The Impact of Settlement Design on Tropical Deforestation Rates and Resulting Land Cover Patterns

Jill Caviglia-Harris and Daniel Harris

Policymakers in the Brazilian Amazon face the challenge of meeting environmental and developmental goals as cities and towns within these tropical forests continue to face migration pressure. Alternative government planning strategies have been implemented to address forest clearing in conjunction with meeting social agendas. This paper uses panel estimation methods to investigate the impact of settlement design on land use. Results indicate that new settlement designs developed to further social interaction have had a negative impact on land cover and land use transformation. Thus, while new settlement designs appear to positively impact stated social goals, including greater contact between families and access to water and services, these social advances have come at the expense of environmental goals.

Key Words: deforestation, land use/land cover change, smart growth, settlement design, Amazon, Brazil

Tropical deforestation remains the single most studied land cover transformation on earth. The ecological and climatic value of these forests combined with their rapid rate of loss has captured the attention of researchers from the physical and social sciences. Methodologies to examine and quantify land use and land cover change (LULCC) have been evolving due to advances in remote sensing technology and the techniques used to combine these data with household survey data. However, as our understanding of these processes advances, deforestation continues at historically high levels in many regions of the world. The largest of these tropical zones is the Brazilian Amazon, which houses the world's most extensive contiguous tropical forest. And, though rates have declined in recent years (INPE 2010), the annual area deforested in this country remains the largest across the globe (FAO 2010). Much of the continued progression of the deforestation frontier throughout South America, including Brazil, can be linked to pressures from government settlement programs. In response, colonization design has been promoted by policymakers to meet evolving social and environmental agendas. However, given that the dynamic impacts of settlement design on land cover change are largely unknown, an

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analysis of these varying approaches could be of great interest to policymakers.

The causes and sources of deforestation have been found to differ by scale and location (Angelsen and Kaimowitz 1999); however, there is general agreement that roads are one of the main drivers (Pfaff 1999, Chomitz and Gray 1996, Andersen et al. 2002) and that agriculture and cattle markets have made a significant impact on the amount of cleared forest (Geist and Lambin 2001, Pacheco 2009, Fearnside 2002, Ewers, Laurance, and Souza 2008). Thus, development through the creation of infrastructure and in support of industry has been inexorably linked to deforestation. One can therefore conclude that one policy initiative that could successfully reduce deforestation rates would be to slow or halt infrastructure extension. An alternative approach (on the other end of the development spectrum) would be to implement sustainable planning methods that are informed and designed by landscape ecologists and regional planners.

Landscape ecology is primarily concerned with spatial patterns and their resulting impacts on ecosystems and species survival. The human dimension has been recently highlighted by these researchers as forest disturbances become an increasingly large component of global land cover change (Batistella, Moran, and Robeson 2003). Planners incorporate these lessons into settlement design that can be constructed to protect habitat, accomplish development goals, and manage human impact. Contrary to what is often assumed, the Brazilian Amazon has been colonized and managed from such a planning perspective since its initial large scale occupation in the 1970s, although the degree to which these plans were adhered to differs by region. Conflicting developmental and environmental goals within and between different levels of government and administrative departments has resulted in a patchwork of development plans that are largely dominated by frontier expansion led by the National Institute of Colonization and Land Reform (INCRA).

Similar planning issues have plagued policymakers in the United States and other developed nations as sustainable development and smart growth have become tools to reduce urban sprawl and increase environmental quality, all while promoting "slow" growth. In these cases, policy is designed with the intention of achieving multiple goals resulting from conflict between developmental and environmental concerns (Turner 2007). Economists have pointed out that it is important to recognize and model the individual land use decisions that play a central role in defining growth pressures, as changes in land use patterns are the cumulative result of numerous individual decisions (Robinson et al. 2007). Thus, a variety of spatial modeling approaches grounded in economic theory have advanced our understanding of these processes. To date, regions that have experimented with smart growth in the United States have been relatively successful in altering subdivision design and channeling development into designated areas (Song 2005, Shen and Zhang 2007). However, it has also been found that objectives are best met only when smart growth is designed in conjunction with the preservation of forests or open space lands (Irwin, Bell, and Geoghegan 2003).

This paper focuses on an Amazonian colonization project typical of those established as part of the Brazilian military government's Amazonian land rush. Ouro Preto do Oeste was originally established in 1970 as a second tier rural center and a single municipality in the western state of Rondônia. Over time, this municipality was divided into four, and later six municipalities, expanding from approximately 4,000 km^2 to just under 6,000 km^2. The subdivision and expansion of the municipality was driven by INCRA settlement phases occurring between 1981 and 2005. Different settlement designs were adopted during these phases, reflecting changing INCRA developmental and environmental goals and resulting in a landscape composed of three distinct landscape patterns: the original orthogonal design, a watershed design, and a radial design. Given the variation in patterns and the number, size, and shape of lots in each design type, the region is ideal for the analysis of the impacts of different colonization plans. Our focus is to identify (while controlling for time of settlement) the impact of settlement design on land use patterns and provide policy suggestions for newly planned settlements that align with the smart growth policy initiatives promoted in the developed world.

Background and History

Much of the Brazilian Amazon was opened for systematic settlement in the 1970s with the assistance of government development programs that included the construction of an Amazonian highway system with towns and cities planned along the main roads. Colonization projects in the states of Rondônia, Para, and Mato Grosso were designed to settle landless migrants emigrating from populated regions of the nation to the nearest new settlement. Colonies were developed by the planning agency INCRA along two specific highway arteries: BR-364, which traverses Rondônia from northwest to southeast and connects state capital Porto Velho to Mato Grosso in the southeast, and BR-230, which bisects the state of Pará and connects the eastern border state of Tocantins with the western border state of Amazonas (Figure 1). Land cover images included in the figure reveal the systematic and geometric nature of land partitioning along these transportation corridors. Of the approximately 23 million hectares impacted by over 1,400 settlements, the state of Pará has the largest area in such projects (32 percent), followed by Rondônia (17 percent) and Mato Grosso (15 percent). Remaining settlement areas are distributed among other Amazonian states (Brandão and Souza 2006).

Most of these early settlements were designed according to a grid blueprint without consideration for the biophysical landscape, the constraints of different biophysical regions, and/or the subsequent environmental impacts. For example, access to potable water and surface topography were not considered in the layout and/or selection of settlement sites or the parceling of property; and natural physical features like waterways were not considered in property boundaries or road design. The resulting pattern is one of straight line roads with rectangular property boundaries forming a grid stemming from the city center. Furthermore, settlement roads were established using a system based on fixed distance intervals between "urban" centers conforming to the Urbanismo-Rural settlement design hierarchy (Smith 1976). The design included an urban hierarchy with three categories ordered from most urban to most rural: (i) ruropolis, (ii) agropoIis, and (iii) agrovila (Figure 2). The ruropolis (first tier) is an "urban" center located approximately every 350 kilometers along the highway and includes extended services such as trade schools and universities, federal police headquarters, banks, hotels, and airports. The agropoIis (second tier) is located approximately every 40 kilometers between ruropolis locations and is considered an intermediate center with secondary schools, hospitals, and light industry. Lastly, agrovilas (third tier) are located on secondary roads off of major highways at approximately 20 kilometer intervals from the ruropolis and agropoIis town centers and often include a common square, medical posts, primary schools, and several municipal-level and extension government-run offices.

Land partitioning around the urban centers produced the orthogonal pattern of 100 hectare lots for settlers (2 kilometers deep by 0.5 kilometers wide in the study area, with the narrow dimension fronting the local road). The orthogonal design, first employed in the 1970s, is the most widespread partitioning system and dominates land cover in the Brazilian Amazonian with its instantly recognizable fishbone pattern of deforestation (Ballester et al. 2003) (Figure 1). This pattern resulted from settlers clearing lots from front to back along these orthogonal lots, beginning on the lot's shorter edge adjacent to the road. Given the dimensions of each lot's frontage, resultant distances between households and to agrovila centers are therefore large, with few neighbors in close proximity. These distances reduce social contacts and increase the cost of infrastructure extension, which when combined with a lack of access to water for many households, prompted a call for the design of new settlement patterns for use in more recently partitioned areas. The original orthogonal design makes up the largest majority (or 84 percent) of the Rondônian study site, accounting for over 186,000 hectares (Figure 3).

