Environmental Development 38 (2021) 100587

Contents lists available at ScienceDirect

Environmental Development

journal homepage: www.elsevier.com/locate/envdev

Land use systems and livelihoods in demographically heterogeneous frontier stages in the amazon

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A R T I C L E I N F O

Keywords:
Household demographic dynamics
Land use systems
Deforestation
Livelihoods
Settlement cohorts
Brazilian amazon

A B S T R A C T

We investigate how Amazonian smallholders' land use systems coevolve with household-level demographic factors associated with changing livelihood strategies over the different stages of frontier development. Few micro-level studies have investigated this association, particularly due to the paucity of longitudinal data on cohorts of farm colonist households and plots. Cohort analysis is the only way to depict how the structural conditions affecting individual and household livelihood decisions differ from earlier to later stages of frontier development. Our methodological approach involves a unique dataset, based on a micro-level panel of farm households depicting 25 years of settlement in the municipality of Machadinho, in the Brazilian Amazon. We use descriptive statistics with paired t-tests, land use classification analysis, latent transition analysis, and longitudinal multinomial regressions to understand which cohorts of households thrived or failed and, most importantly, why and when. Splitting the data into panels of settlement cohorts helped us understand the effect of demographic life cycle markers on land use choices over the different stages of frontier development and the ability of farm households to adapt their livelihoods at the frontier over time. We found that, as the colonization frontier integrated into markets, the most successful original settlers were those who diversified their portfolio of capitals and livelihood strategies as a response to new local and regional market conditions. We also found a progressive change from land use systems based on subsistence agriculture to diversified land use systems that combine on- and off-farm activities. Livelihood diversification is key to preventing households from becoming trapped in a long-term deprivation trajectory, particularly when the frontier becomes more urban and market-oriented. This explains why land use has become progressively independent of household demographic dynamics in advanced stages. We contend that, as frontiers integrate into markets, diversification should not only be incentivized, but should also be used as a technical strategy to enhance access to subsidized rural credit, as it seems to increase farmers' likelihood to thrive and improve their resilience against shocks.

1. Introduction

High deforestation rates are one of the most remarkable features of contemporary (post-1970s) colonist settlements in the Brazilian

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https://doi.org/10.1016/j.envdev.2020.100587
Received 6 November 2019; Received in revised form 21 October 2020; Accepted 26 October 2020
Available online 9 November 2020
2211-4645/

Amazon (Smith, 1982; Skole et al., 1994; Almeida and Campari, 1995). Despite the large stock of deforested areas and degraded forests, studies identified a decline in deforestation rates in the Brazilian Amazon in the first half of the 2010s (INPE, 2010; FAO, 2011). This decline was associated with institutional framework changes (Tomaselli and Sarre, 2005; Nepstad et al., 2014) and actions taken by social movements to impede advances in forest degradation (Schwartzman et al., 2010).

However, since the mid-2010s, deforestation in the Brazilian Amazon has increased (Lovejoy and Nobre, 2018) as a consequence of several recent policy changes, such as reduced environmental licensing requirements, more business and landholder-friendly policies, and a lack of economic incentives for landowners to avoid land clearing beyond legal limits (Azevedo et al., 2017). Less strict environmental policies and surveillance have put all previous efforts to curb deforestation in the region at risk, especially by reducing the size of protected indigenous lands and conservation areas and by easing land grabbing for illegal logging, agribusiness, cattle ranching, and gold mining (Rochedo et al., 2018). Rising deforestation and disturbances in the Amazonian ecosystem are also linked to long-term unsustainable land use choices (Davidson et al., 2012; Sonter et al., 2017; Lima et al., 2018) and large-scale infrastructure development, especially roads and dams (Fearnside, 2006; Perz et al., 2008; Pfaff et al., 2009).

Most studies that provide scientific support to the threat faced by the Amazon basin have used macro-level analysis involving regional, computational, or spatial models based on census data (Aldrich et al., 2012; Sathler et al., 2018). These studies reveal multi-scale dependencies and interactions (e.g., how household land use decisions reflect changes in the political context) to explain land use and deforestation patterns in the Amazon (Barbieri et al., 2009a; Barbieri and Pan, 2012; Brondizio and Moran, 2012). Given the degree of ecological and socioeconomic heterogeneity within areas of the Amazon (Sathler et al., 2018; Guedes et al, 2009, 2009b), some studies have focused on micro-level processes to model demographic dynamics and their linkages to macro-scale processes in order to explain land use and land cover changes over time (See, e.g., Walker and Homma, 1996; Pichón, 1997; Walker et al., 2002; Barbieri et al., 2005a; Caldas et al., 2007; VanWey et al., 2007; Brondizio and Moran, 2012; VanWey et al., 2012a, 2012b; Aldrich et al., 2012). However, some of these studies lack longitudinal survey data following cohorts of farm household colonists and plots over all stages of frontier development that make fully mapping long-term household trajectories possible. The few studies that have used truly longitudinal microdata are based on data depicting the later stages of frontier development, where the structural conditions affecting individual and household decisions are different from earlier stages (see VanWey et al., 2012a; Richards and VanWey, 2016; Guedes et al., 2017, concerning the Altamira/Santarém settlements in the Brazilian Amazon; Caviglia-Harris, 2018, focused on the Ouro Preto D'Oeste region in the Brazilian Amazon; and Barbieri et al., 2005a and Sellers, 2017, regarding the Northern Ecuadorian Amazon).

We argue that focusing our analysis on distinct cohorts in different stages of frontier development allows for a more reliable assessment of how different life cycle constraints/opportunities translate into different land use choices. This is an exclusively demographic perspective of age-period-cohort analysis that is almost entirely absent from many studies of Amazonian non-indigenous settlements because data covering an area and resident families since the beginning of settlement are quite rare. In this regard, we use a dataset for the municipality of Machadinho d'Oeste, in the state of Rondônia, in the Brazilian Amazon, which combines demographic, plot, and land use data from a panel of plots and farm households ranging from the initial colonization of the area in the mid-1980s until 2010. This is the only study area in the Amazon with panel survey data for the same plots since the start of occupation. We examine how household-level demographic factors and livelihoods may explain the evolution of land use systems and deforestation in agricultural settlements in the Amazon. Similar to Carr et al. (2005) and VanWey et al. (2007), we hypothesize that household life cycle markers, such as household size, composition, and migration strategies, play an important role in explaining deforestation and land use changes. However, these roles depend on farm households' stages of development when arriving at the frontier (Guedes et al., 2017). Splitting our 25-year-long dataset into panels of settlement cohorts helps us understand why previous studies have found that demographic life cycle markers have little impact on land use choices. We show that as the colonization frontier integrated into markets, the original settlers most likely to thrive were those who diversified their portfolio of capitals and livelihood strategies in response to new local and regional market conditions. In this context, there was a progressive change from land use systems based on subsistence agriculture to diversified land use systems that combine on- and off-farm activities. This was particularly true for a subgroup of original settlers and for select new farm households entering the frontier at later stages. Consequently, the frontier landscape has shifted from a homogenous pattern of family farming to a highly heterogeneous space, where consolidated commercial farming coexists with impoverished, traditional subsistence practices.

By following the plots and cohorts of colonists over distinct stages of frontier development, we are able to provide evidence that supports the three following hypotheses: 1) *household demographic dynamics take an increasingly different trajectory from plot dynamics over the stages of frontier development* (*stage dependence hypothesis*). This hypothesis implies that two households with the same demographic composition and the same portfolio of capitals will experience different returns depending on their time of arrival at the frontier; 2) *increasing articulation of urban and labor markets, as the frontier evolves and creates new opportunities for households to diversify their livelihoods, leads to a growing probability of adopting a diversified land use system and, consequently, increased resilience (dynamic resilience hypothesis)*. Here, we explore the different ways that rural households respond to constraints and opportunities as frontiers evolve from subsistence to market-oriented rural spaces; and, 3) *as the time since initial settlement increases, market integration requires increasing economies of scale in farm production (selective land consolidation hypothesis*). This hypothesis assumes that land use choices with higher profitability are more likely to be concentrated among farmers with larger number of plots, where land consolidation reflects the required economies of scale.

Our panel data allows for the assessment of these hypotheses since it controls for the duration and time since arrival, from the original (pioneer) settlement until the contemporary, market-integrated frontier. Thus, our analytical strategy combines: i) a descriptive analysis of demographic characteristics, livelihoods, and land use at distinct stages of frontier development, ii) a latent transition model that estimates the trajectories and the transition probabilities of household livelihoods and their associated land use systems over time, and iii) a panel multinomial logistic model that analyzes how the probability of adopting different types of land use systems is associated with distinct household and plot characteristics, net of unobserved fixed effects that are key to land management decisions, such as land quality, soil fertility, and the distance to local markets.

We explore three key concepts in this paper. *Household demographic dynamics* refers to the temporal changes in household size (i.e., the number of people living in a dwelling unit) and composition (i.e., the proportion of adults and children, age and gender structure, education, and family type). *Plot dynamics* encapsulates the temporal changes in land use and land cover (i.e., annuals, perennials, cattle ranching, and deforestation). Finally, *land use systems* describes the combination of income-generating activities regarding forest resources, annual crops and perennials, cattle, land consolidation (through the acquisition of additional plots), and non-farm activities.

1.1. Farm household demographics, livelihoods, and land use in the amazon

We constructed our theoretical framework based on the assumption that the degree of interdependence between plot and household demographic dynamics varies at different stages of frontier development, ranging from a highly dependent relationship at the initial stages to an increasingly independent trajectory at later stages. We call this trend *stage dependence*. This type of interconnection translates into different effects that demographic and plot dynamics exert on how land use systems are formed and modified over time. When demographic and plot dynamics favor the development of more diversified livelihood strategies, households are more likely to thrive over time, a tendency we call *dynamic resilience*.

Although some frontiers occupied by non-indigenous populations (particularly colonists) may experience boom-and-bust cycles of development – from intense deforestation to land abandonment – there is a general trend characterized by demographic and economic shifts from subsistence agriculture to progressive market integration (Walker, 2004; Barbieri et al., 2005a, 2009a; Caldas et al., 2007; Barbieri and Pan, 2012; VanWey et al., 2012b; Perz et al., 2013; Guedes et al., 2017). Over time, rural households become more market-oriented and develop endogenous strategies to adapt to local environments (Browder et al., 2004; Caldas et al., 2007). For example, some studies suggest that land turnover, migration, and fertility changes are triggered by changing local conditions (VanWey et al., 2012b; Pan and Carr, 2016). This learning-by-doing process allows them to diversify across economic sectors and specialize in more profitable land use systems over time (VanWey et al., 2007, 2012a).

Building upon the findings of Barbieri et al. (2014), we define three stages of frontier development. In the *opening frontier* stage, deforestation is mostly explained by colonist production strategies to meet family reproduction needs. These needs reflect colonist households' high youth dependency ratios, low levels of on-farm production, and the available household labor supply, which may necessitate agricultural off-farm employment as a means to overcome the absence of initial on-farm capital. Evidence from different colonist frontiers in the Amazon suggests that government-led settlement projects, such as Machadinho d'Oeste, favored larger families (VanWey et al., 2007), who also benefited from better soil quality upon arrival (Castro and Singer, 2012).

