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Sustainability of Colonist Land Uses in the Amazon: A Demo-Livelihoods Perspective

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Abstract: Amazon, the largest global tropical forest, is central to counterbalance the effects of climate change. However, the extant literature has not fully explained the effects of demographic changes on land use and livelihoods sustainability that reconciles production and conservation. Using a case study of 28 years in the Brazilian Amazon, this article provided novel empirical evidences on the co-evolution of household demographic dynamics (composition and life cycles), land use and livelihoods as depicted by the demo-livelihoods theoretical framework. Methods of analysis involve the combination of exploratory (descriptive, cluster and correlation) and a multivariate hazard model. The results validated the demo-livelihoods theory and showed that livelihoods adaptation over time involves diversification combining perennials and cattle ranching, land consolidation and off-farm strategies (remittances, wage labor, cash transfers). These strategies are conditioned by demographic dynamics. Households are less likely to diversify livelihoods with annual crops due to unsustainable environmental conditions and costs associated with land intensification and market accessibility. While diversification historically occur at the expense of primary forest, household ageing may create a momentum to limit deforestation and allows the future incorporation of plot-based natural capital as a source of diversified, sustainable land uses and livelihoods for carbon emissions and bioeconomy markets.

Keywords: demography; livelihoods strategies; farm households; colonist frontier; agriculture; cattle ranching; Brazilian Amazon

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1. Introduction

The sustainability of land-use systems (the combination, at the plot level, of livelihoods that can involve a combination of agriculture, cattle ranching, extractive resources and off-farm labor) in the Amazon and its importance to mitigate the impacts of climate change and biodiversity loss involves the combination of strategies that farm households use to achieve consumption and market-oriented production needs, and forest and biodiversity conservation. Achieving this sustainability involves reconciling demands for the conservation of natural resources and mitigation of carbon emissions, and the need to improve wellbeing and reduce poverty of rural populations.

A previous study in the literature proposes the demo-livelihoods theoretical framework as a novel contribution to integrate theories that aim to understand how the co-evolution of demographic characteristics of farm households with land-use systems and livelihoods at the plot and farm household level [1]. Farm households in colonist frontiers are, in this case, units of production and social reproduction. This relationship between household demographic dynamics and land use is also affected by opportunities and constrains in the macro-contextual levels, such as environmental policies, infrastructure development such as the opening of roads [2] and national policies for poverty alleviation.

The objective of this article was to provide novel empirical evidences to test the adherence of the demo-livelihoods theoretical framework [1] with a retrospective case study of 28 years for the municipality of Machadinho, Brazilian Amazon. In this sense,

and hypothesizing that land uses are not independent from demographic dynamic, it analyzed the association between demographic composition and the sustainability of land use production over time—specifically, cattle ranching and cultivation of annuals and perennials, land consolidation through plot acquisition and the use (or conservation) of forestland.

The article is organized in three parts. First, it summarizes key aspects of the Demo-livelihoods theoretical framework [1] to discuss how and why land-use decisions and the combination of other livelihoods strategies respond to changes in demographic composition, and when they take place at different stages of frontier settlement. Then, it tests the demo-livelihoods hypotheses using retrospective data on the evolution of the colonist frontier of Machadinho, in the southwestern Brazilian Amazon. This study area has been historically characterized by large deforestation (it is within the so-called "arch of deforestation" in the Brazilian Amazon) due to a combination of small- and large-scale agriculture and cattle ranching and infrastructure development projects. Furthermore, four surveys since 1987 collected data on plots and farm households that allow a long-term assessment of changes in livelihoods and demographic dynamics.

The subsequent parts bring a combination of exploratory (descriptive, cluster and correlation) and multivariate hazard analysis to unveil the linkages between land use strategies and household demographic composition changes over stages of frontier settlement in Machadinho.

2. Theories on Demographics Dynamics and Livelihoods over Stages of Frontier Settlement

Several theories have explained the adaptative capacity of farm households to the specific conditions of frontier environments, including the role of household size and composition as causes and/or consequences of these changes. For instance, the *Household Land Use and Life Cycle* approach, drawing upon Chayanov's peasant cycle [3,4] and adapted by several authors to the Amazonian context [3,5–13] states that land use and farm labor allocation decisions are contingent on household size and composition at specific stages of frontier development and household life cycles. According to Barbieri [1]:

> "*households adopt specific land uses in periods of low labor availability [initial frontier stages], such as clearing small forests and raising annual crops (at earlier stages when couples have young children). As households accumulate capital over time and have a higher availability of labor (young children becoming teenage children or young adults), they adopt or diversify land use from annual crops to cash crops, perennials and pasture, and increase deforestation (. . .) [while] Old Dependency Ratio and smaller household size in the post-frontier may indicate an "empty nest effect" [14] with sons or daughters reaching adulthood and leaving to constitute his or her own household, or in search of education or labor opportunities elsewhere*."

Thus, it is assumed that demographic dynamics co-evolves with land use strategies at earlier and intermediate frontier stages, but evolve separately when connections to markets become another component of livelihoods at later stages of frontier development [1,11].

Recent studies have reviewed the linkages between demographics and livelihoods framework to discuss strategies beyond land use and off-farm employment in the Household Land Use and Life Cycle approach [1,15]. The *Household Livelihoods and Capabilities approach* considers "rural livelihoods" as the capacity, assets (or capitals) and activities (and portfolios combining them) of farm households to guarantee livings and subsistence [1,13,16–20], as well as to diversify livelihoods and risks to subsistence. The way farm households decide for a combination of five types of capitals in order to meet expected livelihoods: natural capital (e.g., forests, water, soil, ecosystem services), social capital (e.g., social and migration networks, access to institutions, family/household and other interpersonal network or arrangements, human capital (e.g., education, qualification, knowledge about local environmental and ecological conditions, health status), physical capital (e.g., means of production owned by the household such as land, tractors and other

equipment, communal assets and access to infrastructure development such as road and electricity) and financial capital (e.g., cash income from farm production or from off-farm labor, remittances, government cash transfers) [13]. The access and profitability of such combination (or portfolio of capitals) is dynamic over time and reflects distinct temporal and spatial specificities at each stage of frontier development [1,14].

The third theoretical framework relating household demographics and livelihoods strategies is the *Extended Multiphasic Responses approach*. It was built upon Davis [21] discussion about demographic (fertility regulation and migration) responses to perceived changes in status and welfare given population pressures on limited resources. Bilsborrow [22,23] extends Davis multiphasic responses (originally representing urban, industrialized societies) to rural contexts in developing countries, classifying responses as a combination of demographic (fertility control) [23–25], economic-demographic (mobility) or economic. This last represents strategies involving land extensification (incorporation of new cultivated land) or intensification (technological improvements in the land). As in Davis [21], the adoption of responses is concurrent (meaning that when a household choose one response and it delivers the desired outcome, it is less likely the adoption of another response) or "multiphasical" (farm households can also choose simultaneously two or more responses).

Previous studies on the Household Land Use and Life Cycle, Household Livelihoods and Capabilities and Extended Multiphasic Responses approaches have shown that land use and other sources of livelihoods may be connected to household demographic dynamics, including, for example, the effects of household lifecycles on land-use decisions during initial and intermediate stages of frontier development [11] and the consolidation and diversification of land use systems over stages of frontier development [19]. While previous studies have focused on specific demographic aspects discussed in the three theoretical frameworks, the Demo-livelihoods Theoretical Framework assess their combined and synergic effects on livelihoods [1]. This article adds to the extant literature by empirically testing the demo-livelihoods framework, departing from the assumption that farm household production (e.g., land uses and other subsistence and/or market-oriented livelihoods) respond to, and foster further changes, in the demographic composition of farm households. For instance, the Household Land Use and Life Cycle and the Household Livelihoods and Capabilities approaches associate household exposition (time living in frontier environments) with changes in land use strategies (annuals, perennials, pasture, keeping forestland or cattle ranching). While the Household Land Use and Life Cycle approach expand the concept of household exposition to include household size and composition in terms of ageing of household members (a demographic-composition effect of household exposition), farm household labor composition (on and off-farm) and age structure (e.g., dependency ratios), the Household Livelihoods and Capabilities approach expand the portfolio of potential livelihoods to sources of capital not directly related to land uses.