Two subsequent designs were implemented in the study region to address limitations identified with the orthogonal system: the watershed and radial settlement patterns. The watershed design established property boundaries with an understanding of local drainage basins, ensuring settlers access to streams and rivers. Road networks were laid out to border and meander waterways, in contrast to the straight line grid road network of the orthogonal design. This property design enables access to water for a greater number of properties, and by utilizing smaller individual lot sizes, increases social contact while decreasing distance to the nearest agrovila. This settlement pattern is not nearly as common within the Amazon but can be found throughout the "arc of deforestation" (Escada et al. 2005, Batistella, Moran, and Robeson 2003). Within the survey area, lots within this project type amount to approximately 76,000 hectares, or 12 percent of the region (Figure 3).

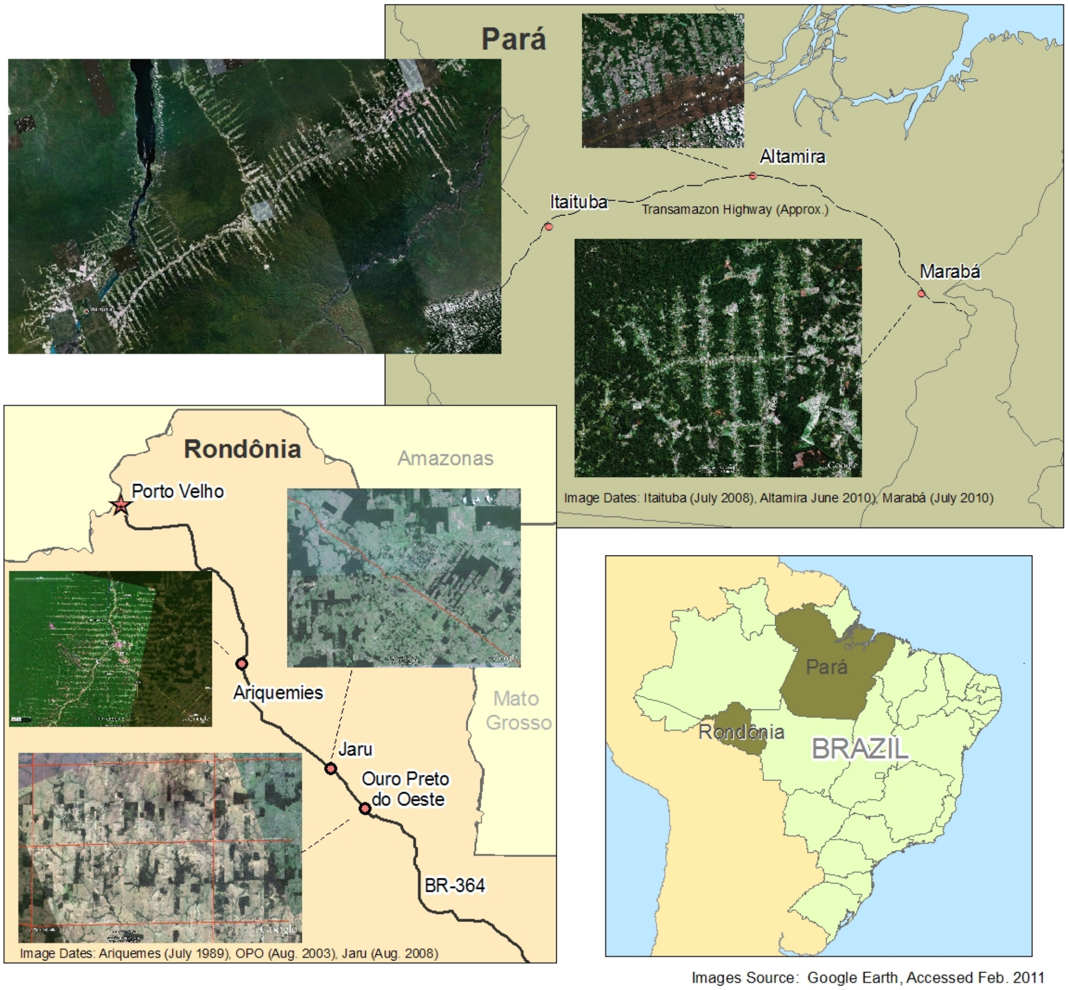

Figure 1. Urban (Ruropolis) Centers Settled Along Federal Highways in Pará and Rondônia

The most recent settlement design introduced in the region is the radial pattern, inspired by the Israeli kibbutz, with the intention to encourage social interaction by locating homes within close proximity to each other and near to a central hub (Lorena and Lambin 2009). Within these projects, lots form pie wedges around a common, central area that often contains a church, school, and soccer field. Given the smaller lot sizes (approximately 12 hectares in size), settlements include multiple "pie" forms joined by a road network that bisects the pie and connects adjacent central areas. These projects are less common than both the orthogonal and watershed designs but are found scattered throughout the "arc of deforestation" (Pfaff et al. 2010, dos Santos Silva et al. 2008). Most areas in the study region partitioned by the radial method are former forest preserves and/or areas of complex topography surrounded by orthogonal settlements; thus, these lots account for only approximately 19,000 hectares, or 3 percent of the total area. Both of the more recent partitioning systems were also designed to reduce deforestation levels, as each household has a smaller lot, and hence less land available to clear.

Study Area

The research area selected for this study includes six municipalities located in south-central Ron-

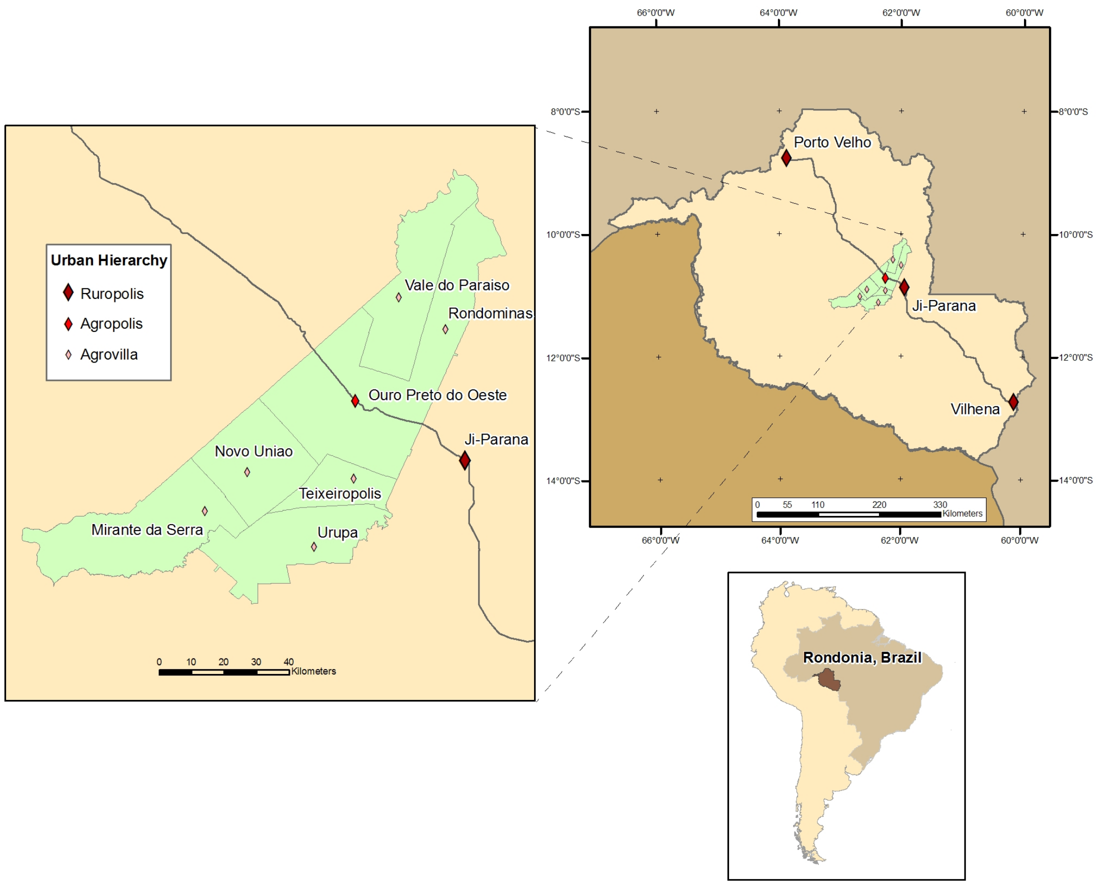

Figure 2. Study Site and Urbanismo-Rural Settlement Design Hierarchy

dônia. The state of Rondônia lies in the southwestern region of the Brazilian Amazon, bordering Bolivia, and is bisected by federal highway BR-364 (Figure 2). This state has experienced some of the highest rates of deforestation in the Brazilian Amazon since colonization, resulting in a current land cover patchwork of mature forest, secondary forest, and widespread pasture propagating northeastward and southwestward from the federal highway (INPE 2007). Forest clearing in the settlements was primarily accomplished by small landholders guided by government settlement programs, notably POLAMAZONIA (Amazon regional development program) in the 1970s and PLANAFLORO (Rondônia Natural Resources Management Project) in the 1990s, with INCRA-led programs that continue into the current period (Browder et al. 2008).