The second stage corresponds to an *expansion frontier*, in which farm households move from mostly annuals to a balance between annual crops and more profitable land uses, such as perennials and cattle ranching. This strategy shift reflects the tendency of colonists to take advantage of smaller dependency ratios, as their children reach working age.

Finally, a *consolidated or post-frontier* stage prevails in aging households and increases household livelihood diversification on and off the farm, encompassing urban-oriented off-farm activities, the integration of rural livelihoods into local and regional urban markets, and the expansion of the welfare state to the Amazon through cash transfer programs.

The literature has associated each of these three stages with distinct household demographic and plot characteristics. Drawing upon Chayanov's peasant cycle (Thorner et al., 1986; Ellis, 1988), several authors have investigated the evolution of household and plot (land use) cycles, as well as their potential relationship, in the Amazonian context (e.g., Walker and Homma, 1996; Marquette, 1998; McCracken et al., 1999; McCracken et al., 2002; Perz, 2001; Walker et al., 2002; Moran et al., 2003; Barbieri et al., 2005a; Caldas et al., 2007; Guedes et al., 2017). Despite the acknowledgement that land characteristics, such as soil quality and topography, as well as how the use of financial capital and nearby markets can affect production choices, household labor supply is considered to be a key demographic factor in determining the farm production level that fulfills household consumption needs under the "Household and Land Use Life Cycle" approach. This is particularly true in the early stages of frontier development and in areas where labor opportunities outside family production are scarce. In this regard, household and plot dynamics would be essentially endogenous over time in determining farm household production (land) and reproductive (demographic) levels (Barbieri et al., 2005a; Guedes et al., 2017).

The "Household and Land Use Life Cycle" approach implies a predictable pattern of deforestation that is elevated upon arrival at the property to fulfill the immediate consumption needs of the recently established farm. This is followed by a phase of low deforestation rates, as the household ages and consolidates its land use strategy toward more profitable land uses, such as cattle ranching (Barbieri et al., 2005a; VanWey et al., 2012a). When the household reaches later stages in its life cycle, some children may leave home to establish their own residences within the original property boundaries (*generational shift*) or migrate to urban or other rural areas (*empty nest*) (Perz, 2001; VanWey et al., 2012b). In the case of the empty nest scenario, deforestation should decrease further; however, if the generational shift pattern prevails, we should observe additional deforestation to fulfill the immediate consumption needs of second-generation households (Perz, 2001; McCraken et al., 1999).

The Chayanovian perspective on the coevolution of plot (land use and land cover) and demographic processes implicit in the life cycle approach is challenged when we consider non-demographic responses related to land use management decisions, in terms of both extensification (Malthusian) or intensification (Boserupian) responses. As suggested by Bilsborrow (1987), households can adopt demographic responses that ultimately define household size and composition simultaneously with land management responses. Consequently, deforestation and land use trajectories may follow a pattern that is not entirely causally explained by household composition. For instance, cattle ranching (a typical extensification response in the Amazon) might not be confined solely to later life cycle stages, given the accumulation of capital and land, as well as older household age compositions (intensification response). It may also be a response at earlier stages, even in a context of low accumulation of capitals and younger dependency ratios.

The increasing integration of agricultural frontiers into national and global markets (Brondízio, 2008) and the practice of selling and hiring paid labor at low wages in critical stages of agricultural management (VanWey et al., 2007, 2012b) may also diminish the effect of demographic responses over time. In this regard, recent efforts to adapt the household and land use life cycle approach to the Amazon assume a progressive and linear integration of rural households into markets, despite the nonlinear paths followed by demographic and plot dynamics (Guedes et al., 2017). They also suggest that changes in household demography modify household preferences toward riskier activities, as properties consolidate their agricultural practices (Walker, 2004; Caldas et al., 2007). Land use strategies and demographic responses regarding fertility regulation and mobility may also change, as colonists perceive shifts in socioeconomic conditions at the frontier (Bilsborrow, 1987; Pichón, 1997; Barbieri et al., 2005a, 2009a; VanWey et al., 2012b; Pan and Carr, 2016).

In a similar vein, the *capability framework* (Bebbington, 1999) states that farm households develop the ability to derive their livelihoods from distinct sources or *capitals*, such as natural, human, social, physical, and financial capital (Sherbinin et al., 2008; Guedes et al., 2012; Guedes et al., 2014; VanWey et al., 2012a). Although, at later frontier stages farmers may become more market-oriented, they may adopt a type of land use system in which they derive their livelihoods from a combination of on-farm sources, such as extractivism, crops, and livestock husbandry, in addition to off-farm sources, such as pensions, wage labor, circulation, and remittances (Perz et al., 2013). The adoption of distinct strategies over time reflects two processes, encompassing households' ability to shift their portfolio of available capitals in response to their perceived utility (returns) (VanWey et al., 2012a; Hull and Guedes, 2013) and their response to contextual factors, such as the frontier's social, economic, and political environment (Sherbinin et al., 2008; VanWey et al., 2012a).

Farm households take advantage of the penetration of urban, financial, and labor markets in the post-frontier in order to diversify their livelihoods and potentially achieve the means to substitute capitals. Increased economic returns to scale in advanced frontier stages incentivize households to increase physical capital, favoring both land extensification (the acquisition of new plots), as well as land intensification through the acquisition of chainsaws, tractors, and pesticides. For example, Barbieri et al. (2014) provide evidence of this process in Machadinho from 1995 to 2010. Land consolidation in Machadinho increased during this period, with 32.4% of farm households owning other plots in 2010 compared with just 20.2% in 1995. Their use of rural credit or loans also increased (47.3% versus 20.7%), as did off-farm labor opportunities for household members (16.8% versus 6.7%) and the use of hired farm labor (44% versus 29.8% in 1987; data for 1995 is unavailable).

Households can also adapt their livelihoods to constraints and opportunities by accessing global commodity markets (especially soybeans) and by taking advantage of economic liberalization and macroeconomic conditions (Richards et al., 2012; Weinhold et al., 2013; Richards and VanWey, 2016). Furthermore, the penetration of cash transfer programs in the Amazon, such as the *Bolsa Familia* and rural retirement pensions, (Lima and Braga, 2016), and the increasing flow of remittances from international and internal migration (Guedes et al., 2009a,b; Raad and Guedes, 2015) have provided new momentum for rural livelihoods and have reduced farm households' dependence on on-farm production (Barbieri et al., 2014).

These livelihood-redefining elements may also reinforce the independence of plot and farm household demographic dynamics as the frontier becomes more urbanized and rural livelihoods become increasingly articulated to exogenous markets at several levels (Barbieri et al., 2005a). Further research concerning the Amazon has provided evidence supporting this assertion, based on both later (Caldas et al., 2007; VanWey et al., 2007; Barbieri et al., 2009a; Aldrich et al., 2012; Barbieri and Pan, 2012; Guedes et al., 2014, 2017) and earlier frontier stage data (Barbieri et al., 2005a).

Not all livelihood strategy changes brought on by the market integration of non-indigenous settlement frontiers, such as land consolidation and intensification, are driven by thriving, resilient households. These changes may also be the result of land turnover, when new farmers buy the land of struggling farm households (VanWey et al., 2012b). This selective process ownership turnover is usually followed by farm specialization in commercial land use systems – mainly cattle ranching – and increases in property size through land consolidation.

In summary, the evolving frontier scenario is a result of four distinct factors. First, household demographic dynamics affect land use choices, as predicted by household life cycle theories (Ellis, 1992; Sherbinin et al., 2008; Walker et al., 2002). Second, the growing independence of plot dynamics from household dynamics emerges during the transition to later stages of frontier development (Barbieri et al., 2005a; Guedes et al., 2017). Third, evolving frontiers are characterized by the increasing connectivity of rural and urban areas through the migration of select family members, dual-residency, and growing market-oriented land use systems (Andersen et al., 2002; Barbieri et al., 2009b; VanWey et al., 2012b), as well as the extension of road networks (Barbieri et al., 2009a; Pfaff et al., 2009). Finally, institutional changes, namely political and economic changes, affect farmers' perceived returns to their capital stocks (Sawyer, 1984; VanWey et al., 2012a; Barbieri et al., 2014) or attract new farmers who take advantage of economic returns to scale in the advanced stages of frontier development. While initial frontier stages are characterized by greater household dependence on their ability to provide and use family labor to fulfill their consumption needs, later stages reflect the combination of multiple land use and income generation strategies (e.g., a mix of crops, perennials, cattle ranching, and off-farm employment), as well as some highly specialized land use options, such as cattle ranching.

1.2. Study area: machadinho, Brazilian Amazon

Machadinho D'Oeste (abbreviated as Machadinho, Fig. 1) is a municipality located in the state of Rondônia, in the southwestern part of the Brazilian Amazon. Machadinho is within the so-called "arc of deforestation," the area with the highest historical rates of