The Extended Multiphasic Responses approach does not explicitly incorporate a temporal dimension (neither by exposition nor ageing) impacting household responses to threats in livelihoods [26]. However, its integration with Household Land Use and Life Cycle and Household Livelihoods and Capabilities approaches into the demo-livelihoods theory considers fertility and migration (a combination that ultimately, over time, determines household size and composition), together with economic (land use) responses, as adaptation strategies to perceived negative changes in living standards.

The demo-livelihoods theoretical framework implicitly assumes that demographics and livelihoods may be heterogeneous according to specific stages of frontier development. The household portfolio of capitals and livelihoods strategies respond both to the household demographics as well as spatial-temporal contingencies: spatially, given the location-specific characteristics such as infrastructure, connection to regional and national markets and environmental characteristics; and temporally, regarding time of exposure in the frontier and historical, political and cultural factors at each stage of frontier settlement.

Several authors have suggested evolutionary perspectives about the opening and consolidation of frontier areas, especially in the Amazon [1,6–9,11,12,14,19]. While these perspectives vary in terms of pace, levels and characteristics of development, there is a reasonable consensus in terms of (i) progression from subsistence or semi-subsistence land uses to intermediate and then diversified land-use systems with some degree of market integration [1,6,11,12,19,27,28]; (ii) frontier evolution being conditioned by macroeconomic and contextual processes articulated to capitalist accumulation strategies [29–33]; (iii) frontier evolution, including demographics, livelihoods, the trajectories of settlers and how Amazon frontiers have different ways to connect among them and with local, regional and national markets [14,34,35]; and that (iv) at later frontier stages the influence of household demographic dynamics on land use change decrease due to frontier integration to urban and regional markets [1,11,12,19,36,37].

In a demo-livelihoods perspective, the definition of frontier evolution involves understanding how a given cohort of colonists may experience over time distinct period effects (spatial-temporal contingencies) that are materialized in specific (pioneer, mature, post) frontiers with certain household and livelihoods compositions. As discussed in Barbieri [1], a pioneer frontier is characterized by initial settlement years (Years representing each stage of frontier development are for illustration purposes since stages may follow, as previously discussed, temporal and spatial contingencies) with relatively low conversion of primary forest to meet basic subsistence needs (mostly using annual crops), younger age composition (and high youth dependency ratio) with cohorts of pioneer migrant colonists living in predominantly nuclear families. Pioneer colonists are also likely to be involved in rural labor circulation and, given the absence of structured labor markets, in informal (including cooperative) labor arrangements. The mature frontier may involve around 7 to 14 years of settlement, when Dependency Ratio decreases since those children in the pioneer frontier age and enter in the farm household labor pool, thus creating advantages to invest in land uses offering higher profitability (pastureland for cattle and perennials). A consequence of these land use strategies is the rapid conversion of primary forest. On the other hand, ageing of pioneer colonists in the post-frontier (15 years or more) increases (particularly old) dependency ratios. This composition change, together with out-migration of sons and daughters (empty nest effect), reduces household labor supply. Farm households are more likely to combine different sources of capital to diversify livelihoods (both on-farm and off-farm).

These conditions in each frontier stage determine specific hypotheses, depicted in Table 1, on the association between household demographics and livelihoods strategies defining the household portfolio of capitals. It lists a non-exhaustive list of livelihoods/capitals as example. The hypotheses follow three assumptions [1]. First, while demographic composition in the frontier may change due to the settlement of new cohorts of in-migrants, we assume that changes over time are mostly due to pioneer descendants that stay and eventually assume plot ownership (family plot succession). Second, capitals are not mutually independent in the composition of the household portfolio; rather, they may be conditional or synergic (e.g., social networks, a source of social capital, may be a condition to access urban labor markets and, thus, remittances and wage labor). The release of farm labor for urban employment and/or emigration and out-migration may also be facilitated by multigenerational household arrangements (different generations of families living in the same household). Third, accumulation and accessibility to some capitals depends of household exposition and investments over the medium and long run—particularly regarding sources of human (e.g., education and labor qualification), physical (e.g., land consolidation, cattle) and financial (e.g., income from annual crops and perennials and off-farm employment) capitals, while other capitals may inversely be depleted over time, such as sources of natural capital that depends on keeping forestland in the plot. Other sources, especially social capital, may oscillate over frontier stages due to different accessibility to migration/social networks, markets (e.g., credit, urban labor), governmental institutions and social programs, among others.

Table 1. Hypotheses on the Demo-livelihoods Theoretical Framework [a].

Demo-Livelihoods	Pioneer (0–5 Years); 1970s–1980s	Mature (6–14 Years); 1980s–1990s
Demographics		
Dependency Ratio	High (due to high Youth Dependency Ratio)	Low (due to high acvtive population)
Mobility (migration, off-farm employment)	High due to frontier in-migration and off-fram employment strategies (rural labor circulation, land turnover)	Low due to on-farm labor-intensive activities and most of land availbale settled (less pioneer in-migration)
Time in the frontier	Short time	Longer time on average (including new settlers)
Age of the head	Younger	Older
Livelihoods		
Human Capital	***Low levels overall***	***Intermediate levels overall***
Education	Low: pioneer settlers among the most vulnerable from origin areas, including low education	Low: predominates education of pioneers, albeit increasing overall due to access of second generation to schools
Off-farm employment	Low consolidation of labor markets (especially urban), but high labor circulation due to cooperative rural work	Low due to on-farm labor-intensive activities and less developed urban markets
Physical capital	***Low levels overall***	***Intermediate levels overall***
Cattle ownership	Low investment in and ownership of cattle	Moderate to high investment in and ownership of cattle
Plot ownership	High (if in governmental land reform program), low otherwise	High (if in governmental land reform program), moderate otherwise
Owning other plots	Low investment in land consolidation	Moderate investment in land consolidation
Financial Capital	***Low levels overall***	***Intermediate levels overall***
On-farm income	High income proportion from farm production	High income proportion from farm production
Receive cash transfer	Low, with limited government policies and access to institutions	Moderate, with expansion of government policies and access to institutions
Receive credits/loans	Low, with limited government policies and access to institutions	Moderate, with expansion of governmet policies and access to institutions
Land in pasture	Low: lack of capital to invest in pastureland and cattle and needs to meet immediate consumption with annual/cashcrops	Higher: labor-demanding farm land uses that are more profitable, involving mixes of pasture/cattle ranching and perennials
Land in annuals and perennials	High use of annual crops to meet immediate family subistence needs	Higher: labor-demanding farm land uses that are more profitable, involving mixes of pasture/cattle ranching and perennials
Natural capital	***High levels overall***	***Intermediate levels overall***
Land in primary forest	High proportion of forestland	Lower due to intensive defotrestation for pastureland, annuals perennials
Forest Extractivism	High due to forest availability	Lower due to deforestation and low profitability
Social Capital	***High levels overall***	***Intermediate levels overall***
Birth in a given frontier area	Low proportion due to the profile of frontier in-migrantion	Moderate proportion due to the profile of frontier in-migrantion combined with increasing proportion of those born in the frontier
Multigenerenational households	Low proportion; mostly nuclear famililies with relatively younger head and spouse	Low proportion; mostly nuclear famililies with relatively younger head and spouse
Access to institutions (formal and informal)	High due to migration networks favoring in-migratio to the frontier; access to land reform and settlement institutions	Lower access to land settlement programs (informal land markets may arise and low migration networks due to on-farm labor demands (mobility pull)