The climate of the research area is classified as humid tropical (i.e., Awi: Köppen) with a distinct north-south precipitation gradient. Southern regions in the state receive less precipitation than northern regions, as well as experience increased dry season length (Ferraz et al. 2005). In most of Rondônia, the pronounced dry season is experienced from June to August, with resulting vegetation taking the form of open tropical forest, with areas of savanna often found on poor soils and on high tablelands (Batistella, Moran, and Robeson 2003). Average annual precipitation totals just over 2,000 mm in the northern capital Porto Velho, and annual average temperature is 25.5°C. Elevations in the state range between 100 and 500 meters, with terrain varying from deeply weathered plateaus and undulating hills to meandering, alluvium-filled river valleys. Soils identified in the

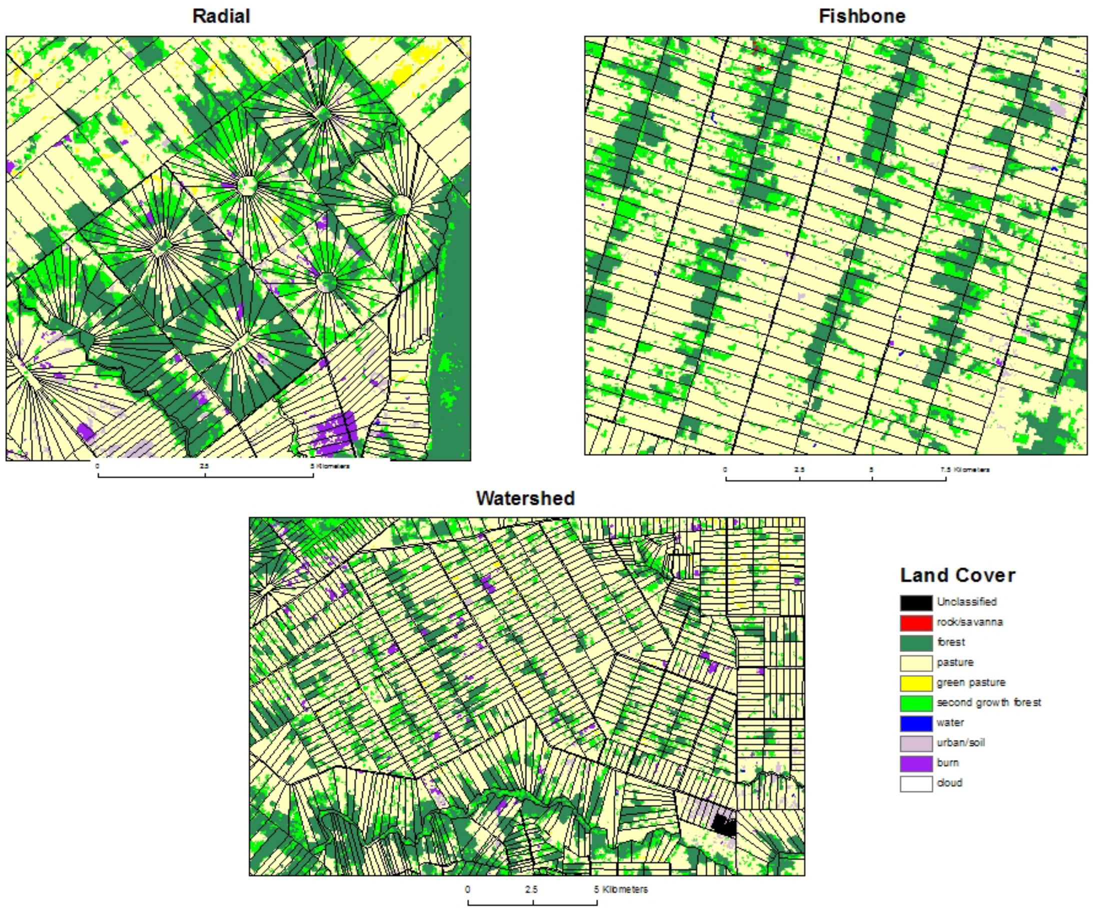

Figure 3. Lot Settlement Patterns with 2000 Land Cover

settled region primarily include alfisols, oxisols, ultisols, and alluvial soils, with other soil types found less frequently and in limited spatial distributions (Bognola and Soares 1999).

The six municipalities in this study contain areas of the three settlement patterns described previously. As presented in Table 1, the orthogonal pattern is the dominant settlement type as measured by total area, average lot size, and lot number. The second most prevalent settlement type (and second implemented) is the watershed pattern. The watershed model followed as the settlement frontier extended south from BR-364 into the watershed drained by the Urupá River. While these lot sizes are on average smaller than orthogonal lots, most of the municipality of Urupá was subdivided based on this settlement design, therefore accounting for its larger spatial extent when compared with recent radial subdivisions. The radial pattern is concentrated in the southern portion of the study region along an escarpment, with the exception of a single radial settlement in the north (Figure 4). Radial subdivisions were applied to areas in formerly protected forest reserves and abandoned ranches, thereby explaining their smaller overall extent in the municipalities. Because of continued immigration into the state of Rondônia and the need to maximize the number of individual farm properties, average lot sizes within the radial settlements are significantly smaller than both orthogonal and watershed settlements.

Data

Geospatial datasets stored and managed in a geographical information system (GIS) and household survey panel were merged for the six municipali-

Table 1. Study Region and Sample Size by Settlement Type

	Study Region			Survey Sample		
Year	Orthogonal	Watershed	Radial	Orthogonal	Watershed	Radial
1996	5327 (68.51)	2448 (31.49)	0 (0)	114 (81.43)	26 (18.57)	NA (NA)
2000	5363 (68.2)	2501 (31.8)	0 (0)	112 (81.16)	26 (18.84)	NA (NA)
2005	5363 (58.29)	3170 (34.45)	668 (7.26)	203 (70.00)	58 (20.00)	29 (10.00)
2009	5600 (59.33)	3170 (33.59)	668 (7.08)	292 (62.39)	123 (26.28)	53 (11.32)

Note: Percentages are in parentheses.