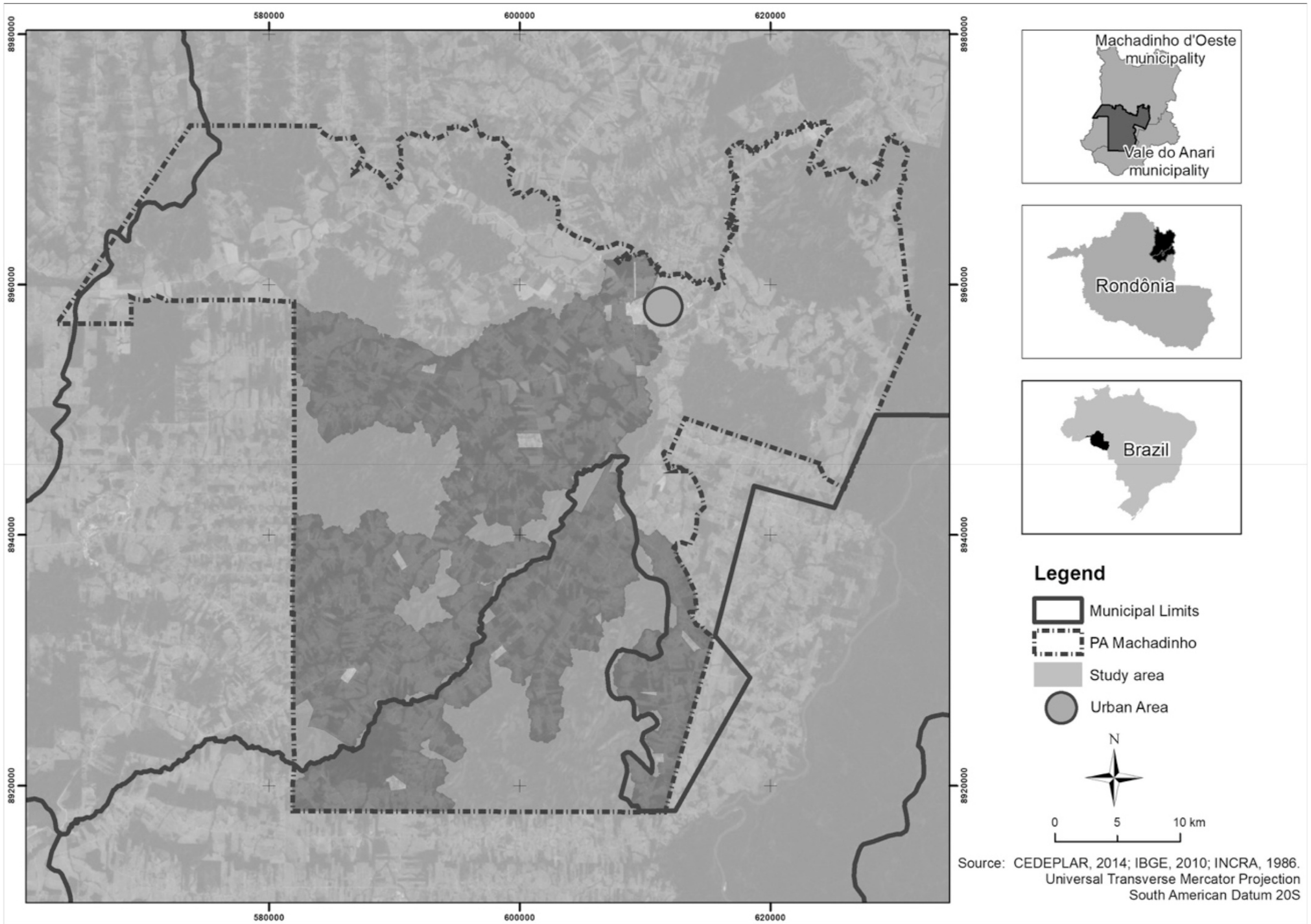

Fig. 1. Study area in Machadinho, Brazilian Amazon.

primary forest conversion in the Brazilian Amazon. Located within the municipality of Machadinho, the *Machadinho Settlement Project* (*PA Machadinho*) is a former planned colonization project that was conceived by the Northwest Region Integrated Development Program (Polonoroeste), which was approved in 1981 and was partly financed by the World Bank. One of its distinguishing features related to other colonization areas in the Brazilian Amazon was the settlement design: "the traditional 'fish-bone' pattern of settlements was replaced by an irregular land division that accounts for local hydrology and topology, resulting in plots with frontage to roads and rear access to a natural water sources" (Castro et al., 2006b, p.2453). The occupation of plots by farm colonists began in 1984 (see further discussion in Monte-Mór, 2004). By July 1985, Machadinho's urban nucleus had become a small boomtown, with over 1, 500 houses, although approximately 30% of them were unfinished or only used as a second home – an "urban base" – for rural families (Monte-Mór, 2004). With an area of 8,500 km^2 – with approximately 32% of this area being preserved and protected extractive reserves – Machadinho's population grew from hundreds of initial residents in the mid-1980s to approximately 17,000 in 1991, 23,000 in 2000, and 31,000 in 2010 (Sydenstricker, 2012).

The research on Machadinho has added relevant knowledge concerning the socioeconomic, demographic, and environmental drivers of malaria prevalence in the Amazon (Castro, 2002; Castro and Sawyer, 2006; Castro et al., 2006a, 2006b). It has also furthered knowledge regarding urbanization and migration patterns since the onset of colonization (Sydenstricker, 1992; Monte-Mór, 2004; Barbieri et al., 2009b, 2014; Sydenstricker, 2012; Castro and Singer, 2012).

2. Methods

2.1. Dataset and descriptive analysis

We obtained plot and farm household samples from the *Machadinho Settlement Project*, which encompassed 808 farm households and 3,961 individuals in 1987 (*opening frontier*), 1,069 farm households and 5,031 individuals in 1995 (*expansion frontier*), and 259 farm households and 914 individuals in 2010 (*consolidated frontier*). The 1987 and 1995 data correspond to the universe of all plots originally settled and occupied in the PA Machadinho, while the 2010 data corresponds to a two-stage sample of the same plots surveyed in 1987 and 1995. Although this last sample is smaller than the other two, it depicts a later stage of frontier development, during which land consolidation (as shown in Table 1) and land turnover led to a larger proportion of farm households owning more than one plot. In addition, and, in consideration of the time elapsed since the most recent data collection in 1995, we believe that our 2010 plot selection minimizes the probability of omitting a farm household interviewed in 1985 or in 1987.

Based upon these surveys, we built three different panels to analyze plot and household demographic dynamics over time:

i) *Panel 1:* 78 farm households and their plots interviewed in 1987, 1995, and 2010. These include two groups: a) the same extended nuclear household (i.e., the original head of household or spouse, or his sons and daughters) that settled the plot in 1987 or earlier, and who remained on the plot in 1995 and in 2010, and b) plots settled in 1987 that had different household ownership in 1995 or in 2010. The former group represents 56% of the 78 farm households.

ii) *Panel 2:* 419 farm households and their plots, comprised of two groups: a) the same extended nuclear household that settled the plot in 1987 or earlier and remained on the plot until at least 1995, but which was no longer present in 2010, and b) plots showing a change in household ownership between 1988 and 1995. The former group represents 70% of Panel 2 farm units.

iii) *Panel 3*: 73 farm households and their plots, formed by two groups: a) the same extended nuclear household inhabiting the plot in 1995, but not in 1987 (i.e., households that settled the plot between 1988 and 1995), that remained on the plot until 2010, and b) plots with a change in household ownership between 1996 and 2010. The former group represents 79% of the 73 farm units.

Our three-panel strategy follows previous discussions about the importance of time since original settlement in a frontier environment to understanding the evolution of land use systems. In other words, we assume that a crucial way to unveil how demographic differences impact land use systems over time is to control for the duration and time since the original settlement of different cohorts in the study area and the development of their land use strategies. By controlling for settlement duration and time since original settlement, our panel datasets allow us to understand how settlement cohorts affect the evolution of land use systems over the different stages of frontier settlement, including the likely selective effect of market opportunities on new settlers through land consolidation and land turnover in the post-frontier stage. As previously shown, Panel 3 (depicting more recent cohorts settling in Machadinho) comprises 79% of farm households living on the same plot for a long period of time (both in 1995 and in 2010). However, for Panel 2 (depicting a shorter time period for cohorts settling plots from 1987 to 1995, but not surviving until 2010), this proportion decreases to 70%, indicating a higher turnover rate at earlier frontier stages. These figures suggest an important distinction between Panels 2 and 3. Panel 2 reflects higher land turnover intensity in the expansion stage, where failed farm units are acquired by thriving farm households through endogenous land consolidation. Conversely, Panel 3 reflects a cohort of new settlers better positioned to take advantage of economic returns to scale in more advanced stages of frontier development, who, thus, possess a greater ability to remain on the same plot. Finally, Panel 1 shows the long-term survival of a cohort of farm households present from the original to the consolidated frontier (at least twenty-three years), as well as land turnover processes at earlier frontier stages. In fact, among the 44% of farm households that changed plots in the 23-year period between 1987 and 2010, 54.6% did so during the first eight years (prior to 1995).

Because household (demographic) and plot life cycles may be dependent on the stage of frontier development, splitting panels helps us understand why some studies found few effects of demographic life cycle markers on land use choices. Panel 3 would be an example of this situation, as it depicts new farm households entering a frontier with strong market links, where plots have accumulated their

Table 1
Means and paired difference-of-means tests for plots and types of farm households according to panels – Machadinho, 1987 to 2010.

Dimension of analysis	Variable	Panel 1 (n = 78) 1987	2010	Difference[a]	Panel 2 (n = 419) 1987	1995	Difference[a]	Panel 3 (n = 73) 1995	2010	Difference[a]
Demographic dynamics and livelihoods	Number of years in Machadinho	1.47	19.88	18.41**	1.63	6.62	4.98**	5.18	18.48	10.78**
	Mean household size	5.57	3.50	−2.06**	5.18	4.68	−0.50**	5.07	3.56	−1.29*
	Mean age of head of household (years)	39.26	54.78	15.19**	40.64	43.26	2.61**	44.78	54.81	6.18
	Household dependency ratio[b]	0.43	0.33	−0.10*	0.42	0.38	−0.04**	0.41	0.40	−0.07
	Heads\more than 4 yrs Education (prop.)	0.02	0.09	0.08*	0.07	0.11	0.04*	0.08	0.10	0.02
	Spouses\more than 4 yrs Education (prop.)	0.08	0.09	0.02	0.04	0.18	0.15**	0.15	0.16	−0.02
	Income from off-farm sources (prop.)	0.63	0.20	−0.43**	0.86	0.25	−0.61**	0.25	0.16	−0.07
	Head owns the plot in Machadinho (prop.)	0.91	0.90	−0.02	0.91	0.82	−0.09**	0.85	0.93	0.07
	Owns other rural plots (prop.)	0.03	0.31	0.27**	0.07	0.017	0.10**	0.30	0.36	0.07
	Owns land/house in the city (prop.)	0.17	0.17	0	0.18	0.16	0.03	0.19	0.18	−0.01
	Plot mobility (prop.)	–	0.22	0.22**	–	0.30	0.30**	0.42	0.19	−0.22**
Land use and plot dynamics	Mean number of cattle	0.67	44.86	44.19**	0.69	11.10	10.05**	24.68	62.15	37.27*
	Mean plot size in hectares	46.02	46.02	0	44.52	44.52	0	44.36	44.36	0
	Primary forest (prop.)[c]	0.78	0.23	−0.54**	0.77	0.42	−0.35**	0.41	0.25	−0.19**
	Secondary forest (prop.)[c]	0.05	0.14	0.10**	0.06	0.02	−0.04**	0.15	0.16	0.14**
	Annual cropland (prop.)[c]	0.04	0.17	0.13**	0.03	0.21	0.18**	0.21	0.15	0.06**
	Perennial cropland (prop.)[c]	0.04	0.16	0.12**	0.05	0.19	0.14**	0.16	0.18	0.02
	Pastureland (prop.)[c]	0.01	0.26	0.26**	0.00	0.02	0.01*	0.01	0.22	0.21**
	Bare soils (prop.)[c]	0.08	0.03	−0.05**	0.08	0.13	0.05**	0.19	0.05	−0.16**

[a] Considering * $p \leq 0.05$ and ** $p \leq 0.01$.
[b] Household dependency ratio: the proportion of the sum of household members 0–14 years and over 60 years old to the total household population.
[c] The sums of some proportions of plot land use are not exactly, but are approximately one. These differences are due to residual measures not included in the calculations such as water, clouds, and unclassified data.

own history of land use and where a local market for labor has developed. In this setting, household markers are less important, since family labor shortages can be readily compensated by locally hired labor. By splitting our sample into three different panels, we are able to better understand and control the different types of selection effects in each panel, a strategy that would have been limited if we had utilized one larger, highly unbalanced panel. As Panel 1 encompasses the longest period, the "survival of the strongest" might be a major cause of success, with "stronger" signalizing a more suitable mix of capitals to face the opportunities and constraints of each frontier stage. Finally, Panel 2 reflects the opposite type of selection, which helps us understand which strategies were used by those who failed as the frontier enters a new logic of production.