Table 1. *Cont.*

Demo-Livelihoods	Pioneer (0–5 Years); 1970s–1980s	Mature (6–14 Years); 1980s–1990s
Demo-livelihoods	**Post-frontier (15 years or more); 2000s**	
Demographics		
Dependency Ratio	High (due to high Old Dependency Ratio)	
Mobility (migration, off-farm employment)	High due to emigration and out-migration (empty nest effect), off-farm employment (especially in growing urban areas)	
Time in the frontier	Long time on average (including new settlers)	
Age of the head	Old	
Livelihoods		
Human Capital	***Higher levels overall***	
Education	Moderate to high: remaining stock of lower education of the pioneers; increasing weight of education of second and subsequent generations	
Off-farm employment	High due to integration in/or access to labor markets (especially urban) as well a in rural areas and infrastructure development areas	
Physical capital	***High levels overall***	
Cattle ownership	High investment in and ownership of cattle	
Plot ownership	High (if in governmental land reform program or otherwise)	
Owning other plots	High investment in land consolidation	
Financial Capital	***High levels overall***	
On-farm income	Lower compared to previous stages due to off-farm diversification	
Receive cash transfer	High, with expansion of government policies and access to institutions	
Receive credits/loans	High, with expansion of government policies and access to institutions	
Land in pasture	High: livelihoods diversification combining a mix of on-farm (cattle, annuals and perennials) and off-farm strategies	
Land in annuals and perennials	High: livelihoods diversification combining a mix of on-farm (cattle, annuals and perennials) and off-farm strategies	
Natural capital	***Low levels overall***	
Land in primary forest	Low due to deforestation and the consolidation of land uses	
Forest Extractivism	Low due to deforestation and low profitability	
Social Capital	***High levels overall***	
Birth in a given frontier area	Smaller proportion due to frontier fertility, death of older household members, and household succession with those born in the frontier	
Multigenerenational households	Higher proportion due to co-habitation arrangements involving older and younger household members	
Access to institutions (formal and informal)	High, with consolidation of urban markets, public policies/welfare state and other institutions; social/migration networks favoring mobility	

[a] In the case of the Brazilian Amazon, chronological (calendar years) definitions of each stage represent the history of settlement policies in the Brazilian Amazon, beginning during the Military Regime in the 1970s–1980s and extending after the Democratic elections in 1984.

3. Material and Methods

3.1. Study Area: Machadinho, Brazilian Amazon

Figure 1 shows the location of the Amazonian municipality of Machadinho, in the Brazilian state of Rondonia, and its spatial distribution of rural plots. It has an area of 8509 km^2 (being 32% in preserved and protected extractive reserves). A colonization projected conceived by the Federal government in 1981 with funding from the World Bank, its initial large-scale occupation began in 1984 with settled landless families mostly from the Brazilian South [38]. According to the last Brazilian censuses, population in the municipality ranged from 13,848 in 1984 (initial year of settlement), 16,765 in 1991; 22,739 in 2000, 31,135 in 2010, to 30,707 in 2022 (data available at: https://censo2022.ibge.gov.br/panorama, accessed on 5 July 2023).

Machadinho is located in the "arc-of deforestation", the region on the southernmost, westernmost and northernmost regions of the Brazilian Amazon that have historically faced the largest pressures in terms of land occupation by farm colonists, large-scale cattle ranching, land speculation and infrastructure projects. Ecological conditions for settlement were considered the best compared to other colonization projects in the Brazilian Amazon since the 1960s [39]. Despite average soil fertility, there were several spots of high fertility soils, and the project design (distinct from the traditional "fishbone design" in Amazonian colonization projects) privileged the accessibility of plots to water streams [39]. The location of roads on basin dividers, in addition to guaranteeing water access to almost all plots, reduced erosion and assured connectivity to the main road connecting to the town of Machadinho [39].

Another distinguishing feature is that in addition to rural plots, the town was planned to serve as urban base (and even second-residence) for families of pioneer colonists, having almost 1500 urban houses in 1985 [38,39]. This settlement design aimed to adjust to the living style of most colonists in Machadinho who came from small urban areas in the most-developed areas in Southern Brazil [38,39].

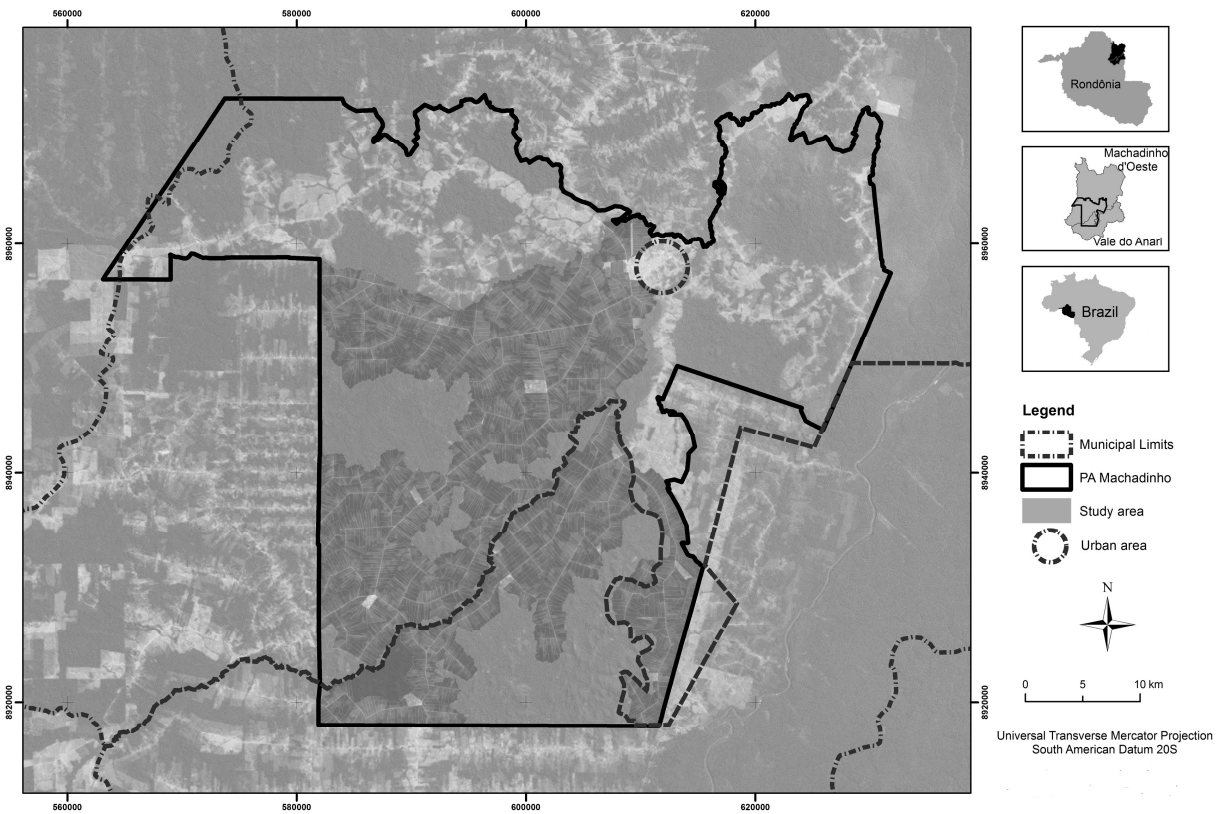

Figure 1. Study Area: Machadinho D'Oeste (Machadinho for short), Brazilian Amazon. Source: [40,41]. Cartography prepared by Alisson Barbieri and Reinaldo Santos.

