current smallholder lives on the property (*on the property* life cycle).

*Modeling Strategy*

We start with a descriptive association between household life cycle indicators and three land use/cover indicators: deforestation (area deforested in hectares), commercial land use (area in perennials and pasture), and subsistence land use (area in annuals and secondary succession). This correlation analysis is performed by estimating Pearson correlation coefficients between the household dependency ratio and land use/cover indicators by the number of years living on the property.

We then move to regression analysis to further investigate the associations between LULCC, household and property life cycles, and integration into markets. Our key dependent variables for the deforestation models are: the proportion of the property deforested until 2005, and the additional area deforested between 1997/98 and 2005. The dependent variables for the land use models are the area (in hectares) of the property in perennials, pasture, annuals, and primary forest.

*Modeling Land Use/Cover Classes*

We run scalar models (seemingly unrelated regressions system - SUR) for land use classes to account for unobserved joint decision of land use classes in the same property. SUR models are used whenever unobserved variables that are correlated to all dependent variables at the same time (such as farmers' ability with agriculture) cause correlation between the errors of variables for each dependent variable. In this case, the sample standard errors of the coefficients are inefficient, producing larger p-values (Davidson and MacKinnon 2004). A simple solution to gain efficiency is to model errors covariance from the system of equations. In our case, because we have one equation for each land use or land cover class for the same rural property, we can use the covariance structure of these regression equations to gain efficiency on the vector of standard errors of coefficients for the independent variables. We applied the Full Information Maximum Likelihood method to take advantage of any non-missing information for variables across the equations of land use/cover classes.

*Modeling Deforestation*

The deforestation models required another estimation method. Because the dependent variables for these models are expressed in proportions of the property area, they are bounded between the normalized interval [0,1]. In this case, the best models are the beta regression, the generalized fractional logit, or the zero-inflated beta regression. The choice between methods depend on the distribution of the variable. The last method is appropriate when there is a very high proportion of zeros, which implies that the data generation process (DGP) for zeros is different from the DGP for the other values. For models where the dependent variable is continuously measured in the interval ]0,1[, the beta regression model assumes that the conditional error follows the very flexible beta distribution (Ferrari and Cribari-Neto 2004).

The beta regression only models dependent variables lying in the interval 0 <y <1. If 0's and 1's are included in the empirical range, two alternatives are commonly used: (i) 0's and 1's are very low (or high) proportions that occur accidently in the random realization. In this case, it implies a fractional logit generating process, following the same DGP of the other measures along the 0,1 spectrum; (ii) 0's and 1's are realizations of a different DGP from the other values in the range, implying a mixed (beta-logistic) process. Because in our sample the 0's and 1's are feasible but rare, the first strategy was used.

*Covariates (key and control variables)*

Our key independent variables, measured in 1997/98, are: household life cycle indicators (number of children, adults and elderly in the household, age of the household head, and demographic dependency ratio), *on the property* life cycle (household owner's time living on the property), social/familial networks (membership in a union/association, out-migrant children, remittances from out-migrant children), and integration into market (distance to Altamira urban center and the proportion of the production sold). Control variables are: *property* life cycle (time since property was first occupied), land use classes (perennials, annuals, pasture, measured from survey data), land cover class (primary forest), lot size, household income, and use of non-familial labor (paid, sharecropper).

## Results

*Descriptive Analysis*

We start looking at the level and evolution of deforestation in the study area between 1997/98 and 2005. Comparing data on deforestation and forest cover from survey data with remote sensing provides an overall assessment of data quality. Panel A of Table 2 suggests that land cover indicators from remote sensing slightly underestimate deforestation extension (area deforested), although they are very similar in terms of deforestation intensity (change from 1997/98 to 2005). This is expected, since even in supervised classification with trained samples some areas classified as primary forest might be, in practice, advanced stages of secondary succession (Lu et al. 2008). Regardless of the data source, however, Table 2 shows that in 1997/98 more than half of the property were already deforested. Between 1997/98 and 2005, the area deforested increased significantly by 15%.