We use descriptive statistics of variables representing farm household demographics and their livelihood strategies and land use in 1987, 1995, and 2010, as well as paired t-tests to determine the probability that the absolute value of the mean of the difference between the starting and ending points within panels is significant. We also classify plot land use as annuals, perennials, pasture, primary forest, secondary forest, and bare soils for each year by using *object-based classification*. This classification method applies algorithms to identify objects or segments and then provides a more refined classification of the spatial contents of pixels, including tree shadows or water, in comparison with pixel-by-pixel spectral classification (Zhou et al., 2009; Walter, 2004). We use images provided by Landsat 5's TM (Thematic Mapper) sensors for the three months closest to the survey dates, corresponding to July 1987, August 1995, and June 2010. For the purpose of analytical land use and cover classes, we combine bare soils and pasture into a sole class in our statistical models.

2.2. *Latent transition model*

Land use systems are more complex than simple combinations of categorized land use classes. As stated in the introduction, land use systems are a combination of means that households use to manage forest resources, annual crops and perennials, cattle, and off-farm income. However, this combination cannot be directly observed as a pattern and must be estimated. As a result, we used a latent transition model (LTM) to find the most likely combinations that could replicate the patterns observed in our datasets.

We model the dynamics of household livelihoods and their associated land use systems by looking at settlement cohorts. The statistical models described below are based on Panel 1 only, since this is the only panel covering all three stages of frontier development for the same plot/household. Our goal here is two-fold, seeking to create a land use systems measurement (not directly observed in the data), in addition to obtaining estimates of transition and permanence probabilities among land use systems over time. To this end, we used latent transition analysis (LTA), with observation units representing each rural plot and its associated farm household in 1987, 1995, and 2010. These statistical models are adequate to estimate the trajectories or the incidence of transitions over time among latent states. By latent state, we mean a categorical unobserved variable that is be measured by an LTA model. In this case, the latent states represent land use systems.

Although its measurements can contain errors, the states obtained using our LTA allowed for the estimation of each land use system's prevalence at each stage of frontier development (latent status prevalence). It is also used to describe how land use at the plot evolved from opening to post-frontier stages, using the estimated probabilities of transition. For instance, if our model result is three latent states, we designate these states as types of land use systems, with the transition probabilities representing the probability of migrating to a new type of land use system between 1995 and 2010, or between 1987 and 1995. In the three states example, the transition probabilities matrix would be a 3×3 matrix, with rows representing each type of land use system in the previous survey year and columns representing the same land use systems in the next survey year. The values in the main diagonal represent the probability of starting a given survey year and ending the next survey year with the same type of land use system.

The LTM is a type of latent Markov model, because, instead of modeling an entire vector of transitions for each time period, it provides transition probability estimates solely between two periods (Everitt, 2006). A general assumption of the LTM is that transitions among states in all directions are possible.[1] In this paper, we use the general mixture latent Markov model with covariates (Schmittman et al., 2005; Vermunt et al., 1999), defined as:

$$f(\mathbf{y}_i|\mathbf{z}_i) = \sum_{x=1}^{K} \sum_{x_0^d=1}^{K^d} \sum_{x_1^d=1}^{K^d} \cdots \sum_{x_T^d=1}^{K^d} P(x|\mathbf{z}_i) P\left(x_0^d \middle| x, \mathbf{z}_i\right) \prod_{t=1}^{T_i} P\left(x_t^d \middle| x_{t-1}^d, x, \mathbf{z}_{it}\right) \prod_{t=0}^{T_i} f\left(\mathbf{y}_{it} \middle| x_t^d, x, \mathbf{z}_{it}\right) \quad (1)$$

The model described in Eq. (1) has four sets of probabilities. The first set, $P(x|\mathbf{z}_i)$, refers to the size of each latent state, x, (latent status prevalence), which depends on a vector of time-constant covariates, $\mathbf{z}_i$.[2] The second set, $P(x_0^d|x, \mathbf{z}_i)$, designates the initial state probabilities, which depend on both states' time-constant covariates. The third set, $P(x_t^d|x_{t-1}^d, x, \mathbf{z}_{it})$, references the transition probabilities, which depend on the single period lagged states (Markovian assumption), state sizes, and time-varying covariates. The fourth set, $f(\mathbf{y}_{it}|x_t^d, x, \mathbf{z}_{it})$, denotes the conditional distribution of indicators used to measure the latent states. The indicators' distribution is modeled as in a traditional cluster model, with a mixed distribution, allowing for different types of indicators (e.g., continuous, count, binomial, etc.) combined in a multivariate mixed-type distribution function. This approach is important in our modeling strategy, because we use different types of indicators, such as the number of cattle (count), the percentage of a plot that is dedicated to each land use type (truncated continuous), and the percentage of farm household members living on the plot engaged in off-farm activities (truncated continuous).

We tested several LTMs with a distinct number of states. The best fit is a model with three latent states and homogeneous transition probabilities[3] among states for all pairs of adjacent years (from 1987 to 1995 and from 1995 to 2010). We interpret the latent states as land use systems, which we named diversified land use, off-farm based land use, and low-intensive land use. We compared different model fit possibilities by using the lowest BIC and AIC and classification errors under 2%. We also modeled an LTM utilizing the demographic covariates household dependency ratio and household size (representing household age composition and the household labor pool, respectively) and type of family (representing household family structure). Hypothesis testing (see Table A1, Appendix) shows that, in general, the estimated coefficients in the LTM are significant for the two state parameters (transition probabilities) and the measurement component (latent states), justifying the use of the mixed-type specification given in Eq. (1).

2.3. *Multinomial logit panel analysis*

To analyze how land use systems are associated with distinct household and plot characteristics over the three stages of frontier settlement, we built three multinomial logit panel models (MLPM) for Panel 1. The dependent variables are the latent states (land use systems) created by the LTA described in the preceding section. We utilized two modeling strategies. First, we used a multinomial model with pooled data for the three years. Second, we took advantage of the panel structure of our data to implement a multinomial model with fixed and random effects. The fixed effects model eliminated the influence of constant unobserved heterogeneity at the plot level (e.g., soil inclination, access to water, soil insulation, and household members' sex). The random effects model modeled error components at the plot level by eliminating the effect of both constant and varying unobserved heterogeneity (e.g., soil productivity) at the plot level. We performed a Hausman-type specification test to decide which model to select. However, we estimated the random effects panel model under a restrictive assumption of constant effects of the unobserved plot characteristics over time and modeled only the autocorrelation of the observed variables within lots over time. Furthermore, due to sample size limitations, it is not possible to eliminate potential endogeneity biases due to simultaneity, creating an additional limitation for trusted guidance of the specification test.

Although we presented results for the three methods, we asserted that the fixed effects model provided the best model alternative due to the implausibility of the random effect model's assumptions, resulting from the independence among unobserved constant variables and exogenous independent variables. However, the differencing strategy used in the fixed effects model requires variability in the differenced exogenous variables. Some of our variables in difference showed limited variation over time in *Panel 1* due to the

[1] This assumption can be relaxed with an absorbing state (as in increment-decrement life table models from demography), or by imposing linear constraints on transitions in a specific state (known in the technical literature as the *stayer state path*).

[2] Whenever covariates are time-varying, state size is based on the time-indicator array of covariance patterns only.

[3] In an LTM that assumes *homogeneous transitions*, transition probabilities among latent states for each pair of years (i.e., 1987 and 1995, 1995 and 2010, and 1987 and 2010) are constrained to the same results. An LTM with *heterogeneous transitions* allows transition probabilities to differ for each pair of years.

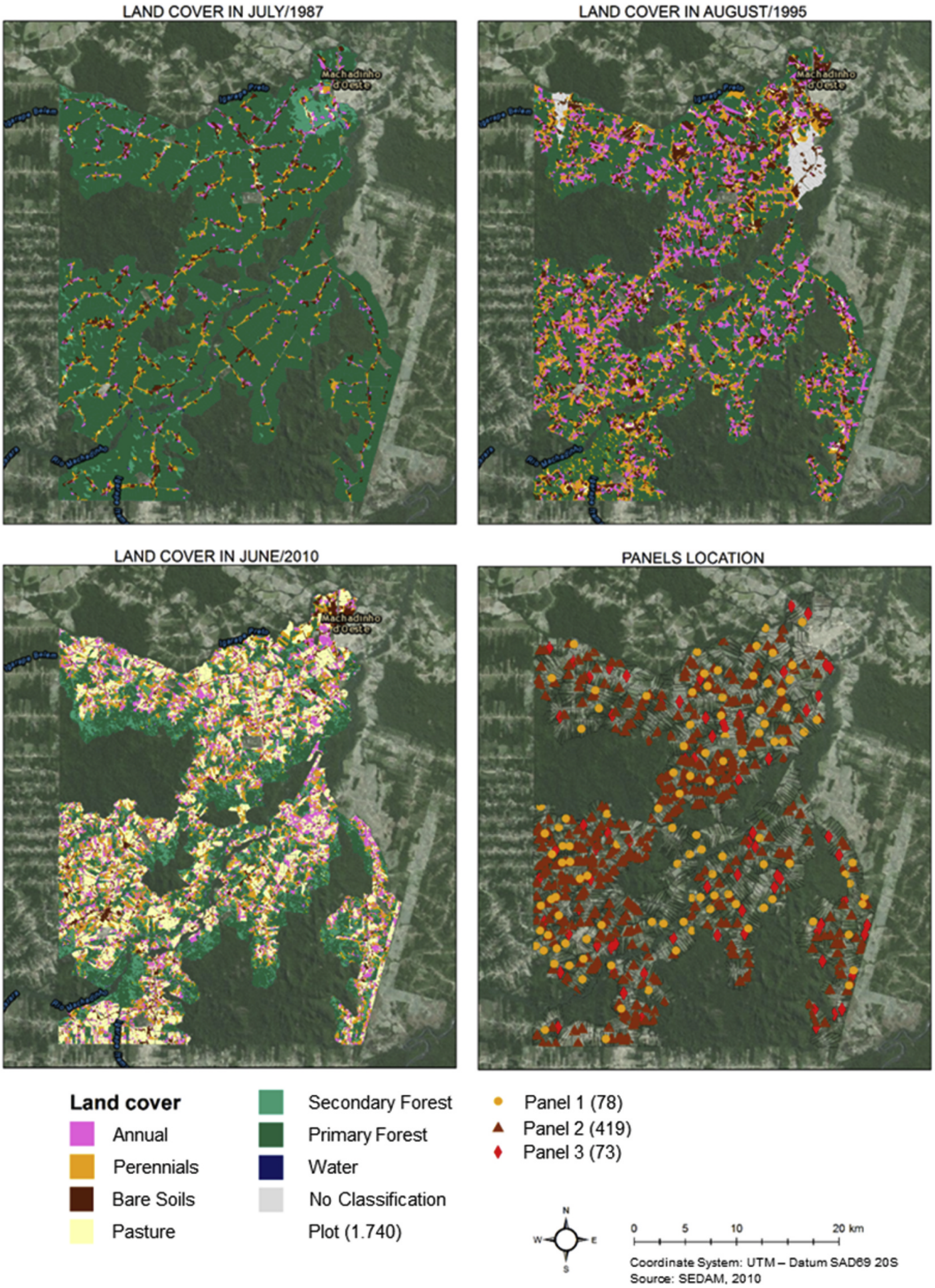

Fig. 2. Land use trajectories by plot and farm household panel in Machadinho (1987) to 2010.

limited sample size, increasing the sampling variance of final estimates. Due to the combined sources of limitations, a safer approach to interpreting the model results is to examine the direction of effects, rather than their significance, as they require asymptotic behavior.