3.2. Data

Four household surveys from 1987 to 2015 cover the three stages of frontier development in Machadinho: the pioneer frontier in 1987, the mature frontier in 1995 and the post-frontier in 2010 and 2015. The household surveys were implemented by investigators of the Center for Regional Development and Planning (CEDEPLAR), at the Federal University of Minas Gerais in Brazil. The last two surveys (2010 and 2015) were implemented through research grants coordinated by the author of this paper. The 1987 survey had 136 questions on migration history, malaria cases, knowledge about malaria and its transmission, use and access to health services, land uses and agriculture and cattle production, socioeconomic characteristics of settlers and their families, and housing conditions. The 1995 increased the number of questions to 292 on these same topics. The 2010 and 2015 had, respectively, 174 and 237 questions and excluded information on malaria, health services and migration history, and included questions on governmental cash transfers, and on attitudes towards risks to production and health (2015 only).

The number of farm households and individuals in the datasets were, respectively: 808 and 3961; 1069 and 5031; 259 and 914; 181 and 561. The first two were censuses (all plots settled and containing a household) in the portion of the original colonization project in Machadinho (depicted in Figure 1 as "study area"). The same plots in 1987 were revisited in 1995, and it was identified that *plot ownership* changed in some of them. As such, new plots from subdivisions of original plots were added to the analysis in 1995.

The initial post-frontier survey (2010) used a two-stage sampling strategy. In the first stage, the study area was divided in six clusters (named *setores*) following logistics and field cost criteria (travel time from the town of Machadinho and from the main road). In the second stage, there was a random selection of plots with farm households, keeping as similar as possible the number among clusters. Overall, the smaller number of farm households and plots compared to 1987 and 1995 was expected since later frontier stages may be characterized by land property turnover and/or accumulation of plots (land consolidation). The 2015 survey is a follow-up of all plots and farm households surveyed in 2010. There were 181 (70%) farm households interviewed; 30% informants were not found, or farm household had a new owner different from the nuclear family (head, spouse and sons, or one-member household) in 2010, or the plot was sold or consolidated in another farm.

Each dataset represents a mix of different settlement cohorts (with distinct arrival time in each frontier stage). A particularity of the post-frontier datasets is that they represent a panel of both plots and nuclear farm households. In addition to data from household surveys, information on land use and land cover were classified into annuals, perennials, pasture and forest cover using object-based classification [18].

3.3. Methods

In order to test the demo-livelihoods hypotheses presented in Table 1, the investigation in Machadinho employed the methods described in the following subsections.

3.3.1. Descriptive, Principal Components and Correlation Analysis

The first step was a descriptive analysis of key characteristics of farm household composition and life cycles, and livelihood strategies at each stage of frontier development (see Section 4.1). The goal was to assess if the behavior of each individual characteristic followed the predicted behavior in the demo-livelihoods hypotheses in Table 1.

Following the demo-livelihoods theoretical framework [1], the next step was to assess demographic patterns that synthetizes variables representing household composition and life cycle variables at each stage of frontier development. Then, a typology of household composition over life cycles based on the Demo-livelihoods framework using Principal Component Analysis (PCA) was created to reduce the variables Dependency Ratio and Proportion of Household Members in Off-farm Employment (composition); Time in the Frontier (Machadinho) and Age of the Household Head life cycles); and Household Size

(I considered household size as both a marker of frontier aging and of changing household composition and labor pool due to the *empty nest* effect) in new variables (principal components) that accounts for most of their variance. In order to assure the assumptions underlying PCA, these variables were standardized in the interval-level measurement and had a normal distribution [38]. The principal axis method was used to extract the components followed by a varimax (orthogonal) rotation, a method used to simplify the interpretation of a matrix involving the principal components and the variables. It maximizes variances in a way to reduce the number of factors associated with the variables used in the analysis [42]. The variance was, thus, maximized along the first axis (or, the first principal component). Additionally, the eigenvalue-one criterion (Kaiser criterion) was employed to retain and interpret components with an eigenvalue greater than one [42]. Variables presenting large loadings (0.40 or above) in a given component were retained for analysis [42].

Finally, the correlation analysis investigated the association between demographic patterns (the principal components) identified in the previous step and the evolution of livelihoods variables at each stage of frontier development.

3.3.2. Multivariate Hazard Model of Production Sustainability

The Concept of "Production Sustainability" in this article refers to, strict sensu, a Purely Economic and Market-oriented Sustainability of land uses. It contrasts to "Fully Land Use and Livelihoods Sustainability" which combines environmental and social (including economic) sustainability) over time.

It was assumed as an objective of the article that the sustainability of land-use production over time is not independent from demographic patterns (composition and life cycles).To test this assumption, the Cox semi-parametric regression [39] with a binomial dependent variable estimates the likelihood (or the probability of a hazard occurring) that a farm household in 2015 will maintain (or terminate) the production of annuals/perennials (cultivation) or cattle ranching for any given plot acquired over time in Machadinho. The hazard is influenced by independent variables representing time-varying physical and financial capitals (respectively, plots; cultivation, cattle ranching), and two time-invariant variables measured for 2015: the amount of forestland in the plot (natural capital) and demographic composition and life cycles in 2015 according to the typology defined in the cluster analysis.

Considering that a farm household may have acquired and produced in more than one plot over time, the dataset may be clustered (more than one plot within a farm household) and, thus, violates the assumption of independence of observations, leading to underestimated standard errors [43]. Robust standard errors are employed to address the problem of underestimating standard errors, thus improving parameter estimates' efficiency [43].

The hazard model is complemented with a descriptive analysis, based on the 2015 survey, of the household motivations to terminate production in the plot that are related to the consequences of increasing dependency ratios (ageing, labor drudgeries, health issues), environmental factors (plagues, environmental legislation, land degradation, extreme climate events), market accessibility and land conversion from agriculture to pasture. This analysis, by type of production (cattle, annuals, perennials), adds information to understand factors influencing the sustainability of land use production over time.

4. Results

4.1. Descriptive Analysis

In a first step in the verification of the demo-livelihoods hypotheses, Table 2 shows descriptive results for variables representing household composition and life cycles and livelihoods, at each stage of frontier development (pioneer, mature, post-frontier). Annuals, perennials and land in pasture are classified as financial capital since they generate income flows from cash crops, cattle ranching or subsistence price-equivalent crops. Primary

forest is classified as natural capital since they represent potential income from plot-based natural resources.

Table 2. Descriptive statistics of household demographics and life cycle and livelihoods over stages of frontier development in Machadinho, 1987, 1995, 2010 and 2015.

		Stages			
Dimension of Analysis	**Variable**	**Pioneer 1987**	**Mature 1995**	**Post-Frontier 1 2010**	**Post-Frontier 2 2015**
Sample characteristics	Number of farm households	808	1069	259	179
	Number of individuals in the plot	3961	5031	914	557
Farm households: composition and markers of life cycle	Total Dependency Ratio [a]	0.40	0.38	0.35	0.34
	Household head—age (mean, years)	40.0	42.3	52.2	54.7
	Time in Machadinho (years)	1.6	5.8	17.7	20.6
	Mean household size	4.9	4.7	3.5	3.1
	Farm households hiring laborers (%)	31.4	-	44.0	-
	Sex ratio	1.3	1.3	1.2	1.3
	Out-migrants in the last 5 years (%)	-	-	60.0	-
	At least one international out-migrant (%) [b]	-	-	13.4	-
Human Capital	Heads with more than 4 y. education (%)	7.0	11.3	8.3	6.1
	Spouses with more than 4 y. education (%)	4.5	17.6	14.9	16.1
	% over 14 y.o. in off-farm employment	9.3	6.7	16.8	15.2
Physical Capital	Farm households owning cattle (%)	13.6	62.6	85.3	65.4
	Head own the plot in Machadinho (%)	88.1	76.0	89.2	88.7
	Own other rural plots (%)	8.4	20.3	32.7	37.4
	Ownership of land/house in the city (%)	16.3	13.1	16.2	-
Financial Capital	% income from on farm production	32.7	73.8	82.5	-
	Households with cash transfers (%)	-	-	44.4	62.9
	Households with credit or loans (%)	-	18.2	46.9	61.2
	Land in pasture (%)	9.9	41.0	39.1	29.8
	Land in annuals and perennials (%)	4.4	5.5	26.0	39.2
Natural capital	Land in primary forest (%)	80.1	49.2	28.1	14.7
	Farms with extractive production (%) [c]	1.2	18.4	9.6	0.1
Social capital	Heads born in South/Southwest Brazil (%)	71.3	73.7	72.0	48.2
	Nuclear family—parents and sons only (%)	83.9	88.0	76.9	79.9
	Multigenerational household (%) [d]	2.8	2.0	15.4	15.8

