ORIGINAL ARTICLE

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

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Abstract

The impact of deforestation in Brazilian Amazonia is a global concern, and land occupation in public lands contributes to increased deforestation rates. Little is known about the spread of deforestation in landholdings in undesignated public lands located on cattle-ranching frontiers. We use a case of Matupi District, a hotspot of deforestation along the Transamazon Highway in the southern portion of Brazil's state of Amazonas, where spontaneous squatters and land grabbers are the main actors occupying landholdings. We assessed the advance of deforestation and the spatial distribution of landholdings in relation to the main road and to land categories (e.g., protected areas and undesignated public land). Landholdings up to 400 ha were the majority in numbers (52%) and larger landholdings (> 400 ha) were located farther into the forest, contributing to expanding the deforestation frontier. By 2018, 80% of the remaining forest was in larger landholdings (> 400 ha), increasing the susceptibility of this forest to being cleared in the coming years. Thus, greater attention should be given to these larger landholdings to control the spread of deforestation. By analyzing the clearing pattern in the landholdings, deforestation monitoring can focus on specific sizes of landholdings that contribute most to the advance of the deforestation frontier. Brazil's current trend to facilitating the legalization of illegal claims in undesignated public lands, such as the large and medium landholdings we studied, implies vast areas of future deforestation and should be reversed.

Keywords CAR · Land grabbing · Arc of deforestation · Transamazon Highway · Amazon forest · Land occupation

Introduction

Deforestation (i.e., clearcutting of forest cover) and forest degradation (i.e., reduction of services provided by standing forest due impacts such as logging and forest fire) threaten the remaining Amazonian rainforest. The loss of tropical rainforests is one of the world's great environmental problems because the impacts on forest ecosystem services affect local populations and have global repercussions (Foley et al. 2007). Brazil's Amazon forest is being cleared and converted to pasture on deforestation frontiers, and this can be expected to increase in response to global demand for commodities (e.g., beef, timber, and soybeans), with incorporation of more land into existing deforestation frontiers and the emergence of new frontiers (Beckert et al. 2021).

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Approximately 20% of the 4 million km^2 originally forested portion of Brazil's 5 million km^2 Legal Amazonia region had been cleared by 2021. Annual deforestation rates have been trending upwards since 2012, reaching 13,325 km^2 in 2021, or 2.9 times the 4571 km^2 year^{-1} rate in 2012 (Brazil, INPE 2021). The spatial distribution of deforestation differs depending on the advance of frontier development through the time. Although old frontiers have more deforestation, on new frontiers, deforestation is more rapid because these areas attract new deforestation actors (Schielein and Börner 2018).

Land occupation and deforestation in Brazilian Amazonia mostly occur in "undesignated public lands" ("terras públicas não desistinadas," which are areas of federal or state land for which the government has not specified any particular use, such as a protected area or a settlement). Occupation is done by spontaneous squatters ("posseiros") and land grabbers ("grileiros") (Araujo et al. 2009; Fearnside 2008a; Ferrante et al. 2021). "Land grabbing" (*grilagem*) in Brazil refers to illegal appropriation (usually of government land) by large operators, often using falsified documents. They may clear a small portion of the land to indicate possession, and the intention of the land grabber is often to later subdivide and sell the land (Brito et al. 2019). This is different from the use of the term "land grabbing" in Africa and Asia, where it refers to purchase of agricultural land by foreign interests for production of export crops.

Undesignated public lands are at high risk of future deforestation due the expansion of land speculation and cattle ranching (and later soy plantations) in frontier areas in Brazilian Amazonia. This risk is heightened by new laws that facilitate land grabbing. In 2009, Law 11,952 (Brazil, PR 2009) increased the area that could be legalized by a single claimant from 100 to 1500 ha, and in 2017 Law 13,465 increased this area to 2500 ha (Brazil, PR 2017). The 2017 law grants amnesty to landholders who illegally occupied public land from 2005 to 2011 and allows claimants to purchase public land at prices below market value (Brito et al. 2019). These laws stimulate land grabs and deforestation, and a temporary executive order or "provisional measure" (MP 910) that was in force from 10 December 2019 to 9 April 2020 allowed claims to land occupied by 2014 to be legalized on the basis of a mere "self-declaration" of ownership (Brazil, PR 2019). This measure was converted to a proposed law (PL 2633/2020) that has been approved by the lower house of the National Congress (Brazil, Câmara dos Deputados 2021) and is moving towards a vote in the Senate. In addition to "self-declarations," it would allow legalization of occupations up to 2018, thus providing even greater stimulation for land grabbing (Fearnside 2020). We use the terms "landholdings" and "landholders" (rather than "properties" and "owners") so as not to imply any judgement on their legal status. We also use the term "legalization" rather than "regularization," which is a euphemism commonly used by proponents with the implication that the claimants have a moral right to the land that has not yet been formally recognized due to the inefficiency of government bureaucracy.

Although cattle-ranching is the main replacement for rainforest in Brazilian Amazonia (Fearnside 2005), rates and patterns of deforestation have shown high spatiotemporal variability in the region's recent history and between frontier types (old frontiers versus new frontiers), especially because land occupation and deforestation reflect the actions of different types of actors (Fearnside 2008a, 2017; Schielein and Börner 2018; Strand et al. 2018). Due to the complexity and uncertainties of land tenure in Brazilian Amazonia, we still have gaps that need to be better understood, such as identifying the main actors who claim land on deforestation frontiers, the clearing behavior of these actors, how they are spatially distributed, and how they contribute to the expansion of deforestation frontiers. Most recent studies on these topics were done in settlement projects, where the landholding distribution and the process of occupation are different from those in undesignated public land (Carrero et al. 2020; Yanai et al. 2020). Here, we focus on the landholdings of different sizes that were occupied spontaneously along the Transamazon Highway and along illegal endogenous roads connected to the highway. Spontaneous squatters and land grabbers are the main actors who occupy these landholdings. This occupation is characterized by a disordered pattern that is different from land occupation in settlement projects, which are government-led colonization areas where the land is divided in lots of roughly uniform size (e.g., 100 ha) and deforestation forms a fish-bone pattern.