**Table 2: Descriptive statistics (mean and standard deviation) of the indicators of land cover and land use levels and change between 1997/1998 and 2005 – Altamira Study Area**

| Variable | Source | 1997/98[I] | 2005 | Change[II] (97/98 → 2005) |
|---|---|---|---|---|
| **Panel A - Land Cover Indicators** | | | | |
| Area in primary forest (ha) | Survey data | 48.2 ± 33.7 | 33.2 ± 27.5 | -15.0 ± 19.7*** |
| | Remote sensing | 55.7 ± 35.2 | 40.9 ± 34.0 | -14.8 ± 26.3*** |
| Deforested area (ha) | Survey data | 60.1 ± 50.2 | 75.0 ± 57.2 | 15.0 ± 19.7*** |
| | Remote sensing | 48.6 ± 41.7 | 64.1 ± 51.9 | 15.5 ± 23.9*** |
| Proportion of lot in primary forest (%) | Survey data | 45.3 ± 22.9 | 31.3 ± 21.1 | -14.0 ± 14.3*** |
| | Remote sensing | 53.6 ± 21.9 | 39.1 ± 21.6 | -14.5 ± 19.7*** |
| Proportion of lot deforested (%) | Survey data | 54.7 ± 22.9 | 68.7 ± 21.1 | 14.0 ± 14.3*** |
| | Remote sensing | 44.7 ± 21.6 | 59.2 ± 21.2 | 14.5 ± 19.7*** |
| **Panel B - Land Use Classes** | | | | |
| Area in pasture (ha) | | 40.1 ± 48.6 | 51.5 ± 59.6 | 11.4 ± 22.4*** |
| Area in perennials (ha) | | 8.6 ± 13.8 | 10.8 ± 15.6 | 2.2 ± 7.3*** |
| Area in annuals (ha) | | 2.8 ± 3.9 | 1.3 ± 2.6 | -1.5 ± 4.4*** |
| Area in secondary succession (ha) | | 7.5 ± 12.5 | 9.9 ± 12.4 | 2.4 ± 13.4*** |
| Proportion of lot in pasture (%) | | 34.6 ± 22.9 | 44.4 ± 26.8 | 9.9 ± 16.1*** |

| | | | |
|---|---|---|---|
| Proportion of lot in perennials (%) | 8.8 ± 13.8 | 11.2 ± 16.0 | 2.3 ± 7.6*** |
| Proportion of lot in annuals (%) | 2.7 ± 3.9 | 1.3 ± 2.7 | -1.4 ± 4.5*** |
| Proportion of lot in secondary succession (ha) | 7.3 ± 11.2 | 9.9 ± 11.9 | 2.7 ± 11.4*** |

Source: Authors' elaboration based on survey data for Altamira (1997/1998, 2005), Landsat imagery TM Maper (1995, 1996, 1997 and Landsat 7 ETM+ (2004, 2005, 2006).

Notes: I – For variables based on remote sensing, year of classification is 1996.

II – For change in forest cover: 2005 – 1997/1998 (1996) / For change in deforested area: 2005 – 1997/1998 (1996)

III – Pared test of difference in means 1997/1998 (1996) and 2005: *** $p < 0.01$; ** $p < 0.05$.

