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Title: Deforestation dynamics in Brazil's Amazonian settlements: Effects of land-tenure concentration

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Abstract

Brazil's Amazon deforestation is a major global and national environmental concern, and the ability to model and project both its course and the effect of different policy options depends on understanding how this process occurs at present and how it might change in the future. The present paper addresses one key factor in Amazon deforestation: land-tenure concentration in settlements. Brazil's policies for establishing and regulating settlement projects represent critical government decisions shaping the landscape in the 5×10^6 km^2 Legal Amazonia region. We used remote-sensing data and information provided by the National Institute for Colonization and Agrarian Reform (INCRA) to evaluate the effect of land-tenure concentration in a settlement project (*Projeto de Assentamento*) located in a frontier area where cattle-ranching is expanding. We identified the actors and their deforestation patterns in the Matupi settlement in the southern part of Brazil's state of Amazonas. We spatially identified actors who concentrated "lots" (the parcels of land distributed to individual settlers) in 2011 and assessed whether the concentration was done by individual landholders or by "families" (where members merged their lots and the clearing was done together). Deforestation rates (1995-2011) were estimated for each type of actor and the trajectory of deforestation in the settlement (cumulative deforestation to 1994 and annual deforestation 1995-2016) was also analyzed. Concentrators occupied 28% (9653 ha) of the settlement and 29% of the lots (152 lots) analyzed; the numbers of lots concentrated ranged from two to ten. Concentrators of two lots and non-concentrators were the predominant actor types in the settlement. The mean annual clearing per landholding for concentrators of two lots (families: 4.1 ± 2.8 ha (mean ± SD); individuals: 5.1 ± 4.6 ha) was greater than for non-concentrators (1.7 ± 1.2 ha), despite their having similar patterns of small clearings. Concentrators of three or more lots had mean annual clearing per landholding between 6.2 ± 12.2 ha and 23.9 ± 38.7 ha and, the pattern of patches cleared per year > 34 ha in area was predominant. The deforestation rate per lot was higher among concentrators as compared to non-concentrators, showing that lot concentration speeds deforestation. Analysis of deforestation patterns helps to better understand the process of lot concentration by spatially identifying the predominant patterns of each type of actor. The approach used in our study could assist authorities in identifying and monitoring land-tenure concentration in settlements. Agrarian-reform policymakers need to monitor this process, since it speeds deforestation in Amazonian settlement projects, as well as undermining the social objectives of the agrarian-reform program.

Keywords: Agrarian reform; Settlement project; Colonization; Deforestation pattern; Amazon forest; Land concentration

Highlights:

- Deforestation in Brazilian Amazonia is increased by land-tenure concentration.
- Settlers receive 1 lot per family, but newcomers buy out the original settlers.
- "Concentrators" in settlements establish ranches of 2-10 lots (56 to 600 ha).
- In the Matupi settlement, 29% of the lots had been concentrated after 16 years.
- Concentrators with ≥ 3 lots typically clear in patches > 34 ha in area.

1. Introduction

Brazil's Amazonian settlements have an important role in the region's land-use dynamics. Direct and indirect vectors of deforestation (e.g., extensive cattle ranching and illegal occupation of several lots by a single landholder) contribute to increasing deforestation rates in settlements (Alencar et al., 2016). Because most settlements are located near major roads (e.g., the Transamazon Highway), deforestation pressure in these areas tends to be intense (Godar et al., 2012a). Deforestation results in the loss of important environmental services provided by the forest, such as maintenance of water cycling, carbon stocks and biodiversity (Fearnside, 1997, 2008a).

Settlements contributed 17% (160,410 km^2) of the total clearing (clearcutting of both forest and non-forest vegetation) from the "premodern" condition to 2013 in Brazil's 5 × 10^6 km^2 administrative region denominated "Legal Amazonia", which represent 20% (2.6 Pg C) of the total carbon lost in Legal Amazonia through 2013 (Yanai et al., 2017). "Premodern" refers to a time prior to major increases in disturbances beginning in approximately 1970 (Nogueira et al., 2015).

"Federal settlement project" (*Projeto de Assentamento Federal*) is the type of settlement with the largest number of settlements and encompasses 72% (115,634 km^2) of the total clearing in settlements (Yanai et al., 2017). Federal settlement projects are established by Brazil's National Institute for Colonization and Agrarian Reform (INCRA), which distributes plots of land called "lots" (*lotes*) with one lot for a single person or family. When a settlement begins, all or almost all lots are held by individual families (i.e., "non-concentrators"), but as time passes many original settlers sell their lots to wealthier neighbors or to newcomers who "concentrate" several lots to manage the area as a larger property, even though the lots are held under different names. When the original settlers sell their lots to wealthier newcomers, this creates a new wave of landless migrants, leading to a continued cycle of land invasion and subsequent legalization and/or resettlement in new INCRA projects (Fearnside, 2001).

In 2017, Law 13,465 (formerly MP-759), popularly known as the "land-grabbers' law" or "*lei da grilagem,*" was passed allowing illegal land claims up to 2500 ha to be legalized (Brazil, PR, 2017, Art. 6). This law also specifies that illegally occupied lots in settlement projects can be legalized after only two years of occupation (Art. 26B) and that lots can be sold after 10 years of legal occupation (Arts. 18, §1 & 22, §1). In addition, the law specifies (Art. 17, §6) that settlements be considered "consolidated" 15 years after they were founded (thereby allowing lots to be sold, whether or not the same owner has occupied the lot for 10 years). A particularly pernicious effect for settlements is ending a provision that allows settlers to start paying installments owed to the government for the original purchase of the lot only after adequate infrastructure (access roads, etc.) has been installed (e.g., Branford and Torres, 2017). These debts can now be called for immediate payment, and this can be demanded independent of the adequacy of infrastructure (Art. 17, §8). All of these provisions can be expected to result in the less-wealthy settlers, who have only one lot, selling their land to wealthier neighbors or to newcomers. Irrespective of the effect of lot concentration in speeding deforestation, newcomers who buy lots in settlement areas have been found to clear forest at a substantially faster rate per lot than the original occupants (Carrero and Fearnside, 2011; Fearnside, 1987).

Land concentration is an important issue in Amazonian rural settlements because it violates the principles of Brazil's agrarian reform program, which is intended to distribute land to landless families. In addition, concentration of lots transforms settlements into large cleared areas used mainly for cattle pasture (Browder et al., 2008; Carrero and Fearnside, 2011; Martins and Pereira, 2012). For cattle ranchers, one of the main motivations for land concentration is expansion of pasture. Because law enforcement is currently not sufficient to control this process, concentration of lots is a typical feature of settlement projects.

The present study addresses the question of whether the effect of lot concentration results in distinct patterns and rates of deforestation between concentrators (either families or individuals) and non-concentrators. We answer the question by (1) spatially identifying concentrators and non-concentrators and whether concentration is done by "individuals" (i.e., several lots identified by INCRA as occupied by a single person) or "families" (i.e., a family with lots in the names of several family members), (2) defining typologies of deforestation based on the types of actors, remote-sensing data and data-mining techniques and (3) evaluating the rates and trajectories of deforestation through the time in each type of land-tenure concentration.

The term "deforestation pattern" refers to a spatial configuration of patches of deforestation with similarities in size, shape and location that can be mapped from satellite imagery (Zipperer, 1993; Geist and Lambin, 2001; dos Santos Silva et al., 2008). The term "actors" refers to landholders (either individuals or families), whether or not they were settled by INCRA.

A spatial and temporal analysis at the level of "polygons" (areas on a digital map in a geographical information system, with each polygon enclosed by a continuous perimeter and associated with attributes such as land-use type) can provide data at the patch scale in order to evaluate and understand changes resulting from human action in space and through time (Lu et al., 2013). Identifying the actor types and the deforestation patterns associated with them can improve our comprehension of how carbon stocks have been lost by the different actor categories and how deforestation might proceed in the future as the process of land concentration continues. Understanding the deforestation behavior of different actor types is essential if the future course of land-use change is to be predicted and appropriate measures taken to avoid unfavorable outcomes.

2. Materials and Methods

2.1. Study area

The present study was carried out in the Matupi Federal Settlement Project in Matupi District. A "district" is an administrative unit within a municipality, in this case the municipality of Manicoré in the state of Amazonas, Brazil. The Matupi settlement is located in the southern part of Amazonas state near the Transamazon Highway (BR-230), which provides a road connection to the state of Rondônia (a major source of migration) via the BR-319 Highway, which connects Porto Velho (Rondônia) with Manaus (Amazonas) (Fig. 1).

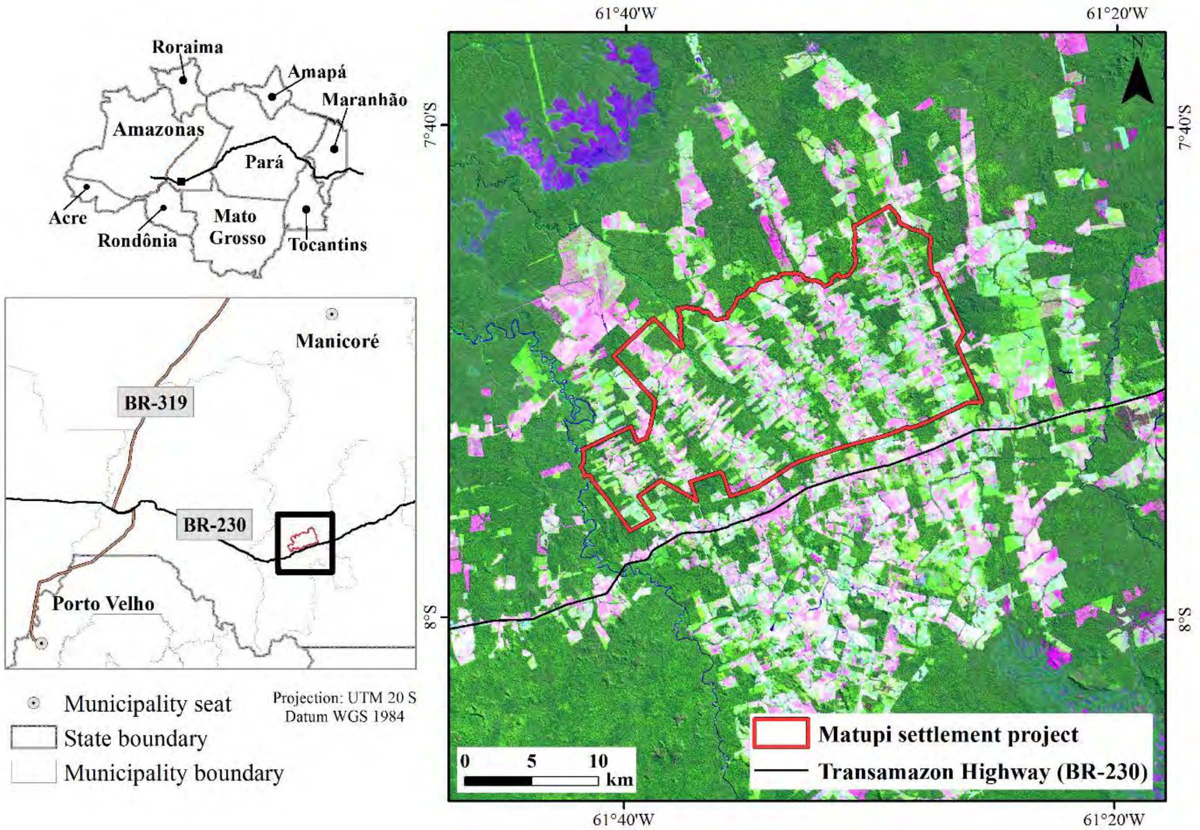


Fig. 1 Location of the study area. Landsat-8 OLI image (2016): R (6), G (5), B (4).

Most actors in Amazonian settlements originate from locations near the settlement or from the southern and southeastern regions of Brazil (Fujisaka et al., 1996; Fearnside, 2008b; Caviglia-Harris et al., 2013). Land prices are low in settlements in frontier areas as the Matupi settlement, which attracts farmers from Rondônia, where the farmers in this former frontier area can sell their land for a good price and use the proceeds to buy a larger area in an area where the deforestation dynamic is intense.

