Supplementary Online Material

Brazil's Amazonian deforestation: The role of landholdings in undesignated public lands

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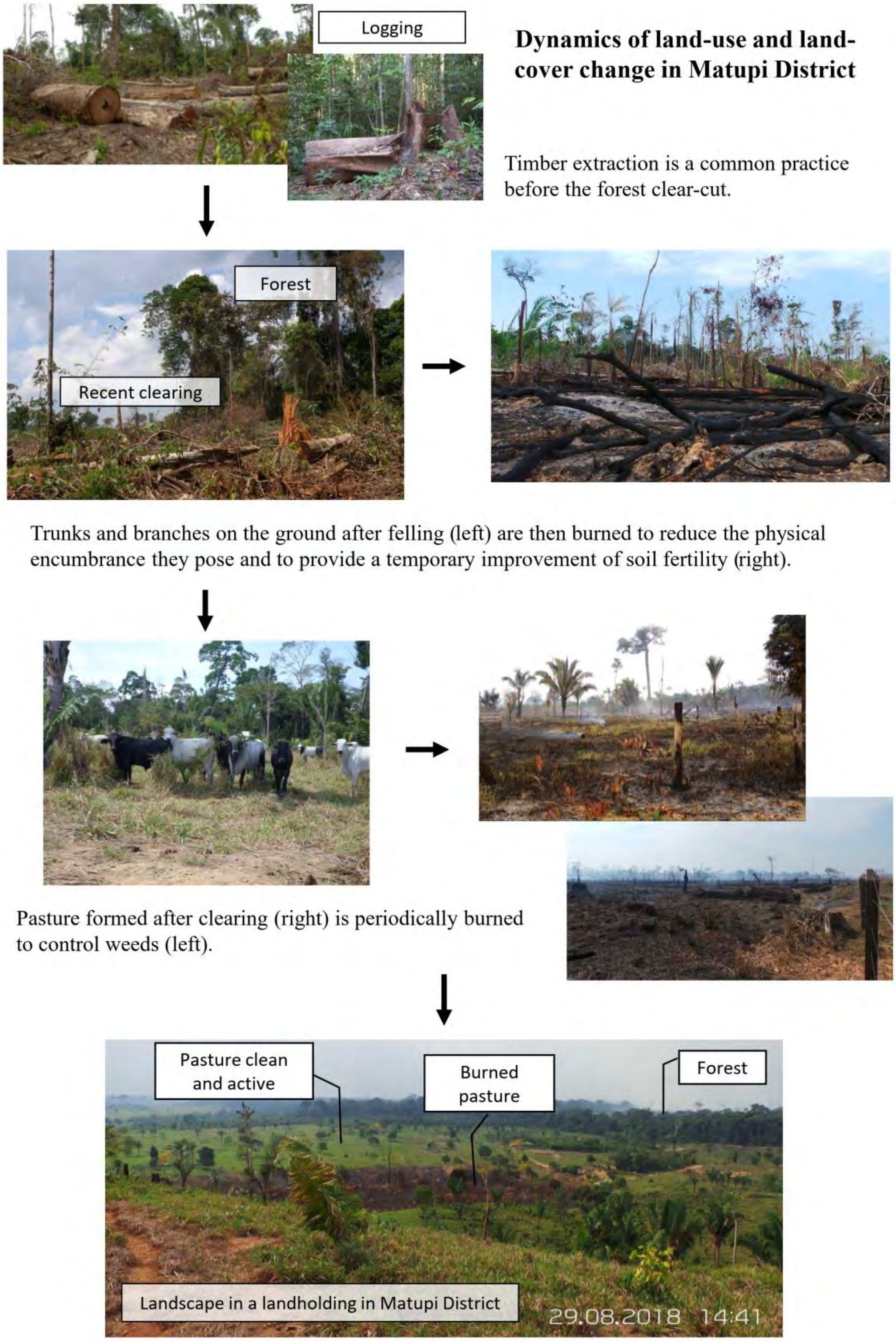
Online Resource 1. Dynamics of land-use and land-cover change



Dynamics of land-use and land-cover change observed during fieldwork in Matupi District in 2016 and 2018 (Photos by A.M. Yanai and P.M.L.A. Graça).