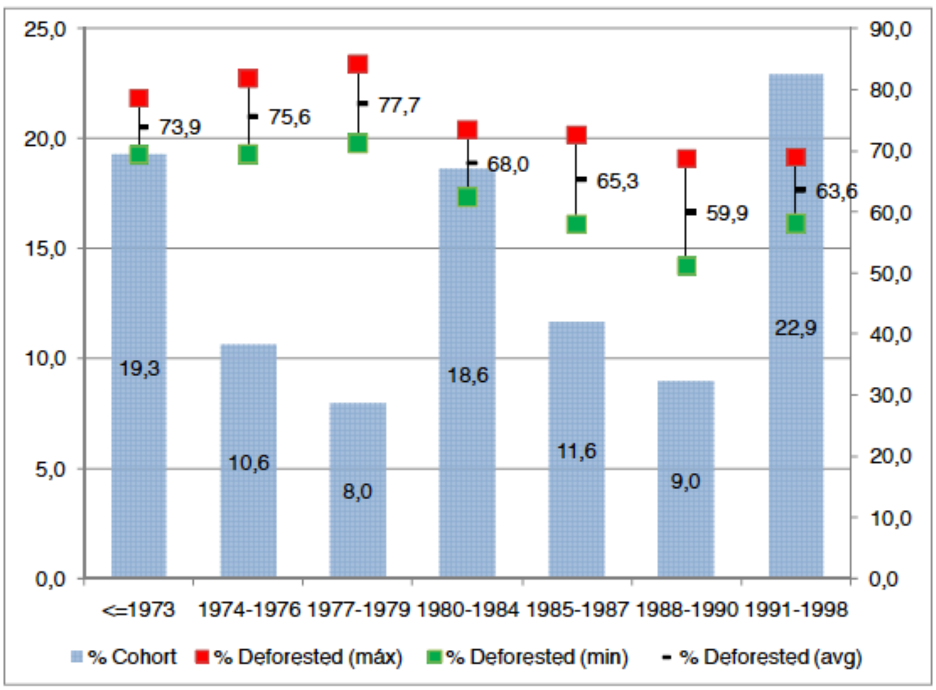
Figure 3 further investigates deforestation patterns, now associated with cohorts of settlement. As suggested by Brondízio et al. (2002), Figure 3 is indicative of *deforestation pulses*, describing a synodical pattern of increased deforestation intensity upon settlers' arrival on the property, followed by another pulse – but with less intensity – approximately 15 to 20 years later. Summers (2008) argues that this second "pulse" is likely to reflect the new possibilities open with the influence of the markets at the stage of frontier consolidation. Brondízio et al. (2002) state that the decline in deforestation intensity in the 1980's settlement cohorts is likely to reflect the adverse macroeconomic setting in Brazil, such as the high inflation rates and economic recession, leading to the reduction in subsidized credit for cattle ranching. The surge in deforestation rates in the 1990's is "(…) probably related to the economic stabilization, the low inflation rates (…) and the return of credit incentives from the FNO (Fundo Constitucional de Financiamento para a Região Norte)" (Brondízio et al. 2002: 155-156).

Table 2 also shows some indicators of land use classes and their evolution over time in the region. In general, pasture is the main type of land use in the region (34.6% in 1997/98 and 44.4% in 2005). The predominance of pasture in relation to other land use classes is common in extensive land use systems, especially in multi-crop systems where pasture and annual crops alternate to increase productivity (Ludewigs et al. 2009). Perennials appear in second. Between 1997/98 and

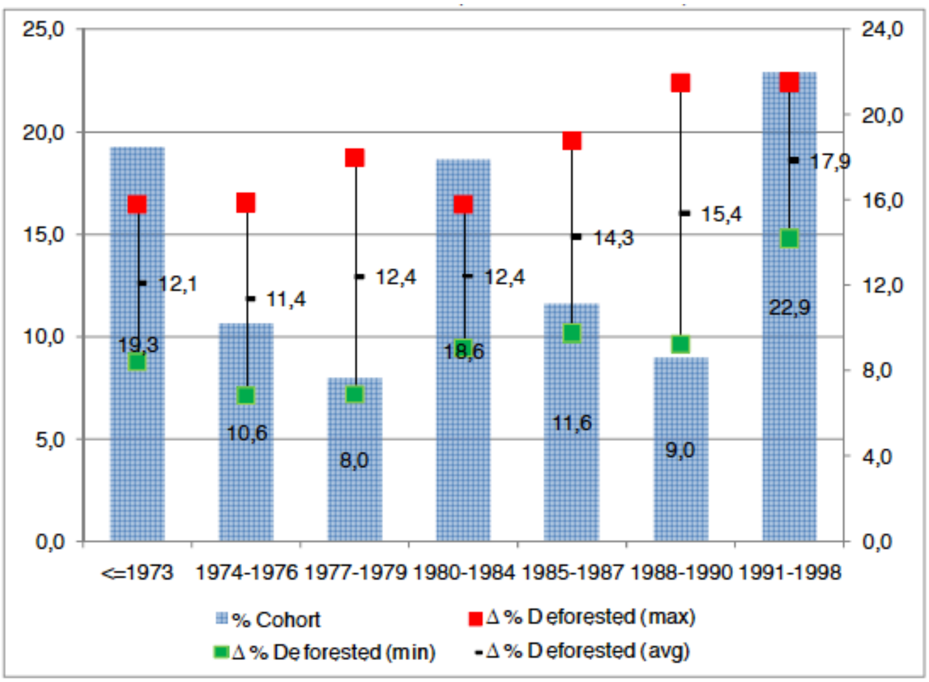
2005, there was an increase in the areas for pasture (9.9%), followed by perennial crops (2.3%), while annual crops declined by 1.4%. The increase in areas for commercial use is a natural scenario of frontiers in advanced stages of development, since agricultural households can derive a larger share of their livelihoods from the selling of agricultural production to the local and regional emerging markets.