Matupi District (formerly known as "km 180") is an area characterized by expansion of logging and cattle ranching. This general area was indicated as having a very high density of forest loss (>10 km^2 per 100 km^2 of land area) from 2001 to 2014 (Kalamandeen et al., 2018). Carbon loss in the Matupi settlement through 2013 was estimated at 3,389,406 Mg C (18,168 ha of area cleared), while estimated carbon stock in the remaining forest in 2013 (16,762 ha) was 3,129,204 Mg C (Yanai et al., 2017).

The Matupi settlement was officially created on 20 July 1992, initially with 465 lots covering 30,810 ha. However, the occupation process in the Matupi settlement began in 1995 with the establishment of 91 families (da Silva et al., 2011). In 1997 the settlement area officially increased to 34,345 ha (decree n° 24 of August 1997) and the total number of lots increased to 537, with area of each lot between 25 and 135 ha (mean lot size = 64 ha). The Matupi settlement has nine access roads (known as "*ramais*"): Nova Vida, Bela Vista, Matupi, Matupiri, Santa Luzia, Boa Esperança, Maravilha, Triunfo and Bom Futuro (Supplementary Material, Fig. S1). The total area of the Matupi settlement is 34,938 ha, based on a vector map of the settlement's boundary provided by INCRA.

2.2. Mapping deforestation through 2016, identify actors and linking actors to deforestation patches

We manually mapped cleared areas from 1994 to 2016 in the Matupi settlement by visual interpretation at 1:20,000 scale, where the appearance of areas in a satellite image displayed on a large high-definition computer screen is used to identify deforestation. Cleared areas mapped in a given year (e.g., 2000) were used as a mask for mapping cleared areas in the next year (e.g., 2001). The area of each polygon was then calculated and areas < 1 ha were excluded to reduce noise caused by small polygons, which means that the minimum map unit considered in our study was 1 ha.

Polygons (i.e., patches) of clearing for each year were delimited based on the visual appearance of the cleared areas, which reflects their spectral response. When boundaries between adjacent cleared areas were visible, then each area was mapped as a distinct polygon for the year in question. We used this refined approach since the clearing process could help distinguish the actions of different actors. Because the occupation process in the Matupi settlement started in 1995, we began mapping clearing using the 1994 Landsat image as a reference. The polygons of cleared areas mapped for 1994 therefore represent cumulative areas and those from 1995 to 2016 represent annual clearing. Additional information on methods used for mapping deforestation is available in the Supplementary Material.

Identification of the actors and their clearing (i.e., polygons of deforestation) was done based on the dataset for the Matupi settlement provided to us by the Amazonas office of INCRA in Manaus. This dataset consisted of (i) a vector map of lot boundaries (n = 537 lots), (ii) occupation survey (*Levantamento Ocupacional*) data on families in the Matupi settlement collected in October 2011 in 526 lots, and (iii) data on property diagnoses collected by INCRA in 164 lots from 2014 to 2016. Datasets (ii) and (iii) were obtained during *in loco* visits to the lots by an INCRA officer. In our analysis, we used information on the landholder and the beginning date of occupation for the lot. We also used data obtained during our fieldwork in 2016, which consisted of GPS points of the lot boundaries on the six access roads we visited (Matupi, Matupiri, Maravilha, Triunfo, Bom Futuro and Nova Vida; Supplementary Material, Fig. S1).

All of these data assisted us in identifying and spatially locating the landholders and their polygons of deforestation. Thus, for example, if data in INCRA's 2011 occupation survey indicated that a landholder had occupied a given lot since 2004, then the polygons of deforestation from 2004 to 2011 were attributed to that landholder. In addition, if the same landholder occupied the lot in 2016, then any 2012-2016 deforestation polygons were also attributed to the landholder. When the year of occupation was not mentioned, only polygons of deforestation from 2011 were attributed to the landholder. We used this approach to be sure of correctly associating the actor and his or her clearing in the lot because the polygons of deforestation in a lot could be made by different actors who occupied the lot at different times. Out of a total of 2551 polygons of deforestation mapped in the Matupi settlement, we could identify the actors in 732 polygons (29%). We performed chi-square and Fisher's tests to assess the association between the actor type and deforestation pattern based on the samples of polygons where we identified both the actors and their clearing patterns. For classification of the deforestation pattern, we used 164 of the identified polygons as the dataset, which we divided between training and validation samples.

2.3. Classification of deforestation patterns

The method used to classify deforestation patterns was based on the deforestation polygons mapped in the previous step. We used the GeoDMA (Geographic Data Mining

Analyst, Version 0.22a) plugin (Körting et al., 2013) in Terra View 4.2.2 software to classify the patterns of deforestation. The classification steps consisted of (i) feature extraction based on the characteristics of deforestation patches (i.e., polygons), where patch metrics (size and shape of polygons) were calculated for each patch and stored in the attribute table of the deforestation vector map, (ii) selection of patch samples in which we only included patches where the actor type was known based on INCRA data and where the previously defined deforestation spatial pattern as defined in Table 1 was also known, (iii) classification of all deforestation patches by running the C4.5 data-mining algorithm for decision-tree classification (Quinlan, 1993), and (iv) assessment of the classification. The typology of deforestation patterns was determined based on exploratory visual analysis by superimposing the vector map of deforestation on the vector map of lot boundaries and based on the authors' previous knowledge of actor types and their clearing behavior from field observations in the settlement project.

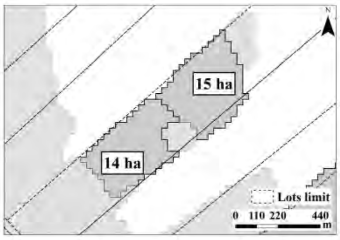
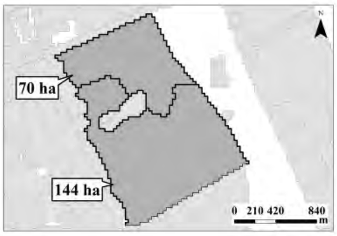
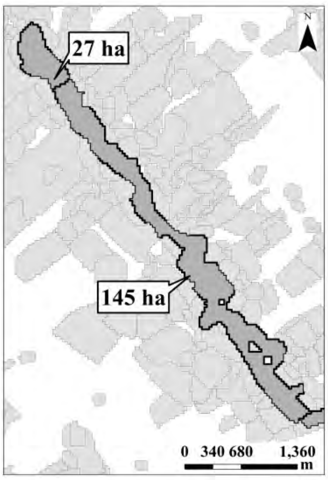
Deforestation pattern	Actors associated with the pattern	Description
Small irregular 	This is the most common pattern for landholders who do not concentrate lots;	**Main activity:** cattle ranching and agriculture; Small patches (either grouped or isolated) indicate a small clearing each year inside of the lot. Cleared areas are for pasture or agriculture.
Small geometric 	This is most common in landholders who do not concentrate lots. The cleared areas are small and respect the boundary of the lot.	**Main activity:** cattle ranching and agriculture; Patches can be isolated, which could be associated with the new pasture areas or grouped with older patches that could indicate the expansion of pasture.
Large geometric 	This is a predominant pattern in landholdings of individual and family landholders who have concentrated lots.	**Main activity:** cattle ranching Large areas cleared in one year by actors who concentrate lots.
Large irregular 	We assumed that this pattern is mainly associated with the first families or individuals who occupied the settlement, each receiving a single lot from INCRA.	**Main activity:** cattle ranching and agriculture; This pattern represents the beginning of the occupation process along access roads in the Matupi settlement. The occupation is characterized by clearing at the front of the lots, which can have the effect of indicating land tenure.

Table 1 Deforestation patterns in the Matupi settlement.

We separated the classification into two periods: (i) 1994 to 1999 and (ii) 2000 to 2016. This was done because the initial process of ocupation in the Matupi settlement resulted in large polygons of deforestation (large irregular) that could be confused with similar polygons deforested in recent years (large geometric) (Table 1).The separation into these periods results in better distinguishing the process of deforestation and the types of actors. The large irregular areas cleared along access roads in the first years are the result of the first landholders who occupied the lots each clearing the front of the lot to indicate land tenure. We could not differentiate the clearing done by these landholders in the satellite images. In contrast, the large geometric polygons cleared in recent years are attributed to lot concentration when the polygons span several lots.

In total, 239 polygons were used to assist the classifications. Out of this total, in 164 polygons the actors who cleared them were known, and for 61 polygons we have no information about the actors (these polygons were used only for the first classification period). In the first classification period (1994-1999) we considered the "large irregular," "small geometric" and "small irregular" patterns. For the second classification period (2000-2016) we considered the "small irregular," "small geometric" and "large geometric" patterns (Table 1). The "small irregular" (n = 62) and "small geometric" (n = 66) patterns were in areas with the non-concentrating actor type. The "large geometric" cases (n = 22) were in areas of lot concentration.

2.4. Estimation of lot concentration in 2011 and deforestation rates by landholders

Since the data from the 2011 occupation survey of families covered most of the lots in the Matupi settlement, we used these data to classify the vector map of lot limits for each actor type. The actors were divided into two major groups: non-concentrators and concentrators, the latter group including both individual and family actor types. When concentration in neighboring lots was found, we merged these lots into one representing the landholding of a concentrator. For non-concentrators, the landholding and the lot area are the same. We use the term "landholding" to refer to the area occupied by a single actor (individual or family); the area may be one or several lots and the occupation may or may not be legal.

The criterion used to identify concentration by families was if the members of the same family occupied neighboring lots and one of the family members resided in the neighboring lot (e.g., a parent living in his or her child's lot). We also considered as concentration by a family the cases where both (i) lots are occupied by people with the same surname and (ii) the polygons of deforestation they made, which were identified by the period that the landholders occupied the lots, span these two or more lots. We also considered a type of concentration of non-neighboring lots. This refers to concentrators of neighboring lots who also occupied one nearby lot on the same access road. We placed these cases in a separate category as "concentrators of non-neighboring lots" with the aim of comparing the dynamics of clearing in these lots with those of non-concentrators.

Lots excluded from our analyses (n = 21 lots) were those with unknown actors (4 lots), lots that were not visited by an INCRA officer due to inaccessibility (10 lots) and "community" lots (7 lots). The "community" lot refers to a lot allocated by INCRA to construct infrastructure such as a school, church and space for recreational activities (e.g., a soccer field). The clearing in the community lot is therefore not associated with a specific actor. In most cases there is one community lot per access road. On one of the access roads (Boa Esperança) the community lot was occupied by a landholder, and it was included in our analysis.

We then performed an intersection between the vector map of lot boundaries updated to 2011 and the vector map of deforestation patterns classified to estimate 1995-2011 deforestation rates per landholder (i.e., clearing per year in the area occupied by each landholder). Although we are aware that deforestation in the lot could be done by different actors who occupy the lot at different times, we consider that it is important to establish the deforestation trajectories and rates of deforestation in areas where it was known whether or not the lot was occupied by concentrators in 2011. Landholders who were identified in this analysis as occupying the lot or area (in the case of concentrators of neighboring lots) in 2011 had inherited clearing done by previous landholders. To estimate the remaining forest in 2011, deforestation from 2012 to 2016 was considered to have been forest in 2011, and this total was summed with the forest in 2011. Because our dataset lacked normality, a non-parametric statistical test (Mann-Whitney U) was performed. Additional information on methods is available in the Supplementary Material.

3. Results

3.1. Spatial and temporal dynamics of deforestation

The total area cleared through 2016 in the Matupi settlement was 22,945 ha (66% of the 34,938-ha settlement area), and the mean clearing per year (1995-2016) was 1026 ha. Peaks of deforestation occurred in 1997 and 2005 (9% and 10% of the total deforestation, respectively). In 2011 and 2016, high rates of deforestation were observed again, each of these years representing 8% of the total deforestation. In contrast, substantial reductions in deforestation were observed in 2006 (with a decrease of 1622 ha in relation to 2005) and in 2012 (with a decrease of 1199 ha in relation to 2011). The largest deforestation increment (1891 ha) occurred when the settlement area was officially expanded in 1997 (Supplementary Material, Fig. S1 and S2).