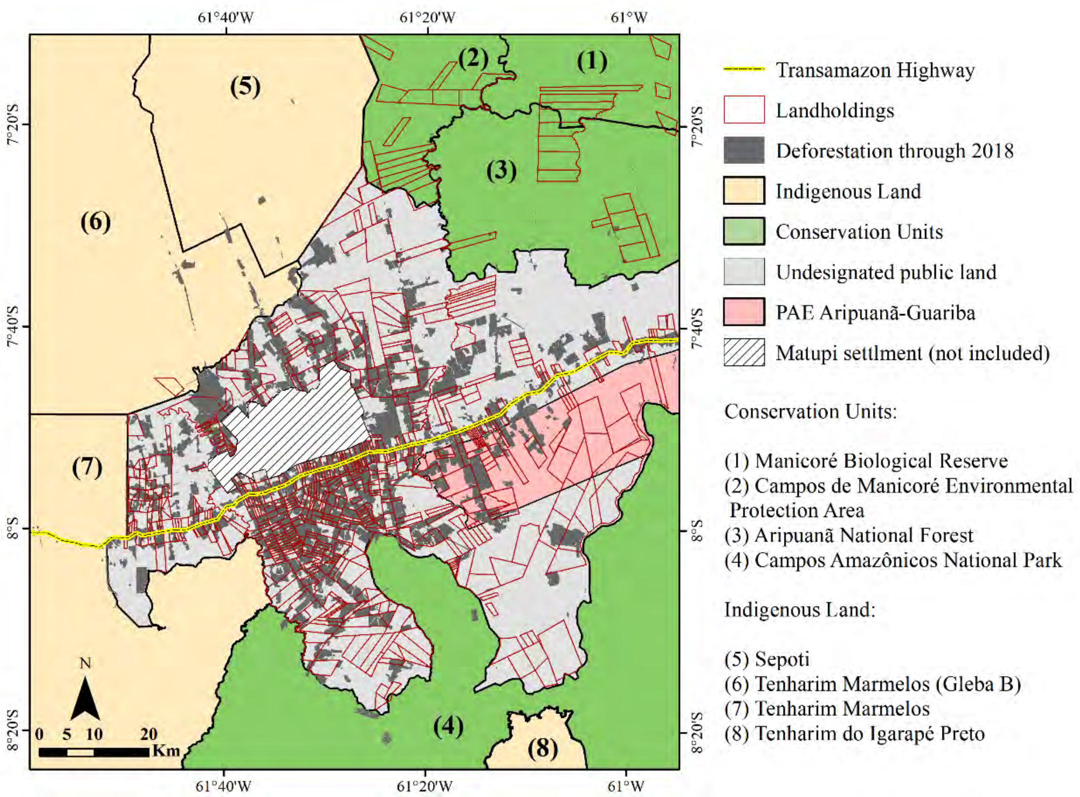
Online Resource 2. Addition Information on the Study Area

The conservation units (protected areas for biodiversity) in the "sustainable use" category are: one national forest and one environmental protection area (APA: *Área de Proteção Ambiental*), while conservation units in the "strictly protected" category are: one national park and one biological reserve. In conservation units of "sustainable use" it is allowed the direct use of part of natural resources (e.g., extraction for commercial and non-commercial purpose) respecting the maintenance of the local biodiversity. In the "strictly protected" it is only allowed the indirect use since the aim of these areas are the maintenance of natural resource free from human interference (Brazil, SNUC, 2000).

Reference:

Brazil, SNUC (Sistema Nacional de Unidades de Conservação da Natureza) (2000) Lei N°9.985, de 18 de julho de 2000. http://www.planalto.gov.br/ccivil_03/leis/L9985.htm

Protected areas, agro-extractivist settlement, landholdings and deforestation



Distribution of protected areas, agro-extractivist settlement (PAE: *Projeto de Assentamento Agroextrativista*), landholdings and deforestation in the study area.

Online Resource 3. Landholding types based on fiscal modules

Landholding types based on fiscal modules (1 fiscal module in our study area = 100 ha).

Landholding type	Size of landholding (ha)	Fiscal modules per landholding
Small	< 100	< 1
Semi-small	100 - 400	1 to 4
Medium	> 400 – 1500	4.1 to 15
Large	> 1500	> 15

Online Resource 4. Additional Information on Materials and Methods

The Brazilian Rural Environmental Registry (CAR = Cadastro Ambiental Rural)

Our study provides estimates of clearing patterns for pasture for different types of actors in undesignated public lands by using a dataset from the Rural Environmental Registry (CAR: *Cadastro Ambiental Rural*). For each rural landholding the CAR registers the areas of the landholding, the “legal reserve” (a portion of each land holding required to be kept in forest by the Forest Code) and the “area of permanent preservation” (areas where clearing is prohibited, such as those within a defined distance from watercourses). The information in the CAR is intended to be used for environmental monitoring and to control deforestation (Brazil, SFB 2019). Unfortunately, the CAR also greatly facilitates land grabbing by providing a self-declared record of land claims (Azevedo-Ramos et al. 2020). When complete and validated, CAR data will provide a public dataset for all of Brazil’s landholdings, including their boundaries, and in its present state this dataset has proved its value in recent studies to better represent the situation of landholdings in Legal Amazonia (Gollnow et al. 2018; Roitman 2018).

Through June 2019, 543,489,672 ha of Brazilian territory had been registered in the CAR system (5,040,807 landholdings), representing 63.8% of the total area of Brazil. In Amazonas State, 49,772 landholdings had been registered in the CAR system, encompassing an area of 54,496,772 ha, or 34.7% of the state (Brazil, SFB 2019).

The CAR is a public dataset, although the names of landholders are sensitive information. In the CAR dataset for Manicoré and Novo Aripuanã municipalities we spatially identified the landholdings in Matupi District. Through the intersection between landholdings and deforestation data, we could evaluate the area cleared, where the cleared area was spatially distributed and when the clearings were made. This makes it possible to monitor the speed of land-use change in the landholdings.

We could not determine whether a large landholding was divided into several small landholdings since the landholding registry is self-declared. Because the landholding registry can be rectified, it is reasonable to use the most-recent record for each landholding. The overlapped landholdings indicated in previous versions of the registry were therefore excluded.