Source: Machadinho Dataset (1987, 1995, 2010, 2015). [a] Sum of the population below 13 years old and the population 60 years old or more, in the numerator, divided by the total population in the denominator. [b] Living in the household or abroad at the survey date; 50 international out-migrants identified in 35 households. [c] It refers, before 2010, to the existence of seringas (rubber trees); in 2010 and 2015, to seringas, apiculture and fish ponds. [d] Farm households cohabitated by at least grandsons, granddaughters, and grandparents.

As suggested by the demo-livelihoods theory, the mean age of the head and time in the frontier increased over time (resulting from the accumulation of years since arrival in Machadinho), while age dependency ratios decreased from pioneer to the mature stage. Given ageing of pioneers, we assumed that dependency ratios progressively shift from predominantly young to old ratios over time. Older household age structure combined with the empty nest effect and higher on-farm diversification due to capital accumulation may explain higher reliance on hired (off-farm) labor in 2010 vis à vis 1987. There were no data to compare in 1995 and 2015, but the percentages of households with emigrants and out-migrants in 2010 showed the importance of migration as a livelihood strategy.

Mirroring the demographic transition in Brazil and the empty nest effect, household size declines over time. In the 2010 and 2015 post-frontier, the small increase in Sex Ratios may suggest a "masculinization" due to selective female out-migration, with males more likely to stay in the farm due to land succession (while we do not have information on out-migration in 2015, the proportion of females in off-farm employment in 2015 is a good proxy (and hypothetically a prior step) for out-migrant: 56.2%, against 53.8% for males).

This selectivity may indicate that the "empty nest effect" due to mobility implies not only accelerating household aging, but also unbalanced sex ratios.

Regarding human capital, education was consistently low for both head and spouse, albeit education of (female) spouses being higher compared to heads. It can be expected that the education of younger generation increases with the expansion of the public education and welfare system in the frontier. As an example, *Bolsa Familia* is a conditional federal cash transfer program in which vulnerable families receive a monthly remuneration to keep their children attending school and vaccinated (thus increasing levels of human capital). This helps to explain the higher off-farm (especially urban) labor opportunities that demand more, or other types of, qualification and education. Finally, mobility due to off-farm employment also approximates the hypotheses predicted by the demo-livelihoods theory.

Physical capital increased over time in terms of land consolidation (owning other rural plots) and cattle ownership, showing the importance of land extensification. However, there is an important decline in ownership of cattle in 2015, coherent with the decline in pastureland. While cattle ranching continued to be a profitable strategy, its decline may be associated with smaller household size, ageing and labor shortage. As will be seen below, these household compositional changes may trigger adjustments of livelihoods strategies towards less cattle and pastureland vis à vis other sources of financial capital, including off-farm employment and cash transfers (these last increased 42% between 2010 and 2015, from 44.2% to 62.9%). The high proportion of households owning the plot shows that land tenure is a remarkable characteristic of the Machadinho colonization project. Owning a house in the town showed little variation over time.

Income from on-farm activities predominate in the mature and post-frontiers, when farm households increasingly diversify financial capital toward off-farm employment, remittances from out-migration and cash transfers. In fact, access to loans and credits increased from 18.2% in 1995 to 46.9% in 2010 and 61.2% in 2015. These results, combined with the increasing proportion of hired labor, suggest the advancement of institutions (financial and labor markets and the Welfare State) in the post-frontier. Finally, the depletion of plot-based forest and extractive production over time indicates a smaller reliance on natural capital.

The diversification of household portfolio may be facilitated by multigenerational cohabitation arrangements that favor allocation of farm labor pool in activities outside the farm and, thus, reduce risks from relying only on on-farm production. Furthermore, these arrangements are associated with household income security through retirement pensions (usually for the pioneers), or for families with children in vulnerable socioeconomic conditions (the *Bolsa Familia* federal cash transfer program). Multigenerational arrangements also facilitate intra-household transfers among members of different generations. Finally, Table 2 shows that most pioneers were born in the South or Southeast regions of Brazil [38], but over time, the second generation that was born in Machadinho—and hypothetically more adapted to the frontier environment—became relatively larger [19].

Overall, and as suggested by the demo-livelihoods theory, longer time of exposure to the frontier environment may facilitate the accumulation and diversification with certain types of capital, such as physical and financial, and some human capital. This accumulation occurs at the expense of the depletion of natural capital (decreasing proportion of forest and use of extractive resources). Social capital may provide access to distinct sources of livelihoods over time, such as institutions promoting land tenure and land accessibility during the pioneer stage [38], or cohabitation patterns and migration networks favoring labor allocation in profitable off-farm opportunities in the post-frontier.

4.2. Principal Components and Correlation Analysis

While the preceding section show descriptively the evolution of farm household demographics and livelihoods variables over time, the next step was to identify how each frontier stage is related to specific demographic patterns represented by typologies of household composition and life cycles, according to the hypotheses in Table 1. Using

Principal Components Analysis (PCA), only the first two components (I named them scores) showed eigenvalues greater than 1 and, thus, were retained for rotation. Table 3 shows the estimates for rotated factors, final communalities and the variance accounted for each pair of scores. The labels in the columns define the substantive meaning for each score.

The pairs of scores for pioneer and mature stages have similar meanings. The first score was named younger demographic score (1), since young household composition (dependency ratio) and household size were positively associated and load in the first component. The second score was loaded by off-farm labor negatively associated with age of the head and time in the frontier; thus, it was named early on-farm specialization score (2). Both scores (1 and 2) defined an early position in the life cycle, as predicted by household life cycle approaches.

Since older dependency ratio and age of the head (rather than household size) positively load in the first score of the post-frontier, it was named older demographic score (3). In 2015, time in Machadinho combined with age of the household head to reinforce the importance of ageing households. In contrast to the predominance of age-composition factors, household size and off-farm labor positively loaded in Score 4. Contrary to previous frontier stages when the negative score for the percentage of household members in off-farm employment was not significantly correlated with household size (Score 2), the positive association suggests that larger household size (hypothetically in multigenerational arrangements) combined with less time in the frontier favors off-farm diversification rather than farm labor retention. It was named off-farm specialization score (4).

The next step (Table 4) was to analyze correlations between demographic patterns (the typology of household composition and life cycles and livelihoods) at each frontier stage. For comparison and simplification, the analysis kept only the variables in Table 2 that were available in three frontier stages (1987, 1995 and 2010).

All scores in the pioneer and mature frontiers showed a negative association with human capital variables (education of the head and spouse and off-farm employment). In contrast, off-farm employment was positive for all scores in the post-frontier and, in 2015, education was positively significant for off-farm specialization. Considering that, over time, descendants from pioneers in both scores may achieve higher education levels as discussed in the descriptive results, they have access to an important source of human capital that favors off-farm labor allocation in markets demanding higher qualification.