The polygons (i.e., patches) ranged from 1 ha (minimum area considered) to 167 ha. In general, as patch size increased the numbers of polygons decreased for all periods analyzed. Most patches (74% or 1892 polygons) were in the < 5 and 5 - 10 ha size ranges (Fig. 2). The 2000-2004 period had the lowest number of patches in comparison with other periods for the three first classes (< 5, 5 - 10 and 10.1 - 20 ha). In contrast, the 2010-2016 period had a greater number of patches for most sizes analyzed in comparison with other periods (Fig. 2).

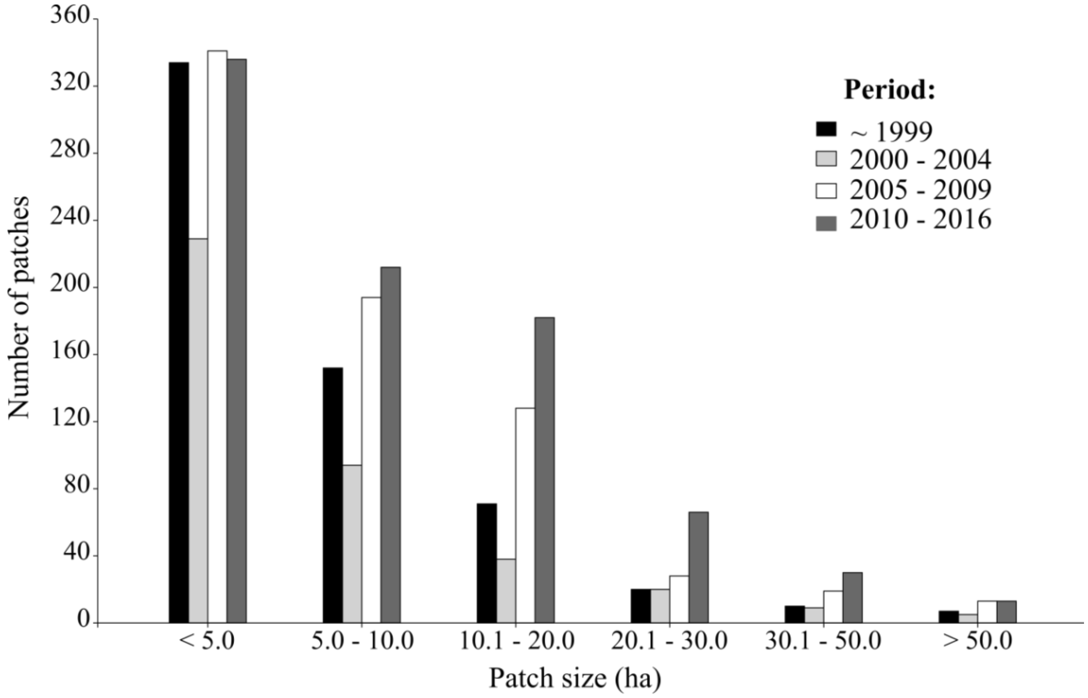


Fig. 2 Numbers of patches (polygons) of different sizes and in different periods of time.

3.2. Classification of deforestation patterns by actor type

A decision tree for the first classification (1994 – 1999) identified compacity and normalized perimeter as the best landscape metrics for separating the deforestation patterns (Fig. S3). The normalized perimeter metric transformed values between the minimum and maximum perimeters into values in the interval between 0 and 1. In the second classification (2000 – 2016), compacity and area best differentiated the “small irregular” from the “small geometric” and “large geometric” patterns (Fig. S3). “Compacity” (which was used in both classifications), is a metric of patch shape (Eq. 1) that is greatest for irregular patch shapes and allows these to be separated from geometric shapes. Clearing of larger landholders can be expected to have more regular geometric patch shapes because these actors hire outside groups to clear predefined areas, rather than using family labor supplemented by individual day laborers (who may choose to avoid unfavorable topography or other obstacles). Polygons > 33.7 ha were identified as the “large geometric” pattern.

$$Compacity = (perimeter/area)/\sqrt{area} \tag{1}$$

The confusion matrix in the first classification indicated that four polygons of the “small geometric” pattern were classified as “large irregular” (Supplementary Material, Table S2). The Kappa values were 0.97 (training sample versus classification) and 0.87 (validation sample versus classification). In the second classification the confusion matrix indicated that only one sample of the “large geometric” pattern was misclassified as “small geometric” and one sample of the “small geometric” pattern was misclassified as “small irregular” (Supplementary Material, Table S3). The Kappa values were 0.96 (training sample versus classification) and 1 (validation sample versus classification).

Deforestation-pattern classification through 2016 indicated that “small geometric” (44% or 9988 ha) and “small irregular” (31% or 7092 ha) were the most representative patterns in the Matupi settlement. The “large geometric” (18% or 4045 ha) and “large irregular” (8% or 1820 ha) patterns accounted for less area as of 2016 (Fig. 3).

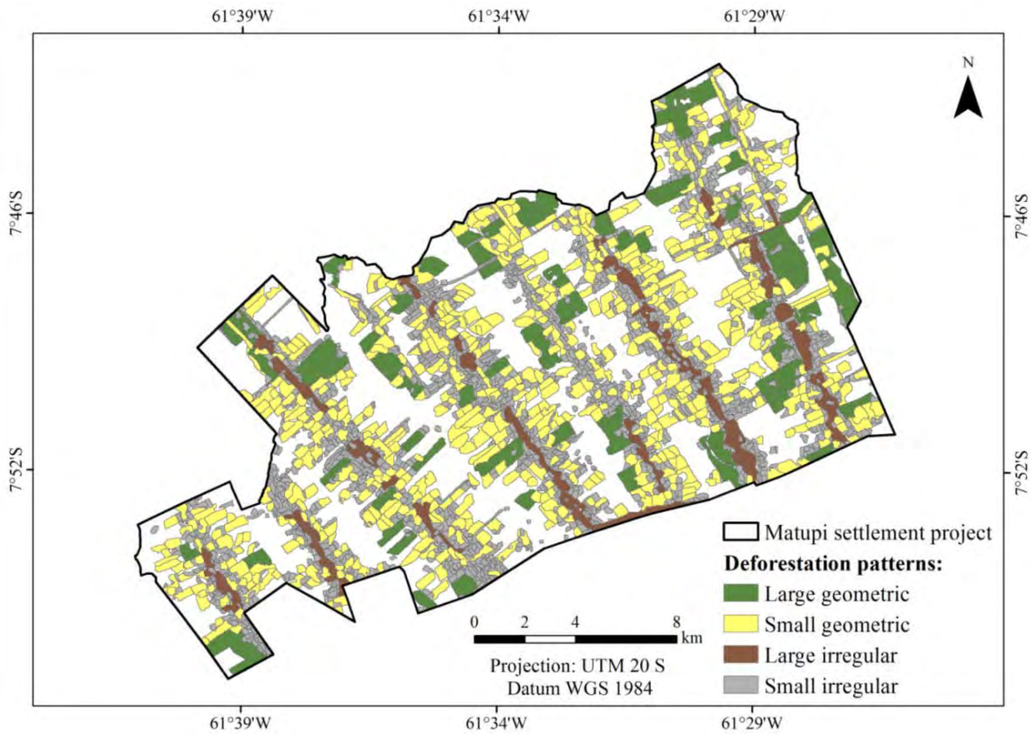


Fig. 3 Deforestation pattern classification in the Matupi settlement (2016).

"Small irregular" and "small geometric" were the patterns that encompassed the greatest numbers of patches (2428 polygons or 95% of the total). The mean size of "small irregular" polygons (4 ha) was smaller than that of the "small geometric" polygons (15 ha). However, both categories had some polygons with the same size (range = 1 – 20 ha for "small irregular" and 6 – 33.8 ha for "small geometric"). The "large irregular" pattern (mean = 34 ha) had the least polygons (54) but had the widest size range (13 – 145 ha). "Large geometric" (mean = 59 ha) also encompassed a wide range of polygon sizes (34.1 – 167 ha), with some polygons larger than those in the "large irregular" category (Fig. S4).

3.3. Temporal dynamics of deforestation patterns

The mean contribution per year of each deforestation pattern to the total for the Matupi settlement over the period from 1995 to 2016 indicated that "large irregular" was the pattern with the largest area cleared per year (322 ha) from 1995 to 1999, followed by "small irregular" with a mean of 314 ha per year (Fig. 4). Since 2000 the mean area of the "small geometric" type cleared per year was the largest in comparison with the other patterns. The mean area cleared per year in the "small geometric" pattern increased progressively from the 1995-1999 period to the 2010-2014 period, followed by a decrease in the 2015-2016 period. The "large geometric" pattern did not exist prior to 2000, so we only included this pattern from 2000 onwards (excluding it from the earlier period avoids confusion with the initial contiguous clearings along the access roads at the fronts of the lots). Since 2000 the "large geometric" pattern had an increase in the annual mean, rising from the 2000-2004 period to the 2005-2009 period and decreasing in the subsequent periods. "Small irregular" followed the same trend as "large geometric" but with greater mean areas cleared per year in all of the periods.

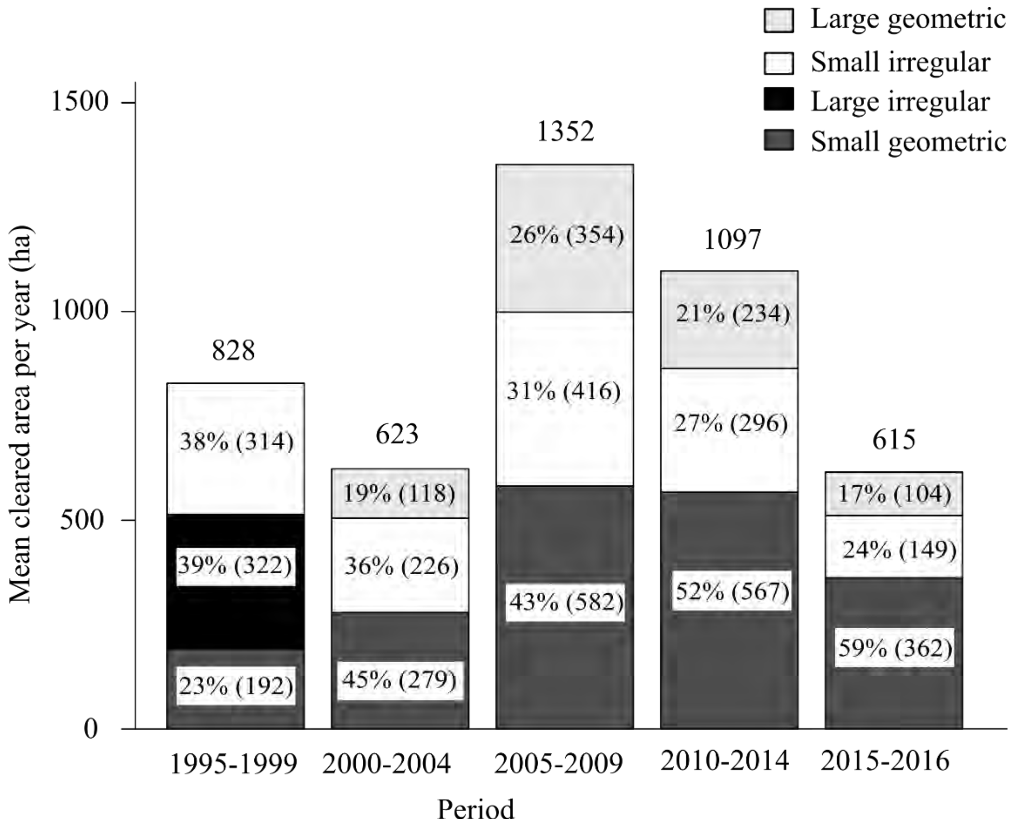


Fig. 4 Mean area cleared per year for each time interval and deforestation pattern. Values in parentheses represent the areas in hectares.