Overlap between landholdings and land categories (conservation units and settlements)

The intersection between landholdings and protected areas provides a warning of possible threats to forest that is under protection. We found medium and large landholdings in an Indigenous Land and in a conservation unit.

The tolerance threshold for conservation units and settlements with landholdings are those of Carvalho (2017):

- Landholdings > 15 Fiscal Modules (FMs): 3% of a landholding;
- Landholdings > 4 FMs and ≤ 15 FMs: 4% of a landholding;
- Landholdings ≤ 4 FMs: 10% of a landholding.

For our study area 1 FM = 100 ha.

Identification of lots

To identify the landholdings in the SIGEF dataset we used the codes of the boundary markers ("*marcos legais*") found at some of the boundaries of landholdings during our fieldwork. The boundary markers are used to identify the legal limits (vertices) of the landholding. We only used SIGEF data for 8 landholdings because most of the boundary markers checked during our fieldwork were already recorded in the catalog of agrarian landholdings and in the CAR data.

We only maintained in our analysis landholdings with 100% of their area inside our study area. In cases of overlap between two or more landholdings we used the same approach as L'Roe et al. (2016), maintaining the most-recent information based on the registry data or last rectification of the landholding information. However, when data from our fieldwork (i.e., the GPS point for a corner of a landholding obtained along the roads in 2016 and 2018) were more recent than the CAR data, we maintained the boundaries of the landholding in accordance with the data from our fieldwork.

References:

Azevedo-Ramos C, Moutinho P, Arruda VL da S, Stabile CC, Alencar A et al (2020) Lawless land in no man's land: The undesignated public forests in the Brazilian Amazon. Land Use Pol 99: art 104863. https://doi.org/10.1016/j.landusepol.2020.104863

Brazil, SFB (Serviço Florestal Brasileiro). 2019. Cadastro Ambiental Rural (CAR). SFB, Brasília, DF, Brazil. http://www.car.gov.br/publico/imoveis/index (Last access 4 June 2019).

Brazil, SFB (Serviço Florestal Brasileiro) (2019) Cadastro Ambiental Rural – CAR (Cartilha Orientações Básicas). SFB, Brasília, DF, Brazil. http://www.florestal.gov.br/publicacoes/504-cadastro-ambiental-rural-car-orientacoes-basicas. Accessed 18 August 2019

Carvalho, N.S. 2017. Texto guia: Análise Geo: Sobreposição do IR. Universidade Federal de Lavras (UFLA), Lavras, MG, Brazil. 129 pp.

Gollnow F, Hissa LDBV, Rufin P, Lakes T (2018) Property-level direct and indirect deforestation for soybean production in the Amazon region of Mato Grosso, Brazil. Land Use Pol 78:377-385. https://doi.org/10.1016/j.landusepol.2018.07.010

L'Roe J, Rausch L, Munger J, Gibbs HK (2016) Mapping properties to monitor forests: Landholder response to a large environmental registration program in the Brazilian Amazon. Land Use Pol 57:193-203. https://doi.org/10.1016/j.landusepol.2016.05.029

Roitman I, Vieira LCG, Jacobson TKB, Bustamante MMC, Marcondes NJS et al (2018) Rural Environmental Registry: An innovative model for land-use and environmental policies. Land Use Pol 76:95-102. https://doi.org/10.1016/j.landusepol.2018.04.037

Online Resource 5. Mapping of deforestation polygons

Deforestation polygons were mapped visually rather than using data from PRODES (Project for Monitoring Amazonian Deforestation), which is a Brazilian government program for annual deforestation monitoring carried out by INPE. We used our mapped polygons because the PRODES vector maps do not have digital mapping of annual deforestation before 2000 for our study area and because the minimum area mapped by PRODES is 6.25 ha. The number of small patches of deforestation (< 6.25 ha) has increased in Brazilian Legal Amazonia (Montibeller et al. 2020), which indicates the importance of including small patches in spatial-temporal analyses of deforestation, especially at the landholding level. In addition, the PRODES deforestation dataset had undergone a spatial adjustment of the previous deforestation mask (i.e., cumulative deforestation up to 2007), which limits the use of PRODES deforestation maps for our spatial-temporal analysis. However, we used the PRODES maps to assist the mapping in specific areas to verify the agreement between our mapping and the PRODES dataset and to assist in the identification of non-forest vegetation, such as savanna (Brazil, INPE 2019, 2020).

Deforestation can be identified in the images because the limit is well defined between the area with exposed soil or recently planted pasture (geometric regular shape) and forest. In the satellite images, cleared areas appear in magenta or light green color when using a color composition (R: Short wavelength infrared band; G: Near-infrared band; B: Red band) (Brazil, INPE 2019).

The area (ha) of each polygon was then calculated and, to reduce noise from small polygons, those polygons < 1 ha in area were excluded, which means that the minimum area analyzed in our study was 1 ha. We then performed an intersection between the vector map of landholding boundaries and the mapped deforestation. To estimate the remaining forest, we subtracted from the total area of landholdings the areas of deforestation through 2018, non-forest vegetation, and water. The areas of non-forest vegetation and water were obtained by supervised classification based on maximum likelihood, and these areas for each landholding type are presented in the following table.

Water and non-forest vegetation in each type of landholding.