This diversification strategy may be facilitated by multigenerational household arrangements. The demographic scores (1) in the pioneer and mature frontiers showed similarity in terms of positive association with multigenerational households. Both scores (3 and 4) in the 2010 post-frontier, and score 4 (off-farm specialization) in 2015 were positively significant (contrasting to the negative significance of nuclear households), showing the importance of multigenerational households as a source of social capital. Households with the head born in the Amazon (more adapted to the environment) were similar in the specialization scores 2 in the pioneer and mature; and 4, in the post-frontier.

Financial capital showed a positive association with the specialization score (2) in the pioneer and mature frontiers, and a gradual transition of direction from the positive association of on-farm specialization land in pasture in the pioneer and mature frontiers (score 2) to no-significant (2010) and negative association with off-farm specialization in 2015. In contrast, annuals and perennials became positively associated with off-farm specialization strategies, while the negative association of annuals and perennials with older demographic structure and positive significant association with pastureland (as well as cattle, physical capital) in 2015 seemed coherent with the adaptation of ageing household composition to less labor demanding land uses. Thus, household ageing acts to differentiate land use specialization scores within the post-frontier and across frontier stages.

Table 3. Rotated Factor Pattern [a] and Final Communality (h^2) Estimates from Principal Components Analysis (PCA) of Farm Household Composition, Labor Allocation and Lifecycles [b].

Variable	Pioneer 1987			Mature 1995			Post-Frontier 1 2010			Post-Frontier 2 2015		
	younger demographic score (1)	early on-farm specialization score (2)	h^2	younger demographic score (1)	early on-farm specialization score (2)	h^2	older demographic score (3)	off-farm specialization score (4)	h^2	older demographic score (3)	off-farm specialization score (4)	h^2
Dependency ratio	**0.86**	−0.03	0.75	**0.83**	−0.05	0.70	**0.77**	0.12	0.60	**0.72**	−0.03	0.51
mean age of head of household	0.21	**0.62**	0.44	0.13	**0.63**	0.42	**0.84**	0.01	0.71	**0.88**	−0.06	0.71
Time in Machadinho (years)	−0.14	**0.71**	0.52	−0.15	**0.69**	0.50	−0.10	**−0.41**	0.17	**0.74**	−0.05	0.56
Mean household size	**0.86**	0.08	0.75	**0.83**	0.09	0.70	−0.22	**0.62**	0.54	−0.24	**0.72**	0.57
% over 14 y.o. in off-farm employment	−0.01	**−0.45**	0.18	−0.05	**−0.62**	0.39	0.22	**0.73**	0.55	0.12	**0.82**	0.69
Accounted variance			0.53			0.54			0.52			0.62

Source: Machadinho Dataset (1987, 1995, 2010, 2015). [a] Values in bold present large loadings (0.40 or above) in a given component. [b] "Score" represents the demographic pattern combining variables measuring household composition and life cycles.

Table 4. Correlation and significance statistics between typology (scores) of farm household demographics and life cycles and livelihoods, at the pioneer and mature (1987 and 1995) and post-frontiers (2010 and 2015) [a].

Dimensions of Analysis and Variables	Pioneer (1987)		Mature (1995)		Post-frontier 1 (2010)		Post-frontier 2 (2015)	
	Younger Demographic Score (1)	Early On-Farm Specialization Score (2)	Younger Demographic Score (1)	Early On-Farm Specialization Score (2)	Older Demographic Score (3)	Off-Farm Specialization Score (4)	Older Demographic Score (3)	Off-Farm Specialization Score (4)
Human Capital								
heads with more than 4 y. education (%)	−0.16 **	−0.09 *	−0.01	−0.12 **	−0.16 **	−0.13 *	−0.24 **	0.25 **
spouses with more than 4 y. education (%)	−0.09 *	−0.07 *	−0.28 **	0.01	−0.15 *	0.05	−0.29 **	0.31 **
% over 14 y.o. in off-farm employment	−0.01	−0.45 *	−0.05	−0.62 **	0.12 +	0.73 **	0.13 **	0.82 **
Physical Capital								
farm households owning cattle (%)	0.06 +	−0.02	−0.01	0.20 **	−0.08	−0.03	0.10 **	−0.03
head own the plot in Machadinho (%)	0.09 *	0.13 **	0.10 **	0.41 **	0.15 **	0.07	−0.03	0.11 **
own other rural plots (%)	−0.03	−0.05	−0.06 *	0.11 **	−0.02	0.04	−0.06 +	−0.06
ownership of land/house in the city (%)	−0.01	0.05	−0.12 **	0.09 **	0.12 *	−0.08	–	–
Financial Capital								
% income from on farm production	−0.01	0.13 **	−0.05	0.31 **	0.13 +	−0.23 **	–	–
land in pasture (%)	−0.02	0.08 *	0.02	0.08 *	−0.02	−0.02	0.15 **	−0.12 **
land in annuals and perennials (%)	0.02	−0.02	0.01	−0.02	−0.01	−0.11 +	−0.08 *	0.16 **
Natural capital								
land in primary forest (%)	−0.03	−0.07 *	−0.02	−0.08 *	0.07	0.06	0.06 *	−0.09 **
farms with extractive production (%)	0.02	0.04	−0.05 +	0.20 **	0.02	−0.03	–	–
Social capital								
heads born in South/Southwest Brazil (%)	0.05	−0.12 **	0.03	−0.09 **	−0.01	0.03	0.13 **	−0.27 **
nuclear family—parents and sons only (%)	−0.09*	0.02	−0.09 **	0.04	−0.09	−0.31 **	0.01	−0.40 **
multigenerational household (%)	0.06*	−0.03	0.10 **	−0.03	0.17 **	0.26 **	0.09	0.40 **

Source: Machadinho Dataset (1987, 1995, 2010, 2015). ** $p < 0.01$, * $p < 0.05$, + $p < 0.1$. [a] "Score" represents the demographic pattern combining variables measuring household composition and life cycles.

The results showed a significant accumulation of on-farm physical capital from pioneer to mature frontier, strengthening on-farm specialization (score 2). Ownership of other plots was not significantly associated with older demographic composition in 2010, but its negative significance in 2015 suggests that older household structures are less associated with land diversification through plot acquisition or consolidation. On the other hand, demographic scores (1 and 3) showed high correlation from pioneer to mature and post-frontiers in terms of plot ownership and, particularly from mature to 2010 post-frontiers, of ownership of land and/or house in the town (which favors rural–urban mobility). However, as farm households age towards the post-frontier, plot ownership loses significant association with older demographic structure and becomes positively correlated with off-farm specialization.

Natural Capital followed the predicted pattern in Table 1, but the depletion rate of forests was faster in the pioneer and mature frontiers in the specializations core (2). This indicates a rapid consumption of forests and their replacement by other types of capital, as indicated by higher land in pasture and higher proportion of on-farm income in Table 2. The results also showed weak or non-association with the demographic score (1) in the pioneer and mature stages and positive association with extractive production in the mature stage. While there was no association with the scores in the post-frontier in 2010, the percentage of forestland in 2015 was positively associated with older demographic score, but negatively associated with off-farm specialization score. This last case suggests that, considering the positive and significant association with land and annuals and off-farm income, land diversification may be achieved at the expense of forestland.

4.3. Multivariate Hazard Analysis of Production Sustainability

Following the hypothesis that the sustainability of land-use production over time is not independent from composition and life cycles, Table 5 shows the estimates of the multivariate hazard model of production sustainability in 2015. The Old Demographic Score was consistently negative for all categories of plot uses: the higher the association with this score, the lower the hazards of maintaining farm production over time. In contrast, higher association (scores) of farm households with off-farm specialization increases the hazard of keeping the farm production for intermediate levels of physical capital (owning 2 or 3 plots).