We assessed the dynamics of deforestation up to 2018 in landholdings of different sizes located on a new deforestation frontier where the low price of land and the influx of cattle ranchers interested in buying land make the area much more attractive for land speculation than parts of Amazonia where deforestation is already consolidated. We use the case of Santo Antônio do Matupi District (hereafter, "Matupi District") in southern Amazonas to investigate the patterns resulting from these processes. The area of undesignated public land in Brazilian Amazonia totals at least 498,000 km^2 (Azevedo-Ramos et al. 2020), although the total could be larger: Almeida et al. (2021) identified 582,899 km^2 just in the state of Amazonas, or 37.5% of the state. These areas are approximately the size of France, while the area of Brazilian Amazonia is approximately that of western Europe. Our study area represents a harbinger of likely trends if the invasion and deforestation of public lands continue into these vast areas of undesignated public land. Roads planned to branch off the BR-319 (Manaus-Porto Velho). Highway would open the largest block of undesignated public land in Amazonas to entry of land grabbers and other actors (Fearnside et al. 2020).

We focus on answering the questions: (i) How do deforestation rate and percentage of remaining forest vary by landholding size? (ii) Has the patch size of the annual clearing in the landholdings changed through the years? (iii) How are the landholdings distributed spatially in relation to the main road (i.e., the Transamazon Highway) and among different land categories (undesignated public land, protected areas, and an agro-extractive settlement)?

The way that landholders use the land has a substantial effect on the amount of forest available for clearing through time (D'Antona et al. 2006; Michalski et al. 2010). This type of study can contribute to improving policies intended to inhibit the expansion of hotspots of land occupation and forest loss in Brazilian Amazonia. Although Matupi District has local characteristics, the mechanisms and strategies for occupation of public land, establishing land tenure, and expanding pasture and cattle production are similar to those on new deforestation frontiers in other parts of Brazilian Amazonia (Hecht et al. 2021; Costa et al. 2021). Our study therefore contributes to the discussion of frontier expansion in the region as a whole.

Materials and methods

Study area

The study was carried out in Santo Antônio do Matupi District. "Districts" are administrative units within a municipality (county), in this case, the municipality of Manicoré in the southern portion of Brazil's state of Amazonas. Matupi District, formerly known as "km 180" (the distance between Humaitá and Matupi), is located on the Transamazon Highway (BR-230). This main road provides a connection to Rondônia State via Highway BR-319 (Manaus-Porto Velho). The study area encompasses parts of Manicoré, Humaitá, and Novo Aripuanã municipalities covering a total of 20,767 km^2, an area the size of Wales (Fig. 1).

Two fieldwork campaigns were conducted in Matupi District (22 August–1 September 2016 and 20–30 August 2018) with the aim of better documenting land-use and land-cover change in the region. We verified that logging and cattle ranching are the main economic activities driving forest degradation and clearing in the region. New pasture areas
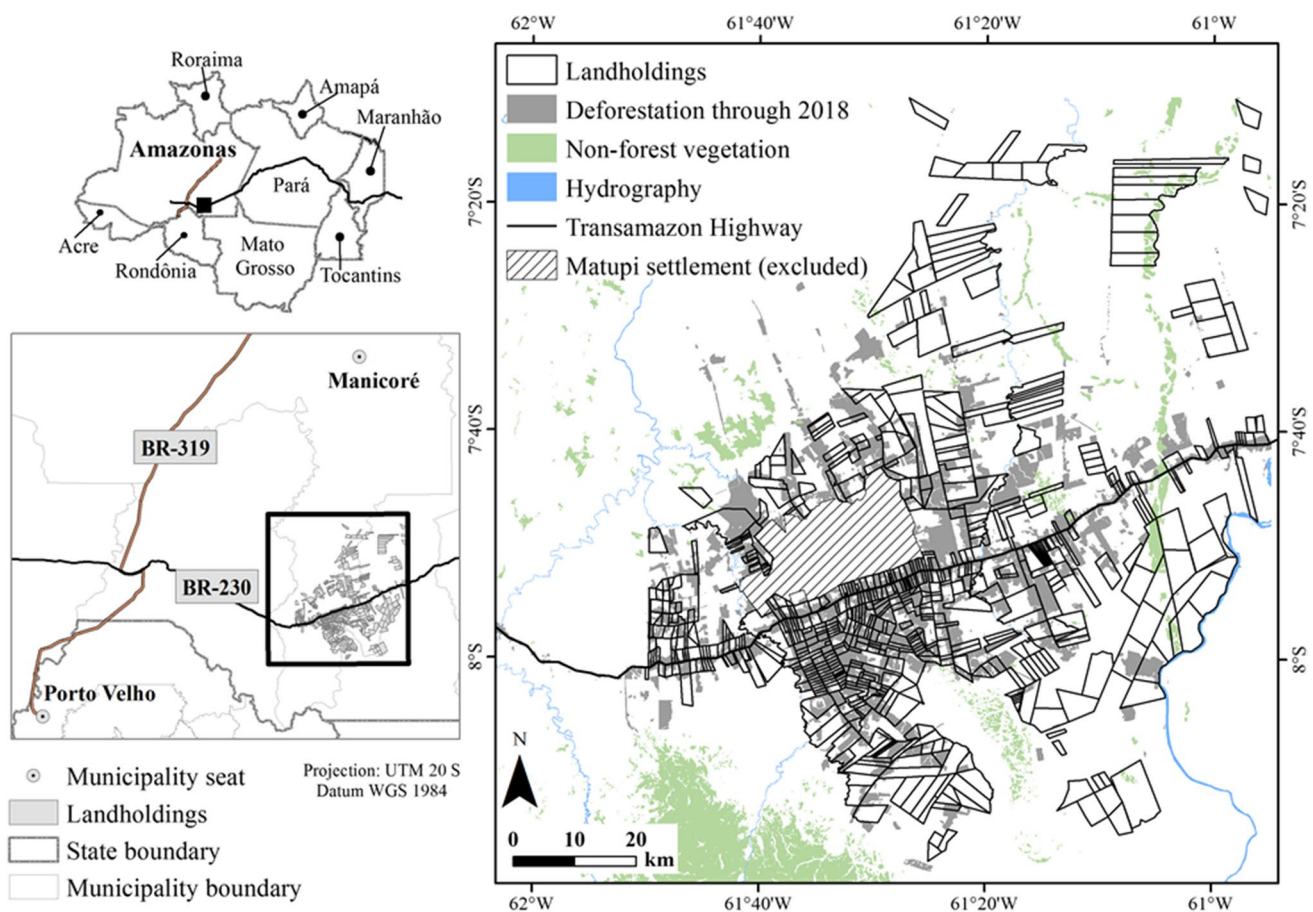

Fig. 1 Location of the study area

are created by the typical slash-and-burn process (Online Resource 1).