3. Results and discussion

Table 1 shows the descriptive statistics and paired t-tests for the demographic, land use, and livelihood variables. We provide statistics for the initial and final years of each of the three panels and test if changes over time in each panel are statistically significant. This approach allows us to investigate changes in plot and household characteristics as a settlement cohort analysis, rather than as a period analysis. If we had decided to examine differences in attributes by survey year (a cross-sectional, period analysis), this would require mixing different cohorts, and; thus, detracting from the main objective of this paper.

As expected, farm households at later frontier stages (2010) have a significantly older age structure (indicated by a higher head of household mean age, smaller household size, and lower dependency ratio). Higher dependency ratios for Panels 1 and 2 in 1987 (0.43 and 0.42, respectively) and for Panel 2 in 1995 (0.38), combined with lower head of household and spouse mean ages compared to 2010, reflect a younger household age composition. Additionally, the relatively high dependency ratio in 2010 in Panels 1 and 3 (0.33 and 0.40, respectively) and higher head of household and spouse mean ages reflect the increased aging of the dependent population, compared with previous years. The overall level of human capital (education) increased over time for all panels, especially for women, albeit with significant differences solely in Panels 1 and 2.

In accordance with Perz et al. (2013), we analyzed livelihoods according to off-farm labor and on-farm (sales from farm production) cash earnings. Off-farm earnings are very high at the initial frontier stage and decrease significantly over time in Panels 1 and 2, suggesting a change in the livelihood compositions across frontier development stages, including the increasing availability of family labor as households age. Virtually all off-farm income is from rural employment in 1987 (99%) and 1995 (97%). However, Barbieri et al. (2014) analyze three sources of off-farm income in Machadinho. First, they show that 35% of the working-age population living on plots in 2010 were engaged in off-farm employment (e.g., being commuters or seasonal movers) and, among these workers, 25% were working in urban areas. Second, 33% of all off-farm income is derived from cash transfers, such as the *Bolsa Familia* and rural retirement pensions. Finally, approximately 60% of farm households had at least one out-migrant (those who used to live on the plot and now live elsewhere), among whom 17% contributed to the farm household via remittances (financial or material) or seasonal farm labor.

This study's proxy for physical capital (ownership of an urban plot), which facilitates rural-urban mobility and supports urban-based activities and dual residency strategies, remains relatively stable over time. The significant increase in the ownership of another rural plot, especially in Panels 1 and 3, follows typical strategies of land consolidation and farm production expansion during frontier expansion and consolidation. Plot mobility indicates that 22% of all household members in Machadinho have moved to different plots since 1987 (those moving within plots in Machadinho may be registered as a new family on the plot, vis-à-vis extended nuclear families who have remained on the plot from 1987 to 2010). Finally, land ownership is high over time across all panels, with significant differences being found only for Panel 2. The significant decrease in plot ownership for this panel reveals a very particular type of selection, with settlers who failed to maintain their living standards being concentrated in this panel. However, the higher and more stable proportion of rural plot ownership in Panels 1 and 3 suggests the influence of successful strategies to "survive" the impacts of death and emigration in Panel 1 and the selective nature of more capitalized farmers entering the frontier at later stages (Panel 3).

The number of cattle reflects a reserve value and form of "insurance" against imperfect markets (Barbieri et al., 2005a), as well as representing a key component of profitable land use systems. The increase in cattle is very high and significant across all panels, which helps explain the significant increase in pastureland and decrease in primary forests. The average number of cattle for Panel 2 is the lowest for all panels, reinforcing the selection of failing farms operating among colonist farmers in this panel.

Fig. 2 shows the evolution of land use in Machadinho. The remarkable increase in deforestation mimics patterns typical of other colonist frontiers and can be attributed to two distinct causes, encompassing high deforestation for annuals and perennials cultivation between 1987 and 1995 (Panel 2) and the long-term transition to cattle ranching between 1987 and 2010 (Panel 1). Over time, pastureland advances on the landscape in an inverse relationship with deforestation. This pattern is prevalent for the different panels over time. In 1995, the presence of a high proportion of bare soils may indicate recent forest burning and deforestation for pastureland and cash crops in the years following deforestation.[4] From 1995 to 2010, the proportion of annuals becomes smaller, and the proportion of perennials remains stable, which indicates plot diversification toward cattle ranching and greater investment in profitable perennials, such as coffee.

When analyzed together (Table 1 and Fig. 2), the descriptive evidence suggests that the most important differences in demographics, livelihoods, and land use over time are only observed among Panels 1 and 2, with no significant differences for Panel 3, despite observing significant differences in land use and plot dynamics variables for all panels. Although these results do not allow us to draw conclusions regarding the independence between plot/land use and farm household dynamics, they demonstrate that demographic differences have less significant impacts on the evolution of later stages of frontier settlements. Nonetheless, significant changes in livelihoods over time are increasingly related to the articulation of urban-based activities and cash transfers, in addition to the specialization of more profitable land uses, particularly cattle and perennials. However, land use systems show marked differences

[4] Land use classifications for 1987, 1995, and 2010 were taken during the peak period of forest burning in the Amazon (i.e., the dry season). In 1995, in particular, the high presence of bare soils (typical in degraded soil or soils where primary forest was recently removed) coupled with a relatively high mean number of cattle indicates a primary forest to pastureland conversion process.

across panels, indicating high levels of land use specialization for Panel 3 (cattle), commercial (predominantly cattle and perennials) and subsistence (annuals) land use diversification for Panel 1, and subsistence agriculture (annuals and perennials, with increasing bare soil areas) for Panel 2.

3.1. The latent transition model (LTM) and multinomial logit panel models (MLPM)

Table 2 shows the mean number for each indicator (cattle, land use proportions, and off-farm income), as well as the proportion of time plots spent under each land use system (latent state) between 1987 and 2010. We named the first state *diversified*, as most frontier farm households transitioned to diversified land uses over time, with 60.5% of the time from 1987 to 2010 spent under this system. We entitled this state diversified because it represents plots with higher levels of on-farm diversification (except primary forest), large numbers of cattle, and a proportion of off-farm income sources similar to plots with low-intensive land use. This type of land use system is typical of the expansion and consolidated frontier stages. The *off-farm* land use system is characterized by a high reliance on off-farm income (93.8%), virtually no annual crops or perennials, and a high proportion of primary forest. On average, farm plots remained under this system for 19.7% of the time between 1987 and 2010. This land use system is most common during the initial frontier stage. The *low-intensive* land use system was used by farm households for a similar proportion of time as the off-farm system. It presents a low proportion of land dedicated to annuals and perennials, as with the off-farm land use system, but is characterized by a higher number of cattle (11.5 versus 0.64) and a lower percentage of off-farm income sources (18.7% versus 93.8%). Given the small number of plots in this state in 2010 (Fig. 2), we observe an initial stage of frontier settlement where rural off-farm activity is a transitory activity until on-farm production begins and expands over time.

Plots whose owners were able to diversify their land uses, especially with cattle and a share of off-farm income, were more likely to "survive" at the frontier over time. Table 1 suggests that this plot selectivity[5] occurs regardless of the type of family or other demographic factors. We assert that it is likely that new families entering a new plot (those in Panel 3), even if in a different household demographic life cycle stage than the previous household, encounter and adapt to existing plot land uses (e.g., deforested plots with bare soils or pasture) or diversify their livelihoods (e.g., through off-farm employment) by taking advantage of *ex-ante* plot land use conditions. Cattle ranching is a highly selective activity that demands risk-diversification strategies, such as the most profitable land uses (perennials) and off-farm income, to build financial capital to invest in cattle and plot consolidation (the acquisition of other rural plots).

Table 3 shows how transition probabilities between land use systems may indicate potential plot selectivity over time among an already highly selective group of farmers. We complemented this analysis with the multinomial logit panel models (MLPM) shown in Table 4 to assess how land use systems (defined as the LTM latent states) are associated with distinct household demographic and plot characteristics. The "overall" transition probabilities between land use systems (values repeated in the two columns in Table 3) suggests that immobility within the same state over time is rare (values in the main diagonal). As displayed in Table 1 and Fig. 2, this result indicates that most plots surviving over time advance in or complete the transition from low-intensive and off-farm land use systems to diversified land use systems at the consolidated frontier stage. Notably, all the MLPMs in Table 4 suggest that plot owners who diversify land use systems are much more likely to have other rural plots, rather than owning only one plot. Furthermore, at the consolidated or post-frontier stages, these households are much more likely to diversify plot land uses in comparison with the earlier stages of frontier development, whereas specialization in off-farm activities is highly unlikely. This final result and the results from Table 2 suggest that plots that "survive" over time (those in Panel 1 compared to the other panels) are predominantly older and distinct from earlier settlement stages (especially in 1987), when incipient land uses and the large share of plots composed of primary forests forced specialization in rural off-farm income-generating activities. As ownership turnover is a reality and increasingly common at later stages, we cannot assert that those plots with members who have been at the frontier for a longer period of time are more likely to diversify, as this is only part of the story. Selection processes regarding land acquisition also help explain the association between plots with more elderly demographic compositions and the likelihood of diversification, even if aging is due to changes in land ownership.

Table 3 also shows the transition probabilities between land use systems, considering the influence of household demographic covariates. For simplicity, we recoded dependency ratios as "low" (if less than the mean sample value of 0.44) or "high" (greater than or equal to 0.44) and household size as small (two people at most), medium (between three and five people), or large (six people or more). We summarize the seven key findings from Table 3 by focusing on transitions related to diversified land use systems, as these systems became predominant over time.

3.1.1. Younger households tend to move toward diversified land use systems over time

When we consider the presence of low dependency ratios, small or medium household sizes, and nuclear families, that is, features that indicate young households on the plot, there is a high probability of shifting to diversified land use systems over time. When the number of younger households (defined by a combination of a high dependency ratio and a low mean age of the head of household and spouse) is high, the level of transition probability depends on the other two demographic variables. Overall, these results show that a favorable age composition, with a smaller number of dependents and a relatively higher number of working age individuals, favors the

[5] We also tested the differences in the independent sample means between the years in Panel 1 (i.e., 1987, 1995, and 2010), the years in Panel 2 (i.e., 1987 and 1995), and in Panel 3 (i.e., 1995 and 2010) (results not shown). Plots from 1987 through 2010 (Panel 1) had significantly different mean values compared with plots in 1987 and 1995 (Panel 2) and plots in 1995 and 2010 (Panel 3). Long run "survival" at the frontier implies distinguishing selectivity effects for plots in Panel 1.

Table 2
Composition of each indicator for land use systems (latent states) over time using the latent transition model.