The direction of the signal for type of production also differed by plot size. Considering farm households having only one plot, the hazard of keeping production for those having cattle was only 58% of the hazard for those having cultivation. While the association was positive when we considered two or three plots, the hazard ratio practically equal to one suggests that both farm households with cattle or cultivation had a similar risk to maintain the production.

The combination of these results suggests that higher levels of physical capital (especially two and three plots) and off-farm specialization is associated with sustaining farm production for both cattle and perennials. More physical capital (plots) and investment in these land uses allows for diversification strategies that may be synergic (e.g., off-farm income invested in land consolidation and cattle), and thus, more resilience in farm production over time. Thus, if, on one hand (as in Table 4), farm households with off-farm specialization strategies are less associated with land in pasture (contrary to the older demographic profile), on the other hand, they are more likely to maintain its production over time (Table 5) and to diversify livelihoods in perennials, off-farm income and sources of human capital (Table 4). The higher likelihood of farm households with an older demographic profile to terminate production over time seems to be explained by the fact that (Table 4) the positive association with land in pasture and having cattle is constrained by smaller possibilities to accumulate physical capital (other plots) that create scale and profitability for cattle ranching.

Table 5. Parameter estimates, robust standard errors, significance tests (Pr > ChiSq) and hazard ratios for the binomial hazard model of farm household production sustainability in 2015 [a].

Variable	Parameter Estimate	Standard Error	Pr > ChiSq	Hazard Ratio
Old Demographic Score, 2015 [b]				
1 plot	−0.76	0.15	<0.0001	0.47
2 plots	−1.42	0.25	<0.0001	0.32
3 plots	−0.87	0.29	0.003	0.42
4 or more plots	−1.08	0.37	0.004	0.34
Off-farm Specialization Score, 2015 [c]				
1 plot	−0.05	0.10	0.62	0.95
2 plots	0.40	0.23	0.09	1.49
3 plots	0.65	0.33	0.05	1.96
4 or more plots	0.35	0.32	0.27	1.42
Production (1 = cattle, 0 = cultivation)				
1 plot	−0.55	0.14	<0.0001	0.58
2 plots	0.01	0.01	0.10	1.01
3 plots	0.02	0.01	0.009	1.02
4 or more plots	0.01	0.01	0.58	1.01
Land in forest, 2015 (%)				
1 plot	−0.06	0.78	0.94	0.94
2 plots	−0.23	1.55	0.88	0.79
3 plots	1.18	1.61	0.46	3.26
4 or more plots	2.66	1.34	0.04	14.30

Source: Machadinho dataset (2015). [a] Considering, as binomial dependent variable, if the farm household maintain the production in a given plot over time (=1) or terminate the production over time in the plot (baseline, =0). All models fit (for number of plots) were significant ($p < 0.0001$) in the −2LogL and Wald (sandwich) tests. Parameter estimates correspond to the (positive or negative) strength of statistical association of each covariate on the likelihood of maintaining the production over time. The robust standard error is a measure of the statistical accuracy of the parameter estimate; it is usually higher than normal standard errors but is more efficient to correct for the clustered nature of the data (more than one plot within a farm household). Significance tests (Pr > ChiSq) indicates if the parameter estimate is statistically significant. Hazard ratio is the comparison between the likelihood of households maintaining the production compared to the likelihood of households terminating the production for a given covariate. [b] score of each farm household on the component. "Score" represents the demographic pattern combining variables measuring household composition and life cycles. Mean −0.0159592, st.dev. 1.0064427. [c] Score of each farm household on the component. Mean 0.000146367, st.dev. 0.9945439.

Table 6 unveils the motivations behind land use and livelihoods strategies. The reasons to terminate farm production of the main perennial production (coffee, a highly labor-intensive land use) was associated with household ageing and related factors such as labor drudgeries and health issues. In fact, Table 4 shows that farm households in the older demographic profile had a negative association with perennials (and, thus, smaller diversification with on-farm sources of financial capital). On the other hand, cattle ranching remains the most important production being kept over time (25% of the plots settled).

Contrary to coffee production in Table 6, annuals (especially subsistence crops such as rice and corn, but also other annuals) seemed less resilient over time and termination was more related to environmental problems (plagues, land degradation) rather than ageing-related factors. Problems of access to markets—including hiring in local labor markets to replace ageing and/or small farm labor pool—is also important to explain terminating the production of some annuals and perennials. Keeping the production of profitable perennials (especially coffee) continues to be important, particularly for farm households with off-farm diversification strategies (as shown in Tables 4 and 5).

Finally, Table 5 shows that the stock of primary forest was significantly positive only for farm households owning four or more plots (which seems consistent if we assume smaller pressure on deforestation for smaller ratios of population per hectares). In this case, an additional increase in the proportion of forest increases the hazard of keeping farm production. While diversification with physical capital (owning four or more plots), financial capital (maintaining land uses) and natural capital (primary forest) allows produc-

tion sustainability over time, farm household demographic composition seems to mediate deforestation levels. In fact, farm households associated with older demographic scores (higher age of the head, longer time in Machadinho and higher old dependency ratio) are more likely to terminate or limit farm production when owning four or more plots and, thus, use less forestland (consistent with the positive association with primary forest in Table 4).

Table 6. Main causes or motivations for land-use decisions regarding production maintenance or termination in a given plot over time in Machadinho, Brazilian Amazon, by type of production.

Land Use Decision	Cattle	Other Animals	Coffee	Other Perennials	Rice	Corn	Manioc	Other Annuals
Keep production (%)	25.0	6.7	11.0	5.9	2.5	1.8	3.0	3.9
n	234	63	103	55	23	17	28	36
Terminate production (%)	4.1	0.9	8.0	3.7	9.6	6.3	1.2	6.4
n	38	8	75	35	90	59	11	60
Motivation [a] to not produce (%)								
Ageing	0.63	-	2.19	0.31	0.31	1.25	-	0.63
Labor drudgery	0.31	0.31	2.50	0.63	0.94	0.31	0.31	1.25
Plagues	0.94	0.63	0.63	1.88	7.19	4.69	-	3.75
Environmental legislation [b]	0.63	-	0.31	0.31	0.94	0.31	-	0.31
Market [c]	0.94	1.25	5.00	3.75	1.88	0.63	0.94	1.56
Land degradation [d]	0.63	-	4.06	1.25	6.25	4.38	0.31	3.44
Health issues	-	-	1.88	0.63	2.19	0.94	0.31	1.56
Convert to pastureland	-	-	0.63	-	1.88	1.56	0.31	2.50
Climate/extreme events	0.63	-	0.31	0.94	0.94	0.31	-	0.31
Others	3.44	0.31	0.31	0.94	1.56	0.63	-	0.94

Source: Machadinho dataset (2015). [a] Percentage regarding motivation are estimated based the total responses (100%) for "Do not continue to produce". [b] Legislation defining limits to deforestation or plot regularization. [c] Include production costs, low prices, and high cost of hired labor. [d] Includes land degradation due to overuse and loss of fertility, and lack of capital to invest in intensification to correct land fertility and/or expand production.

5. Discussion

Overall, the results show adherence to the hypotheses on the demo-livelihoods theoretical framework (Table 1). The definition of demographic patterns combining household age composition and life cycle factors are particularly relevant to explain livelihoods strategies at each frontier stage, as predicted by the demo-livelihoods theory. The time of exposition in the frontier allows farm households to accumulate physical and financial as well as some human capital that facilitates access to off-farm employment. Each stage is also related with the accessibility to different sources of social capital that may favor improving and diversifying livelihoods, for example, cohabitation patterns in multigenerational households and migration networks favoring labor allocation in profitable off-farm opportunities in the post-frontier. In the opposite direction, sources of natural capital rapidly decrease over time.