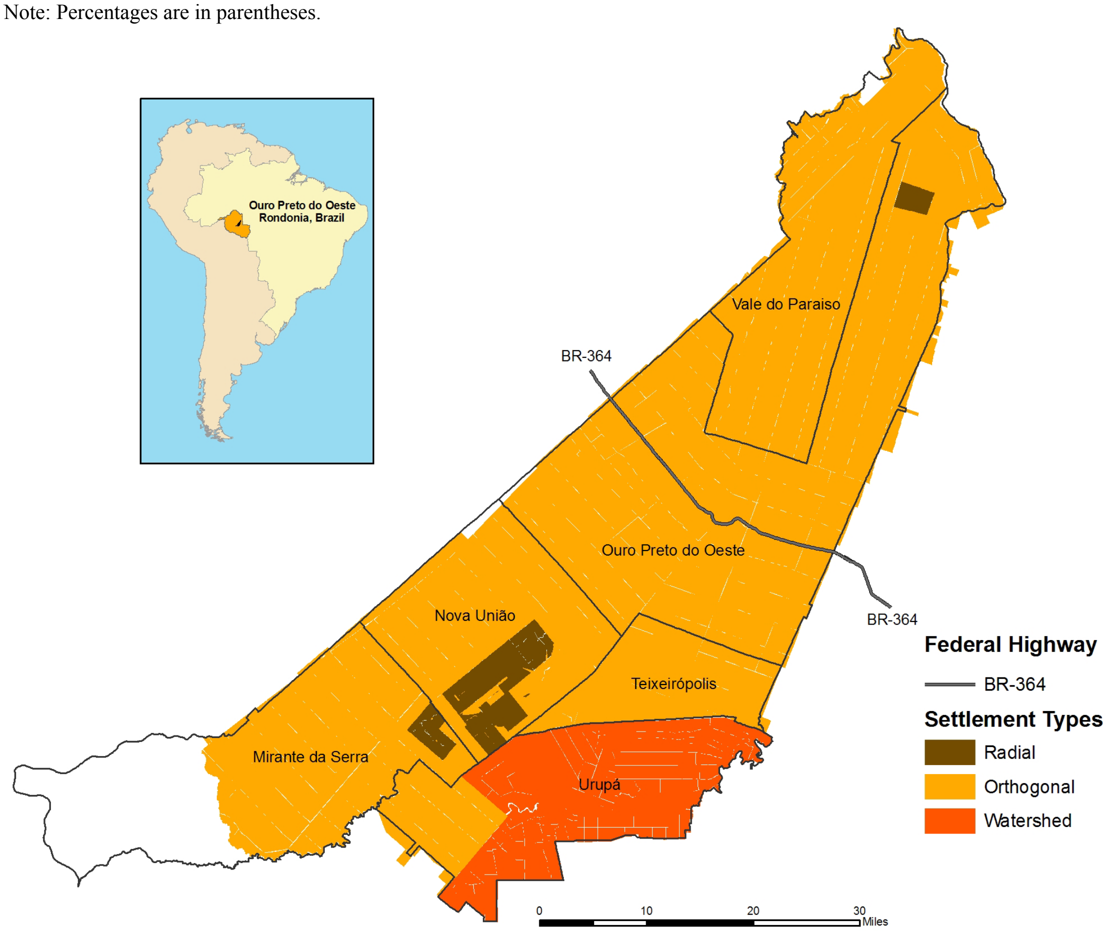

Figure 4. Location of Settlement Patterns

ties to examine the impact of settlement design on deforestation patterns and rates. The geospatial datasets include classified, dry season satellite imagery for each of the survey years (i.e., 1996, 2000, 2005, and 2009) and an INCRA-produced, vector-based geographic information system layer designating household land ownership in the six Rondônian municipalities. The landholding layer was obtained from INCRA in a shapefile format and then edited for topological consistency (i.e., slivers and overlaps were removed) and to update recent settlements not yet included in the INCRA layer. New settlement lot boundaries were added from digitized hardcopy plans and georeferenced or imported from computer-assisted drafting (CAD) files provided by local consulting firms. Land cover for the municipalities is classified from Landsat 5 multi-spectral imagery using a spectral mixture analysis technique and includes the following classes: mature forest, secondary forest, savanna/rock, pasture, burned pasture, green pasture, bare soils, water, and clouds (Roberts et al. 2002, Roberts et al. 1998). Additional geospatial layers incorporated within the analysis included a Shuttle Radar Topography Mission (SRTM) 90 meter digital elevation model (DEM) and soil layer produced by the Brazilian Agricultural Research Corporation (EMBRAPA). Positional accuracy for the geospatial datasets as well as the surveyed lots was improved with the collection of ground control points during the 2005 and 2009 field campaigns.

The survey panel consists of data collected in four waves, including a stratified random sample of 1,009 observations divided between 138 households surveyed in 1996, 139 surveyed in 2000, 286 surveyed in 2005, and 446 households surveyed in 2009 . The survey methodology and design were consistent between each of the waves, although the sampling frame increased in recent years. The sample size was expanded in 2005 and 2009 to include new settlements that had been established in the study region (on forest reserves or large ranches that were expropriated) and to maintain a representative sample population. Also initiated in 2005, panels were maintained by property (owners of same lots always interviewed) and by family (same families always interviewed). Thus, households and individual tracking expanded the survey region in this year to include the original six municipalities in addition to surrounding municipalities. These data provide full information on farm production outputs and purchased inputs, hectares reported in different land uses, measures of wealth (such as consumer durables equipment, livestock, vehicles, and reported value of parcels), and a standard set of socioeconomic characteristics.

A majority of households in the region are small-scale producers that originally established farms with annual and perennial crops. Similar to agricultural households in other developing regions, a portion of the harvest is consumed at home, and income originates from a variety of sources including crops, milk, non-timber forest products, cattle, and off-farm labor. Income sources have changed significantly over the survey time frame, suggesting that many households are moving from the production of crops to a greater focus on cattle and off-farm labor. For example, crops contributed to 33 percent of income in 1996 but by 2009 this figure had dropped to 8 percent. Milk sales contributed to 40 percent of income in each time period, while the cattle trade increased from less than 1 percent in 1996 to 19 percent in 2009. Off-farm income also increased, from 25 to 34 percent in the same interval. These trends suggest that households are moving away from traditional agriculture; however, households continue to rely on their own harvest for their livelihoods and still (on average) remain 40 percent below the national median income (IBGE 2010). Thus, there is significant evidence that these lots operate as homesteads, and given that the households both consume and sell their production, the agricultural household model (Singh, Squire, and Strauss 1986) best represents the decision framework of these individuals. This model was first developed to explain why households would consume more of goods as prices rose (Kurodo and Yotopoulos 1978) and has since become the basic building block of microeconomic frameworks used to explain the decisions of households within developing regions (Taylor and Adelman 2003).

Survey data suggest that several notable changes have occurred in the study area over the four survey waves (and 13 years), including changes in deforestation levels and rates, lot ownership, family size, cattle herds, and income (Table 2). First, average lot size fell over this time period as lots were subdivided and new settlements (which are significantly smaller in size) were added to the sampling frame. At the same time, the rate of deforestation declined from an average four hectares per year to approximately two; while the total amount of primary forest cleared increased from approximately 75 percent to over 93 percent. In terms of household size, the average number of family members declined from just over nine members to five by 2009, while the average year of lot acquisition changed from 1984 to 1991, suggesting that a greater number of lots were either acquired in new settlements or pur-

Table 2. Descriptive Statistics by Year

		1996 (n = 138)		2000 (n = 139)		2005 (n = 286)		2009 (n = 446)	
Variables	Definition	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
LOT CHARACTERISTICS—GIS DATA									
Lot size	Size of property, hectares	71.81	48.70	64.16	34.51	62.37	61.99	52.98	46.68
Distance	Kilometers to the city center	37.15	19.29	37.20	19.19	39.35	18.55	40.41	17.48
Slope	Average slope gradient on the lot, percent	5.46	2.96	5.43	2.95	5.40	3.07	5.56	3.44
Soil	Dominant soil type on lot, characterized by initial ability to support agriculture[a]	2.26	0.71	2.28	0.72	2.35	0.69	2.39	0.70
Rate of deforestation	Average number of hectares deforested per year	3.84	3.33	3.16	2.05	2.82	1.77	2.35	2.18
Percent deforest	Percent of the lot that is deforested	74.94	17.74	84.70	13.98	90.18	11.54	93.27	10.11
LOT CHARACTERISTICS—SURVEY AND MUNICIPALITY DATA									
Year est.	Year the lot settlement was established[b]	1976	8.62	1976	8.70	1980	11.66	1982	11.86
Turnover	= 1 if the property was purchased by a new household in the survey period; 0 otherwise	0.36	0.48	0.37	0.48	0.58	0.49	0.67	0.46
HOUSEHOLD CHARACTERISTICS—SURVEY DATA									
Family	Number of family members living on the lot	9.06	6.35	7.31	5.68	5.57	3.41	5.20	3.34
Cattle	Number of adult cattle (heifers and bulls) owned by the household	53.60	63.49	77.76	85.05	154.93	283.76	123.78	213.89
Calves	Number of calves owned by the household	15.42	18.38	20.06	20.84	25.84	28.89	18.35	19.56
Year property acquired	Year the property was purchased by the household	1984.36	6.74	1985.12	7.40	1989.54	10.33	1991.26	10.37
Price milk	Annual average price, inflation adjusted, R$2,000	0.19	0.02	0.23	0.03	0.26	0.04	0.26	0.04
Income	Total household income, R$2,000	8,083	8,649	15,416	14,384	15,367	20,278	17,929	21,231

[a] Values range from 1 to 4, where scale is as follows: 1 = good, 2 = moderate, 3 = restricted, 4 = unsuitable (for agriculture).
[b] Calculated as the year that the settlement in which the lot resides was established. Collected from municipality and INCRA records.

chased from the original owners through in-migration or second-generation moves (i.e., children of the original inhabitants). Income saw an increase from over R$8,000 to more than R$18,000 (inflation-adjusted) in the sample time period. And income was not the only variable of interest to exhibit tremendous change. The average cattle herd for these households more than doubled, from an average of almost 70 to over 140 by 2009.