Indicators	Latent State		
	Diversified	Off-farm	Low-intensive
Time spent in each state (%)	60.50	19.77	19.73
Cattle	357.499	0.6435	11.482
Annuals (%)	0.2086	0.0379	0.0363
Perennials (%)	0.1686	0.0400	0.0700
Primary forest (%)	0.2887	0.7729	0.7938
Secondary forest (%)	0.0981	0.0474	0.0429
Off-farm income (%)	0.1807	0.9375	0.1867
Pasture + bare soils (%)	0.2457	0.1093	0.0608

Table 3
Transition probabilities among land use systems (latent states) in Machadinho between 1987 and 2010, according to household demographic size and composition.

Initial State	Final State			Initial State	Final State		
	Diversified	Off-farm	Low-intensive		Diversified	Off-farm	Low-intensive
Overall				*Overall*			
Diversified	0.0269	0.5436	0.4295	Diversified	0.0269	0.5436	0.4295
Off-farm	0.8859	0.0476	0.0665	Off-farm	0.8859	0.0476	0.0665
Low-intensive	0.7771	0.0285	0.1944	Low-intensive	0.7771	0.0285	0.1944
Low dependency ratio, small household size, and nuclear family				*High dependency ratio, small household size, and nuclear family*			
		0.5367	0.4177	Diversified	0.0024	0.4354	0.5622
Off-farm	0.8357	0.1514	0.0129	Off-farm	0.9674	0.0113	0.0213
Low-intensive	0.9701	0.0139	0.0160	Low-intensive	0.3742	0.3938	0.2320
Low dependency ratio, small household size, and new family				*High dependency ratio. small household size, and new family*			
		0.4361	0.2555	Diversified	0.0230	0.4953	0.4817
Off-farm	0.1994	0.6749	0.1257	Off-farm	0.4721	0.1028	0.4251
Low-intensive	0.9954	0.0005	0.0042	Low-intensive	0.8387	0.0285	0.1328
Low dependency ratio, medium household size, and nuclear family				*High dependency ratio, medium household size, and nuclear family*			
		0.5341	0.4655	Diversified	0.0000	0.4088	0.5912
Off-farm	0.9861	0.0096	0.0044	Off-farm	0.9931	0.0006	0.0063
Low-intensive	0.9636	0.0052	0.0312	Low-intensive	0.3825	0.1504	0.4671
Low dependency ratio, medium household size, and new family				*High dependency ratio, medium household size, and new family*			
Diversified	0.0040	0.6013	0.3946	Diversified	0.0002	0.4786	0.5212
Off-farm	0.7340	0.1332	0.1327	Off-farm	0.7875	0.0092	0.2033
Low-intensive	0.9916	0.0002	0.0082	Low-intensive	0.7550	0.0096	0.2354
Low dependency ratio, large household size, and nuclear family				*High dependency ratio, large household size, and nuclear family*			
		0.6672	0.3322	Diversified	0.0000	0.5476	0.4524
Off-farm	0.9994	0.0006	0.0001	Off-farm	0.9999	0.0000	0.0001
Low-intensive	0.9688	0.0005	0.0308	Low-intensive	0.4480	0.0161	0.5359
Low dependency ratio, large household size, and new family				*High dependency ratio, large household size, and new family*			
		0.7232	0.2711	Diversified	0.0003	0.6163	0.3834
Off-farm	0.9866	0.0103	0.0032	Off-farm	0.9948	0.0007	0.0045
Low-intensive	0.9919	0.0000	0.0080	Low-intensive	0.7653	0.0009	0.2338

transition from low-intensive and off-farm systems to diversified land use systems.

3.1.2. Younger, new households tend to take over and maintain plots in diversified land use systems over time

When a household has a low dependency ratio and small size, as in a), but the family is new (occupied the plot after 1987), the probability of maintaining a diversified land use system over time is much higher than average and for any other combination of land use systems and demographic variables.

3.1.3. Positive and negative plot selectivity

Regardless of demographic factors, diversified land use systems predominate over time ("positive" selection). Notably, there is a "negative" selection of off-farm systems, as shown in Table 4 by the strong inverse association between the presence of off-farm systems in 2010 compared with low-intensive systems. This finding reinforces the previous discussion (Table 1) concerning how off-farm systems based on rural labor exchange are a "specialized" system characteristic of the earlier frontier in Machadinho. At later stages, there is a process of plot selectivity favoring the survival of those who specialize in intensive and diversified land use systems.

3.1.4. High dependency ratios, aging households, and larger household size trap plots in a low-intensive land use system

When the dependency ratio is high, regardless of the family type, the probability of becoming "trapped" in a low-intensive land use system over time is much higher when compared with the overall mean. This probability is even higher for medium- and large-sized

Table 4
Multinomial Logit Panel Models (MLPM) of demographic and plot characteristics affecting land use systems in Machadinho between 1987 and 2010.

Variable	Pooled Multinomial Logit (Robust Variance)		Fixed-Effects Panel Multinomial Logit	
	Diversified	Off-farm	Diversified	Off-farm
Year (2010)	3.055**	−13.487**	2.387*	−22.218
	[0.769]	[0.781]	[1.090]	[21108.450]
Head of household age	0.015	−0.029	0.037	−0.178*
	[0.016]	[0.023]	[0.043]	[0.086]
Household size	0.068	0.175	0.128	0.543*
	[0.092]	[0.109]	[0.169]	[0.262]
Household dependency ratio	−1.734*	−1.778	−1.644	−1.688
	[0.867]	[1.206]	[1.365]	[1.826]
Same family on lot	0.500	0.463	dropped (collinearity)	dropped (collinearity)
	[0.383]	[0.504]		
Own the interviewed lot	0.822	0.711	0.949	1.257
	[0.759]	[0.838]	[1.184]	[2.021]
Own other lot in MDO	1.843**	−1.132	1.954*	−0.385
	[0.651]	[1.225]	[0.896]	[1.782]
Own urban lot	0.059	0.333	0.253	0.783
	[0.636]	[0.722]	[0.812]	[1.555]
Constant	−1.071	0.219		
	[1.111]	[1.362]		
Latent Variable				
Constant	−1.071	0.219		
	[1.111]	[1.362]		
Variance (Latent Variable)				
Observations	230	230	225	225

Robust standard errors in brackets. The “low-intensive land use” category is omitted.
**p $<$ 0.01, *p $<$ 0.05, + p $<$ 0.1.
Source: Panel Data from Machadinho (1987), 1995, 2010.

households. Table 4 shows that when the dependency ratio is high, plots are more likely to be under a low-intensive land use system than a diversified land use system. This context is characterized by an elevated reliance on off-farm income sources that are mostly rural at earlier stages of frontier development, but which involve a higher share of urban income and government transfers at later stages. Additionally, high dependency ratios over time encompass qualitative changes, more specifically, a decrease in younger household members and a shift toward older households with smaller labor pools, as suggested in Table 1 by the mean head of household age.

3.1.5. Low dependency ratios favor land use and livelihood diversification

Independent of family type and household size, the probability of shifting from low-intensive to diversified land use is very high (above average) when the dependency ratio is low. As shown in Table 4, the higher the dependency ratio, the less likely a plot will be diversified, compared with a less intensive land use system. This result reflects an expected stage of frontier development when plot occupation and expansion (through consolidation) predominates. Notably, this is not a homogeneous process and the transition probabilities are much lower when dependency ratios are high, indicating that household labor composition is an important trigger of land use and livelihood diversification over time.

3.1.6. The type of family helps explain land use system transitions when the dependency ratio is high

In nuclear households with a high dependency ratio, the probability of transitioning from an off-farm (typically opening frontier) to a diversified (typically post-frontier) land use system is much higher, while probabilities are much lower for transitioning to low-intensive systems. In the case of new households, transitioning from off-farm and low-intensive to diversified land use systems is less likely when the household is small and has a high dependency ratio, that is, older households often become “trapped” in low-intensive land use systems and are highly dependent on off-farm income, given their older age structures.

3.1.7. Increasing the labor pool leverages transitions toward diversified land uses and livelihoods

When the same nuclear household on a plot becomes large through the incorporation of productive members (larger labor pool) over time and maintains a low dependency ratio, the transition probabilities from other states to diversified land use systems are high and greater than the average.

4. Discussion and conclusion

The panel data depicting the heterogeneity of settlement trajectories at the frontier provide a better understanding of survival capabilities at the frontier over time because of the ability to change portfolios of capitals and changing demographic compositions. We predicate the advantage of our analysis based on three factors.

First, using household, micro-level, instead of macro-level data (municipality- or census-based data or regional land use classification data), is appropriate to capture the endogenous coevolution of demographics, livelihoods, and land use at the local level. Second, and contrary to self-reported (survey) land uses or pixel-to-pixel classification, we use object-based land use classification at the plot level over a period of 25 years. This strategy considers the context of the pixel and reduces classification errors. Finally, cross-sectional micro-level studies concerning the Amazon frontier may conclude that the demographic effects on livelihoods and land use system choices are small or inexistent. Such studies have failed to capture the heterogeneity of household trajectories through the distinct stages of frontier settlement and households' capacity to survive and adapt their livelihoods as a response to changes in initial resource stocks (in particular, natural capital), to varying capital returns, and to shifting environmental, socioeconomic, political, and institutional contexts over time.

Due to the length of our data measurements (1987, 1995, and 2010) and our study's truly longitudinal nature, we were able to test three hypotheses. Regarding the *stage dependence hypothesis*, we show that plot dynamics are increasingly independent from household demographics over time (as previously found in Barbieri et al., 2005a; Guedes et al., 2017). Although most of the means of the demographic and livelihood variables display significant differences between 1987 and 2010 (Table 1), they do not significantly explain conditional differences in plot land use systems (Table 4), and the dependency ratio is only marginally significant in two of the three models.

Different combinations of demographic variables, namely the labor pool (household size), labor composition (dependency ratio), and type of family (proxy for the timing of occupation), do not change the predominant transition *pattern* toward a diversified land use system, but affect the *level* of the transition probabilities in three specific ways. First, new families with a low dependency ratio and a small family size have a higher probability of maintaining diversified land use systems over time, compared with all other combinations of demographic variables (*timing* – when entering the frontier is key). Second, regardless of family type, the probability of shifting to a diversified system is much higher when the dependency ratio is low, demonstrating the importance of household labor composition (*how* – older cohorts benefited from high fertility regimes, even during accelerating processes of market integration). Third, when the dependency ratio is high, the plot has a smaller probability of moving from a low-intensive to diversified land use system over time (*why* – labor scarcity and the inability to build up capital to take advantage of market opportunities, rendering them dependent on off-farm, cash transfer income). Thus, as the frontier becomes more urban- and market-oriented, household livelihoods from exogenous sources (wage labor, remittances, and cash transfers) may relieve pressure on farm production, reinforcing the independence between household and plot dynamics.

Regarding the *dynamic resilience hypothesis*, we show that plots that started as off-farm or low-intensive land use systems became increasingly diversified instead of maintaining the same strategy over time. This explains why, on average, plots spent 60.5% of their time in a diversified state compared to only roughly 20% in the other two stages (Table 2). The characteristics of diversified land use systems – comprised by a larger number of cattle and a higher proportion of commercial perennials such as coffee – reflect the opportunities that emerge at later stages when links with urban centers and the development of agricultural and cattle markets become predominant. In addition, a non-negligible proportion of individuals engaged in off-farm activities reflects the advantages provided by the development and expansion of regional labor markets.