3.4. Lot concentration (2011) and deforestation rates (1995-2011) by actor type

Lot concentration by individuals and families was found in 152 lots or 29% of the total analyzed (n = 516 lots). The area covered by landholders who concentrated lots represented 28% (9653 ha) of the settlement area (Fig. 5). Out of this total, 68% (6546 ha) represented concentration by families (n = 42 families and 105 lots concentrated) and 32% (3107 ha) by individuals (n = 18 individuals and 47 lots concentrated). The numbers of lots concentrated ranged from two to ten, with the most frequent number being two lots. Of the total area concentrated by actors with two lots (5905 ha), families represented 69% (4065 ha) and individuals 31% (1840 ha) (Fig. 5 and Table 2).

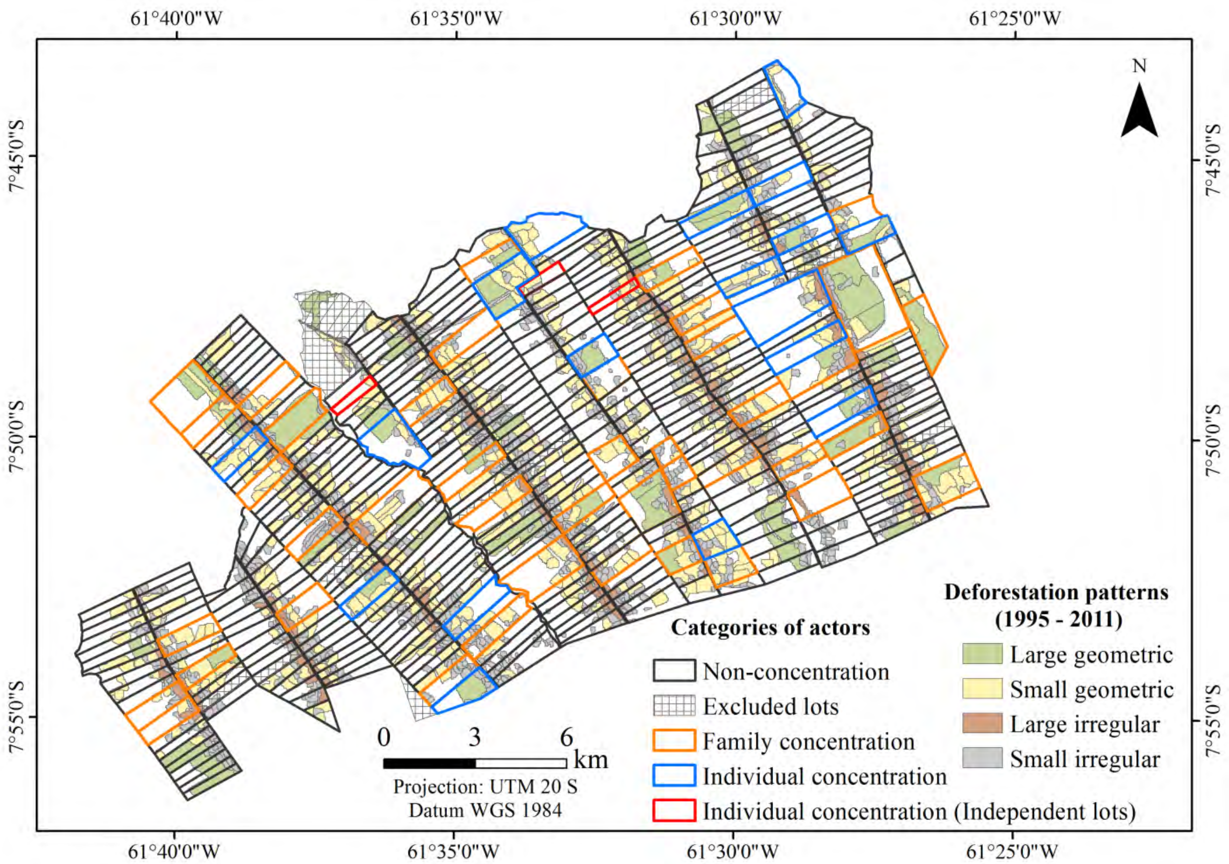


Fig. 5 Boundaries of landholdings updated to 2011 and deforestation patterns (1995 - 2011). The “Individual concentration (Independent lots)” is the same as “concentrators of non-neighboring lots” mentioned in the text.

Concentration category	Numbers of landholders (concentrators)	Number of lots concentrated per landholder	Total numbers of lots concentrated for each actor type	Minimum and maximum areas of landholdings (ha)	Mean area of landholdings (ha)	Total area concentrated (ha)
Individual	14	2	28	118.5-163.3	131.4	1,840.2
	4	4	16	229.9-398.7	276.3	1,105.3
Individual (non-neighboring lots, in addition to contiguous lots counted above)	3	1	3	49.5 - 60.2	53.9	161.8
Family	33	2	66	55.7-194.4	123.2	4,064.5
	4	3	12	181.8-246.3	213.0	852.0
	3	4	12	232.5-272.7	246.4	739.1
	1	5	5	-	-	291.3
	1	10	10	-	-	599.0
Total			**152**			**9,652.8**

Table 2. Types of concentration found in 2011 and numbers of lots concentrated in the Matupi settlement.

Landholders with one lot were the largest category in terms of numbers (364 lots or 71%). The total area covered by this category was 23,517 ha or 68% of the Matupi settlement area in 2011 (34,796 ha, based on the vector map of lot boundaries) (Fig. 5). The sizes of the lots of non-concentrating actors ranged from 40.5 to 134.6 ha (mean = 64.6 ha).

Non-concentrators and concentrators of non-neighboring lots had similar mean annual clearing per landholding from 1995 to 2011, the annual rates being 1.7 ± 1.2 ha (mean ± SD) and 1.2 ± 1.5 ha, respectively. Concentrators of two lots had similar mean rates per year whether the concentration was by families (4.1 ± 2.8 ha) or individuals (5.1 ± 4.6 ha). Mean annual clearing per landholding in the case of families was similar for concentrators of three lots (9.0 ± 12.8 ha) and four lots (9.6 ± 11.3 ha), but individuals with four lots had a slightly lower mean rate (7.2 ± 8.8 ha) in comparison with families with the same numbers of lots (9.6 ± 11.3 ha). A family concentrating five lots had a lower mean (6.2 ± 12.2 ha) compared to those with three or four lots, and a family with ten lots had the highest mean (23.9 ± 38.7 ha).

The mean annual clearing from 1995 to 2011 per landholding indicated significant differences in all pairwise tests ($p < 0.001$) in comparing non-concentrators ($n = 364$ landholders or lots) with concentrators of two lots ($n = 47$ concentrators) and of three or more lots ($n = 13$ concentrators) (Fig. S5). Similarly, the mean annual clearing per lot for the same period showed significant differences ($p < 0.001$) in comparing non-concentrators (1.7 ± 1.2 ha) with concentrators of two lots (2.2 ± 0.8 ha) and of three or more lots (2.2 ± 0.9 ha). No significant differences ($p = 0.54$) were found in the mean annual clearing per lot between concentrators of two and three or more lots (Table 3). However, when concentrators were analyzed separately in categories distinguishing families and individuals and the numbers of lots concentrated, we found that non-concentrators and three types of concentrators did not differ significantly ($p > 0.05$) in their mean annual clearing per lot. The categories were a family concentrator of 5 lots, individual concentrators of 4 lots and family and individual concentrators of non-neighboring lots (Supplementary Material, Tables S4 and S5).

Actor category	Total no. of lots	Mean annual clearing per lot	SD	Mean total clearing per lot
Concentrators				
Concentrators of 2 lots	94	2.2	0.8	37.3
Concentrators of 3-10 lots	55	2.2	0.9	38.1
Non- concentrators	364	1.7	0.8	29.5

Table 3. Deforestation rate per lot from 1995 to 2011 in three groups of actors categories.

In general, non-concentrators and concentrators of non-neighboring lots had less clearing in comparison with concentrators of neighboring lots. From 1995 to 2011 the total area cleared by non-concentrators was 10,750 ha and the mean clearing per landholding was 30 ha. For concentrators of non-neighboring lots the total area cleared was 64 ha and the mean clearing per landholding was 21 ha. The total clearing (1995-2011) in the lots of non-concentrators ranged from 4 to 73 ha per lot and for concentrators of non-neighboring lots the total clearing ranged from 8 to 30 ha per lot. For concentrators (families and individuals) of two adjacent lots, the total area cleared was 3504 ha and the mean clearing per landholding was 75 ha. The total area cleared (1995-2011) per landholder of this category ranged from 21 to 128 ha. The total clearing by concentrators of three lots was 609 ha, with the mean clearing per landholding being 152 ha and the total area cleared per landholding ranging from 134 to 181 ha. In the case of concentrators of four lots, the total area cleared was 978 ha with mean clearing per landholding of 140 ha and the clearing per landholding ranging from 79 to 222 ha.

Only 2% of non-concentrators (n = 8 landholders) had <20% clearing in their lots (i.e., in accordance with the Forest Code). All concentrators had total clearing >20% in the landholdings that they occupied (Fig. 6). Furthermore, 74% (n = 268) of non-concentrators had cleared more than 50% of their lots. In the landholdings of concentrators, the percentages of landholdings with more than half of their area cleared were: 87% (n = 41) for concentrators of 2 lots, 100% (n = 4) for concentrators of 3 lots and 86% (n = 6) for concentrators of 4 lots. The family that concentrated 5 lots had less clearing (37%) in comparison with most of the concentrators. The family with 10 lots had 68% clearing in the landholding (Fig. 6).

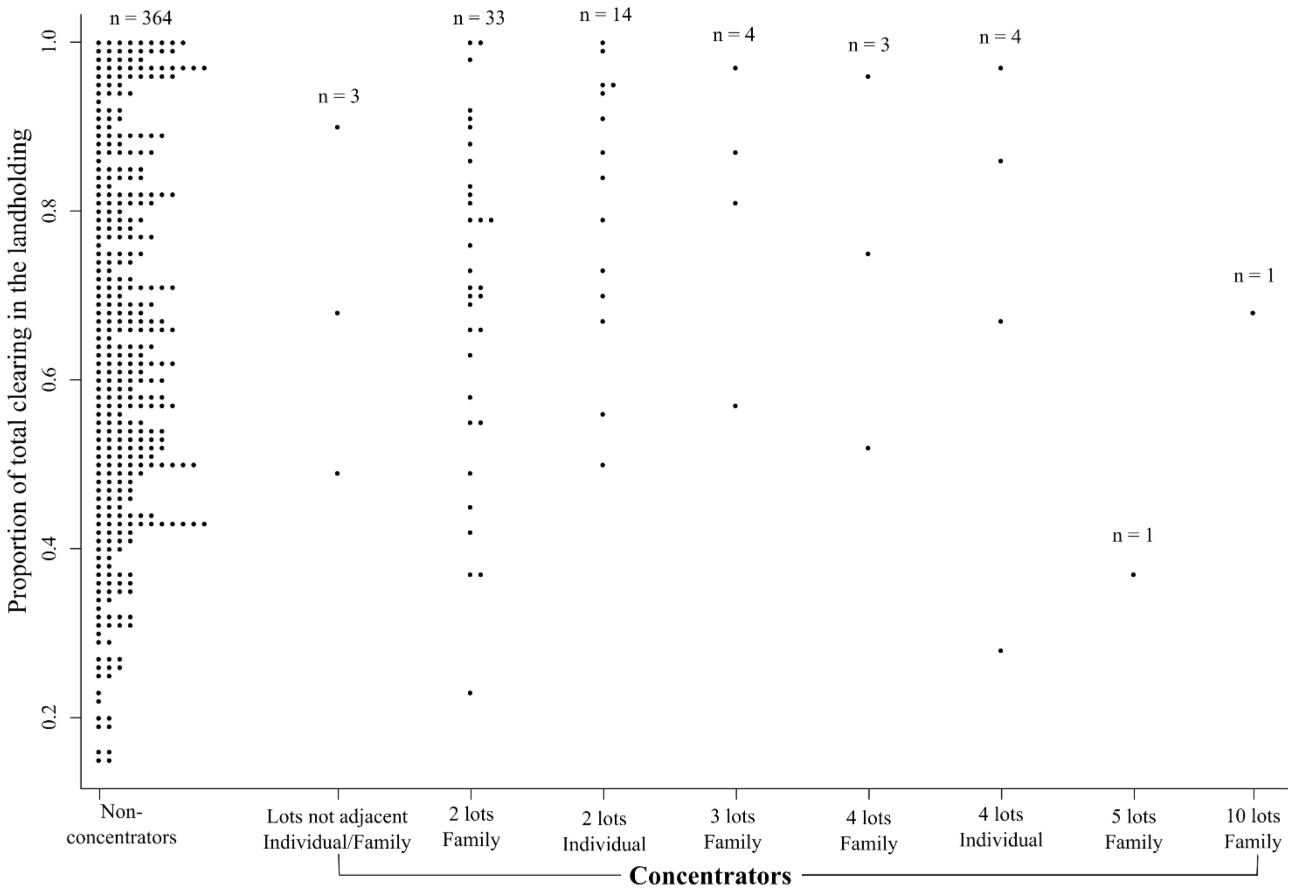


Fig. 6 Proportion of total area cleared per landholding from 1995 to 2011 (n = number of landholders per category).