Finally, milk prices (inflation-adjusted) increased in the early survey waves (from 0.19 centavos, or cents, per liter to 0.24) but stabilized in the later survey waves. These prices do not differ significantly by distance to processing facility or by municipality, likely due to the farm gate pickup of milk by the processing plant trucks (the households do not deliver the milk). Approximately 70–75 percent of households participated in the milk market in any given year. These annual data are divided by settlement type to draw inferences about the households that reside in these cohorts (Table 3). We begin with comparisons for 1996 and continue through the dates of each survey wave, as notable changes occurred in the establishment of the lots within these cohorts in different time periods. In 1996, the average orthogonal lot was almost three times the size of the watershed lot, and located closer to the main federal highway (BR-364) and the region's central market. The physical environment (i.e., soil productivity) was similar for these settlement types. However, orthogonal lots were shown to occupy slightly steeper slopes on average (i.e., 5.8 percent vs. 3.8 percent). A greater number of individuals were found to reside on orthogonal lots, nine residents compared to seven, which also housed significantly larger cattle herds (97 versus 27). Household income is also significantly higher for households on these properties. Finally, the average rate of deforestation between 1984 and 1996 was significantly higher on the orthogonal lots—4.4 hectares per year—compared to the average rate of 1.5 hectares per year for the watershed lots. While a notable difference, the cumulative effect for each settlement pattern was that, by 1996, almost three-quarters of the original forest on each lot had been cleared.

The 2000 household demographic, physical, and economic data exhibit similar differences between these settlement types. In both cases, the rates of deforestation decreased slightly as the total cleared area rose to an average of 83 percent for orthogonal lots and 91 percent for watershed lots. Thus, even with slower rates of deforestation in watershed settlements, the smaller lot size enabled households to clear the lot area more quickly.

The radial settlement pattern was implemented in several municipalities within the survey region by 2005. According to data collected from a sample of these households, the newly settled radial lots were significantly smaller in size and located farther from BR-364 relative to most orthogonal properties. Given their more recent settlement date and smaller lot size, significantly fewer cattle were owned by these households (an average of 39 as compared to 132 on watershed lots and 214 on orthogonal lots). Similarly, lower household incomes were reported on these lots. Rates of deforestation in the new radial settlements were found to be similar to existing settlement types; however, given their smaller lot sizes, these lots were cleared of almost 88 percent of original forest cover in less than 10 years.

In 2009, the sample size and the number of lots of each settlement type increased; however, comparable differences are noted between the settlement types according to both the biophysical traits and socioeconomic characteristics. Most notably, over 90 percent of the original forest was cleared by 2009, with rates ranging between 2 and 2.5 hectares per year. And, although average household income remained lowest for those on the radial lots, a remarkable increase of over 200 percent (compared to an increase of over 120 percent for the orthogonal residents, and over 80 percent increase for the watershed residents) suggests a "catch-up" for these households likely facilitated by recent road improvement, school construction, and extended energy networks, along with functioning local governments.

Empirical Approach

The rate and percentage of the property deforested are estimated with fixed-, random-, and mixed-effects models using data collected in four survey waves. These data include dynamic information on the household and land use allocation, and time-invariant information on the biophysical conditions of the lot. The panel used in this analysis is maintained by property; therefore, changes in ownership and household type are accounted

Table 3. Descriptive Statistics, by Year and Settlement Type

		1996 (n = 138)			2000 (n = 139)			2005 (n = 286)			2009 (n = 446)		
Variables	Definition	Orthogonal (n = 112)	Watershed (n = 26)	Radial (n = 0)	Orthogonal (n = 113)	Watershed (n = 26)	Radial (n = 0)	Orthogonal (n = 198)	Watershed (n = 60)	Radial (n = 28)	Orthogonal (n = 275)	Watershed (n = 119)	Radial (n = 52)
LOT CHARACTERISTICS—GIS DATA													
Lot size	Size of property, hectares	95	29	NA	95	28	NA	88	28	23	87	39	24
Distance	Kilometers to the city center	36.35	41.39	NA	36.32	41.1		37.06	45.16	46.14	37.69	47.88	44.24
Slope	Average slope gradient on the lot, percent	5.81	3.83	NA	5.82	3.75	NA	5.69	4.32	5.79	5.97	4.56	5.9
Soil	Dominant soil type on lot, characterized by initial ability to support agriculture[a]	2.28	2.27	NA	2.27	2.23	NA	2.32	2.37	2.48	2.34	2.47	2.5
Rate of deforestation	Average number of hectares deforested per year	4.43	1.54	NA	3.57	1.34	NA	2.89	2.42	2.92	2.53	2.35	2
Percent deforest	Percent of the lot that is deforested	73.93	79.32	NA	83.20	91.23	NA	89.71	92.71	88.09	91.81	95.39	96.13
LOT CHARACTERISTICS—SURVEY AND MUNICIPALITY DATA													
Year established	Year the lot settlement was established[b]	1975	1981	NA	1975	1981	NA	1976	1986	1998	1977	1987	1998
Turnover	= 1 if the property was purchased by a new household in the survey period; 0 otherwise	0.34	0.31	NA	0.34	0.31	NA	0.61	0.66	0	0.75	0.85	0
HOUSEHOLD CHARACTERISTICS—SURVEY DATA													
Family	Number of family members living on the lot	9	7	NA	8	6	NA	6	4	4	6	5	5
Cattle	Number of adult cattle (heifers and bulls) owned by the household	61.54	19.38	NA	88.25	32.15	NA	184.71	116.35	27.04	168.42	56.63	42.65
Calves	Number of calves owned by the household	17.46	6.65	NA	32.15	10.81	NA	32.13	12.78	9.29	22.29	13.13	9.56
Year property acquired	Year the property was purchased by the household	1984	1988	NA	1984	1989	NA	1987	1994	1999	1989	1994	2000
Price milk	Annual average price, inflation adjusted, R$2,000	0.2	0.19	NA	0.23	0.22	NA	0.26	0.26	0.26	0.27	0.27	0.27
Income	Total household income, R$2,000	8,659	4,950	NA	16,340	10,752	NA	17,481	12,645	5,627	39,634	22,536	17,734

[a] Values range from 1 to 4, where scale is as follow: 1 = good, 2 = moderate, 3 = restricted, 4 = unsuitable (for agriculture).
[b] Calculated as the year that the settlement in which the lot resides was established. Collected from municipality and INCRA records.

for with dummy variables. Moreover, given the exogenous nature of settlement design, the endogenous variable of interest in the model is land use (i.e., rate of land-clearing). This choice is expected to be determined by a variety of property and household characteristics along with exogenous factors predetermined prior to settlement by either the time of settlement or the land settlement agency (INCRA). While policymakers cannot change settlement design once a property is allocated to a household, settlement designs continue to be chosen for new settlements and are often one of the leverages used to dissipate conflicting policy goals. Additional variables chosen for inclusion in the model are guided by the conceptual framework (noted below) and the wealth of economic models used to estimate deforestation (Angelsen and Kaimowitz 1999).

The conceptual framework guiding this study is a dynamic version of the household production model, which represents households as unified production and consumption units, maximizing utility subject to input and endowment constraints (Shively 2001, Singh, Squire, and Strauss 1986). In this context, cleared land is used as an input to production and is therefore modeled within a derived demand framework. Thus, the determinants of demand include exogenous prices, inputs (including household labor and biophysical conditions of the lot), and household physical characteristics. These biophysical conditions of the lot include original soil type, slope, and distance to the town center (representing transport costs and controlling for other factors correlated with distance); the household characteristics include income, age, and the cattle herd (representing both wealth and degree of need for cleared land); and labor is represented by family size. Given the enormous impact of the expanding dairy farming in the region (Faminow 1998, Walker et al. 2009), the price of milk is used to represent exogenous prices most closely tied to deforestation choices, as a majority of households use pasture as the only form of subsistence for the herd. While exogenous prices most closely linked to the derived demand for land would more commonly be a function of its own price, in this case land used for agriculture is not bought and sold in the market, but rather produced by households clearing property forest. The assumptions here are therefore that markets are not perfect, in particular the markets for land and labor. And, in contrast to the profit-maximization framework used in many models, under these conditions production and consumption decisions are not separable (Angelsen and Kaimowitz 1999). These specifications provide a realistic representation of markets in the study region (as land markets are limited and labor markets tend to be seasonally driven) given the well-established property rights regime (e.g., ownership is uncontested as more than 98 percent of the owners hold legal title).