The study area is apportioned into the following land categories: undesignated public land (23.4%), protected areas (conservation units: 27.0% and Indigenous Lands: 46.2%) and an agro-extractive settlement (PAE: *Projeto de Assentamento Agroextrativista*) (3.4%). The agro-extractive settlement is a category intended for traditional populations to promote activities with low deforestation impact (e.g., agro-extractive activities and forest management). More information about the types of conservation units and the spatial distribution of each land category (with detailed boundaries) is provided in Online Resource 2.

Since our goal is to understand the spontaneous land occupation that results in a chaotic and disordered land distribution in the different land categories we analyzed, we excluded the lots in the Matupi Settlement Project (PA Maputi) from the present study. A separate analysis is available for the settlement project (Yanai et al. 2020).

Identification of landholding sizes

Landholdings were separated into size groups based on "fiscal modules" defined by Brazil's National Institute for Colonization and Agrarian Reform (INCRA). For our study area, the size of a fiscal module is 100 ha. We disaggregated INCRA's current "small" category (1 to 4 fiscal modules) into two types due to the large number of landholdings with sizes less than 400 ha and to allow comparisons with previous studies that defined "small landholdings" as < 100 ha. Landholdings in the 100 to 400-ha range were named "semi-small" based on L'Roe et al. (2016) (Online Resource 3). In most of the world a landholding with 400 ha, or even one with 100 ha, would not be considered to be "small." However, in Brazil, the official definition of "small" in Amazonia was < 100 ha until 2004, after which it increased to four fiscal modules (i.e., 400 ha) — a change that allows government assistance programs and other benefits (such as relaxed restrictions under Brazil's Forest Code) to be awarded to landholders at the upper end of this size range while maintaining a political discourse focused on helping "small" farmers. The term "semi-small" coined by L'Roe et al. (2016) for those in the 100–400-ha range allows this group to be distinguished from those who are really small, while at the same time not creating confusion with the "medium" group that now officially begins at 400 ha.

We identified 628 landholdings based on the vector map dataset of landholdings from the following sources: (i) the Rural Environmental Registry (CAR, *Cadastro Ambiental Rural*) updated to 1 November 2018 for Manicoré and Novo Aripuanã municipalities (Brazil, SFB 2018) (*n* = 212); (ii) INCRA's catalog of agrarian landholdings (*Acervo fundiário*) (*n* = 408) updated through 23 August 2018 (Brazil, INCRA

2018a); and (iii) SIGEF (*Sistema de Gestão Fundiária*) (Brazil, INCRA 2018b) (*n* = 8), which is INCRA's system for managing agrarian information in rural areas of Brazil. Since the landholders' names were available in the catalog of agrarian landholdings and in the SIGEF data, we performed a merge between neighboring landholdings with the same landholder's name. More information about the CAR is available in the Online Resource 4. More information on the identification of the lots is provided in Online Resource 4.

Mapping deforestation

Deforestation (i.e., clear-cut forest, including areas in pasture, agriculture, and the initial stages of regeneration) was mapped by visual interpretation on a computer screen at 1:50,000 scale, but to better delimit small polygons, we increased the level of detail to the 1:20,000 scale. We mapped deforestation to estimate the total area cleared, mean annual clearing, and the sizes of patches of clearing (i.e., mapped annual polygons) in the landholdings. Cleared areas were mapped starting in 1994, when land occupation in Matupi District was in its initial stages, although the forest located along the edges of the Transamazon Highway was cleared during the 1970s and 1980s. Thus, the polygons (bounded areas in a digital map) mapped in 1994 represent cumulative deforestation, and the polygons of clearing mapped from 1995 to 2018 represent annual deforestation. We only mapped clearing of forest vegetation (i.e., clearing savannas or secondary regrowth is not included).

We used images from Landsat-5 TM (1994 to 2011), ResourceSat-1 LISS-3 (2012) (paths: 313 and 314; rows: 81 and 82), and Landsat-8 OLI (2013 to 2018) (path: 231; rows: 65 and 66). We chose images with the least cloud cover from the US Geological Survey (USGS) and from Brazil's National Institute for Space Research (INPE). An atmospheric correction was applied to the images to help differentiate land-cover change and, when necessary, to compare clearing in a given year to that in the previous year. Image selection and analysis procedures are presented in Online Resource 5. We estimated the areas of polygons (≥ 1 ha) to assess whether the size of annual polygons of deforestation changed through time from 1995 to 2018. We analyzed the distribution of polygon sizes in four periods: (i) 1995 to 2000; (ii) 2001 to 2006; (iii) 2007 to 2012; and (iv) 2013 to 2018, and the results and discussion of this analysis are presented in Online Resource 10.

Evaluating the spatial distribution of landholdings in relation to the main road and the distribution of landholdings by land category

To evaluate the spatial distribution of landholdings in relation to the main road (Transamazon Highway), we performed

a proximity analysis between the vector map of the Transamazon Highway and the vector map of the landholdings. Proximity analysis estimates distance as the shortest distance between the boundaries of two objects, in this case, between landholdings and road. The distance was equal to zero when a landholding boundary and a road shared at least one coordinate (x, y) or when one of the boundaries (e.g., a landholding polygon) contained or was within another boundary (e.g., a road line). The Transamazon Highway did not change during the analyzed period, since this stretch of the road was built in 1973. We only considered the main road for the analysis, although we added secondary roads in the maps shown in the figures in the "Results" section to better illustrate the spatial distribution of landholdings in relation to the road network.