**Figure 3 – Proportion of the Property Deforested and its 95% Confidence Interval by Cohort of Arrival on the Property – Altamira Study Area, 2005 and Δ (2005 – 1997/1998)**

Panel A – 2005




Panel B - Δ (2005 – 1997/98)

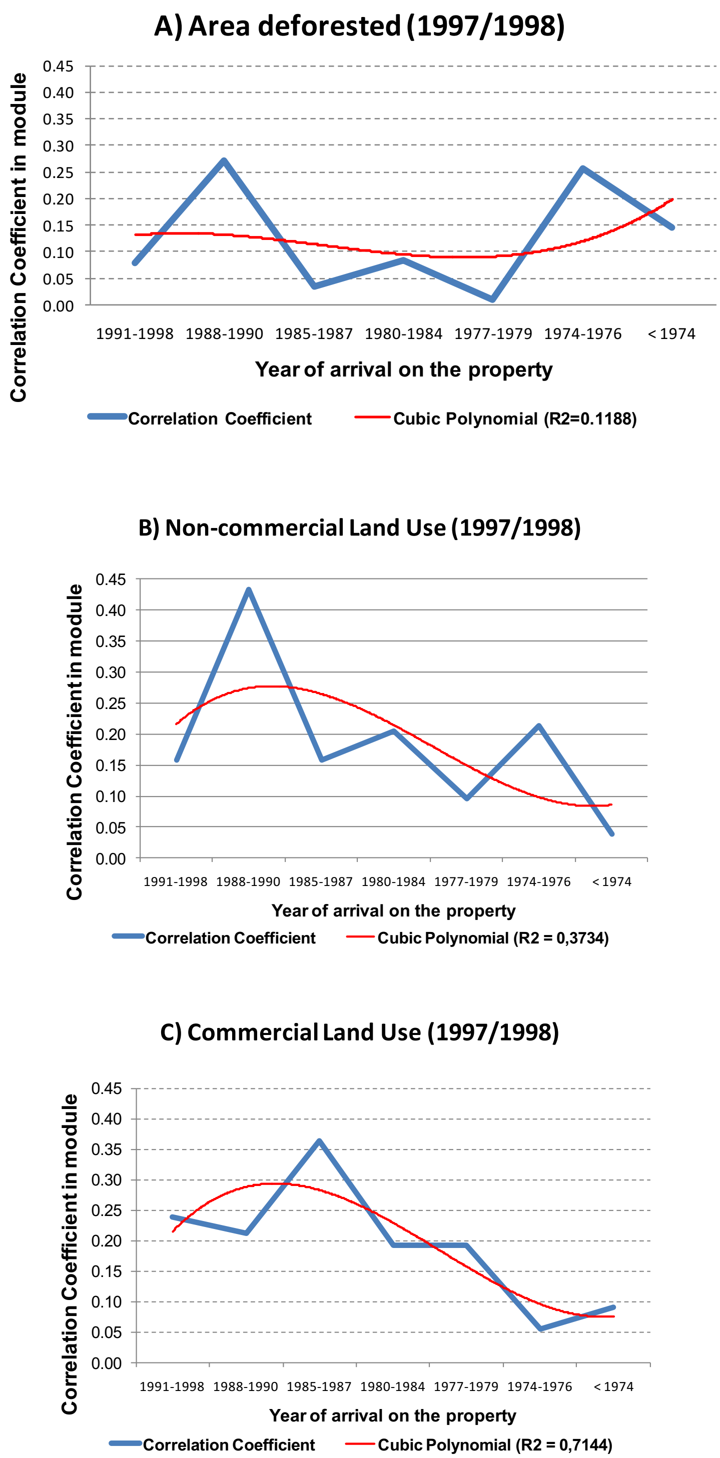



Source: Authors' calculation based on Altamira survey data (1997/98 and 2005)

Figure 4 presents further evidence of the link between settlement cohorts (indicative of the *on property life cycle*) and land use/cover classes. According to our conceptual framework, we should expect decreasing strength in the association between household life cycle and land use/cover as the number of years a household lives on the property increases. We also expect to see this interactive life cycles effect to be more pronounced for land use than for deforestation, and even stronger for commercial land use. This gradient of strength in the association between household life cycle and land use/cover mediated by *on the property* life cycle also depends on the stage of frontier development[8], as suggested by the temporal dimension of Figure 1 (Panel A).