We estimate the area of land cleared in a given year (D_{it}) according to the equation below:

$$(1) \qquad D_{it} = \beta_k x_{it} + \gamma z_i + \mu_i + \varepsilon_{it} ,$$

where D_{it} is the dependent variable, varying over the individual and time, x_{it} is a $1 \times k$ vector of variables that also vary over individual and time, β is the vector of coefficients on x, z_i is a $1 \times p$ vector of time-invariant variables (where p is the exogenous grouping of these indicators) that vary by individuals, γ is the $p \times 1$ vector of coefficients on z, μ_i is the individual-level effect, and ε_{it} is the disturbance term.

There are several panel methods that can be used to estimate equation (1), including (but not limited to) fixed, random, and mixed effects, the choice of which depends on the correlation assumption for μ_i and any clustering of the data. The random-effects model assumes that μ_i is uncorrelated with x_{it}, z_i, and ε_{it} (and the individual-level effects are parameterized as additional random disturbances), the fixed-effects model assumes that μ_i is correlated with x_{it} and z_i, and the mixed model (including both fixed and random effects) assumes correlation for z_i only (Baum 2006). A fixed-effects estimation implies that each individual serves as his or her own control. Comparisons are made within individuals and ignore the between-observation variation. Nonetheless, discarding the between-observation variation can yield standard errors that are considerably higher than those produced by methods that utilize both within- and between-observation variation. Instead of considering the individual-specific intercept as in the fixed-effects model, the random-effects model specifies the individual effect as a random draw that is uncorrelated with the regressors and the overall disturbance term. Rewritten, this equation is

$$D_{it} = \beta_k x_{it} + \gamma z_i + (\mu_i + \varepsilon_{it}) \,, \tag{2}$$

where ($\mu_i + \varepsilon_i$) is the composite error term and the μ_i are the individual effects (Baum 2006).

The mixed model combines the virtues of the fixed- and random-effects models, allowing for the estimation of fixed effects for the time-varying parameters and random effects for the time-invariant predictors (Allison 2010). Thus, in cases where the fixed-effects assumption is supported (i.e., with a Hausman test), the mixed model allows the estimation of time-invariant policy variables that differ by observation but not over time (i.e., settlement design). However, mixed models are most appropriate for cases when observations are clustered in some manner (Allison 2010). The benefit of the mixed model over models that include components of both fixed and random models (such as the Hausman-Taylor method) is that instrumental variables are not required to estimate γ. In this case, the fixed effects are the coefficients from a standard linear regression ($\hat{\gamma}$) and the random effects are summarized by their variance components (Gutierrez 2008). Rewriting equation (2) in this format, we have

$$D_{it} = \beta_k x_{it} + \hat{\gamma} z_i + (\mu_i + \varepsilon_{it}) \,. \tag{3}$$

Therefore, instead of the γ values being differenced out as they would be in a fixed-effects model, the estimates from a linear regression ($\hat{\gamma}$) are represented in this estimation, allowing one to calculate the impact of time-invariant parameters.

Results

The fixed-, random-, and mixed-effects estimates of the rate of deforestation and the percentage of the lot deforested over time are presented in Table 4. A Hausman test is used to test the fit of the fixed (FE) and random effects (RE) models, while a test of clustering effects is used to test the validity of the mixed model. Dummy variables are used to indicate settlement type in the FE and RE models to determine whether the radial and watershed models significantly impact forest clearing. The mixed model includes settlement design as the grouping variable. The rate of deforestation estimates is discussed first, while the percentage of the lot cleared in time *t* follows.

The estimation results for the rate of deforestation—defined as the average number of hectares cleared between survey years (and since the land was first occupied for the 1996 survey wave)—are provided in Table 4 as Models 1–3. The fixed-effects model (Model 1) suggests that the rate of clearing is significantly impacted by family size and the price of milk. The limits of this estimation are quite obvious, as the policy variable of interest is time-invariant and therefore differenced out of the equation. We therefore turn to the random-effects results which provide greater explanatory power (i.e., a higher R-squared) and find a similar impact for family size and the price of milk, as well as the identification of additional significant determinants.

Furthermore, a Hausman test of the difference between the more efficient RE coefficients and the less efficient but consistent FE coefficients suggests that the RE model is the preferred choice. Additional significant determinants for the rate of land cover clearing include the year the settlement was established and lot size, each of which are positively related to the rate of clearing, suggesting that property age is a significant determinant of the rate of deforestation. Younger properties exhibit a higher rate of deforestation, and, after controlling for other factors, larger lots are cleared at significantly greater rates.

The role of settlement type is also shown to significantly impact deforestation rates in the RE and mixed models. The radial settlement pattern is found to have a negative and significant impact on the rate of deforestation (relative to the original and more widespread orthogonal design). In other words, after controlling for the biophysical conditions of the lot, the year the lot was acquired, the time of settlement, and other household characteristics, the lots within the radial design are actually cleared at lower rates. The mixed model (Model 3) confirms the findings of the random-effects model, as the significance and sign of the independent variables remain the same. Soil quality is also found to be marginally significant. According to the sign of this variable, poorer soils are deforested at higher rates. Moreover, settlement type is found to be a significant group determinant, providing further evidence that settlement design does in fact impact land cover transformation rates. Results suggest that there is a significant difference in both the inter-

Table 4. Estimation Results (n = 940)

		Rate of Deforestation			Percent of the Property Deforested		
Independent Variables	Definition	Model 1 (fixed)	Model 2 (random)	Model 3 (mixed)	Model 4 (fixed)	Model 5 (random)	Model 6 (mixed)
Constant		686658.6 (595821.1)	-317.67*** (25.35)	-295.45*** (20.51)	3985849 (4389837)	-332.4 (160.54)	-332.4** (160.54)
Lot size	Size of property, hectares	-9671.23 (8391.99)	0.04*** (0)	0.03*** (0)	-56151.37 (61843.26)	-0.01 (0.01)	0.00 (0.01)
Distance	Kilometers to the city center		-0.01 (0.01)	0.01 (0.02)		-0.18*** (0.05)	-0.22*** (0.04)
Slope	Average slope gradient on the lot, percent		0.01 (0.02)	0.01 (0.02)		-0.65*** (0.16)	-0.59*** (0.14)
Soil	Dominant soil type on lot, characterized by initial ability to support agriculture [a]		0.13 (0.11)	0.16* (0.09)		-0.51 (0.83)	-0.65 (0.71)
Year established	Year the settlement (the lot resides in) was established [b]		0.17*** (0.01)	0.16*** (0.01)		0.07 (0.09)	0.11 (0.08)
Turnover	= 1 if the property was purchased by a new household in the survey period; 0 otherwise		-0.03 (0.17)	-0.13 (0.12)		2.72** (1.23)	2.59*** (0.94)
Family [c]	Number of family members to live on the property	0.02*** (0.01)	0.02*** (0.01)	0.01* (0.01)	-0.25*** (0.1)	-0.22*** (0.08)	-0.17* (0.1)
Cattle [c]	Number of cattle owned	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Calves [c]	Number of calves owned by the household	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.03 (0.02)	0.05*** (0.02)	0.08*** (0.02)
Year property acquired	Year the property was acquired by current household	0 (0.01)	-0.01 (0.01)	-0.01 (0.01)	0.01 (0.07)	0.07 (0.05)	0.10* (0.05)
Price of milk	Annual average price of milk, inflation adjusted, R$2,000	-5.71*** (1.44)	-5.92*** (1.19)	-5.93*** (1.28)	97.7*** (11.11)	87.02*** (9.26)	82.17*** (10.85)
Income [c]	Total household income, thousands, R$2,000	-0.01* (0.00)	0.00 (0.00)	0.00 (0.00)	0.05* (0.03)	0.02 (0.02)	-0.01 (0.03)
Radial design	= 1 if a property in the radial settlement design; 0 otherwise		-1.53*** (0.36)			5.62** (2.7)	
Watershed design	= 1 if a property in the watershed settlement design; 0 otherwise		-0.02 (0.2)			4.02*** (1.5)	
Group constant (variance)				2.92**			8.49**
Group residuals (variance)				2.24**			154.25**
R-squared			0.58		0.00	0.22	
Wald chi-squared				1,028***			220***

[a] Values range from 1 to 4 where scale is as follow: 1 = good, 2 = moderate, 3 = restricted, 4 = unsuitable (for agriculture).
[b] Calculated as the year that the settlement in which the lot resides was established. Collected from municipality and INCRA records.
[c] Variables estimated in the rate of deforestation equations as changes since the previous survey wave.