In this context, and regarding the *selective land consolidation* hypothesis, plots whose owners can diversify land uses over time also invest in other rural plots, favoring the consolidation of diversified land use system. Our results suggest a process of land parcel consolidation as land markets evolve, combined with a growing specialization in commercial land use systems (mainly cattle ranching), as a consequence of the increasing demands in terms of farm production economies of scale in the post-frontier stage. For instance, we found that the likelihood of a farmer with other plots in the region to adopt a diversified instead of a low-intensive strategy is 1.95 (almost two times) higher (Table 4).

We also show that time on the plot does not change the overall deforestation *pattern* over time, but it does affect its *level*. As suggested in Table 1, deforestation in plots where the same family has resided for longer periods of time (Panel 1) is higher than in plots where families settled later (Panel 3). Nonetheless, these more recent arrivals (Panel 3) settled after an average of five years living at the frontier and are very likely to move to different plots over time, as well as to rely more heavily on cattle ownership than households in Panel 1. We argue that this pattern of transition probabilities among land use systems is explained by the higher proportion of households owning other rural plots (especially for cattle raising). Although it is widely acknowledged that diversification improves resilience, we must start looking more closely at how to transform long-term, dynamic resilience into long-term sustainability in order to avoid ecological imbalances. We are not arguing that smallholders are the cause of any sort of ecological imbalance, but, rather, that diversification alone is too generic to be labeled as a sustainable trajectory. Instead, we recommend examining the composition of these systems and improving their ability to combine ecological practices with economic profitability. The use of subsidized credit policies for sustainable diversified land use systems may be a strategy to foster dynamic resilience along with simultaneously improving long-term sustainability.

On the other hand, the group of households without additional rural plots is more likely to become "trapped" in low-intensive land use systems. We posit that this result corroborates the findings in the literature on Machadinho (Barbieri et al., 2014), suggesting that older colonists may "survive" with reduced capital levels and can become "trapped" in a long-term deprivation trajectory. This long-term survival pattern of deprived households was found at other Amazonian agricultural frontiers (Guedes et al., 2014) and elsewhere, such as in Thailand (Hull and Guedes, 2013). A potential "empty nest effect" may also reinforce this deprivation trajectory and explain the high dependency ratios typical of this group. Younger households at the frontier are a selective group with more complex mechanisms for income generation because they inhabit a more urbanized and market-oriented frontier that demands higher land use system diversification capabilities.

The off-farm land use system depicts this first stage of frontier settlement, when incipient land uses and a high proportion of primary forest on plots force settlers to specialize in rural off-farm income sources. Over time, the majority of plots transition from off-farm to diversified land use systems. Although Panel 1 provides a satisfactory picture of plots "surviving" over the different stages of frontier development through diversification, these results should be interpreted cautiously. They do not represent *all* farm households at the frontier, given the potential selection effects caused by out-migration and mortality. However, descriptively, the analysis of all three panels can be understood as being reasonably representative of the evolution of land use systems and their socioeconomic, demographic, and livelihood characteristics under certain assumptions. First, they may reflect the experience of other colonist frontiers where agriculture and cattle ranching are the dominant land uses in the initial and expansion stages of frontier development, while, in the consolidated stage, these land use types are utilized by farm households along with urban activities (e.g., employment in urban labor markets). In this regard, the panel data may represent the experience of some colonist frontiers, such as Altamira, Santarém, and Uruará, in the state of Pará (Caldas et al., 2007; VanWey et al., 2012b; Guedes et al., 2014), or Alto Paraíso, Ouro Preto, and Rolim de Moura, in the state of Rondônia (Browder et al., 2004), but not frontiers where the typical agricultural frontier mixes with other land uses, such as gold mining (Barbieri et al., 2005b) or intensive logging, or with land speculation and conflicts with indigenous communities (Schmink and Wood, 1992; Aldrich et al., 2011). Second, it represents planned colonization schemes vis-à-vis spontaneous colonization schemes, considering that, in the first scenario, some governmental and institutional support are key in differentiating frontier evolution (Barbieri et al., 2005b, 2009b). Third, it represents frontiers where rural-urban linkages become a distinguishing feature in the consolidated stage (Barbieri et al., 2009b; Guedes et al., 2012). Finally, while we depict frontier evolution from the mid-1980s to the early 2010s, distinct entry and end points of frontier development may implicate the interplay of distinct institutional, socioeconomic, and political factors affecting the evolution of land use systems, as is the case with older colonist frontiers in the state of Pará (Schmink and Wood, 1992; Aldrich et al., 2011) or with more recent colonist frontiers in the state of Roraima (Diniz and Lacerda, 2018). Our empirical findings are in line with previous studies using household and plot level data for other government-sponsored colonist frontiers, as demonstrated by the increasing diversification of livelihoods found in frontier municipalities, such as Altamira and Santarém (VanWey et al., 2012a, 2012b), and the decreasing effect of demographic dynamics in explaining land use choices in Altamira (Guedes et al., 2017). Our findings set the foundation for a clear policy-making perspective encapsulated by the idea that, as frontiers integrate into markets, diversification should not only be incentivized, but should also be used as a technical strategy to enhance the use of subsidized rural credit, as it appears to increase farmers' likelihood to thrive and improve their resilience against shocks.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Funding for this research was provided by the follwoing sources: i) Inter-American Institute (IAI), Project CRNIII3036 "LUCIA – Land Use, Climate and Infections in Western Amazonia" (CRNIII3036). IAI is an intergovernmental organization supported by 19 countries in the Americas, with the main office located in Uruguay; ii) Minas Gerais Research Foundation – FAPEMIG, Brazil, grant APQ-01-553-16; iii) National Research Council – CNPq, Brazil, grants 447688/2014-6, 431872/2016-3, and 314392/2018-1.

Appendix

A.1
Significance tests for state parameters (transition probabilities) and indicators (latent states).

Parameter	Wald	Df	P-value
State Parameters			
Initial State			
Initial state | family type	49.946,0	2	0.082
Transition Probabilities			
Pr(state <– state$_{-1}$)	446.98	6	<0.001
Pr(state <– state$_{-1}$ | dep. ratio)	12.99	6	0.043
Pr(state <– state$_{-1}$ | household size)	41.04	12	<0.001
Pr(state <– state$_{-1}$ | family type)	15.64	6	0.016
Measurement			
Indicators			
Cattle | state	51.27	2	<0.001
Cattle | dep. ratio	13.46	1	<0.001
Cattle | household size	4.51	2	0.1
Cattle | family type	2.17	1	0.14
Annuals | state	124.97	2	<0.001
Annuals | dep. ratio	1.43	1	0.23
Perennials | state	125.54	2	<0.001
Primary forest | state	833.56	2	<0.001

(*continued on next page*)

A.1 (*continued*)

Parameter	Wald	Df	P-value
Secondary forest | state	11.9	2	0.003
Secondary forest | dep. ratio	0.11	1	0.74
Secondary forest | household size	15.48	2	<0.001
Secondary forest | family type	0.77	1	0.38
Pasture + bare soils | state	88.59	2	<0.001
Off-farm employment | state	22.61	2	<0.001

References

Aldrich, S., Walker, R., Simmons, C., Caldas, M., Perz, S., 2012. Contentious land change in the amazon's arc of deforestation. Ann. Assoc. Am. Geogr. 102 (1), 103–128.

Almeida, L.O., Campari, J.S., 1995. Sustainable Settlement in the Brazilian Amazon. Oxford University Press, Oxford, UK.

Andersen, L.E., Granger, C.W.J., Reis, E.J., Weinhold, D., Wunder, S., 2002. The Dynamics of Deforestation and Economic Growth in the Brazilian Amazon. Cambridge University Press, Cambridge.

Azevedo, A.A., Rajão, R., et al., 2017. Limits of Brazil's Forest Code as a means to end illegal deforestation. Proc. Natl. Acad. Sci. Unit. States Am. 114 (29), 7653–7658.

Barbieri, A.F., Pan, W.K., 2012. People, land, and context: multilevel determinants of off-farm employment in the Ecuadorian Amazon. Popul. Space Place 19, 558–579.

Barbieri, A.F., Bilsborrow, R.E., Pan, W.K., 2005a. Farm household lifecycles and land use in the Ecuadorian Amazon. Popul. Environ. 27 (1), 1–27.

Barbieri, A.F., Sawer, D.O., Soares Filho, B., 2005b. Population and land use effects on malaria prevalence in the southern Brazilian Amazon. Hum. Ecol. 33 (6), 847–874.

Barbieri, A.F., Carr, D.L., Bilsborrow, R.E., 2009a. Migration within the frontier: the second generation colonization in the Ecuadorian Amazon. Popul. Res. Pol. Rev. 28 (3), 291–320.

Barbieri, A.F., Monte-Mór, R.L., Bilsborrow, R.E., E, R., 2009b. Towns in the jungle: exploring linkages between rural-urban mobility, urbanization and development in the Amazon. In: De Sherbinin, et al. (Eds.), Urban Population and Environment Dynamics in the Developing World: Case Studies and Lessons Learned. CICRED, Paris, pp. 247–279.

Barbieri, A.F., Santos, R.O., Guedes, G.R., 2014. The Migration, Environment and Development Nexus in the Frontier: a Review of the Literature Based on Empirical Evidences from the Brazilian Amazon Determinants of International Migration Conference, 2014. Oxford University.

Bebbington, A., 1999. Capitals and capabilities: a framework for analyzing peasant viability, rural livelihoods and poverty. World Dev. 27 (12), 2021–2044.

Bilsborrow, R., 1987. Population pressures and agricultural development in development countries: a conceptual framework and recent evidence. World Dev. 15 (2), 183–203.

Brondízio, E.S., 2008. The Amazonian Caboclo and the Açaí Palm: Forest Farmers in the Global Market. New York Botanical Garden Press, New York.

Brondizio, E., Moran, E., 2012. Level-dependent deforestation trajectories in the Brazilian Amazon from 1970 to 2001. Popul. Environ. 34 (1), 69–85.

Browder, J.O., Pedlowski, M.A., Summers, P.M., 2004. Land use patterns in the Brazilian Amazon: comparative farm-level evidence from Rondônia. Hum. Ecol. 32 (2), 197–224.

Caldas, M., Walker, R., Arima, E., Perz, S., Aldrich, S., Simmons, C., 2007. Theorizing land cover and land use change: the peasant economy of Amazonian deforestation. Ann. Assoc. Am. Geogr. 97 (1), 86–110.

Carr, D.L., Suter, L., Barbieri, A.F., 2005. Population dynamics and tropical deforestation: state of the debate and conceptual challenges. Popul. Environ. (27), 89–113. https://doi.org/10.1007/s11111-005-0014-x.

Castro, M.C., 2002. Spatial Configuration of Malaria Risk on the Amazon Frontier: the Hidden Reality behind Global Analysis. Office of Population Research. Princeton University Press, Princeton, p. 293.