A distinguishing characteristic of frontier settings is that the accumulation of capitals and access to specific sources of capital over time may allow higher resilience through livelihoods diversification and the combination of on-farm and off-farm strategies or, as in the Extended Multiphasic Responses approach, economic and economic-demographic responses [19]. In fact, the results confirm the hypotheses (Table 1) that farm households in the post-frontier have more diversified land uses, with perennials and pastureland for cattle ranching as the most important shares of plot land use replacing forestland, and a mix of distinct off-farm sources of financial capital. Such empirical evidences are fundamental to inform public policies targeting the elimination of long-term deprivation and poverty trajectories that undermines land use sustainability in the Amazon.

Diversification strategies are mediated by demographic composition. In fact, the sustainability of farm production is less likely when it combines smaller levels of physical capital (owning only one plot) and older household age composition. However, indepen-

dent of combinations with physical capital, ageing is a constraining factor in production sustainability, as shown by the negative association between older households and keeping production. This scenario changes when farm household diversify land use systems towards more profitable (and less labor intensive) cattle ranching and some perennials (as shown in Table 4), more physical capital (land consolidation) and off-farm diversification strategies (as shown by the positive association with off-farm specialization score), replacing, in the household portfolio, losses in the stock of plot-based natural capital. Farm households specializing in off-farm strategies are less associated with cattle ranching (Table 4) but more likely to keep its production over time as well as to diversify livelihoods in annual/perennials (more labor demanding, Table 4), physical capital (owning more plots, Tables 4 and 5), and off-farm income and sources of human capital (Table 4). Furthermore, smaller household labor pool due to the empty nest effect and ageing is not necessarily a constrain for diversification if farm households have scale in (less labor intensive) cattle ranching and producing perennials with more plots, thus releasing farm labor for off-farm diversification strategies.

While keeping production of profitable perennials (especially coffee) continues to be important for farm households with off-farm diversification strategies, households over time are less likely to diversify livelihoods in terms of annual crops. Rather than composition (especially ageing) factors only, this also seems a consequence of smaller environmental sustainability due to plagues and land degradation as well as production costs associated with market accessibility (labor and agricultural inputs constraining land intensification strategies, and selling the production).

As argued by Barbieri et al. [19], land use and livelihoods diversification should combine environmental and productive sustainability and improve resilience over time in the frontier environment. However, diversification does not necessarily assure improvements in resilience or are a pathway towards sustainable livelihoods. For example, off-farm employment and migration may deteriorate labor conditions in destination areas such as urban labor markets, mining sites (including gold mining *garimpos*) and construction sites. These precarious labor conditions reproduce the socioenvironmental unsustainable land uses and livelihoods in the Amazon.

There were two limitations in the results. First, while they indicate an overall adherence to the demo-livelihoods hypotheses, some deviances (such as the faster depletion of capital natural) may be at least partially explained by the periodization of frontier stages. Compared to the 15 years separating mature and post-frontier, the relatively close dates for pioneer and mature frontiers (8 years apart) may have blurred a sharper distinction between them. The distance between data measured for the pioneer frontier (1987) and the initial settlement in Machadinho in 1984 may have lost the period of lower initial deforestation. It is possible that this timing did not fully capture the transition to an experimentation stage [6] which involves higher adaptation to frontier land use conditions.

Second, while the applicability of the demo-livelihoods theory to other contexts in the Amazon or elsewhere may be supported by the fact that it is built upon the synthesis of long-standing theories and empirical studies, generalizations to other contexts should be taken with caution. The theory does not intend to be universalistic; accessibility to markets, institutions and territories may define distinct household livelihood strategies, depending on their specific time-space context. As multiple frontiers exist according to temporal and spatial contingencies, there are also heterogeneous populations within the same frontier (as shown by the existence of two scores per frontier stages). In this sense, distinct livelihood strategies and trajectories according to different settlement cohorts, socioeconomic and cultural backgrounds may arise at each frontier stage. In order to overcome this limitation, revisiting and adapting the demo-livelihoods theory to context-specific realities is a pathway to aggregate the validity of empirical findings on the co-evolution of demographics and livelihoods predicted by the demo-livelihoods theory.

6. Conclusions

Reconciling sustainable land-use production and livelihoods with conservation efforts (fully land use and livelihoods sustainability) is a complex effort that involves, among other factors, understanding the mediating role of demographic factors. While extant theories have provided only partial explanations, the demo-livelihoods theoretical framework unveils how the co-evolution of household composition and life cycles and livelihoods over distinct stages of frontier development may inform more precise or focused policies aiming to foster sustainability in the Amazon.

In this sense, the article proposed two novel contributions. First, the literature review in Section 2 showed examples of studies using the farm household life cycles, livelihoods and capabilities or extended multiphasic responses theories to investigate associations between specific demographic factors and sources of livelihoods (mainly land uses) in specific periods of time (that is, these studies are mostly based on cross-sectional surveys). This article used a synthesis of these theories in the demo-livelihoods theoretical framework to evaluate the association between demographic patterns (combining household composition and life cycle factors) and land uses and livelihoods. The justification is that the effects of demographic factors are not independent. For example, selective off-farm employment and emigration (involving younger, adult household labor force), combined with time in the frontier, increase dependency ratios at a specific frontier stage and over time. Thus, the simultaneous combinations of composition and life cycle variables may reveal specific demographic patterns associated with specific livelihoods strategies.

Second, demographic patterns are not static. They may change over time or even show two or more patterns in a population at the same frontier stage, as shown in Table 3. Identifying and measuring context-specific frontier stages (pioneer, mature and post-frontier) and how they reveal specific associations between demographic patterns and livelihoods was possible with the 28-year dataset for Machadinho. No other empirical study in the Amazon has used such long-term analysis capturing all stages of frontier development.

These contributions revealed how demographic processes and scenarios based on study cases are useful to inform policy pathways to fully land use and livelihoods sustainability in the Amazon. This is not only for the fate of the forest itself and its inhabitants. It also meets global demands to reduce carbon emissions and biodiversity conservation, including those demands coming from the Global North, which has the highest responsibility for the causes and consequences of global warming. In this sense, understanding mechanisms and factors, including demographic, that pressure fully land use and livelihoods sustainability is fundamental to build efficient and focused policy actions. The combination of national policies with international compensation mechanisms should be sensitive to the micro (demographic) factors that create positive synergies and opportunities for effective forest conservation combined with improving livelihoods.

Regarding this last aspect, future research may explore the potential for fully land use and livelihoods sustainability given the momentum with the advancement of demographic transition. Its impact on farm household ageing may, hypothetically, positively impact the preservation of primary forest and forest recovery in traditional colonist frontiers. Considering, as shown by the results, that the conservation of forestland is compatible with maintaining land use production by older farm households owning large stocks of physical capital (four or more plots), and considering ageing as a constraining factor to expand cattle ranching or perennials, using the stock of natural capital in climate change mitigation strategies such as carbon emission markets and bioeconomy may meet demands for diversification and improving sustainable livelihoods compatible with the post-frontier demographic composition and life cycle.

This scenario of ageing frontier households highlights the increasing importance of governmental cash transfers (such as pensions) targeting the elder in the definition of livelihoods. In addition to governmental and institutional changes, future research may explore the role of other macro, contextual changes in the mediation of the linkages between household demographics and livelihoods. While this article focused on the micro (plot

and farm household) dynamics in a colonist frontier, it can be articulated with other types of frontiers, such as those associated with the expansion of agribusiness, mining, and large-scale infrastructure development (roads, dams, etc.). As these multiple frontiers may co-exist and compete for resources, they generate conflicts and opportunities that influence the sustainability of colonist livelihoods.

Finally, given the potential impacts of climate change on land use and land cover change in the Amazon [44,45], future research may explore the role of demo-livelihoods transitions on the adaptation to these impacts. This is a particularly important issue since future demographic dynamics may be increasingly conditioned by the pace and level of risks and disasters associated with environmental (particularly climate) change.

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