However, because non-concentrating landholders were numerous, their contribution to total deforestation was greater (63% or 11,047 ha of the 17,426-ha total deforestation through 2011), as well as per year, as compared to the total for landholders who concentrate lots (Fig. S6).

The proportion of area cleared through 2004 was similar for landholders with one and two lots (Fig. 7). After 2004, deforestation in areas of concentrators of two lots increased more, and in 2010 the clearing reached half of the total area of the landholdings in this category. Though 2011, areas cleared by non-concentrators still represented less than half of the total area of landholdings of this category. In areas cleared by of concentrators of ≥ 3 lots, the proportion deforested per landholding was lower through 2002 compared with other categories. However, since 2004 the proportion of clearing in this category increased and reached half of the total area of landholdings occupied by this category in 2008, which is earlier than the years for reaching this benchmark in the case of categories with fewer lots per landholder (Fig. 7).

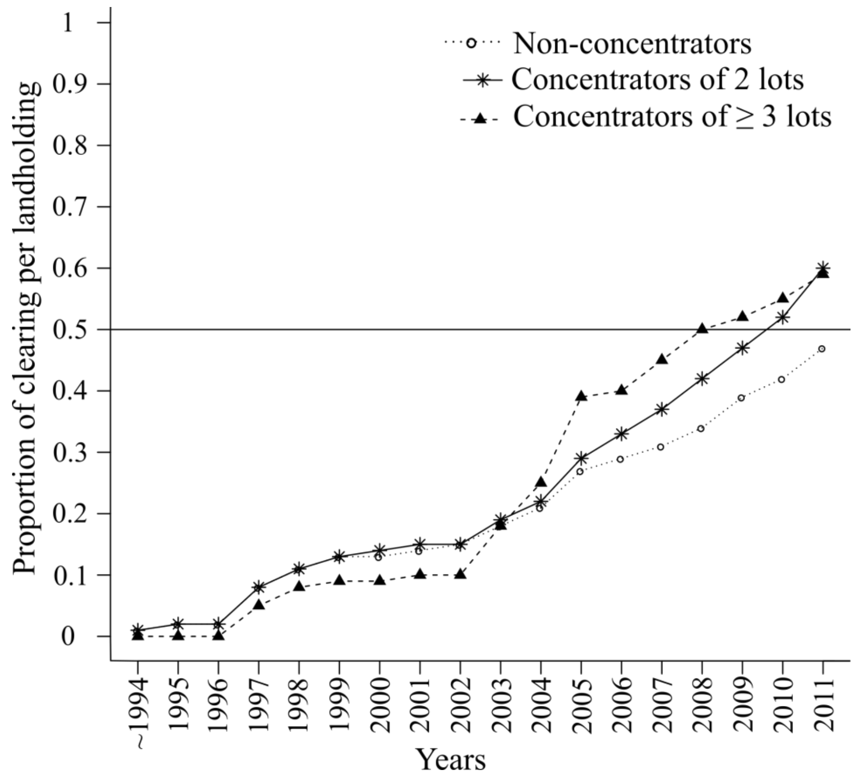


Fig. 7 Trajectory of deforestation through time per area occupied by each type of landholder. Proportion of clearing represents the proportion of clearing in relation to the total area occupied by the category.

The remaining forest in 2011 (17,370 ha) in areas of non-concentrators represented 72% (12,471 ha) of the total forest in 2011. For concentrators, remaining forest represented 23% (3938 ha) of the total forest in the Matupi settlement in 2011. The rest of the remaining forest (5% or 961 ha) was in lots that were excluded from our analyses.

Considering the percentage of forest per landholding for different actor categories, we found that non-concentrators and individual concentrators of four lots had similar results for the mean percentage of forest per landholding (Table 4). Family concentrators of three and four lots had the lowest mean percentage of forest per landholding, followed by a family concentrator of ten lots and individual concentrators of two lots. In contrast, the family concentrator of five lots had the greatest percentage of forest in the landholding (Table 4). This result suggests that landholding size is not related to the proportion of remaining forest in the landholding.

Actor type (n = number of landholders analyzed)	Deforestation through 2011 (ha)	Forest in 2011 (ha)	Percentage of forest (2011) per landholding (mean ± SD)
Non-concentrator (n = 364)	11,047 (47%)	12,471 (53%)	52.5 ± 20.6
Concentration by individuals:			
non-neighboring lots (n = 3)	64 (40%)	98 (60%)	61.0 ± 20.2
2 lots (n = 14)	1,213 (66%)	628 (34%)	32.8 ± 21.0
4 lots (n = 4)	488 (44%)	617 (56%)	52.3 ± 31.8
Concentration by families:			
2 lots (family) (n = 33)	2,332 (57%)	1,732 (43%)	41.4 ± 20.6
3 and 4 lots (family) (n = 7)	1,108 (70%)	483 (30%)	28.3 ± 21.0
5 lots (family) (n = 1)	105 (36%)	186 (64%)	63.9
10 lots (family) (n = 1)	405 (68%)	194 (32%)	32.4

Table 4. Areas and percentages of forest and deforestation per landholding of the different actor types.

4. Discussion

4.1. Landholding size and actor type

Our study focused on better understanding the lot concentration process and how it results in different actor types having distinct forest-clearing patterns. The mean annual clearing per landholding is an important indicator of the environmental impact of accommodating the different actor groups in the settlement. However, it is also important to assess deforestation rate per lot since it reflects the impact of lot concentration on the overall rate of deforestation (Carrero and Fearnside, 2011). We found that concentrators clear more per lot than non-concentrators, which speeds deforestation.

Our finding that, in general, non-concentrators (mean lot size = 65 ha) had a higher percentage of remaining forest than concentrators is similar to the observations of Godar et al. (2012b), who found that actors who focused on cattle ranching with property sizes from 200 to 600 ha (and who were more capitalized) had less remaining forest in their properties in comparison with less-capitalized colonists with property sizes under 200 ha. In addition, a recent study in the Ouro Preto do Oeste settlement in Rondônia found that actors who deforested more for cropland or pasture (the main income activities) obtained larger incomes than those who deforested less. This is because clearing is linked to accumulation of household assets (Mullan et al., 2018). Thus, the income from pasture expansion is a motivation for asset accumulation that could be self-perpetuating for actors who concentrate land (Mullan et al., 2018).

We did not find major differences between annual clearing per landholding of family and individual concentrators. This suggests that the number of lots concentrated has more weight in the dynamics of clearing than does the type of concentration (family versus individual). In addition, the INCRA dataset reported (and we also found in the fieldwork) that cases (n= 10) of family concentration exist where a single member of the family is responsible for clearing in the landholding. The other family members either work in activities not directly related to production in the landholding or live outside of the settlement. Thus, in practice, decisions about clearing are made by one person. In our study, out of a total of 42 cases of family concentrators (105 lots: Table 3), where, in general, each member of the family occupies one lot, 44% (46 members of the concentrator families) lived in the settlement according to data in the INCRA occupation survey conducted in 2011. For individual landholders who concentrated neighboring lots, out of a total of 18 landholders (concentrating a total of 44 lots), 44% (8 landholders) lived in the settlement in one of the lots they occupied.

The small area cleared by concentrators of 2 and ≥ 3 lots was mostly cleared between 1995 and 2002. This suggests that the process of lot concentration started mainly in 2003, or eight years after the initial occupation of the settlement, and that the clearing before 2003 in the concentrated lots had been done by the previous landholders.

Similarly, da Silva (2012) found that 7.3 years is the average residence time of landholders in the Matupi settlement and only 3% of landholders interviewed were originally settled by INCRA. A similar trend was observed in a settlement located in Vale do Anari (in the state of Rondônia), where during the first six years of settlement occupation, cleared areas were concentrated near access roads, and patches had irregular linear patterns. After this early stage, medium and large landholders bought lots from previous settlers to establish cattle ranches. Large clearings started to appear and increased gradually through time as result of lot concentration. The patches associated with these landholders were > 50 ha in area (dos Santos Silva et al., 2008).

4.2. Small patches of deforestation

Our study found a total of 22,945 ha of clearing in the Matupi settlement, whereas PRODES estimated an area of 21,504 ha through 2016 (Brazil, INPE, 2018a). We mapped 1441 ha (6.7%) more clearing than PRODES. This could be due the larger minimum area detected by PRODES (6.25 ha) as compared to our study (1 ha), and because we considered roads as clearing (when visible in the Landsat images). The difference could also be at least partly a result of the different image dates used as the reference for the mapping (30 July 2016 by PRODES versus 12 August 2016 in our study). In addition, because we discriminated clearing considering the spectral response of land-cover change (i.e., clearcut, initial regeneration after clearcutting, and slash-and-burn), the numbers of small polygons increased by 19% (416 polygons), raising the total from 2135 (if interpretation was done without feature discrimination of clearing) to 2551 polygons. The small polygons were classified mainly as “small geometric” and “small irregular” patches. We decided to use the feature-discrimination approach because size and shape of patches are important metrics for differentiating the patterns and because this approach reduced the overestimation of area that occurs when we associate actors with polygons, in comparison to mapping without this discrimination. The result was therefore more detailed and achieved a better separation of deforestation that occurred in nearby areas in the same year but was done by different landholders.

A recent study has found a pervasive rise in small-scale deforestation in Brazilian Amazonia as a whole (Kalamandeen et al., 2018). Despite differences of scale between our study (local scale) and the study by Kalamandeen et al. (2018) (regional scale), we found a similar overall tendency, demonstrating that (i) as patch size increases the number of patches decreases and (ii) the contribution of small patches has increased through time.

In Brazil’s Legal Amazonia region, Escada et al. (2011) found that, of the 6646 km^2 deforested in 2009, 60% (4003 km^2) was in patches <25 ha in area while only 1.7% (113 km^2)

was in patches >1000 ha in area. The same study found that the percentage of deforestation in patches <25 ha in size increased from 22% (5897 km^2 out of 21,650 km^2 of deforestation) in 2002 to the 60% found in 2009. For annual clearing in Legal Amazonia in the same period, Rosa et al. (2012) found that patches 6.25-50 ha in area increased from 30% (6495 km^2) in 2002 to 73% (5449 km^2) in 2009. Rosa et al. (2012) suggested that the decline of large patches could be attributed to the historic trajectory of deforestation in some municipalities, lower deforestation rates being reflected in the smaller size of patches in recent deforestation. In addition, Rosa et al. (2012) suggested that some landholders changed their behavior to avoid detection by environmental monitoring, clearing small patches instead of large areas. Another factor that could contribute to the increase of small patches is fragmentation of some lots into smaller landholdings, despite the fact that the much more common pattern is one of consolidation of lots (i.e., incorporation of several lots in one landholding), as reported by D'Antona et al. (2011) in a rural settlement near Santarém (Pará). These authors found that, out of a total of 587 lots analyzed, 39 (7%) were fragmented into landholdings smaller than the original lot size, 4% were fragmented and partially merged with larger landholdings and 67% of the lots were merged in large landholdings without being fragmented. Although we lack information that would allow analysis of fragmentation of previously concentrated lots, we estimated by visual interpretation that there were 30 lots in the Matupi settlement that had been occupied by non-concentrators in 2011 (Supplementary Material, Fig. S7). This could be a result of fragmentation of previously concentrated landholdings into individual lots, which is one of the processes reported near Santarém by D'Antona et al. (2011).