Castro, M.C., Singer, B.H., 2012. Agricultural settlement and soil quality in the Brazilian Amazon. Popul. Environ. 34 (1), 22–43.

Castro, M.C., Sawyer, D.O., Singer, B., 2006a. Spatial patterns of malaria in the Amazon: implications for surveillance and targeted interventions. Health Place 13, 368–380.

Castro, M.C., Monte-Mor, R.L., Sawyer, D.O., Singer, B., 2006b. Malaria risk on the Amazon frontier. Proc. Natl. Acad. Sci. U. S. A 103 (7), 2452–2457.

Caviglia-Harris, J.L., 2018. Agricultural innovation and climate change policy in the Brazilian Amazon: intensification practices and the derived demand for pasture. J. Environ. Econ. Manag. 90, 232–248.

Davidson, E.A., de Araujo, A.C., et al., 2012. The Amazon basin in transition. Nature 481 (7381), 321–328.

Diniz, A.M.A., Lacerda, E.G., 2018. The complexities of the Brazilian Amazon frontier and its most recent chapter: soybean expansion in Roraima. In: Jones, R., Diniz, A.M.A. (Eds.), Twentieth Century Land Settlement Schemes. 1ed. Routledge, London, pp. 199–224.

Ellis, F., 1992. Agricultural Policies in Developing Countries. Cambridge University Press, New York, p. 357.

Everitt, B.S., 2006. An R and S-PLUS® Companion to Multivariate Analysis. Springer Science & Business Media.

FAO, 2011. 2011: State of the World's Forests. Food and Agricultural Organization of the United Nations, Rome.

Fearnside, P., 2006. Dams in the Amazon: belo Monte and Brazil's hydroelectric development of the xingu river basin. Environ. Manag. 38 (1), 16–27.

Guedes, G.R., Costa, S., Brondizio, E., 2009a. Revisiting the hierarchy of urban areas in the Brazilian Amazon: a multilevel approach. Popul. Environ. 30 (4–5), 159–192.

Guedes, G.R., Queiroz, B.L., L, B., VanWey, L.K., 2009b. Transferências intergeracionais privadas na Amazônia rural brasileira. Nova Econ. 19 (2), 325–357.

Guedes, G.R., VanWey, L.K., Hull, J.R., Antigo, M., Barbieri, A.F., 2014. Poverty dynamics, ecological endowments, and land use among smallholders in the Brazilian Amazon. Soc. Sci. Res. 43, 74–91, 0.

Guedes, G.R., Queiroz, B.L., Barbieri, A.F., VanWey, L.K., 2017. Property and household life cycles, markets, and land use/cover change in the Brazilian Amazon. Notas Poblacion 44, 104.

Hull, J.R., Guedes, G.R., 2013. Rebuilding Babel: finding common development solutions using cross-contextual comparisons of multidimensional well-being. Rev. Bras. Estud. Popul. 30 (1), 271–297.

INPE (National Institute for Spatial Research), 2010. Monitoramento Da Cobertura Florestal Da Amazônia Por Satélites - Sistemas PRODES, DETER, DEGRAD e QUEIMADAS. São José dos Campos: INPE. Retrieved from: http://www.obt.inpe.br/prodes/Relatorio_Prodes2010.pdf.

Lima, E.E.C.D., Braga, F.G., 2016. Nuevos patrones de migración intermunicipal en el Brasil: influencia de la dinámica económica y de los programas de transferencia de ingresos. Notas Poblacion 43 (103), 101–122.

Lovejoy, T.E., Nobre, C., 2018. Amazon tipping point. Science Advances 4 (2), eaat2340.

Marquette, C.M., 1998. Land use patterns among small farmer settlers in the northeastern Ecuadorian Amazon. Hum. Ecol. 26 (4), 573–598.

McCracken, S.D., Brondízio, E.S., Nelson, D., Moran, E.F., Siqueira, A.D., Rodriguez-Pedraza, C., 1999. Remote sensing and GIS at farm property level: demography and deforestation in the Brazilian Amazon. Photogramm. Eng. Rem. Sens. 65 (11), 1311–1320.

McCracken, S., Siqueira, A.D., Moran, E.F., Brondízio, E.S., 2002. Land use patterns on an agricultural frontier in Brazil: insights and examples from a demographic perspective. In: Wood, C.H., Porro, R. (Eds.), Deforestation and Land Use in the Amazon. University Press of Florida, Gainesville, FL, pp. 162–192 (Chapter 6).
Monte-Mór, R.L., 2004. Modernities in the Jungle: Extended Urbanization in the Brazilian Amazon. unpublished Ph.D. dissertation, University of California, Los Angeles (UCLA), Los Angeles.
Moran, E.F., Siqueira, A., Brondízio, E.F., 2003. Household demographic structure and its relationship to deforestation in the Amazon basin. In: Fox, J., Rindfuss, R.R., Walsh, S.J., Mishra, V. (Eds.), People and the Environment: Approaches for Linking Household and Community Surveys to Remote Sensing and GIS. Kluwer Academic Publishers, Boston, pp. 61–89.
Nepstad, D., McGrath, D., et al., 2014. Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. Science 344 (6188), 1118–1123.
Pan, W.K., López-Carr, D., 2016. Land use as a mediating factor of fertility in the Amazon. Popul. Environ. 38 (1), 21–46.
Perz, S.G., 2001. Household demographic factors as life cycle determinants of land use in the Amazon. Popul. Res. Pol. Rev. 20 (3), 159–186.
Perz, S.G., Brilhante, S., et al., 2008. Road building, land use and climate change: prospects for environmental governance in the Amazon. Philosophical Transactions of the Royal Society B 363, 1889–1895.
Pfaff, A., Barbieri, A.F., Ludewigs, T., Merry, F., Perz, S., Reis, E., 2009. Road impacts in Brazilian Amazonia. In: Keller, M., Bustamente, M., Gash, J., Dias, P. (Eds.), Amazonia and Global Change. American Geophysical Union.
Pichón, F., 1997. Settler households and land-use patterns in the Amazon frontier: farm-level evidence from Ecuador. World Dev. 25 (1), 67–91.
Richards, P.D., VanWey, L., 2016. Farm-scale distribution of deforestation and remaining forest cover in Mato Grosso. Nat. Clim. Change 6 (4), 418.
Richards, P.D., et al., 2012. Exchange rates, soybean supply response, and deforestation in South America. Global Environ. Change 22 (2), 454–462.
Rochedo, P.R.R., Soares-Filho, B., et al., 2018. The threat of political bargaining to climate mitigation in Brazil. Nat. Clim. Change 8 (8), 695–698.
Santos de Lima, L., Merry, F., et al., 2018. Illegal logging as a disincentive to the establishment of a sustainable forest sector in the Amazon. PloS One 13 (12) e0207855.
Sathler, D., Adamo, S., Lima, E., 2018. Deforestation and local sustainable development in Brazilian Legal Amazonia: an exploratory analysis. Ecol. Soc. 23 (2).
Sawyer, D., 1984. Frontier expansion and retraction in Brazil". In: Schmink, M., Wood, C. (Eds.), Frontier Expansion in Amazônia. University of Florida Press, Gainesville.
Schmink, M., Wood, C.H., 1992. Contested Frontiers in Amazonia. Columbia University Press, New York.
Schmittmann, V.D., Dolan, C.V., van der Maas, H.L.J., Neale, M.C., 2005. Discrete latent Markov models for normally distributed response data. Multivariate Behav. Res. 40, 461–488.
Schwartzman, S., Alencar, A., Zarin, H., Souza, A.P.S., 2010. Social movements and large-scale tropical forest protection on the Amazon frontier: conservation from chaos. J. Environ. Dev. 19 (3), 274–299.
Sellers, S., 2017. Family planning and deforestation: evidence from the Ecuadorian Amazon. Popul. Environ. 38 (4), 424–447.
Sherbinin, A., VanWey, L.K., Mcsweeney, K., Aggarwal, R., Barbieri, A.F., Henry, S., Hunter, L., Twine, W., Walker, R., 2008. Rural household demographics, livelihoods and the environment. Global Environ. Change 18, 38–53.
Skole, D.L., Chomentowski, W.H., Salas, W.A., Nobre, A.D., 1994. Physical and human dimensions of deforestation in Amazonia. BioScience - Global Impact of Land-Cover Change 44 (5), 314–322.
Smith, N.J.H., 1982. Rainforest Corridors: the TransAmazon Colonization Scheme. University of California Press, Berkeley.
Sonter, L.J., Herrera, D., et al., 2017. Mining drives extensive deforestation in the Brazilian Amazon. Nat. Commun. 8 (1), 1013.
Sydenstricker, J.M., 1992. Parceleiros de Machadinho: história migratória e as interações entre a dinâmica demográfica e o ciclo agrícola em Rondônia. Unpublished Master"s Thesis, Universidade de Campinas, Campinas (Brazil).
Thorner, D., Kerblay, B., Smith, R.E.F. (Eds.), 1986. Chayanov on the Theory of the Peasant Economy. Richard D. Irwin, Homewood, IL.
Tomaselli, I., Sarre, A., 2005. Brazil gets new forest law. ITTO Tropical Forest Update 15 (4), 7.
VanWey, L.K., D'Antona, A.O., Brondízio, E.F., 2007. Household demographic change and land use/land cover change in the Brazilian Amazon. Popul. Environ. 28 (3), 163–185.
VanWey, L.K., Hull, J.R., Guedes, G.R., 2012a. The ecology of capital: shifting capital portfolios, context-specific returns to capital, and the link to general household wellbeing in frontier regions. In: Crews-Meyer, K. (Ed.), The Politics and Ecologies of Health.
VanWey, L.K., Guedes, G.R., R, G., D'Antona, A.O., 2012b. Out-migration and land-use change in agricultural frontiers: insights from Altamira settlement project. Popul. Environ. 34 (1), 44–68.
Vermunt, J.K., Langeheine, R., Bockenholt, U., 1999. Latent Markov models with time-constant and time-varying covariates. J. Educ. Behav. Stat. 24, 179–207.
Walker, R.T., 2004. Theorizing land-cover and land-use change: the case of tropical deforestation. Int. Reg. Sci. Rev. 27 (3), 247–270.
Walker, R.T., Homma, A.K., 1996. O. Land use and land cover dynamics in the Brazilian Amazon: an overview. Ecol. Econ. 18 (1), 67–80.
Walker, R.T., Perz, S., Caldas, M., Silva, L.G.T., 2002. Land use and land cover change in forest frontiers: the role of household life cycles. Int. Reg. Sci. Rev. 25 (2), 169–199.
Walter, V., 2004. Object-based classification of remote sensing data for change detection. ISPRS J. Photogrammetry Remote Sens. 58, 225–238.
Weinhold, D., et al., 2013. Soybeans, poverty and inequality in the Brazilian Amazon. World Dev. 52, 132–143.
Zhou, W., Huang, G., Troy, A., Cadenasso, M.L., 2009. Object-based land cover classification of shaded areas in high spatial resolution imagery of urban areas: a comparison study. Rem. Sens. Environ. 113, 1769–1777.