Notes: *, **, and *** indicate significance at the 10, 5, and 1 percent levels, respectively. Standard errors are in parentheses.

cept and slope as related to settlement type (i.e., the group constant and residuals are significant). Differences between groups (i.e., settlement design) can be attributed to increasing this rate of deforestation by 2.24 hectares (Table 4).

The estimation results for the percentage of lot area cleared in time *t* since the land was first occupied (or fully forested) are provided in Table 4 as Models 4–6. Model results must be interpreted carefully given that the percentage of the lot that is cleared cannot be reduced in size (i.e., clearing tends to be permanent due to the likely introduction and continuation of cattle on the lots); thus, the percentage of forest cleared increases over time for any single property (also see Table 3). The results of the estimations of clearing are dissimilar to the rate models presented above in several important ways. Again, a Hausman test suggests that the RE model is the preferred choice given the coefficients' strength. The random-effects results, which provide greater explanatory power (i.e., higher R-squared) and additional significant determinants (as compared to the FE), are similar to the mixed-effects model results.

Results suggest that the significant determinants of cleared forest include distance from the city center, the lot's slope, lot turnover, the price of milk, change in the number of family members, and the number of calves owned between the survey waves. These results suggest that the physical setting of the lot significantly impacts the percentage of cleared forest as lots located farther from the central market and lots with steeper slopes have deforested smaller portions of their properties. Higher slopes on lots decrease manageable farm and pasture area, and are therefore likely a significant deterrent to land clearing. Household characteristics are also found to be significant factors, as lots that have had more owners and those with households that are falling in size are clearing more intensively. Family size positively impacts the rate of deforestation (as more labor is required to clear in any given year) but negatively impacts the cleared percentage, as households with less forest are likely at a more advanced life cycle stage (and have fewer children on site due to moves from these rural lots for marriage and/or school).

Finally, the impact of the price of milk on the rate and percentage of clearing is particularly noteworthy. The price of milk is negatively related to the rate of deforestation, suggesting that as the price of milk increases, the rate of deforestation falls. However, the price of milk is positively related to the percentage of the lot that is cleared over time, suggesting that increases in milk prices lead to an overall increase in percentage of the lot that is cleared. These differences are likely related to lag effects and influences on income. Since increases in milk prices directly translate into higher income, the immediate impact is to reduce the rate of deforestation, essentially shifting household labor from clearing to production. However, over the longer term, increases in milk prices encourage further land conversion to support additional pasture needs. Finally, the cattle herd is divided between cattle (steer and heifers) and calves as the pasture requirements for these two groups differ. Interestingly, it is the change in the number of calves on the lot (and not the number of adult cattle) that significantly impacts the percentage cleared, highlighting the importance of the dairy industry within the survey region.

Again, settlement type is found to be a significant determinant as the dummy variables for both the radial and watershed lots are positive and significant, suggesting that these designs result in significantly more overall deforestation on the lot relative to the orthogonal design. And, again, the mixed model (Model 6) confirms the findings of the random-effects model, as the significance and sign of the independent variables remain the same. This model also reveals that settlement type is a significant group determinant, providing further evidence that settlement design does in fact impact land cover transformation.

Differing directions of influence are found for several significant variables (including the price of milk, family size, and settlement design), likely resulting from differences between household and property life cycles. To isolate such impacts, we have combined the four-year panel and divided the properties by time since first settled. The graphs in Figure 5 suggest that older lots exhibit greater rates of deforestation and that the rates decline with time on the property (or as the amount of cleared land available for agriculture increases). In addition, the percentage of the lot that is cleared exhibits a positive slope according to property age, indicating that reforestation is not practiced, and that, once cleared, the lot area continues to be utilized for agriculture or pasture. Most interesting is that this pattern holds for each of the settlement designs, although the timing of the rate reduction clearing differs by settlement. Given the observed pattern, the rate change is, in part, explained by lot size. Once most of the lot is

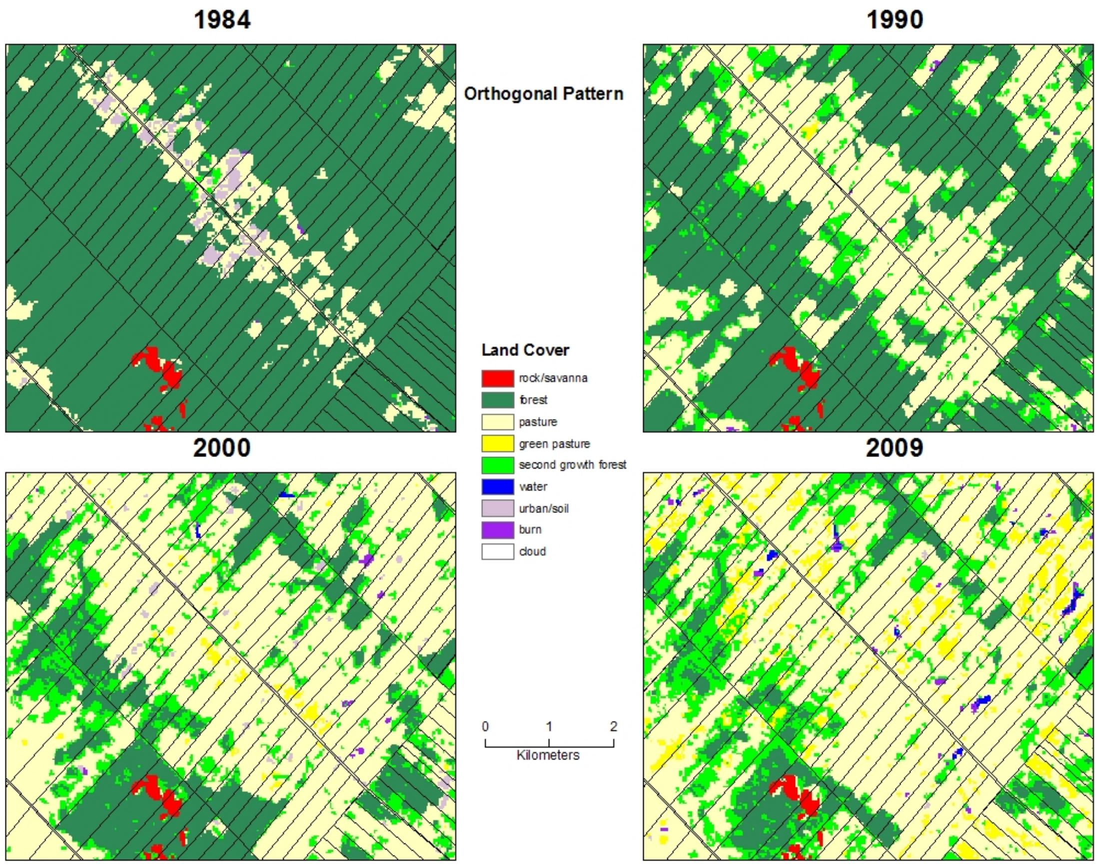

Figure 5. Land Cover Transformation for Orthogonal Properties

cleared—in about 10 years for smaller radial lots and about 15 years for watershed lots—the rate decreases. The larger orthogonal lots appear to be deforested at higher levels for longer periods, given the greater area available for land cover change.

Finally, the pattern of clearing for each of these settlement types since occupation is shown in Figures 5–7. As is evident in these figures, forest clearing begins from the road (and property) front and moves to the back of the lot through time. Property design and/or biophysical characteristics do not impact this general pattern, and in all cases the percentage of the lot cleared is fairly large within only a short period of time.