To evaluate the spatial distribution of landholdings among the different land categories, we made a single vector map with conservation units merged, Indigenous Lands merged, the agro-extractive settlement, and undesignated public land. The vector map of landholding boundaries was intersected with the vector map of land categories to determine where the landholdings were spatially distributed. Information on the tolerance thresholds for overlap between landholdings and land categories is available in Online Resource 4.

Results

Landholdings, deforestation, and remaining forest

We assessed 628 landholdings with sizes ranging from 6 to 4838 ha. Semi-small landholdings (100–400 ha) are the majority in number (52%, $n = 327$); however, medium and large landholdings (> 400 ha) occupied 71% (205,349 ha)

of the area analyzed. Although the small (< 100 ha) and medium (> 400–1500 ha) landholding types showed a similar number of landholdings, small landholdings only occupied 3% (10,109 ha) of the area analyzed (Online Resource 6).

We estimated an area of 78,137 ha of cumulative deforestation by 2018 in the analyzed landholdings and an area of 74,749 ha of deforestation in other landholdings where we do not have information on the landholding type. Out of the total deforestation estimated in landholdings by 2018, semi-small and medium landholdings together accounted for 78% (61,287 ha) of the clearing (Table 1). Small (< 100 ha) and large (> 1500 ha) landholdings represented the lowest percentages of clearing, although, small landholdings encompassed only 1% of remaining forest, areas occupied by large landholdings represented 33% (68,008 ha) of the remaining forest in the landholdings analyzed. Thus, most of the remaining forest was in medium and large landholdings (80% or 165,319 ha) (Table 1) (Online Resource 7).

From 1994 to 2018, cumulative deforestation in the occupied landholdings that we analyzed increased from 16% (1659 ha) to 72% (7298 ha) for small landholdings, 8% (6087 ha) to 49% (36,781 ha) for semi-small, 1% (1080 ha) to 20% (24,511 ha) for medium, and 1% (713 ha) to 12% (9552 ha) for large (Online Resource 8). Online Resource 9 shows the landholdings in our study area and the spatial distribution of deforestation through the years.

Distribution of landholdings in relation to distance to the Transamazon Highway and by land category

Although landholdings of all types were found on the edges of the Transamazon Highway, small landholdings (< 100 ha) and semi-small landholdings (100–400 ha)

Table 1 Estimates of deforestation through 2018 and of remaining forest in hectares per landholding

| Landholding type	Deforestation through 2018 in hectares			Forest in 2018 in hectares		
	Total	Deforestation mean ± SD	Min.–Max	Total	Forest mean ± SD	Min.–Max
Small < 100 ha ($n = 131$)	7298 (9%)	56 ± 26	0–99	2806 (1%)	22 ± 23	0–89
Semi-small 100–400 ha ($n = 327$)	36,780 (47%)	112 ± 83	0–394	37,376 (18%)	115 ± 110	0–394
Medium > 400–1500 ha ($n = 133$)	24,507 (31%)	184 ± 236	0–1324	97,311 (47%)	732 ± 400	0–1486
Large > 1500 ha ($n = 37$)	9552 (12%)	258 ± 509	0–1877	68,008 (33%)	1,838 ± 755	249–4646
Total ($n = 628$)	78,137 (100%)	124 ± 182		205,501 (100%)	330 ± 536	
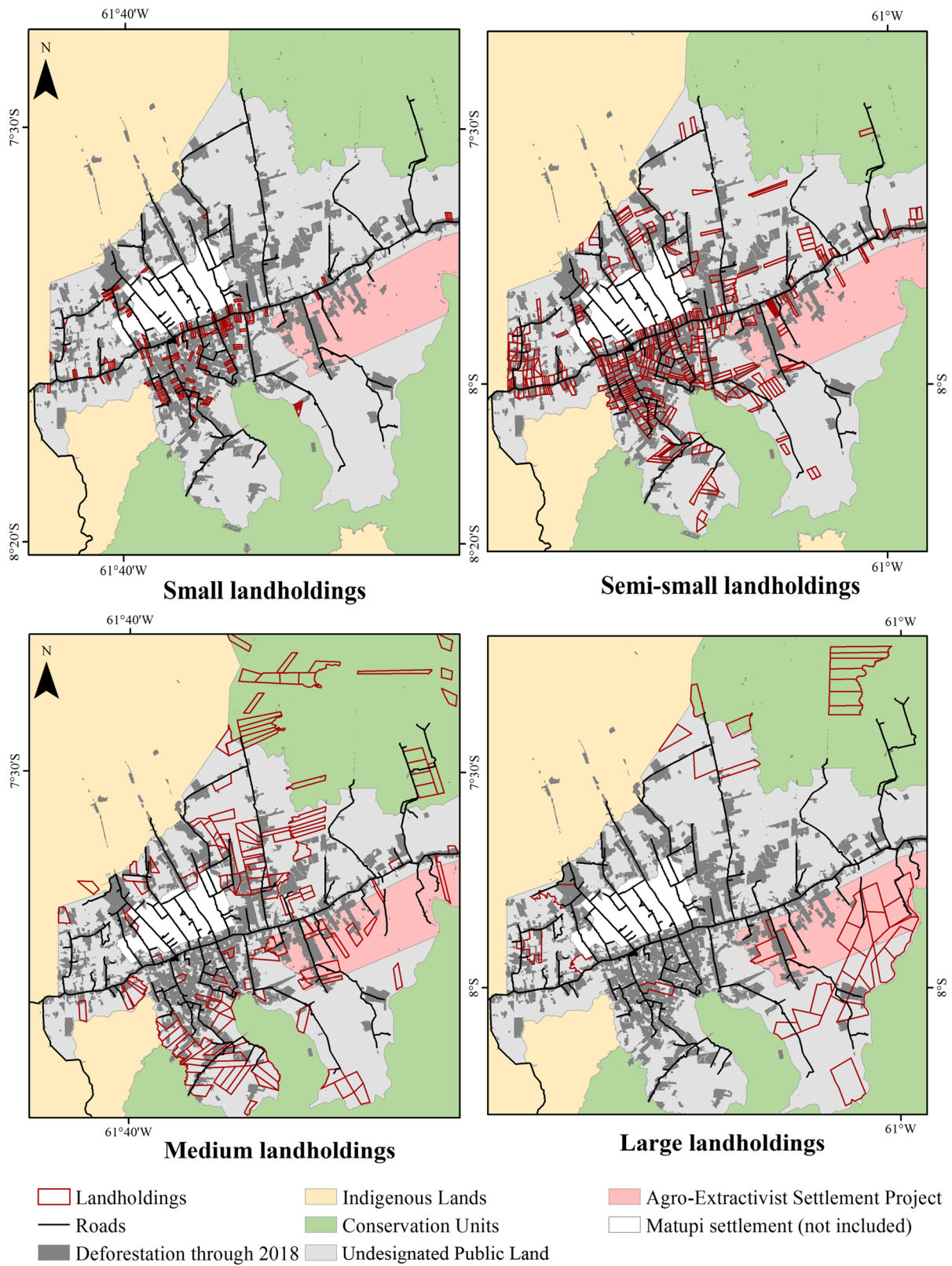
Fig. 2 Distribution of landholding types in the land categories. The Transamazon Highway crosses the study area from east to west, and secondary roads are connected to this main road. Landholding types are: small (< 100 ha), medium (400–1500 ha) and large (> 1500 ha)