4.3. 'Peaks' and 'valleys' in observed deforestation

We observed three important phases in the deforestation trajectory in the Matupi settlement. The first phase refers to an initial occupation process (1994 to 1996) with the arrival of the first settlers. In this phase, clearing started to appear mainly as small patches in the lots in the access roads nearest their connections to the Transamazon Highway, indicating that these lots were the first lots occupied. A study in Altamira (in Pará state) reported that landholders cleared 2 to 5 ha per year in the initial stages of settlement (McCracken et al., 1999).

The second phase started with the official increase of settlement area in 1997, resulting in an increase in the number of lots from 465 to 537. This represents occupation of lots by new landholders settled by INCRA. Clearing is done first at the lot front both to indicate land tenure and due the convenience of proximity to the access road. The "large irregular" pattern found in the early years of occupation along the access roads reflected the clearing done at the front of each lot. Clearing declined from 2000 to 2002, with values similar to the first phase. Only a few landholders lived in the settlement during this period, which could indicate an abandonment of lots occupied initially.

The last phase occurred since 2003 when clearing started to increase with peaks and lows through 2016, indicating that deforestation dynamics were more intense during this period in comparison with the first years of settlement. Since 2003, annual deforestation increased in the Matupi settlement, with a large area being cleared by concentrators, this being added to the continued contribution of non-concentrators. Part of the clearing is legal (up to 20% of each lot); however, most of the clearing is illegal. Between 2005 and 2006, command-and-control actions by the Brazilian Institute of Environment and Natural Resources (IBAMA) were intense in the settlement. Despite this, a major peak of deforestation occurred in 2005, followed by a decrease in 2006. Fines alone are not enough to stop all illegal deforestation in the settlement. Application of a fine, or the possibility of a fine, can result in some landholders forgoing clearing, as we observed during the fieldwork. We believe that command-and-control actions are more effective in the case of landholders who live in the settlement, which is a minority of landholders. For example, for non-concentrators, which is the group with the largest number of actors (364 landholders), only 28% (102 landholders) lived in the settlement in 2011. In the case of concentrators, 44% lived in the settlement.

A study by Schmitt (2015) reported that, although the effect of command-and-control is low and is not enough to stop all illegal deforestation in Legal Amazonia, some of the actors could be influenced by IBAMA's environmental inspection program. Thus, the decline of annual rates of deforestation observed between 2008 and 2013 in Brazil's Legal Amazonia region could be partially attributed to the inspection program (Schmitt, 2015). Note, however, that the bulk of the region-wide deforestation decline that occurred between 2004 and 2012 is explained by other factors (Fearnside, 2017).

The main activity in the Matupi settlement is cattle ranching, although a few families plant some agricultural crops in addition to their pasture. A dairy factory began operation in Matupi District in 2013, and it is currently the largest dairy factory in the state of Amazonas. Landholders reported that beginning in 2010 a dairy-cattle "boom" occurred in the region. This could have contributed to increased deforestation in 2010-2011. During our fieldwork we found many cooling platforms used to store milk at the front of the lots, indicating that dairy cattle were being raised. The milk is sold to the Matupi dairy factory. Landholders reported that dairy cattle are normally confined, in contrast to beef cattle. This means that dairy-cattle ranching requires less pasture area; for landholders who have only one lot it is therefore better to raise dairy cattle than beef cattle. However, both types of cattle need pasture, and clearing in the lots would tend to increase, even if at different speeds.

According to INPE's TerraClass program for quantifying land cover in deforested areas, in 2014 pasture was the main land use in the Matupi settlement, encompassing 82% (14,865 ha) of the total area cleared through 2013 (18,087 ha) (Brazil, INPE, 2018b). This agrees with the large-scale finding of Almeida et al. (2016), who found pasture to be the main land use in Legal Amazonia based on TerraClass data for 2008: out of a total of 707,274 km^2 that had been cleared through 2007, pasture encompassed 63% (447,160 km^2) in 2008 and only 5% (34,927 km^2) was in annual crop cultivation.

Despite the first landholders having received financing under an INCRA program to produce coffee and cacao, they did not have a structured chain to market the products, a means of transportation to distribute the products or technical assistance to better manage production. Lack of conditions to develop agricultural activities makes cattle ranching the best choice for Matupi landholders. This situation is similar to other settlements established along the Transamazon Highway, where settlements were designed without considering local limitations in terms of transportation of products, local markets, soil quality and other factors (Moran, 1981; Smith, 1982; Fearnside, 1986; Mahar, 1989; Caviglia-Harris and Harris, 2011). Amazon forest soils generally have high acidity and low natural fertility, making agriculture difficult. In addition, some areas also have steep topography, which contributes to most of the deforested area being used for pasture.

It is important to note that both increases and decreases in deforestation are influenced by economic factors such as commodity prices (Fearnside, 2017) and agricultural credit (Assunção et al., 2015). Deforestation rates are also influenced by political factors, such as election cycles (Rodrigues-Filho et al., 2015).

4.4. Environmental implications and future studies

Understanding the deforestation patterns of actors in a settlement project located in a region of cattle-ranching expansion can contribute to developing more refined spatial models of deforestation. Deforestation rates and the sizes of patches in the main deforestation patterns need to be associated with the actors in spatial models in order to simulate the contributions of these actors to future deforestation under different scenarios.

Our findings indicate a trend to increasing percentages of concentrators, especially concentrators of three and more lots, where “large geometric” is the predominant pattern (Fig. 4). This category of actor has a substantial impact in the settlement because the clearing per year by each of these actors is larger than that of other actors, since this type of actor is more capitalized in comparison to the other types. This type of concentrator has the potential to increase its contribution to deforestation in the future. The presence of lot concentrators is one of the indications that current agrarian-reform policies are weak. The purpose of the settlements is to alleviate the social problems associated with Brazil’s large population of landless farmers and, despite loopholes, the agrarian-reform program’s regulations are designed to prevent lot concentration.

Next steps are to compare deforestation rates and the patterns of actors in settlements with those located outside of settlements. A suggestion for future studies is to investigate other metrics that could distinguish patches oriented in the horizontal direction (i.e., lot width) in areas of concentration and in the vertical direction (i.e., from the front to back of the lot, which is typical in non-concentrator landholdings). This distinction could better differentiate landholders with one and two lots. The addition of other metrics not related to spatial patterns could be used to better differentiate non-concentrators from concentrators of non-neighboring lots. In addition, future studies could compare the deforestation patterns associated with the actors in different settlement types, such as those in the “conventional” category (e.g., the Matupi settlement) versus those in the “environmentally differentiated” category (e.g., Sustainable Development Projects and Agro-Extractivist Settlement Projects). In the “environmentally differentiated” category, the area is sometimes divided into lots in the same way as in the “conventional” category, but the actors have different profiles.

Brazil’s official position is that deforestation is under control and will be slower in the future, as outlined in the country’s commitments under the 2015 Paris Agreement (Brazil, 2015). However, a variety of trends in underlying forces suggests otherwise: ever greater population, investment and infrastructure development imply more rather than less deforestation (Fearnside, 2017). In addition, there are trends toward weakening environmental licensing and downgrading protected areas, among other reversals of previous achievements in this area (Fearnside, 2016, 2018a,b). Lot consolidation increases deforestation both by increasing the clearing rate in the lots that have been consolidated into larger landholdings and by the deforestation that occurs elsewhere in Amazonia by the former Matupi settlers who have sold their land to lot concentrators and moved on to more-distant frontiers. The land-tenure concentration effect documented in the present study adds one more reason suggesting that future deforestation in Brazil’s Amazonian rural settlements will be faster than it was in the past.

5. Conclusions

The process of land concentration in settlement areas speeds deforestation.

Remote sensing methods are capable of spatially identifying concentration of three or more lots, which is characterized by large geometric deforestation patterns.

The number of lots concentrated is more important in affecting the speed of clearing than is the question of whether the concentration is done by families or by individuals.

Despite the fact that lot concentrators can clear in patterns similar to non-concentrators, non-concentrators rarely clear in patterns similar to those of landholders with large numbers of lots (i.e., clearing patches >34 ha per year).

Due the large number of lots occupied by non-concentrators, their contribution to total clearing was greater than that of concentrators. However, our study suggests that lot concentration is increasing through time. This process threatens to increase deforestation by a few landholders. The social effect of lot concentration on the agrarian reform program is negative, since fewer families are benefitted and the social role of equity in land distribution is not achieved.

Because settlement projects are intended to address the social issues surrounding Brazil's large population of landless farmers, the agrarian-reform program responsible for settlements has regulations designed to limit lot concentration. The lot concentration found in the present study indicates that government authorities need to identify the actors who concentrate lots based on their deforestation patterns and monitor the land-tenure concentration in settlement projects in Brazilian Amazonia, especially in new frontier areas where the conversion of forest to pasture is intense.

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SUPPLEMENTARY MATERIAL

Title: Deforestation dynamics in Brazil's Amazonian settlements: Effects of land-tenure concentration

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Additional information on Materials and Methods

Mapping deforestation through 2016 in the Matupi settlement

Cleared areas were mapped using Landsat-5 TM (1994 to 2011), ResourceSat-1 LISS-3 (2012) and Landsat-8 OLI images (2013 to 2016) (path: 231; row: 65). We used images from the U.S. Geological Survey (USGS), and for each year we chose the image with the least cloud cover. Least cloud cover was determined visually by satellite images preview in the Earth Explorer platform (https://earthexplorer.usgs.gov/). The best images were obtained during the dry season (end of May to October) in our study area. We performed an atmospheric correction using the FLAASH (Fast Line of sight Atmospheric Analysis of Hypercubes) tool available in Envi software to better differentiate land-cover change and to compare cleared areas in different years when necessary. The color composition was shortwave infrared (Red), near infrared (Green), and red (Blue).

We only mapped areas cleared by clearcut and areas of forest loss with severe fire where the spectral response was that of clearing. Areas degraded by logging or by non-severe fire were not mapped. All logging is selective in Amazonia because only large individuals of valuable species are harvested, leaving the remaining trees in the diverse rainforest standing, unlike logging in temperate and boreal areas where forests are clearcut for timber. Likewise, forest fires in Amazonia burn through the understory killing some trees, but do not result in crown fires that kill entire stands as in coniferous forests. Logged and burned areas are therefore not easily distinguished from undisturbed forest on satellite imagery, although techniques exist to identify heavily disturbed areas (e.g., Walker et al., 2020).

Data from PRODES (Project for Monitoring Amazonian Deforestation) were used to assist our mapping when doubts arose concerning specific areas and to verify the agreement between our mapping and the PRODES dataset as a whole (Brazil, INPE, 2018). PRODES is the Brazilian government's program of annual deforestation monitoring carried out by the National Institute for Space Research (INPE). We did not use the PRODES vector map because PRODES does not have annual deforestation mapping before 2000 for the Matupi settlement area and because the deforestation dataset from 2008 to 2014 had been modified with a spatial adjustment of the vector mask (i.e., cumulative deforestation from previous years) (Brazil, INPE, 2015, 2019). This spatial adjustment makes it difficult to use PRODES data for our spatial-temporal analysis in the Matupi settlement.

Training step for automatic classification of deforestation patterns

In the classification's training step 60% of the samples were randomly selected, and these samples were used to automatically create a decision-tree classification and in the validation step (40% of the samples). Assessment of the classification was done using a confusion matrix and the Kappa statistic (Körting et al., 2013). Decision-tree classification is a non-parametric supervised learning method that is relatively simple, explicit, flexible, robust with respect to nonlinear and noisy relation between input features and class labels, and that handles both discrete and continuous attributes and incomplete training data with missing values (Friedl and Brodley, 1997). The decision tree uses the C4.5 algorithm for classification rules (Quinlan, 1993). A dataset is classified based on the smaller subdivisions according to the decision framework defined by the tree, and the label of each class is added according to the leaf node (terminal node) into which the sample falls (Friedl and Brodley, 1997). Smaller decision trees are better because they are easier to understand and because the predictive accuracy tends to be higher than for large trees (Quinlan, 1996). Thus, the deforestation patterns of patches were classified by analyzing a set of instances (i.e., a set of training samples) where the patterns were known. The decision tree then classified all of the patches in the deforestation map by learning based on the training set.