Conclusion

Sustainable development has become a policy goal for governments struggling to grow while addressing environmental concerns related to population growth, global warming, biodiversity loss, and pollution control. As the world's tropical forests continue to be cleared at impressive rates, the challenges that face policymakers and planners are similar to those developing and implementing smart growth plans. Land use design, zoning, and urban planning projects have been applied to address social, economic, and environmental goals in many regions of the world. This paper seeks to determine whether settlement design can be used by policymakers to meet the dual goals of environmental protection and social policy in the Brazilian Amazon. The empirical models highlight that there are differences in rates of deforestation that can be attributed to settlement design. In the short run (or the settlement period) it appears that the alternative settlement designs implemented to meet both environmental

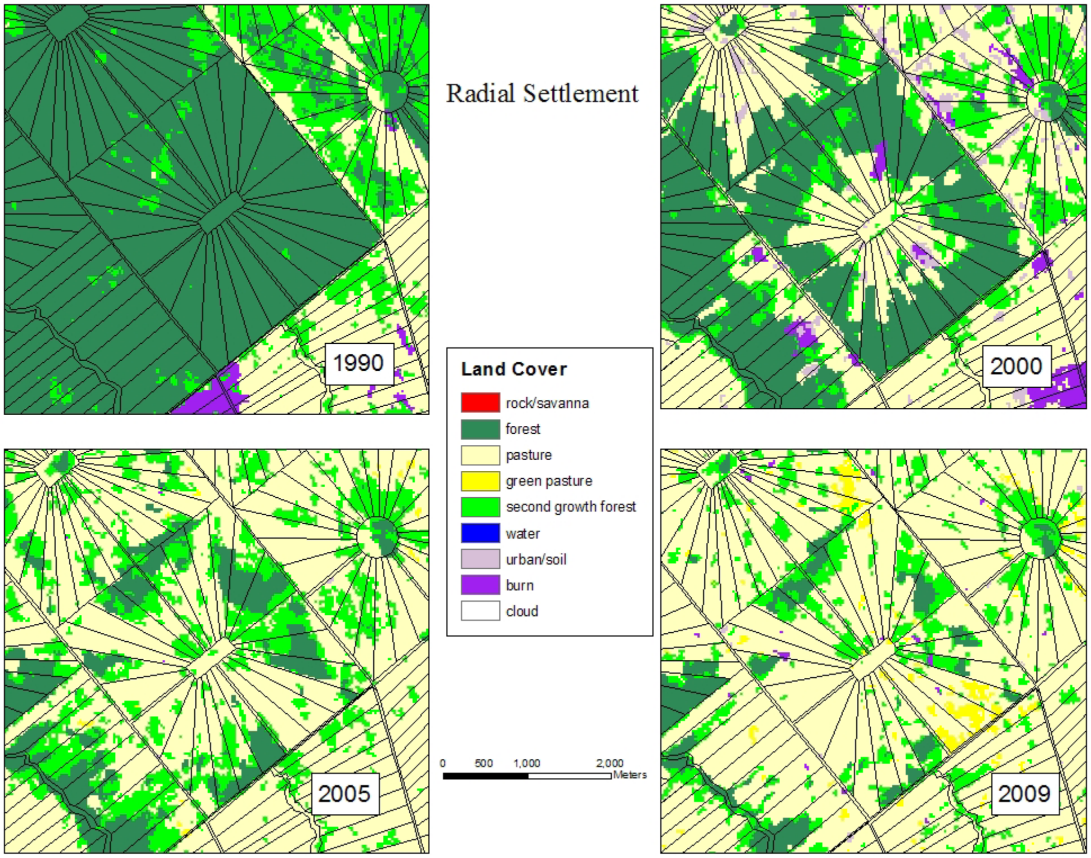

Figure 6. Land Cover Transformation for Radial Properties

and social objectives do meet these goals, providing some evidence for the continuance of these programs.

However, these short-term impacts mask true long-term results as the net effect over time is that the design does not influence land cover choices. Independent of the shape and size of the property, land-clearing is extensive for all these agricultural lots. Observations in this region of Rondônia reveal that a combination of the household and property life cycles dominates the rates and percentages of deforestation on lots. Most of the recently settled lots (of the radial design) that have been cleared at a relatively slower rate surpassed the percentage cleared for the older lots (in the orthogonal pattern) within ten years of the time settled due to their smaller size. Moreover, the pattern of deforestation does not differ by property type, with clearing advancing from the lot's roadside frontage. Remnant forest fragments, however, are impacted by settlement design. Orthogonal and most watershed settlements in the region result in long, linear forest corridors extending along rear property boundaries (and along waterways), creating the well-known fishbone configuration. Radial lot clearing leads to concentric forest rings often resembling doughnuts, isolated from remaining contiguous forest in adjacent orthogonal settlements. However, given the rapid rate of clearing in radial settlements, little forest remains after a 10-year time period.

Thus, this study finds that settlements designed to meet social goals, including greater contact between families and access to markets and services, come at the expense of environmental goals. While laws exist to minimize lot area clearing, our study exemplifies that enforcement is nonexistent and that clearing is more constrained by the physical setting and time on the lot. One of the more generally applicable findings is that

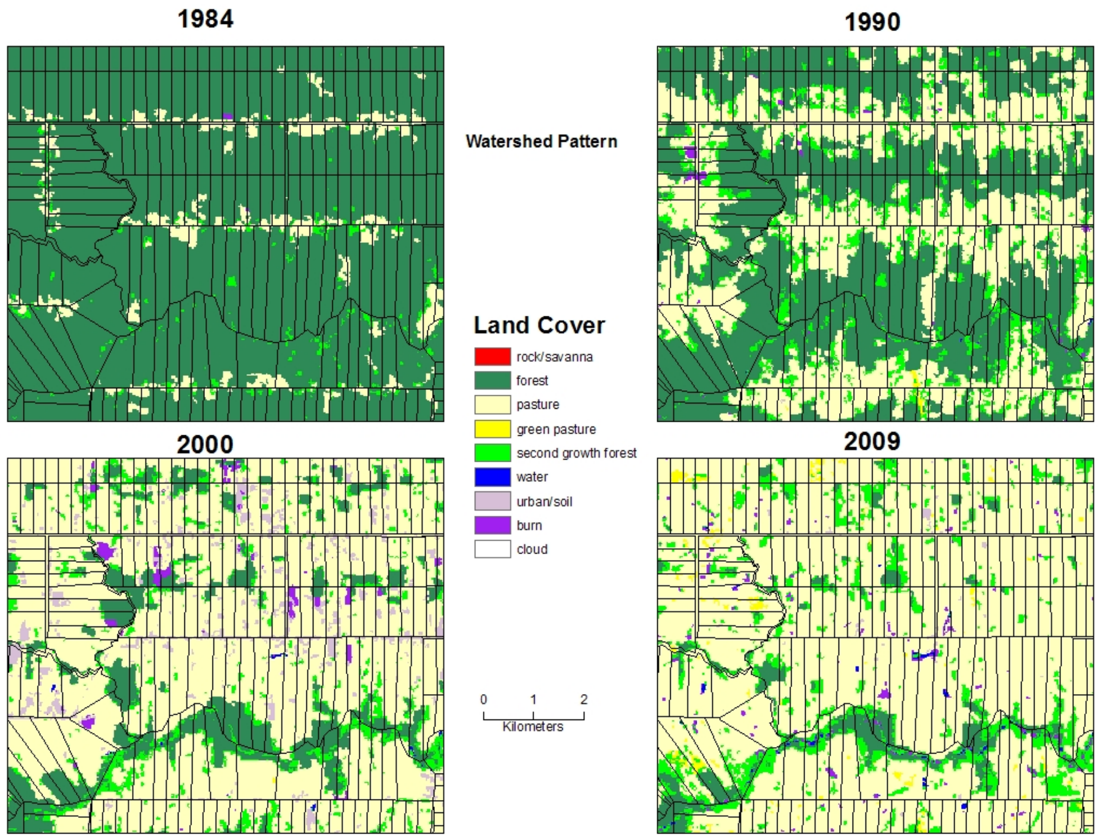

Figure 7. Land Cover Transformation for Watershed Properties

planning policy directed toward intended local impacts may have unforeseen large-scale implications on the landscape (and landscape ecology) as the influences on the greater area are largely driven by these combined effects. As new colonies are settled in the Amazon with support from the Brazilian government, policymakers will likely implement settlement patterns containing smaller lots similar to the radial pattern observed in this study to minimize their landscape footprint and maximize their inhabitant numbers. If policymakers wish to balance the environmental impact with the social advantages resulting from these settlement patterns, real enforcement of existing clearing laws must occur given the lot sizes and speed with which the forest cover can be removed. Moreover, if environmental preservation is a policy objective, the creation and maintenance of forest reserves contiguous to these radial settlements may result in a pattern of linear connectivity similar to the forest corridors noted in the orthogonal settlements, thereby addressing dual goals outlined in this study.

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