were closer to the Transamazon Highway as compared to other sizes of landholdings. The maximum distances at which small and semi-small landholdings were found in relation to Transamazon Highway were 24 km (small) and 41 km (semi-small). In contrast, medium landholdings (> 400–1500 ha) and large landholdings (> 1500 ha) were found at distances of up to 65 km (medium) and 48 km (large) (Online Resource 11). Differences between the mean distances from the main road of landholdings of different types are analyzed in Online Resource 11, showing that smaller landholdings tend to be closer to the main road than larger holdings.

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.

Of the area of undesignated public lands in our study area, 43% (210,264 ha) was occupied by analyzed landholdings. Most of the small and semi-small landholdings were located in this land category, although, one semi-small landholding was found in a conservation unit (Fig. 2). Medium landholdings and large landholdings were also found in the agro-extractive settlement and in conservation units, indicating either occupation or the intention to occupy the land by medium and large landholders (Fig. 2).

One medium landholding was found in an Indigenous Land (Fig. 3a), and 22 medium and 9 large landholdings were found in conservation units (Figs. 2, 3b and c); access to these landholdings is by secondary roads connected to the Transamazon Highway. Small patches of clearing were found inside some of these landholdings (Figs. 3b and c). Because some small and semi-small landholdings are located at the boundaries of Indigenous Lands (Fig. 2), a small portion (< 0.2%) of the boundaries of landholdings intersected Indigenous Lands (Online Resource 12).

Discussion

Deforestation dynamics

In Brazilian Amazonia, the recent increase of forest loss is located mainly on new deforestation frontiers that are dominated by cattle ranching (Schielein and Börner 2018). In Matupi, larger landholders (> 400 ha) are the main actors who have moved into forest, contributing to the expansion of the deforestation frontier for cattle production. The deforestation frontier has been advancing into undesignated public lands, conservation units, and an agro-extractive settlement, which have been converted to cattle pasture.

In Matupi District, the spatial and temporal analysis of deforestation in the landholdings showed that different sizes of landholdings had distinct deforestation processes. The clearing process occurred earlier in areas occupied by landholdings up to 400 ha (small and semi-small) than in areas occupied by landholdings greater than 400 ha. The proximity of small (< 100 ha) and semi-small (100 – 400 ha) landholdings to the Transamazon Highway and to previous deforestation located close to this main road had important roles and contributed to consolidating deforestation in most of the area occupied by these landholdings.

In the mid-1990's, when land occupation in Matupi District was beginning, spontaneous squatters started to occupy areas along the Transamazon Highway and along secondary roads on the southern side of the highway. The Matupi Settlement Project had an important role in the attracting migrants to the Matupi area in general, in addition to migration to the settlement itself. During the field work, we followed access roads (*ramais*) cutting through the settlement that were connected to other roads outside of the settlement and we observed that these access roads contributed to the establishment of new landholdings in the areas surrounding the settlement. Thus, both the settlement and secondary roads have important roles in the advance of land occupation and clearing.