Landholding type	Total area (ha)	Water (ha)	Non-forest (ha)
Small (< 100 ha)	74,537	5 (0.0%)	0
Semi-small (100 – 400 ha)	10,109	43 (0.1%)	336 (0.5%)
Medium (> 400 – 1500 ha)	123,237	188 (0.2%)	1,227 (1.0%)
Large (> 1500)	82,112	81 (0.1%)	4,471 (5.4%)
Total area	**289,995**	**317 (0.1%)**	**6,035 (2.1%)**

References:

Brazil, INPE (Instituto Nacional de Pesquisas Espaciais) (2019) Metodologia utilizada nos projetos PRODES e DETER. http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes/pdfs/Metodologia_Prodes_Deter_revisada.pdf. Accessed 22 July 2020

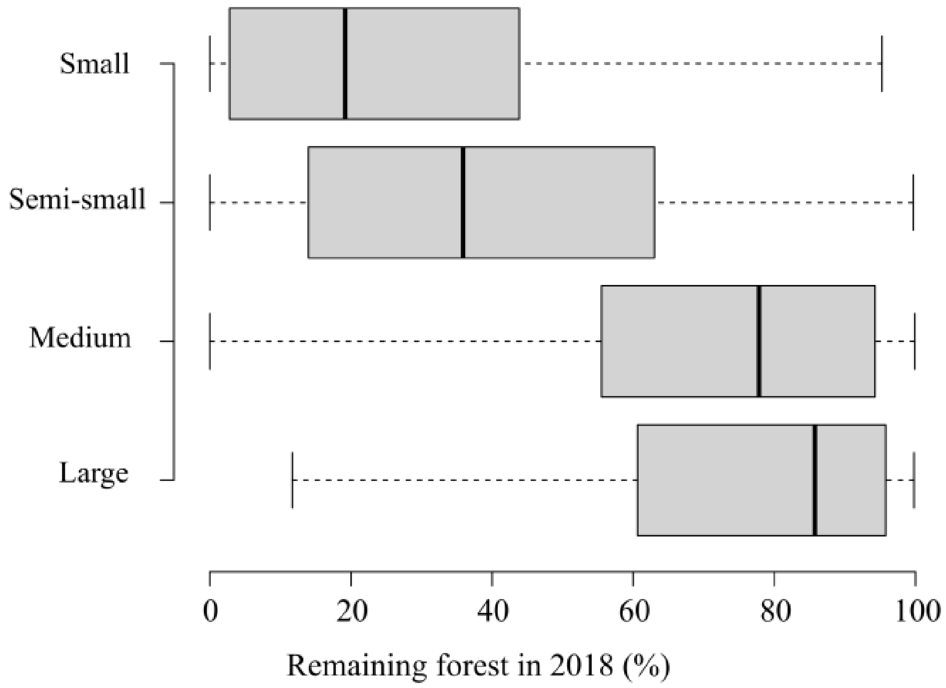
Brazil, INPE (Instituto Nacional de Pesquisas Espaciais) (2020) PRODES Digital. http://www.dpi.inpe.br/prodesdigital/dadosn/2018/. Accessed 8 April 2020

Montibeller B, Kmoch A, Virro H, Mander Ü, Uuemaa E (2020) Increasing fragmentation of forest cover in Brazil's Legal Amazon from 2001 to 2017. Scientific Reports 10: art. 5803. https://doi.org/10.1038/s41598-020-62591-x

Online Resource 6. Characteristics of landholding types

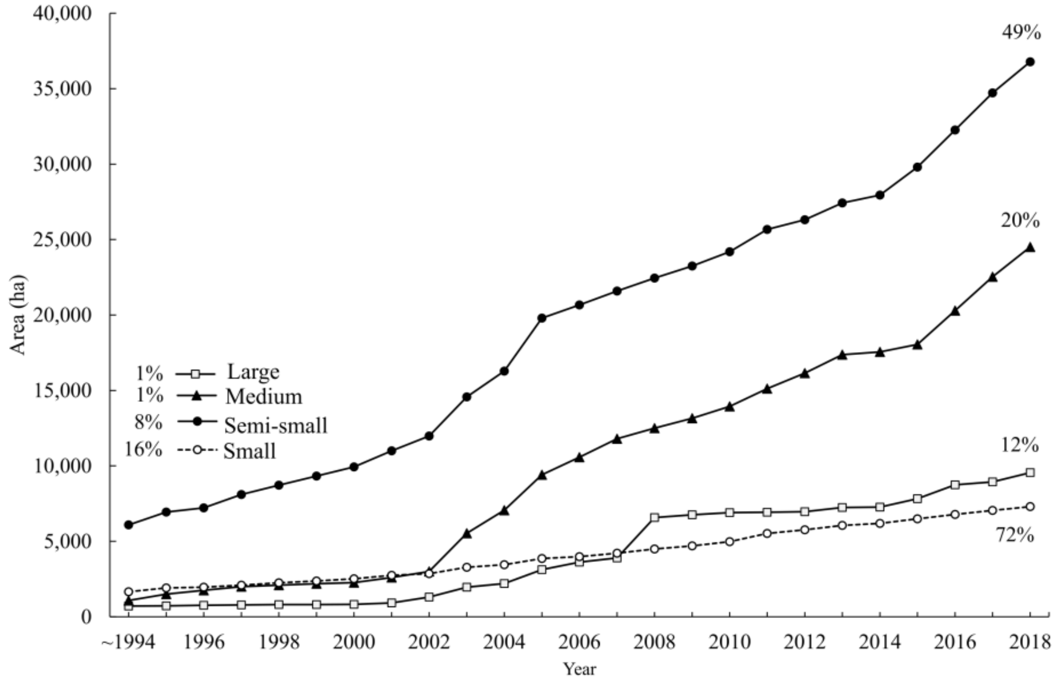
Landholding type	Number	Total area (ha)	Size Mean ± SD (ha)	Min. – Max. size (ha)
Small (< 100 ha)	131 (21%)	10,109 (3%)	77 ± 22	6 - 99.87
Semi-small (100 - 400 ha)	327 (52%)	74,536 (26%)	228 ± 99	100 - 400
Medium (> 400 – 1,500 ha)	133 (21%)	123,237 (43%)	927 ± 355	404 – 1,492
Large (> 1500 ha)	37 (6%)	82,112 (28%)	2,219 ± 590	1,515 – 4,838
Total	628 (100%)	289,994 (100%)		