Classification of deforestation patterns

Fifteen landscape metrics were calculated by GeoDMA. These were examined both in raw form and after being normalized using the minimum and maximum values.

In the second classification period (2000-2016), we could not specify the type of actor exactly in several cases involving large polygons because polygons with the “large irregular” pattern (n = 37 polygons) covered large areas and we do not have information about all actors covered by this pattern. In two polygons we found that parts of the polygons belonged to non-concentrating landholders. In the “small geometric” category (n = 29), 3 samples were from non-concentrating landholders, and for the remaining 26 samples we do not have information about the type of actor, but the sizes and shapes of the clearings are similar to the others in the dataset. All cases of the “small irregular” pattern (n = 23), these clearings were in areas where landholders do not concentrate lots.

After the first classification (1994-1999) we had to manually reclassify 7 polygons from “large irregular” to “small geometric,” where 4 polygons were used as samples in the classification. In addition, 1 polygon classified as “large irregular” was manually reclassified to “small irregular.” We performed the reclassification because these polygons did not reflect the “large irregular” pattern (i.e., large polygons that covered more than one lot and that were located along access roads). The actor type is unknown for these reclassified polygons (and these polygons therefore were not used in the analyses that included actor types).

For the second classification period (2000-2016), concentrators of two lots had 12 polygons sampled and concentrators of three to ten lots had 10 polygons sampled. We had fewer samples of the “large geometric” pattern because the number of polygons available for use as samples was lower in comparison to the “small irregular” and “small geometric” patterns.

Actor types associated with classified deforestation polygons

Association of actor-polygons with deforestation patterns indicated that the “small geometric” and “small irregular” types were the typical patterns of non-concentrating landholders. Only 1% of the area identified as occupied by non-concentrators was classified as “large geometric” because the areas of the one polygon of this type were larger than the threshold (34 ha) that separated “small geometric” from “large geometric” (Table S1).

Although the samples that were used for classification of concentrators of two or more lots were characterized by the “large geometric” pattern, “small” patterns (geometric and irregular) were also found in these landholder types. Thus, of the 2,208-ha total area found to be held by concentrators of two lots, 51% was classified as “small geometric” and 23% as “small irregular.” For concentrators of 3 to 10 lots, “large geometric” was the predominant pattern in terms of area (66%), despite the fact that, in terms of the number of polygons, the most frequent types were “small geometric” (n = 16 polygons) and “small irregular” (n = 19; Table S1). Both the Chi-square and Fisher’s tests showed a highly significant association between deforestation patterns and actor types ($p < 0.001$).

Table S1. Actor-polygons found associated with classified deforestation patterns.

Actor category	**Deforestation pattern** Area in hectares (number of polygons)			
	Large geometric	**Small geometric**	**Small irregular**	**Total**
Non-concentrators	41 (1)	1,780 (118)	1,487 (370)	3,308 (489)
Concentrators of 2 lots	581 (11)	1,122 (74)	505 (111)	2,208 (196)
Concentrators of 3 to 10 lots	707 (10)	295 (16)	67 (19)	1,069 (45)
Total	1,329 (22)	3,197 (208)	2,058 (500)	6,585 (730)

Estimation of lot concentration in 2011 and deforestation rates by landholders

In three cases of concentration (two cases encompassing two lots on the Maravilha access road and one encompassing three lots on Bom Futuro access road) we lacked information on the period that the family members occupied the lots; in these cases, we considered the group of lots to be concentrated based on the spatial distribution of deforestation polygons through 2011 in the landholding as a whole.

Generally there is one community lot per access road, but on the Triunfo and Matupiri access roads we identified two community lots in each access road, while in the Maravilha, Bom Futuro and Santa Luzia access roads there are no community lots.

Table S2. Confusion matrix for classification from 1994 to 1999. Values refer to numbers of samples (polygons) in training step and in the validation step. Total number of samples shown in **bold**.

	Pattern	Large irregular	Small geometric	Small irregular	Total	*Error of omission*
Reference	Large irregular	22; 15 **(37)**	-	-	37	-
	Small geometric	1; 3 **(4)**	16; 9 **(25)**	-	29	13.8%
	Small irregular	-	-	14; 9 **(23)**	23	-
	Total	41	25	23	89	
	Error of commission	9.8%	-	-		

Table S3. Confusion matrix for classification from 2000 to 2016. Values refer to numbers of samples in the training step and the validation step. Total number of samples shown in **bold**.

	Pattern	Large geometric	Small geometric	Small irregular	Total	*Error of omission*
Reference	Large geometric	12; 9 **(21)**	1; 0 **(1)**	-	22	4.6%
	Small geometric	-	39; 26 **(65)**	1; 0 **(1)**	66	1.5%
	Small irregular	-	-	37; 25 **(62)**	62	-
	Total	21	66	63	150	
	Error of commission	-	1.5%	1.6%		

Table S4. Deforestation rate per lot from 1995 to 2011 for each actor category.

Actor category	**Total no. of lots**	**Mean annual rate per lot**	**SD**	**Mean total deforestation per lot (1995-2011)**
Family concentrators of 2 lots	66	2.0	0.8	34.7
Individual concentrator of 2 lots	28	2.5	0.8	43.3
Family concentrators of 3 lots	12	3.0	0.5	50.7
Family concentrators of 4 lots	12	2.4	0.7	40.9
Individual concentrators of 4 lots	16	1.8	1.0	30.5
Family concentrator of 5 lots	5	1.2	0.2	21.0
Family concentrator of 10 lots	10	2.4	0.6	40.5
Individual and family concentrators of non-neighboring lots	3	1.2	0.7	21.2
Non-concentrators	364	1.7	0.8	29.5

Table S5. P-values in pairwise tests comparing actor categories. Values in **bold** indicate significant differences ($p < 0.05$). FC: Family concentrator; FCs: Family concentrators and ICs: Individual concentrators.

	FC of 10 lots	FCs of 2 lots	FCs of 3 lots	FCs of 4 lots	FC of 5 lots	FC and ICs of non-neighboring lots	ICs of 2 lots	ICs of 4 lots
FCs of 2 lots	0.0950							
FCs of 3 lots	**0.0290**	**0.0003**						
FCs of 4 lots	1.0000	0.1139	**0.0373**					
FC of 5 lots	**0.0166**	**0.0237**	**0.0018**	**0.0060**				
FC and ICs of non-neighboring lots	**0.0341**	0.1488	**0.0113**	**0.0424**	0.5486			
ICs of 2 lots	1.0000	**0.0109**	0.0786	0.7339	**0.0007**	**0.0210**		
ICs of 4 lots	0.1873	0.2785	**0.0037**	0.0898	0.3623	0.5755	**0.00624**	
Non-concentrators	**0.0030**	**0.0044**	**0.0000**	**0.0039**	0.0749	0.2861	**0.0000**	0.7907

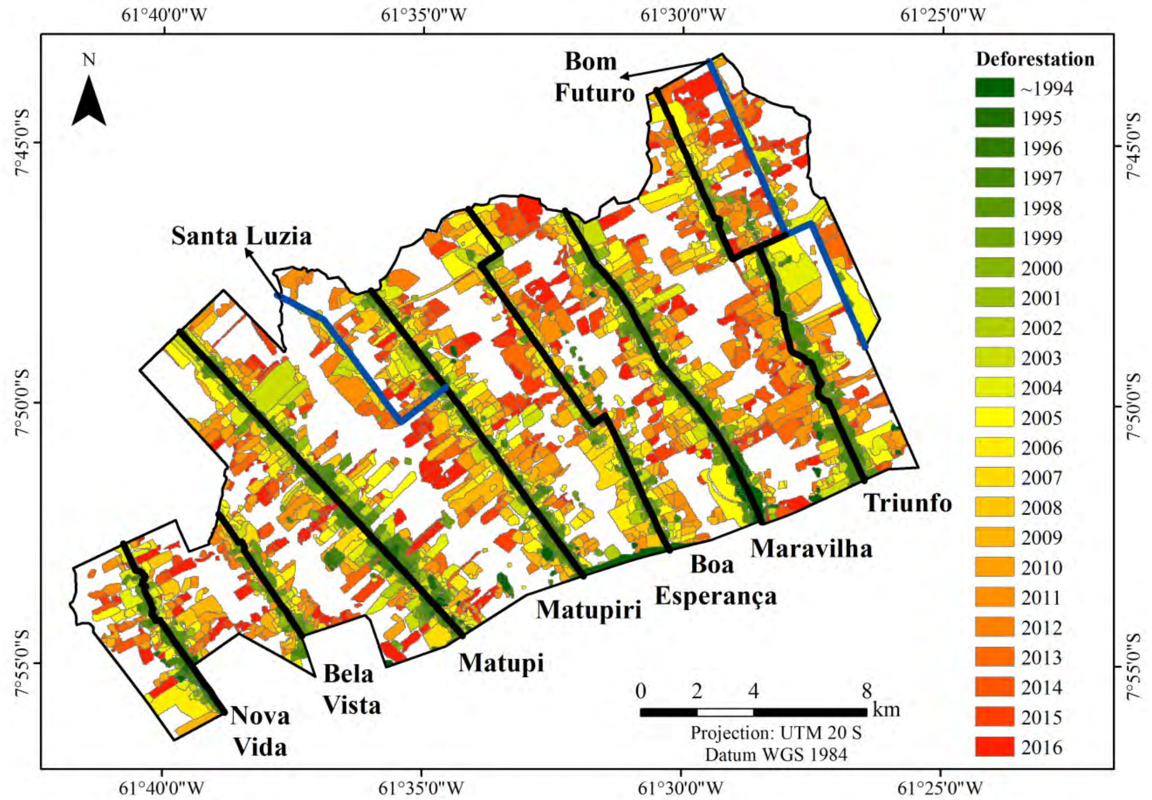

Fig. S1. Lots and access roads in the Matupi settlement, showing deforested areas and dates of deforestation.

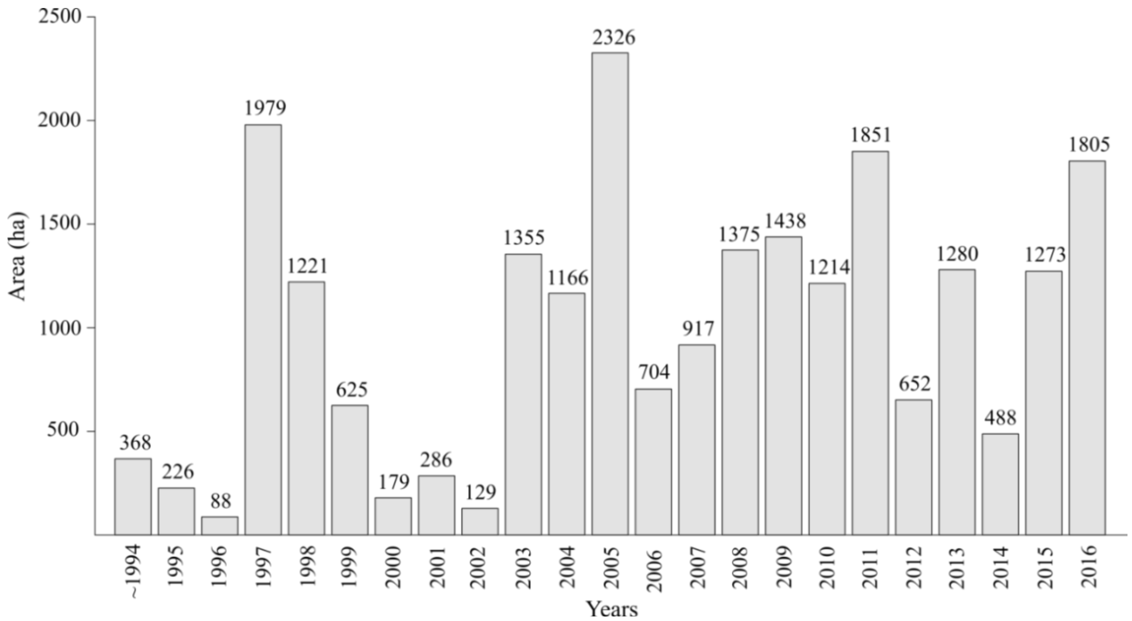

Fig. S2. Total area cleared per year mapped in the Matupi settlement.