Landholdings larger than 400 ha (medium and large) started clearing mainly from 2003 onwards, so they are located further from the main road and are more spread out in the remaining forest than the smaller landholding types. Most of these larger landholdings are not connected directly to the Transamazon Highway, and they are often located on the boundaries between land categories (e.g., undesignated public lands and conservation units) and at the ends of secondary roads in more isolated areas. This pattern for large landholdings has also been observed in the Xingu-Iriri ("Terra do Meio") region in Pará State (dos Santos Silva et al. 2008).
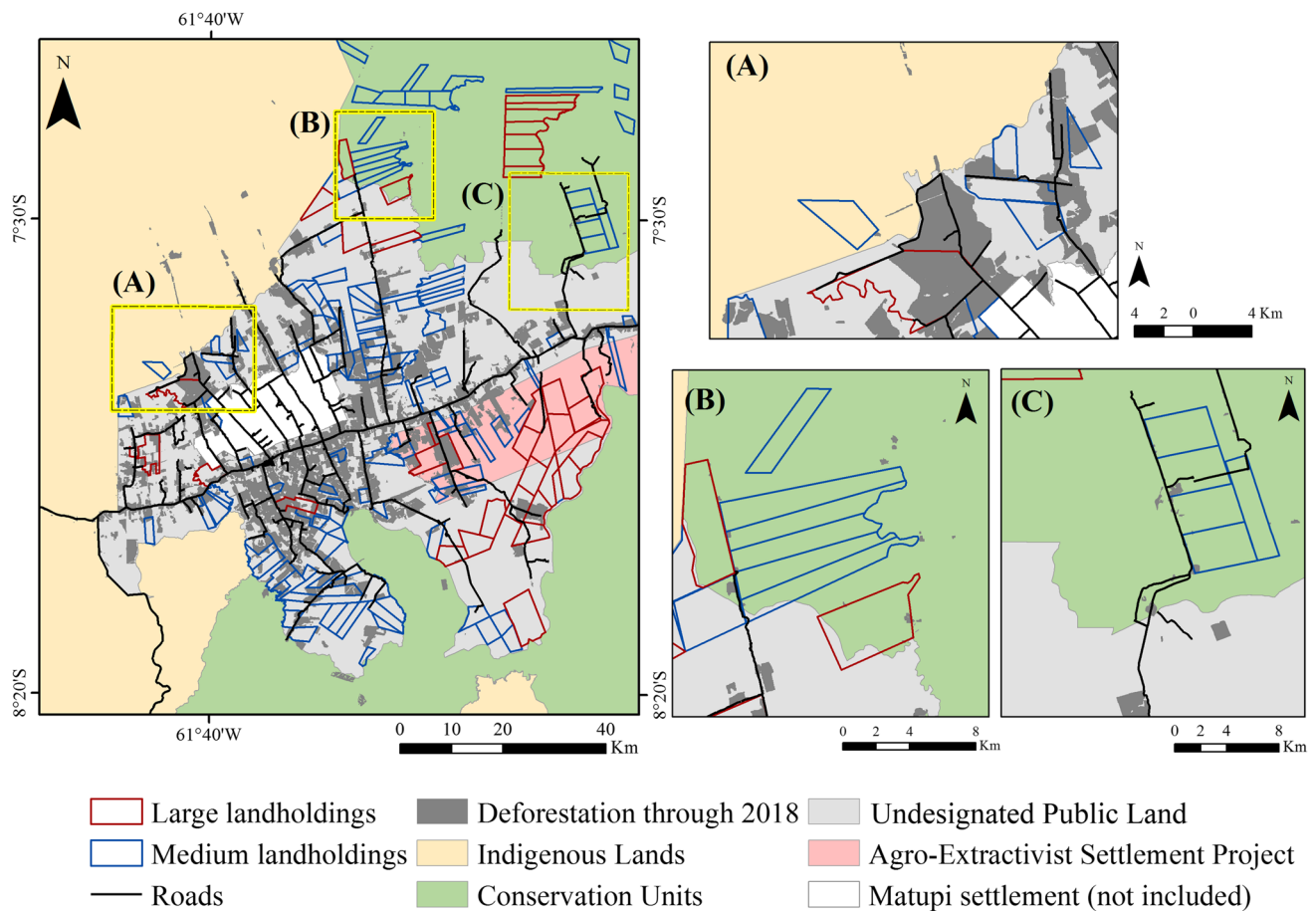
Fig. 3 Distribution of large and medium landholdings. A medium landholding is located in an Indigenous Land (**A**); medium and large landholdings with small clearings along secondary roads can be observed inside conservation units (**B** and **C**)

In this regard, an important concern in our findings is that 80% of the remaining forest in 2018 in the landholdings analyzed was in larger landholding types (> 400 ha). We therefore suggest that medium landholders and large landholders will be the main potential contributors to future deforestation. If clearing continues in medium and large landholdings in the coming years, 27% of the landholdings will be responsible for 71% of the total deforestation. In northern Mato Grosso (i.e., Alta Floresta and neighboring municipalities), larger and younger landholdings also hold more forest than do smaller and older landholdings (Michalski et al. 2010).

In 2019 and 2020, medium landholdings (400–1500 ha) cleared a substantial number of new areas in the Matupi District region. This reinforces our concern about the vulnerability of the forest to deforestation in this type of landholding (Fig. 4).

Large cattle ranchers tend to use the entire area of their landholdings for pasture (although they may be restrained by enforcement of limits specified in the Forest Code), and they open new areas whenever they have the opportunity

(D'Antona et al. 2006; Godar et al. 2012a, b). However, in Matupi District, most of the large cattle ranchers had not yet converted the whole area of their landholdings to pasture either because they started their land occupation recently or because they appear to be land speculators who are planning to sell the landholding after an expected future increase in land value. In Brazilian Amazonia, an estimated 9 to 13% of the land is a speculation frontier where the landholding was acquired at no cost, and land speculation has been found to be a driver that contributes to the profitability of extensive ranching (Bowman et al. 2012). In addition, the strategic location far from the main road reduces the chances that the speculators will be monitored in loco by command-and-control actions. The feeling that they are not going to be punished and the expectation of future "amnesties" through revisions of the 2012 Forest Code encourage more illegal deforestation in areas that are already under high pressure from commodity expansion. A recent study estimated that the revision of the 1965 Forest Code in 2012 contributed an additional of 976,000 ha of deforestation in Brazilian Amazonia from 2012 to 2017 (Albuquerque Sant'Anna and
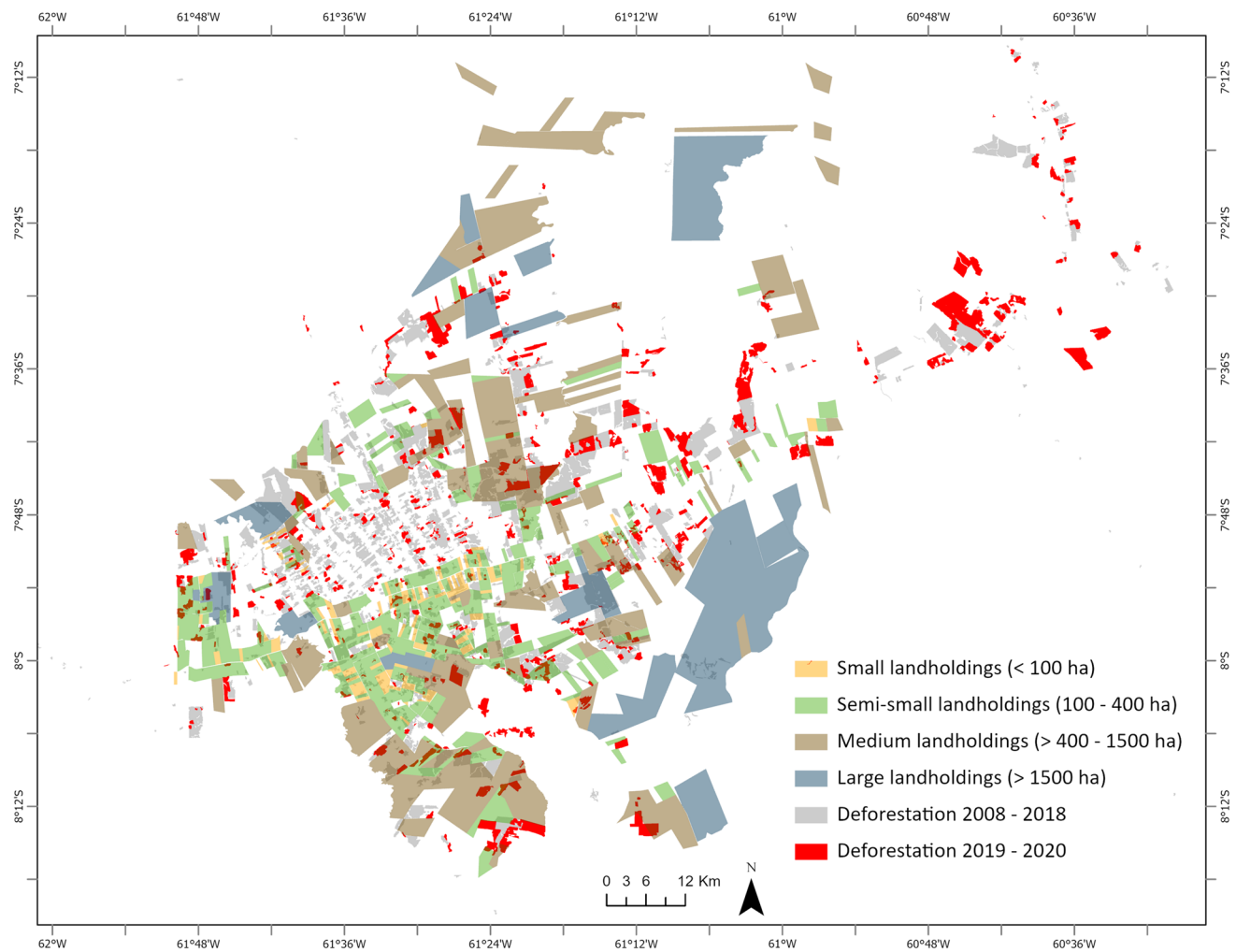
Fig. 4 Increase of deforestation in recent years (2018–2019) mapped by PRODES in the study area