Online Resource 7. Percentage of forest in 2018 for each type of landholding



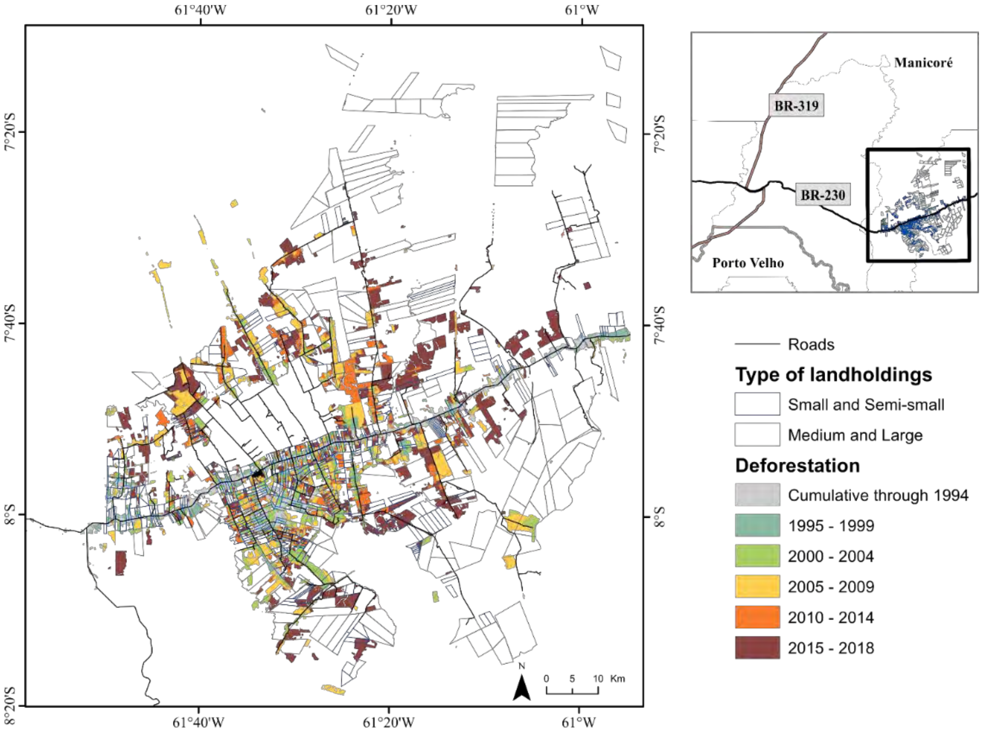
Percentage of forest in 2018 for each type of landholding. The black line dividing each gray box is the median of the data (middle quartile); gray box: interquartile range (IQR) = Q1 (first quartile or 25th percentile) – Q3 (third quartile or 75th percentile); dashed lines (whiskers) represent the range of data outside the middle 50%.

Online Resource 8. Cumulative deforestation from 1994 to 2018 for each landholding type



Cumulative deforestation from 1994 to 2018 for each landholding type. The percentages shown for the initial (~1994 = cumulative deforestation by 1994) and final (2018) years analyzed indicating the total area cleared as a percentage of the area occupied by each type of landholding.

Online Resource 9. Spatial distribution of deforestation (~1994 to 2018)



Spatial distribution of deforestation (~1994 to 2018) in landholdings divided in two main groups: (i) small and semi-small and (ii) medium and large.

Online Resource 10. Patch size of deforestation by landholding size

The sizes of patches (i.e., annual polygons of clearing from 1995 to 2018) for each landholding type were analyzed in six-year intervals to evaluate the temporal dynamics inside the landholdings. In general, comparing the initial interval of land occupation (1995 – 2000) to recent years (2013 – 2018), the patch size (mean ± SD) for all landholdings showed a pattern of increase from 8 ± 15 ha (1995 – 2000) to 19 ± 39 ha (2013 – 2018) (Table of section 10).

Table of Online Resource 10. Patch size estimated in six-year intervals from 1995 to 2018 for each landholding type.

