Farm-scale distribution of deforestation and remaining forest cover in Mato Grosso

Peter D. Richards[1]* and Leah VanWey[2]

An analysis of data on property size and type as well as land use reveals the distribution of deforestation, remaining forest cover and carbon stocks in Mato Grosso, Brazil's third largest state. Nearly two-thirds of remaining forests and carbon reserves, equating to between 2 and 3 Pg of carbon, are located on private properties. Around 80% of forests and carbon reserves are on properties larger than 1,000 ha, with smallholder farms and public land reform settlements controlling only a tiny fraction of the state's remaining forest and carbon reserves. Efforts to reduce emissions from deforestation and forest degradation must target owners controlling most of the remaining forest and land types with the highest deforestation rates. We thus suggest that policymakers seeking to protect the remaining forest should focus both incentives and enforcement of anti-deforestation laws in the larger properties where most of these forests are located.

Over recent decades, Brazil has successfully reduced deforestation, particularly among large farmers and ranchers[1-4], leading to the suggestion that future policy should incentivize smallholder farmers to reduce deforestation in Brazil's Amazon[5,6]. We reassess this conclusion for the state of Mato Grosso, a recent hotspot of deforestation and the heart of Brazil's agricultural production. Using data from Mato Grosso's Environmental Registry of Rural Properties (known as CAR, its Portuguese acronym) and from the Global Forest Cover (GFC) project, as well as Brazil's National Institute of Space Research's Monitoring Deforestation in the Brazilian Amazon by Satellite Project (PRODES) data set, we analyse the distribution of recent deforestation, remaining forest cover, and remaining carbon stocks according to property sizes. This combination of data on property type and size, and land use change shows both the large contributions of larger properties to total deforestation and the extent to which standing forest is concentrated on these properties. Nearly 80% of forests and carbon reserves in private properties registered in the CAR database, or in the assentamantos (public land settlements), are located on properties larger than 1,000 ha. Smallholder farms and public land reform settlements, in contrast, control only a tiny fraction of the state's remaining carbon reserves. Thus, despite high rates of deforestation among settlers and smallholders, policies focused on preserving total forest cover or carbon stocks will need to engage directly with large landowners.

Deforestation in Mato Grosso

Mato Grosso sits at the southern edge of the Amazon Basin. The entire state is in the Brazilian Legal Amazon, an important classification for forest policy and enforcement, but the state contains areas pertaining to each of the Amazon Forest, the Cerrado, and the Pantanal biomes (see Supplementary Fig. 1). These areas vary ecologically, and in the specific requirements for landowners under the Forest Code. Between 2000 and 2012, nearly 80,000 km^2 of forest and cerrado (woody savannah) were razed in Mato Grosso, often making way for pastures and croplands[7], and resulting in average yearly emissions of around 163 million tons CO_2e during the early part of the past decade[8]. Fortunately, in recent years, deforestation in the Amazon as a whole, and in Mato Grosso, in particular, has declined markedly owing largely to enforcement, a battery of policies and protected areas put into place in the past decade[1-3]. However, it is not clear whether low deforestation rates can be sustained, given the increasing value of Mato Grosso's land for agricultural production and cattle ranching.

Historically, deforestation across the Brazilian Amazon has been linked to the expansion of highways and smallholder settlements, and extensive cattle ranching[9-11]. An increase in deforestation in Mato Grosso in the early 2000s was driven by high returns to agriculture, in large part due to the combination of a weak Brazilian real and a strong US dollar[12,13]. However, deforestation rates fell markedly in the second half of the decade[1,14], especially among those landowners with large farms or ranches[6]. This might suggest that enforcement should now target smallholders[5,15], consistent with evidence that small-property owners in the Amazon are more likely to clear a larger percentage of their properties[16-19].

We are entering a period likely to see renewed high rates of deforestation: the dollar–real exchange rate is at a level not seen since 2003, the Brazilian government continues to support export-oriented commodity agriculture, and Mato Grosso's cattle herd is growing. In this context, using newly available data from Mato Grosso's Rural Environmental Registry, we reassess the recent trends in deforestation by property size and type, and assess the remaining stocks of forest and carbon in these different types of property.

Mato Grosso's rural environmental registry

In 2000, Mato Grosso created Brazil's first state-level programme to regularize rural property ownership, the Rural Property Environmental Licensing System (or SLAPR, in Portuguese)[20]. Early versions of SLAPR integrated owner-created GIS files with high-resolution satellite imagery to simultaneously document property boundaries and remaining forest cover, and thus allow landowners to document compliance with environmental laws. Initially targeted at large landowners, the programme was hailed as successful in slowing forest loss, despite the high rates of deforestation after its inauguration[21-23].