[8] For frontiers in initial stages of development, characterized by weak ties to markets, it would be difficult to identify any cross-effect of cycles on land use change, since the influence is almost the same (households with an older demographic structure or households living longer on the property could expect to have similar patterns of land use). Since Altamira settlement is relatively consolidated, the influence of the *on the property* life cycle on the relation between household demography and land use/cover appears more clear in Figure 1.

**Figure 4 – Degree of association between deforested area, land use types, and household dependency ratio by time on the property – Altamira Study Area, 2005**




Source: Authors' elaboration based on primary survey data - Altamira Dataset (1997/98, 2005)

Results from Figure 4[9] are descriptively suggestive of the predictions derived from our conceptual framework. First, the pattern of correlation between household life cycle, *on the property* life cycle, and deforestation is not clear, as both younger and older cohorts of settlement seem to rely on family labor supply to a similar extent. Second, the association between land use/cover and household demography is not linear as time lived on the property increases. Third, the importance of household life cycle for land use/land cover seems to decrease faster for commercial vis-à-vis non-commercial land use, since *on the property* life cycle explains part of the observed association. The observed pattern of association is at the same time suggestive of cross-cycles interactions, but also a response to market integration, since the association is sensitive to the type of land use system, commercial versus non-commercial.

*Regression Analysis*

We use multivariate regression analysis to disentangle the association between *household* and *on the property* life cycle from integration into markets and properly test our proposed cross-cycle influence on land use/cover. We start by analyzing deforestation models. Table 3 shows fractional logit regressions of deforestation extent as well as deforestation activity for our study site. We define *proportion of deforestation prior to 2005* as the proportion of the property

[9] Figure 4 was created as follows: we first created a variable representing the cohort of settlement, or year of arrival on the property, which is used as a proxy for the "on the property" life cycle. We departed from a continuous variable representing the year of arrival and transformed it into an interval variable, with the following intervals: 1991 to 1998, 1988 to 1990, 1985 to 1987, 1980 to 1984, 1977 to 1979, 1974 to 1976, before 1974. This variable was based on the 1997/98 survey data. Then, we calculated the Coefficient of correlation between year of settlement within each interval and the land use/cover class, using a simple Pearson linear coefficient of correlation. Each coefficient was plotted in the graph, and a cubic trend estimation was used to capture some smoothed trend in the association over time (time read here as the cohort of arrival). Non-commercial land-use was created by summing the property area in secondary succession and annuals. Commercial land use was created by summing the areas in perennials and pasture.

deforested by 2005 (deforestation extent), and *proportion of deforestation between 1997 and 2005* as the proportion deforested from 1997/98 to 2005 (deforestation activity).

**Table 3: Fractional Logit Regression of Deforestation Extent (Proportion Deforested) and Activity (Change in Forested Area) in Altamira Study Area, 1997 – 2005**

| Variable | Proportion of Deforestation prior to 2005 (% 2005) | Proportion of Deforestation between 1997 and 2005 (Δ% 1997-2005) |
|---|---|---|
| Age of the household head (years) | -0.00518 | 0.116 |
| | -0.0615 | -0.132 |
| Number of children in the household (#) | -0.507 | 0.142 |
| | -0.523 | -1.058 |
| Number of elderly in the household (#) | 0.696 | -0.901 |
| | -0.858 | -1.778 |
| Number of adults in the household (#) | 0.567** | 0.632 |
| | -0.271 | -0.668 |
| Number of years living on the property (years) | -0.103 | -0.323** |
| | -0.0659 | -0.152 |
| Property first occupied before 1970 (baseline) | | |
| Property first occupied between 1970 - 1979 (0/1) | 2.554** | 1.201 |
| | -1.179 | -3.688 |
| Property first occupied between 1980 - 1990 (0/1) | -0.0369 | -4.945 |
| | -2.131 | -5.122 |
| Property first occupied after 1990 (0/1) | -8.667*** | -11.12* |
| | -3.126 | -5.721 |
| Distance of the property to Altamira urban center (ha.) | -4.38e-05** | -0.000116*** |
| | -2.06E-05 | -4.02E-05 |
| Proportion of agricultural production sold (%) | -0.00653 | -0.0233 |
| | -0.0161 | -0.0324 |
| No participation in unions/associations (0/1) | -2.965** | -0.896 |
| | -1.498 | -2.465 |
| Did any household member migrated from the household? (0/1) | 0.759 | 1.528 |
| | -0.979 | -2.161 |
| Did any migrant remit back to the household? (0/1) | -1.057*** | -1.36 |
| | -0.404 | -0.894 |
| Proportion of the property deforested (%) | 0.202*** | -0.488*** |
| | -0.0281 | -0.0573 |