Landholding type	Patch size in hectares (mean ± SD and range: minimum – maximum ha)			
	First interval (1995 – 2000)	Second interval (2001 – 2006)	Third interval (2007 – 2012)	Fourth interval (2013 – 2018)
All	8 ± 15 (1 – 243)	18 ± 36 (1 – 433)	16 ± 52 (1 – 1,142)	19 ± 39 (1 – 536)
Small (< 100 ha)	5 ± 5 (1 – 28)	8 ± 8 (1 – 50)	8 ± 9 (1 – 51)	9 ± 10 (1 – 62)
Semi-small (100 – 400 ha)	8 ± 10 (1 – 94)	14 ± 27 (1 – 371)	11 ± 15 (1 – 156)	16 ± 28 (1 – 225)
Medium (> 400 – 1500 ha)	21 ± 41 (1 – 243)	29 ± 44 (1 – 364)	21 ± 48 (1 – 530)	27 ± 54 (1 – 536)
Large (> 1500 ha)	4 ± 4 (1 – 22)	44 ± 86 (1 – 433)	65 ± 195 (1 – 1,142)	36 ± 70 (1 – 357)

Landholdings up to 400 ha (small and semi-small) had a tendency of increasing patch size through the years (initial and last interval). The patches in medium landholdings (> 400 – 1500 ha) showed a similar size pattern through the intervals analyzed, with similar values between the first interval and the third interval, and between the second interval and last interval. In addition, since 2007 more large patches (> 500 ha) were found in medium landholdings in comparison to the initial years of land occupation.

Large landholdings (> 1500 ha) showed a substantial increase in the mean size of patches from the first to the third interval. The high values in the third interval were affected by large patches (500 ha, 700 ha and 1142 ha) cleared in 2008. The distribution of patches by landholding type is showed in Figure of section 10 (below).

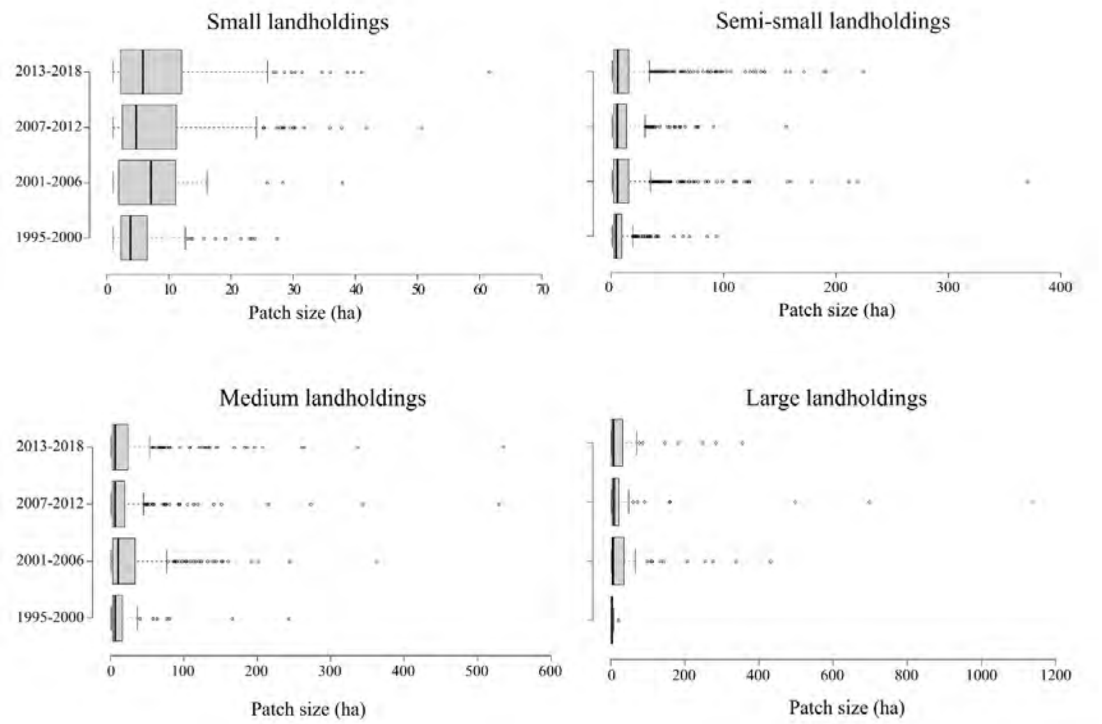


Figure of Online Resource 10. Distribution of polygon sizes (≥ 1 ha) in year intervals for each landholding type.

Discussion: Dynamics of patch size by landholding type

Our results indicate a general trend of increasing size of patches of clearing in the landholdings through the years. Although in medium landholdings (400 – 1500 ha) no substantial change was observed in the size of patches of clearing, in the large landholdings (> 1500 ha), the patches showed a fluctuation in size through the intervals analyzed. In new deforestation frontiers in Brazilian Amazonia, Schielein and Börner (2018) found that the mean size of patches of deforestation showed a decrease due the environmental policies after 2004, but after 2010 the distribution of the deforestation patches returned to a pattern similar to that observed before 2004. In Matupi we found a similar pattern for semi-small (100 – 400 ha) and for medium landholdings. However, for large landholdings the pattern was the reverse, with increase after 2006 and decrease after 2013.