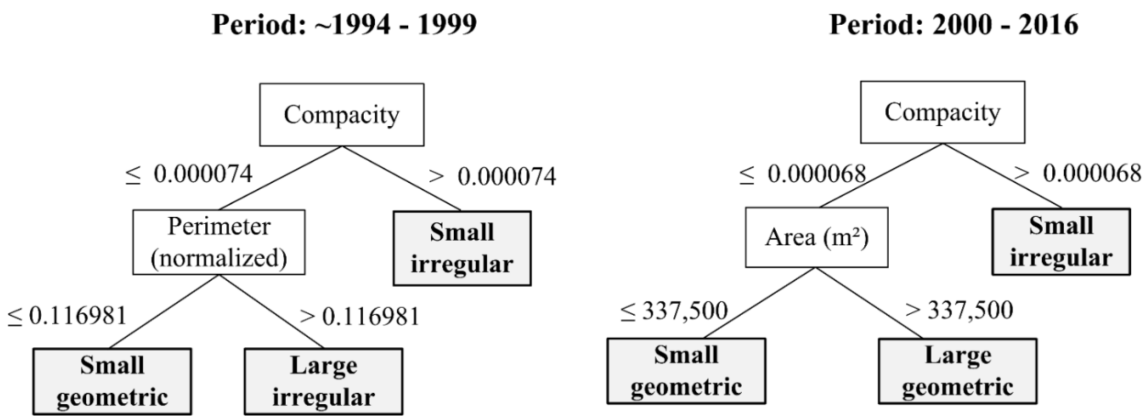

Fig. S3. Results of decision-tree classifications for the first (1994-1999) and second (2000-2016) classification periods.

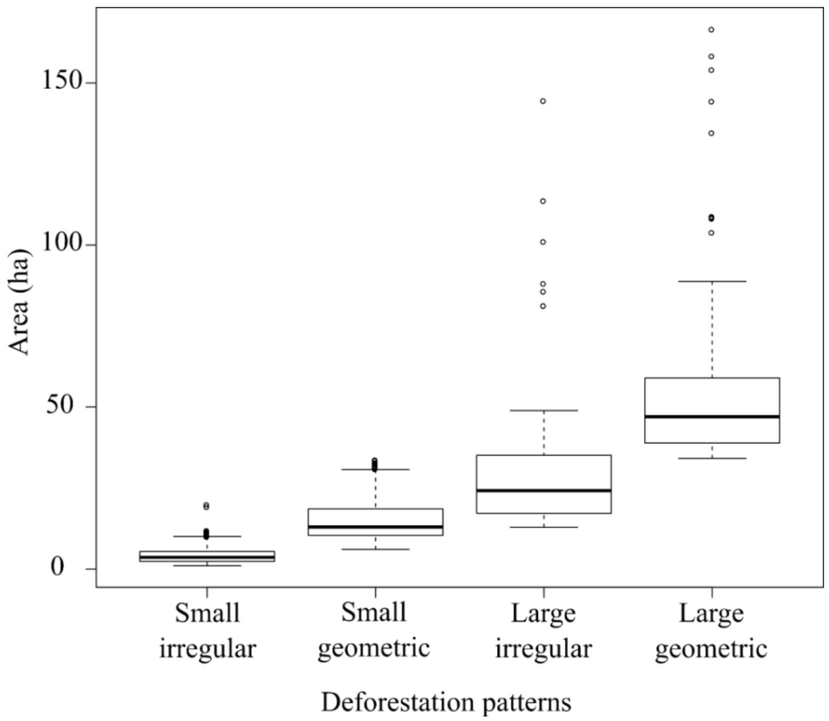

Fig. S4. Distribution of patch areas for each deforestation pattern.

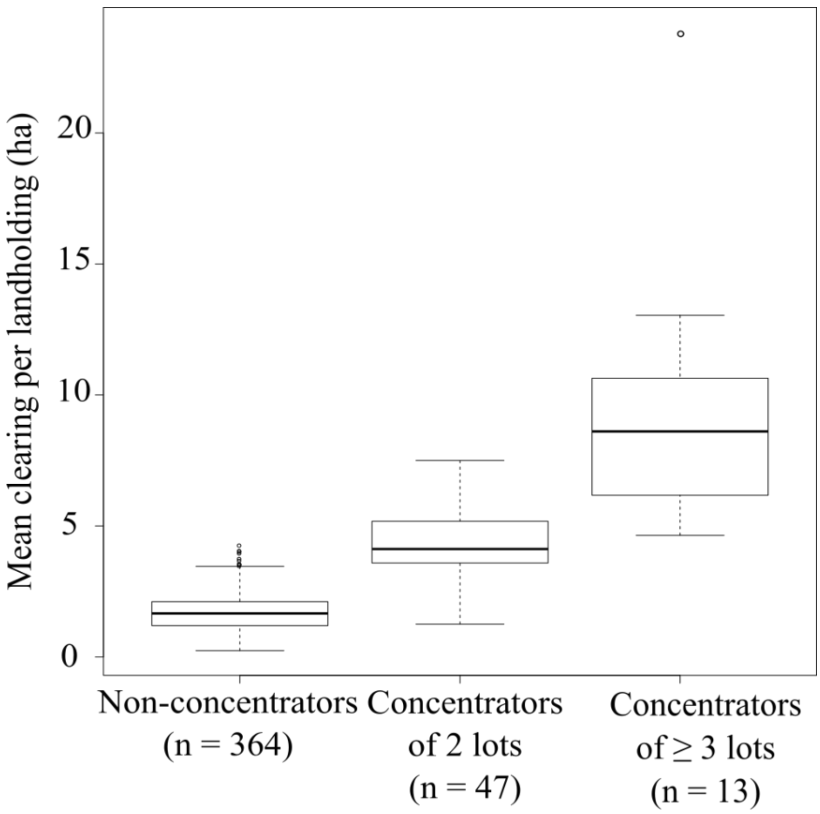

Fig. S5 Distribution of mean clearing per landholding from 1995 to 2011 separated into three groups: non-concentrators (n = 364 landholders), concentrators of 2 lots (n = 47 landholders) and concentrators of ≥ 3 lots (n = 13 landholders).

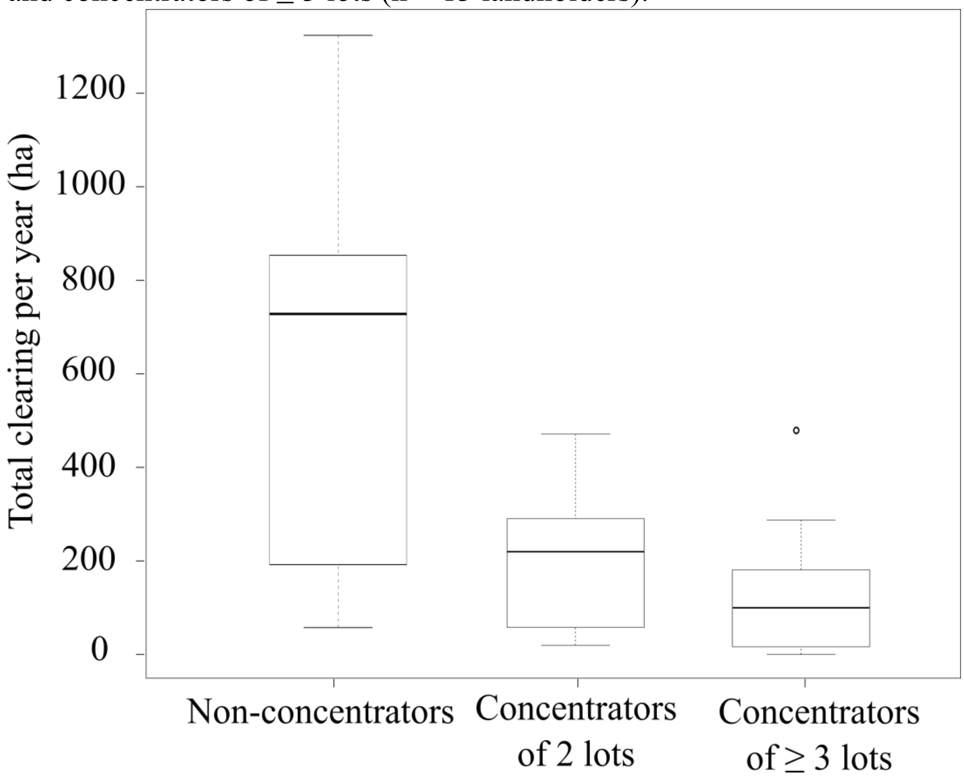

Fig. S6 Total area cleared in the period from 1995 to 2011 by type of actor (n = 17 years).

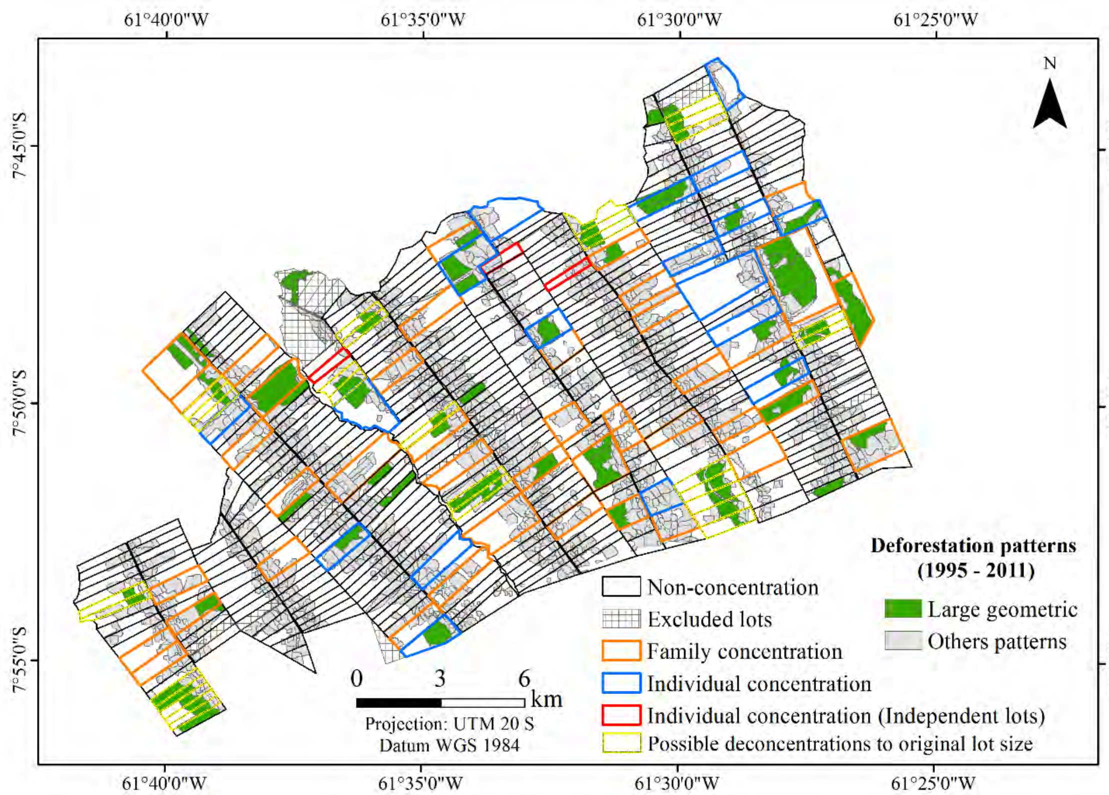

Fig. S7. The Matupi settlement indicating 30 lots held by non-concentrators that had portions of large geometric deforestation patches spanning more than one lot in 2011. This suggests fragmentation of previously concentrated landholdings.

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