| | | |
|---|---|---|
| Property size (ha.) | -0.000964 | 0.00787 |
| | -0.00361 | -0.013 |
| Constant | 47.94*** | 43.73*** |
| | -3.981 | -8.215 |
| Sigma | 7.146*** | 14.14*** |
| | -0.414 | -0.764 |
| Observations | 258 | 258 |
| R-squared | 0,1087 | 0,0552 |

Robust standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1
Source: Authors' elaboration based on primary survey data - Altamira Dataset (1997/98, 2005)

The model for proportion of deforestation *prior to 2005* shows evidence that increasing potential family labor force (number of adults) affects the total area deforested, regardless of the property life cycles[10]. We found no evidence of an independent effect of *on the property* life cycle, although *property* life cycle is non-linearly associated with the cumulated deforestation. For instance, while properties first occupied between 1970 and 1979 had, on average, 2.6% less area in forest than properties settled before 1970, newer settled areas had statistically significantly more forest. This is consistent with the history of Altamira settlement area and other colonization projects elsewhere in the Amazon (Rindfuss et al. 2007). Also consistent with our framework, proximity to markets increases the level of deforestation, as does participation in unions/association[11]. Results for proportion of deforestation between 1997 and 2005 reveal, to the contrary, that *on the property* life cycle plays an important role, but not household demography. This is reasonable, as longer resident households are more likely to consolidate their land use

[10] We recognize that this is not a causal relationship, since all deforestation observed could have happened before 1997/98.
[11] This evidence could also render an endogenous situation where successful farmers are able to join unions. We have not enough data to handle this potential bias.

systems[12]. Meso-level institutions, such as family remittances and participation in unions are forest-protective. This may reflect three scenarios: (1) information and money (remittances) flowing from these networks are being used to improve efficiency of already deforested area, reducing pressure on marginal demand for land; (2) resources are being invested in a more diversified portfolio of assets, reducing reliance on agricultural production, or (3) remittances are allowing them to purchase food and are therefore decreasing area in annuals, which has to be cleared every couple of years.

Table 4 shows results from the model of land use classes. Also consistent with our theoretical framework, integration into markets is important for the increase in commercial land use. Every kilometer away from Altamira urban core reduces the area in annuals and pasture, and increases area in perennials and forest. The positive effect on perennials may seem paradoxical, but it is explained by the spatial concentration of cocoa production in the center-west part of our study area, west of Altamira (Guedes et al. 2014)[13].

**Table 4: Seemingly Unrelated System of Linear Regressions regarding Land Use and Land Cover Classes in Altamira - Area of the Property (hectares), 1997 – 2005**

| Variable | Perennial | Pasture | Annual | Forest |
|---|---|---|---|---|
| Number of years living on the property (years) | 0.226** | -0.791*** | -0.0232 | 0.313 |
| | -0.0967 | -0.292 | -0.0371 | -0.235 |
| Demographic household dependency ratio (dependents/adults) | 12.86*** | -26.83** | 0.711 | 6.54 |
| | -3.96 | -11.94 | -1.519 | -9.624 |

[12] We found no statistically significant effect of interaction between household life cycle and on the property life cycle and excluded it from the final model, as it increased model instability.