Medium and large landholders are able to clear larger areas in a single year as compared to smaller landholders and new clearings can be attributed to the expansion of cattle pasture due the increase in the cattle herd, mainly by the larger landholders. The decline of grass productivity also creates demand for new forest areas to be cleared because the management of cattle pastures in Brazilian Amazonia relies on extensive areas rather than inputs such as fertilizers, and productivity declines rapidly through the years. A study in the neighboring state of Rondônia found that grass productivity in 12-year-old cattle pasture was only 50% as high as that in three-year-old pasture (Fearnside 1989). Skidmore et al. (2021) suggest that landholders tend to use the cattle pasture until it degrades and then open new pasture areas by cutting forest, rather than investing resources in improving land management or recovering degraded pasture. From this perspective, forests adjacent to pastures are more vulnerable to anthropogenic disturbances. The soils in these pastures are net sources of carbon emission (Fearnside and Barbosa 1998).

Clearing to guarantee land tenure is a typical pattern in the land-occupation process in Brazilian Amazonia. This is especially important for large landholders because many of these actors do not live in the landholdings they occupy. A landholder who does not clear could lose the land either by expropriation or by invasion (Fearnside 2001). It has also been suggested that “small” increments in clearing (< 25 ha) in medium and large landholdings could reflect the intention of these actors to avoid detection by the monitoring system (Assunção et al. 2017). In Matupi District, a few patches larger than 500 ha could be found in medium and large landholdings from 1995 to 2018.

References:

Assunção J, Gandour C, Pessoa P, Rocha R (2017) Property-level assessment of change in forest clearing patterns: The need for tailoring policy in the Amazon. Land Use Pol 66:18-27. https://doi.org/10.1016/j.landusepol.2017.04.022

Fearnside PM (1989) Ocupação Humana de Rondônia: Impactos, Limites e Planejamento. Relatórios de Pesquisa No. 5. Conselho Nacional de Desenvolvimento Científico e Tecnológico CNPq., Brasília, DF, Brazil. https://bityl.co/6qIL

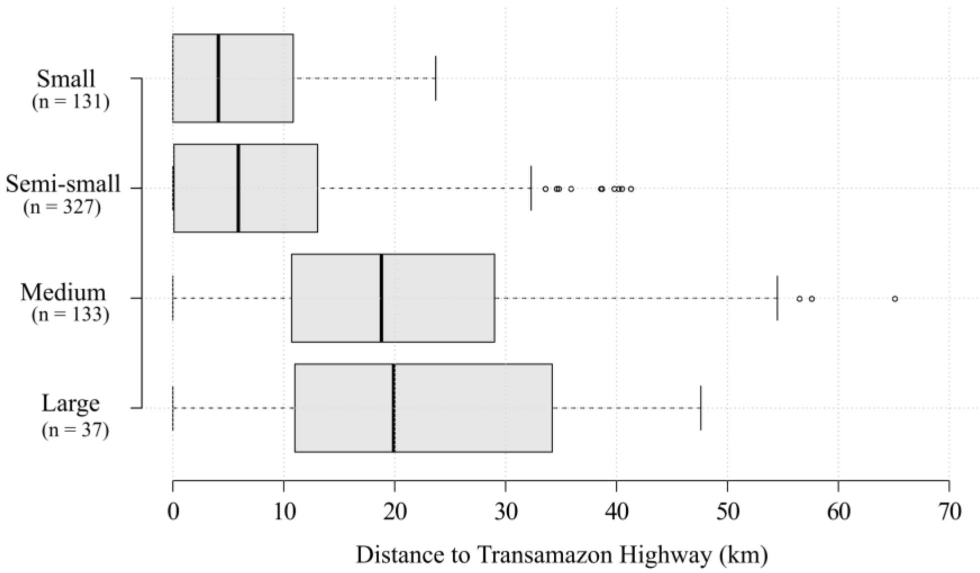
Fearnside PM, Barbosa RI (1998) Soil carbon changes from conversion of forest to pasture in Brazilian Amazonia. For Ecol Manage 108:147–166. https://doi.org/10.1016/S0378-1127(98)00222-9

Fearnside PM (2001) Land-tenure issues as factors in environmental destruction in Brazilian Amazonia: The case of Southern Pará. World Dev 29:1361–1372. https://doi.org/10.1016/S0305-750X(01)00039-0

Schielein J, Börner J (2018) Recent transformations of land-use and land-cover dynamics across different deforestation frontiers in the Brazilian Amazon. Land Use Pol 76:81–94. https://doi.org/10.1016/j.landusepol.2018.04.052

Skidmore ME, Moffette F, Rausch L, Christie M, Munger J et al (2021) Cattle ranchers and deforestation in the Brazilian Amazon: Production, location, and policies. Glob Environ Change 68: art 102280. https://doi.org/10.1016/j.gloenvcha.2021.102280

Online Resource 11. Distribution of landholding types in relation to the Transamazon Highway (BR-230)



Distribution of landholding types in relation to the Transamazon Highway (BR-230).