Costa 2021), indicating that revision of the Forest Code encourages more clearing in landholdings, accelerating the expansion of deforestation frontiers in Brazilian Amazonia. Based on the map of forest loss by Albuquerque Sant'Anna and Costa (2021), we estimated forest loss in the Matupi District region (i.e., Manicoré and Novo Aripuanã municipalities), which was between 1.7–5.9% due to the 2012 revision of the Forest Code.

Matupi is a representative example of how clearing patterns occur on new deforestation frontiers in Brazilian Amazonia. The Matupi case provides a good illustration of the lack of definition of legal instruments in the 2012 Forest Code (Sparovek et al. 2012), the weak enforcement of environmental regulations in recent years (Hecht et al. 2021), promotion land titling for land grabbers (Brito and Barreto 2010; Probst et al. 2020), and how strategic occupation in remote areas by larger landholders contributes to promoting the more illegal occupation of forest land and expansion of deforestation in undesignated public land and in protected areas.

The dynamics of deforestation in frontier regions in Brazilian Amazonia have been shaped by the local actors and their development practices. Here, we focus on small and large cattle ranchers, although the area also has loggers, miners, and other types of actors (e.g., state-owned commercial banks, private banks, pension funds, and hedge funds) that play important roles in shifting the commodity frontier to new forest areas (Hecht et al. 2021).

Our finding that small landholdings (< 100 ha) contributed less to total deforestation by 2018 than other landholding sizes is in line with the findings of a study also performed along the Transamazon Highway, but in the state of Pará, where both the contribution of small landholdings to total deforestation through 2007 and the mean clearing per landholding were smaller than for medium and large landholdings (Godar et al. 2012a). A similar pattern has also been reported for Brazil's Legal Amazonia region as a whole in different time periods: annual deforestation in 1991 (Fearnside 1993), cumulative deforestation through

2003 (Pacheco 2009), and cumulative deforestation through 2011 (Godar et al. 2014).

"Small" landholders (<100 ha) in Matupi District clear forest for cattle ranching. In general, they are not subsistence farmers but rather are migrant families and ranchers from neighboring areas (e.g., Rondônia State) and from southeastern Brazil. The difference in land demand between small and large landholders is that the small landholders prefer to raise dairy cattle rather than beef cattle. According to local landholders, dairy cattle can be raised in more confined spaces and the demand for pastureland is lower. The milk is sold to the local dairy company.

Large landholders are the main actors responsible for the expansion of unofficial roads and for deforestation resulting in frontier expansion (Godar et al. 2012a, b); however, loggers are also important participants in opening access to the forest by building endogenous roads (i.e., "*ramais*") (Arima et al. 2016). Logging activity in Matupi District can be identified on satellite images (Lima et al. 2019). We also identified selective-logging patterns both in Landsat images (2016–2018) and during our fieldwork. Because logging and cattle-ranching are the main economic activities in Matupi, it is likely that areas with logging will later be converted to pasture.

Land categories

Most landholdings were in areas of undesignated public lands as we expected. We also found landholdings larger than 100 ha with either all or a portion of their landholdings located either in a protected area or in an agro-extractive settlement (i.e., the Aripuanã-Guariba agro-extractive settlement project; see Online Resource 13 for discussion of its boundaries), despite land occupation being prohibited in these land categories. As an agro-extractive settlement, only extractive activities are allowed and only smallholders should be living in this area. This agro-extractive settlement was created in 2005, and during our fieldwork in 2018, we found that landholders did not know about this agro-extractive settlement's existence. The deforestation and land occupation by ranchers raising cattle that we observed in the present study reflect the low level of monitoring and governance in this area.

In the state of Mato Grosso, the CAR has registered 50 landholdings (370,366 ha) inside conservation units and Indigenous Lands (Roitman et al. 2018). This shows that the CAR has the potential to help identify the intention of occupying land illegally in protected areas with the expectation of receiving land tenure in the future. Although the CAR was created to improve environmental control, in practice, it also has the opposite effect because it serves as a tool for land grabbing and thus stimulating deforestation (Azevedo-Ramos et al. 2020). In July 2020, Mato Grosso enacted a law allowing legalization of such claims in the 27 Indigenous Lands in this state for which the final confirmation ("homologation")

process has not yet been completed (Mato Grosso 2020), thus encouraging future invasions (Fanzeres 2020).