[13] Because of the topography and soil diversity of Altamira region, distance from Altamira urban center is a combination of a market effect and a biophysical change effect. This is the main reason why, while calibrating regression models, we included proportion of production sold as an independent dimension of integration to markets.

| | | | | |
|---|---|---|---|---|
| Number of years on the property x Dependency ratio | -0.592*** | 0.812 | -0.044 | -0.101 |
| | -0.206 | -0.621 | -0.0789 | -0.5 |
| Time since first occupation of the property | -1.131*** | -1.009 | 0.158 | 1.620* |
| | -0.389 | -1.174 | -0.149 | -0.946 |
| Distance of the property to Altamira urban center (ha.) | 4.62e-05** | -0.000138** | -1.56e-05** | 0.00 |
| | 0.00 | 0.00 | 0.00 | 0.00 |
| Proportion of agricultural production sold (%) | 0.0300** | -0.0408 | 0.000628 | 0.0245 |
| | -0.0145 | -0.0438 | -0.00556 | -0.0353 |
| No participation in unions/associations (0/1) | -1.574 | 1.843 | 0.649 | -0.813 |
| | -1.237 | -3.731 | -0.474 | -3.007 |
| Did any household member migrated from the household? (0/1) | 0.727 | -3.367 | 0.427 | 0.984 |
| | -0.937 | -2.826 | -0.359 | -2.278 |
| Did any migrant remit back to the household? (0/1) | 0.187 | -0.952 | -0.024 | 0.093 |
| | -0.444 | -1.34 | -0.17 | -1.08 |
| Property size (ha.) | 0.00273 | 0.717*** | 0.00470* | 0.227*** |
| | -0.00646 | -0.0195 | -0.00248 | -0.0157 |
| Proportion of the property in primary forest (%) | -0.0533 | -0.0277 | -0.0281* | 0.528*** |
| | -0.0429 | -0.129 | -0.0164 | -0.104 |
| Proportion of the property in perennials (%) | 0.850*** | -0.252 | -0.0117 | -0.149 |
| | -0.0548 | -0.165 | -0.021 | -0.133 |
| Proportion of the property in pasture (%) | -0.110** | 0.797*** | -0.0415** | -0.192* |
| | -0.0433 | -0.131 | -0.0166 | -0.105 |
| Proportion of the property in annuals (%) | -0.250** | 0.208 | 0.0764* | 0.0446 |
| | -0.104 | -0.313 | -0.0398 | -0.252 |
| Constant | 4.455 | -15.72 | 3.858** | -27.44** |
| | -4.711 | -14.2 | -1.806 | -11.45 |
| Observations | 258 | 258 | 258 | 258 |
| R-squared | 0.783 | 0.887 | 0.086 | 0.651 |

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1
Source: Authors' elaboration based on primary survey data - Altamira Dataset (1997/98, 2005)

Household demography also has different impacts depending on each type of land use: household dependency ratio increases area in perennials and decreases area in pasture. This result suggests that households make adjustments not only to their life cycle stage, but also to their knowledge about the returns to the land in face of market stimulus. Medicilândia, for example, has the highest cocoa productivity in Brazil and many smallholders are taking advantage of the increase in the commodity price to shift to intensification of perennial cropping (Guedes 2010). Because cocoa is labor intensive, however, household life cycle continues to play a role, with a likely effect on male labor retention. Finally, also as suggested by our framework, *on the property* life cycle attenuates the effect of household life cycle (as seen by the inverted signal of the interactive term in the land use equations), especially for perennial production. Meso-level institutions, such as familial networks and agricultural associations, show no independent effect on land use classes. Given that these frontier-endogenous institutions have a forest-protective effect but no impact on land use, it might be likely to be working as channels for diversification of household livelihood strategies beyond agricultural production.

## Conclusion: Rethinking the Coevolution of Household Demography and Land Use/Cover over Frontier Development

In the last forty years, pasture formation and cattle ranching were the leading drivers of deforestation in the Amazon (Fearnside 2005). The high deforestation rates observed were attributed, for many years, to the demographic dynamics and livelihood strategies of smallholders entering the area through government-sponsored colonization projects or spontaneous migration (Rindfuss et al. 2007). Most of the micro-level frameworks developed to explain land use/cover dynamics in tropical agriculture frontiers assumed simultaneous influence of household and property life cycles, using hypothetical cohort frameworks borrowed from formal demography (Walker and Homma 1996, McCracken et al. 1999). More recent developments incorporate the influence of market integration in land use strategies at the household level (Walker 2004, Caldas et al. 2007). These models, however, continue to ignore cross-cycle influences over the frontier development.