The mean distances of landholdings of each type to the Transamazon Highway were 6 ± 6 km (small landholdings), 9 ± 9 km (semi-small landholdings), 21 ± 15 km (medium landholdings) and 22 ± 14 km (large landholdings). No significant difference was found between the mean distances of small landholdings and semi-small landholdings ($p = 0.08$) in relation to the Transamazon Highway, and a similar result was found between medium landholdings and large landholdings ($p = 0.62$). However, significant differences were found between large and small ($p < 0.001$), large and semi-small ($p < 0.001$), medium and small ($p < 0.001$) and medium and semi-small landholdings ($p < 0.001$). We found that 51% (67 of 131) of the small landholdings were located ≤ 5 km from the Transamazon Highway, followed by 46% (152 of 327) of the semi-small landholdings, 17% (22 of 133) of the medium landholdings and only 5% (2 of 37) of the large landholdings.

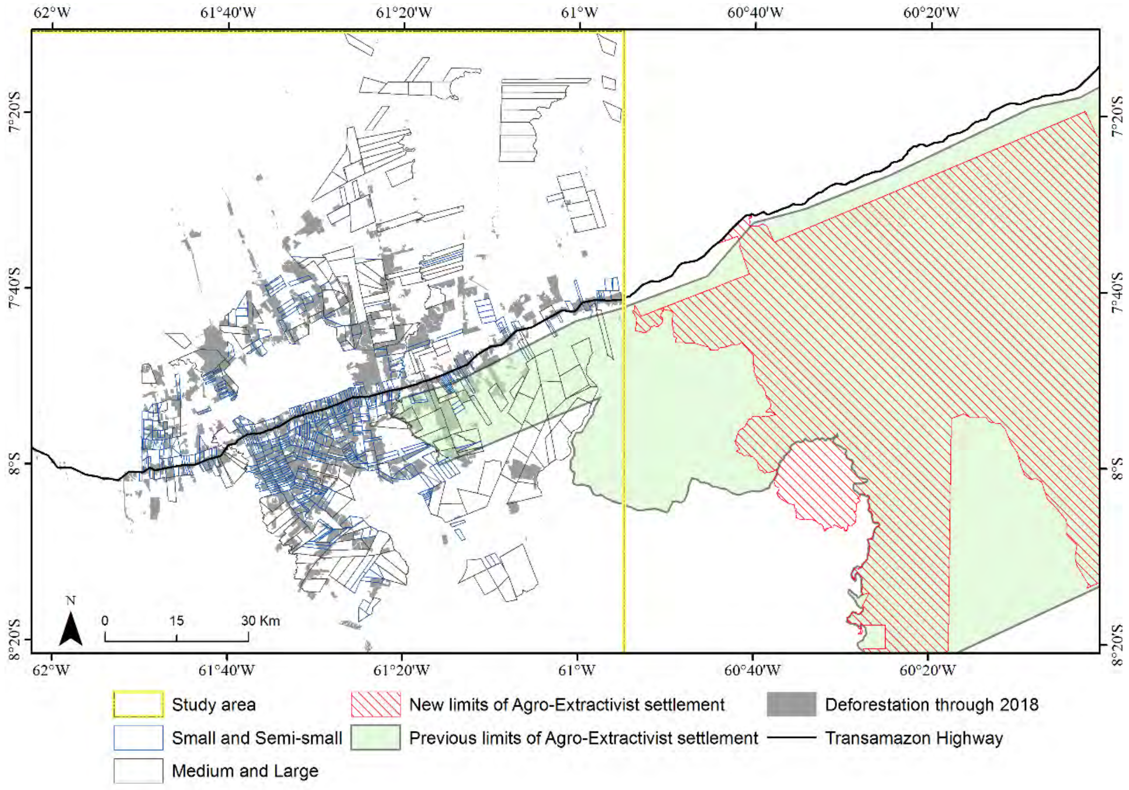
Online Resource 12. Distribution of landholding types in different land categories

Distribution of landholding types in different land categories. Areas in hectares represent the total area of each landholding type in each land category.

Land category	Landholding type				Total
	Small (< 100 ha)	Semi-small (100 – 400 ha)	Medium (> 400 – 1500 ha)	Large (> 1500 ha)	
Public land without destination	10,081 (99.9%)	71,408 (95.9%)	86,659 (70.3%)	42,115 (51.3%)	210,264 (72.5%)
Agro-extractivist settlement	0	2,469 (3.3%)	9,607 (7.8%)	23,026 (28.0%)	35,102 (12.1%)
Conservation units	0	442 (0.6%)	26,011 (21.1%)	16,968 (20.7%)	43,422 (15.0%)
Indigenous Lands	13 (0.1%)	156 (0.2%)	960 (0.8%)	0	1,130 (0.4%)

Online Resource 13. Overlap between the previous and new limits of the Aripuanã-Guariba Agro-Extractivist Settlement in relation to the landholdings analyzed in the present study

We examined new vector maps of settlement projects in the Legal Amazonia region that are available on INCRA's website (Brazil, INCRA 2020) and found that they show the agro-extractivist settlement project in our study area as having new boundaries that are now outside of our study area. We did not find any official document available online reporting this boundary change. The difference in limits is shown in the figure below. The difference in limits is shown in the figure below.



Reference:

Brazil, INCRA (Instituto Nacional de Colonização e Reforma Agrária) (2020) Acervo fundiário do INCRA. http://certificacao.incra.gov.br/csv_shp/export_shp.py. Accessed 4 September 2020