In the future, most of the remaining forest would tend to be located in protected areas if the expansion of deforestation in undesignated public lands proceeds. Municipalities in areas with high deforestation pressure (i.e., the "arc of deforestation") have been shown to have over 55% of their remaining forest restricted to conservation units, and clearing was occurring inside these areas because forest outside of conservation units had almost all been cleared (Rosa et al. 2017).

Undesignated public land

When large actors on a deforestation frontier decide to invest in clearing, they tend to choose areas with lower deforestation restriction and with low enforcement, and Brazil's Amazonian undesignated public lands (49.8 Mha) encompass both aspects: low restriction on clearing and low enforcement by government institutions. Thus, this land category is the main target of land grabbers and, due the easier access, deforestation in federal undesignated forest tends to be greater (5.4 times) in comparison to the undesignated land under state-level administration (Azevedo-Ramos et al. 2020). In Matupi, most medium and large landholdings (>400 ha) are distributed in federal undesignated public land (Online Resource 12), showing how easily larger actors can access and illegally occupy a large area of forest in undesignated land.

The state of Amazonas has the largest area of undesignated public forest in Brazilian Amazonia, and most of this area is under state administration (Azevedo-Ramos et al. 2020). In Amazonas State, most of the public land that has been occupied in the expectation of future legalization is in federal undesignated land, and most of the state undesignated public land is not yet under this pressure because it is located further from roads and existing occupation (Almeida et al. 2021). However, new roads are expected to advance the cattle-ranching frontier from the southern to the central part of the state and allow deforestation to reach an enormous block of intact state undesignated forest located to the west of the Purus River (Fearnside and Graça 2006). This "Trans-Purus" area has great importance for the Brazilian Amazon's environmental services, such as maintaining the region's biodiversity, carbon stock, and hydrological cycle (Fearnside et al. 2020). These services include supplying water vapor that is transported to southeastern Brazil by winds known as "flying rivers," providing rain that is critical for water supply to the city of São Paulo (Arraut et al. 2012; Fearnside 2004, 2021a; Zemp et al. 2014).

The susceptibility of undesignated public land to land grabbing and speculation can be partly attributed to the fact that it is unclear which federal and state agencies should

manage and monitor this category of land (Azevedo-Ramos et al. 2020). In the end, without knowing who should protect the forest in undesignated land, no one does the protection and monitoring. Thus, allocating these areas for protection could be a good option for reducing the susceptibility of these public lands and inhibiting future illegal occupation (Azevedo-Ramos and Moutinho 2018).

In recent years (2015–2018), deforestation in Matupi has been spreading to the southern and northwestern parts of the district, where medium and large landholdings are concentrated (Online Resource 9). Although we have not identified any deforestation patches in some of these landholdings, they are registered in the CAR system, which indicates an intention to claim land tenure. These illegal claims can benefit from a proposed bill (PL 510/2021) that aims to legalize land claims up to 2500 ha in area that were occupied by 2014. A recent analysis shows that landholdings in Matupi District can be legalized under both current legislation (Law 11,952/2009) and under the proposed bill (PL 510/2021) (Rajão et al. 2021). Granting land titles to those who illegally occupy public land, which creates the expectation of future "amnesties," is one of the reasons behind the current acceleration of deforestation. Probst et al. (2020) found that medium landholders who received a land title through the Terra Legal program showed a substantial increase in their deforestation 2 years after the title was received. These authors also found that landholders with a land title clear more area with the increase of cattle prices, indicating they responded strongly to the market after land tenure was recognized. Thus, while prior to titling they may clear a minimal area to indicate occupation and claim land rights, greater investment can be made with a title in hand because the risk is minimal that the investment will be lost. This means that granting land titles to those who illegally occupy public land stimulates deforestation. Ironically, political discourse alleging that titling would reduce deforestation has often been used to justify legalizing illegal land claims. The Terra Legal program, for example, showed in the first year of assessment that deforestation and land conflicts with indigenous and other traditional populations increased due the overlap with titled landholdings (Brito and Barreto 2010). In Amazonas State, the landholdings in the CAR registry overlap 8.5 Mha, which is 5.5% of the state's 156 Mha total area, or 15% of the state's 58 Mha of undesignated public land (Almeida et al. 2021).

In his address to the 22 April 2021 climate summit convened by US President Joe Biden, Brazilian President Jair Bolsonaro promised to end illegal deforestation by 2030 (OC 2021), and this promise was repeated at COP-26 in November 2021. Unfortunately, zero illegal deforestation can be achieved either by stopping clearing or by legalizing the illegal deforestation that is occurring, and it is the second scenario that is playing out under Brazil's current presidential administration (Fearnside 2021b).

Converting the forest to pasture is not an indication of "development" because the number of people benefited per unit area cleared is extremely low and this deforestation does little or nothing to increase the wellbeing of local populations (Fearnside 2017). Alternatives for local populations include mechanisms to reward the forest's environmental services (Fearnside 1997, 2008b). These services include maintaining the large carbon stock in landholdings in the state of Amazonas, which is the state with the largest carbon stock in Brazilian Amazonia (Nogueira et al. 2015).

Conclusions

Undesignated public lands have a crucial role in attracting larger ranchers and farmers, where areas are illegally occupied through "land grabbing" (*grilagem*) and the claims are later sold (either with or without legalization). Medium (400–1500 ha) and large (> 1500 ha) landholdings are more spread out in the landscape than smaller ones and, in general, are located far from consolidated areas of previous clearing, giving the larger actors a key role in expanding the frontiers. Larger landholders also control the great majority of the remaining forest in landholdings, making them likely to be the primary actors in future deforestation.

Landholders could change their clearing behavior if the incentives for clearing were removed, although Brazil's current trend is in the opposite direction — facilitating legalization of illegal land claims and relaxing environmental restrictions. Legalization of large and medium land claims must be halted and policies adopted to curb invasion of government land. Deforestation-repression efforts should focus on large and medium landholders.

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Declarations

Conflict of interest The authors declare no competing interests.

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