Building on the recent schematic capital and livelihoods framework proposed by Emery et al. (2016) and VanWey et al. (2012b), we develop a theoretical framework for land use strategies among smallholders in tropical frontiers that explicitly addresses cross-cycle influences over frontier development. Our proposed framework considers scale issues related to both *space* (or spatial scale) and *time* (or temporal scale) as factors affecting "on the ground" land use choices. The space dimension implies that as smallholders become connected to markets at higher spatial scales (national, global), the link between household demography and land use choices is loosened.

Meso-level institutions emerging along the frontier development, such as familial and social networks, mediate this cross-scale connection between cycles and land use choice. For instance, remittances from family members who out-migrated to other countries or urban states were associated with less deforestation and increased areas in commercial land use. These effects may reflect the more complex nature of social capital in evolved frontier settings, where household composition is expanded over space, using their "external" members (strong ties) and their new connections (weak ties) as an expanded demographic structure of households. Household life cycle, thus, would operate across space through these networks, netting out the effect of local household demography on land use choices[14]. Also assumed by our framework, the temporal scale

[14] Membership to local associations, another proxy for meso-level factors, were not significant for most land use decisions, although was significant for reducing pressure on the remaining forest. This is coherent to the idea that local associations are a type of meso-level institution that has a less complex spatial outreach than migration networks of the family members and its associated remittances of financial and informational resources across space (and thus, across networks carrying different assets) (Wegener, 1991; Emery et al., 2016).

affects land use choices by changing the perceived returns from different land use systems as frontiers evolve to a post-frontier scenario.

We found that this post-frontier is characterized by increasing integration between rural and urban areas, as well as by closer smallholder–market connections. In fact, we show that the further away from Altamira the smaller the amount of land dedicated to annuals and pasture, which are the most profitable land uses when commercial used. At the frontier inception, the influence of the household life cycle is indistinguishable from the influence of the property's life cycle on land use choices, since the first stage represents a phase of experimentation to the new biophysical environment.

As frontier evolves, the two cycles become increasingly distinct, with property's life cycle overtaking the influence of the household life cycle on land use choices. At later stages, household age composition is less important because local paid labor market and laborsaving technologies are more efficient inputs than household demography. At the same time, as discussed in Caldas et al. (2007), the opportunity cost of family labor increases at later stages of development, making it less attractive for households to restrict their family labor pool to family agriculture. In this regard,, we found i) a decreasing importance of household life cycle factors over time for commercial versus non-commercial land uses, ii) that property life cycle is important to explain deforestation over time, but not household life cycle, and iii) that property life cycle attenuates the effects of household life cycle.

Because our theoretical model addresses small-scale agriculture, however, the influence of the household life cycle persists even in later stages of frontier development. We argue that the explicit incorporation of cross-cycle interactions within a time perspective is key to understand two distinct questions: why initial models of smallholders agriculture assumed hypothetical cohort influences over life cycle, and why it is observed the same influence of household life cycle on land use choices among older rural households in younger frontiers or younger households in older frontiers, as suggested by other studies (Rindfuss et al. 2007, VanWey et al. 2007).

This study brings initial theoretical and empirical insights to these questions, although the empirical support is limited due to the absence of a truly cohort study of smallholder frontier development. Using a longitudinal dataset representative of a government-sponsored colonization area in the Amazon, we show how household demography decreases its influence as households age in the frontier and increase their on-site capital. This cross-cycle influence is stronger for commercial land uses in a post-frontier scenario, such as Altamira. Distance from market seems to have a direct impact on the perceived return to agricultural production, de-incentivizing deforestation and commercial crops.

Different from previous studies, we explicitly differentiate three life cycles: household life cycle, *on the property* life cycle, and *property* life cycle. Results from our land use models show that the proposed interaction between household and *on the property* life cycles holds, even after controlling for the history of property use. In future works we intend to expand our empirical analysis to other study sites in the Amazon with different biophysical characteristics, and at different stages of frontier development. Cross-site comparisons will allow us to increase the generalizability of our proposed framework, as well as to verify if later stages of development would lead to increasing within-frontier specialization and between-frontiers diversification. This last prediction, if valid, has important implications for future regional landscape dynamics.

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