[1]Population Studies and Training Center, Institute at Brown for Environment and Society, Brown University, Providence, Rhode Island 02912, USA. [2]Department of Sociology, Population Studies and Training Center, Institute at Brown for Environment and Society, Brown University, Providence, Rhode Island 02912, USA. *e-mail: peter_richards@brown.edu
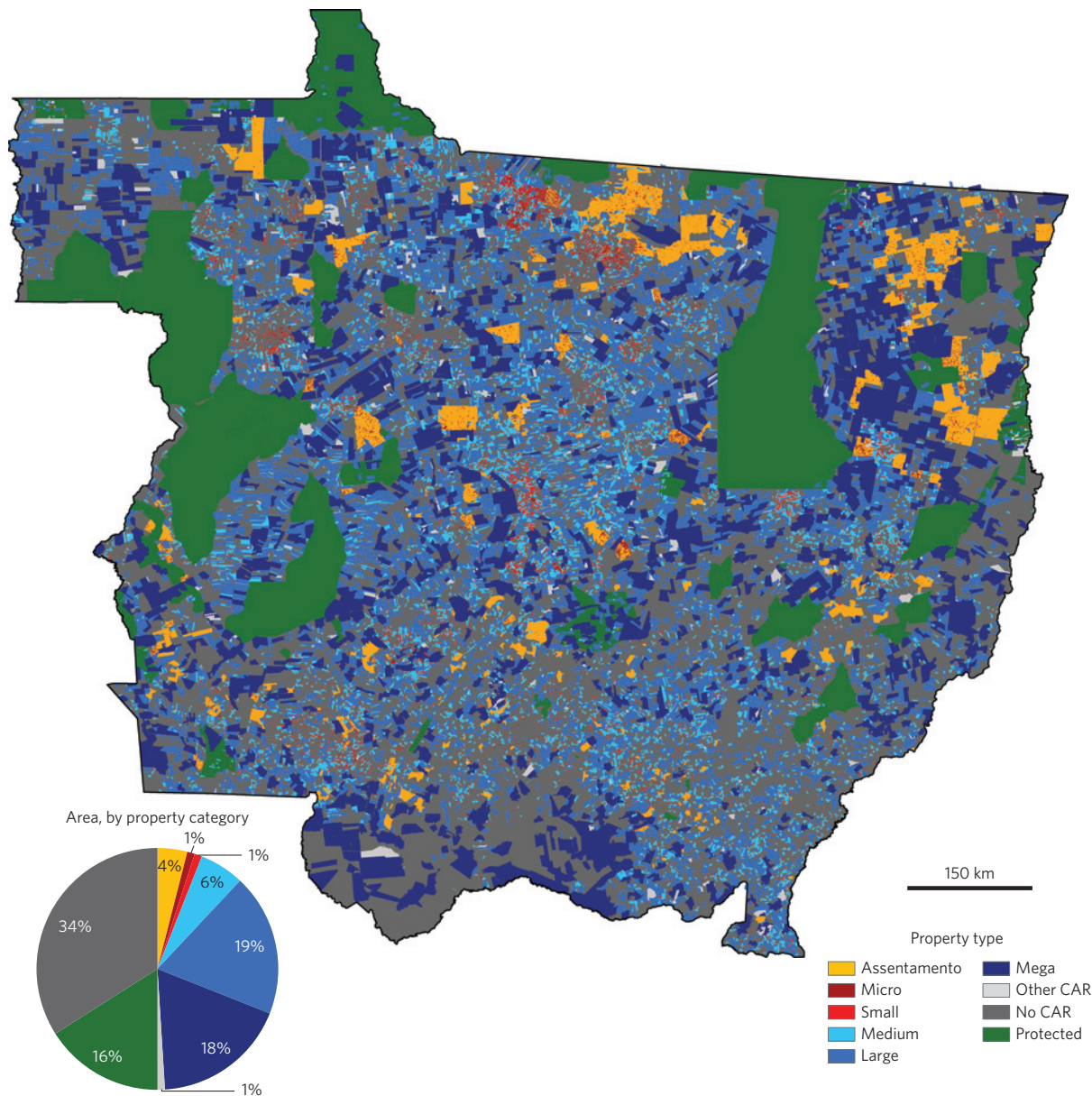
Figure 1 | In Mato Grosso, most areas registered in the CAR database are larger than 1,000 ha. The relative distribution of property institutions and sizes varies across the state. In particular, smaller properties and assentamento areas are heavily concentrated in the north and northwest regions. See main text for definitions of each property type.

In the mid-2000s, Mato Grosso sought to regularize rural properties across the entire state. To meet this objective, the state repackaged the SLAPR into the central component of Mato Grosso's 'Mato Grosso Legal' initiative. As part of this initiative, the State of Mato Grosso launched its governmental Secretary of the Environment (SEMA) tasked with compiling a geospatial database on property ownership for the entire state. To accomplish this, SEMA required that all landowners acquire a Rural Environmental Registration, known as a CAR, which they would receive by submitting a certified GIS shape-file documenting their property boundaries. After a CAR was approved, if landowners could submit proof that their property satisfied environmental regulations, they could obtain an additional document, known as the Environmental License, or LAU (ref. 24).

As of September 2014, more than 31,000 properties, covering approximately 305,000 km² (34% of the state's total area), had been compiled by SEMA in its CAR registry; an additional 11,000 properties, amounting to more than 100,000 km², were registered in the LAU database. We combined the CAR and LAU registries with the location of protected areas and assentamentos to create a property map that covered nearly two-thirds of Mato Grosso (Fig. 1). We used the CAR and LAU registries to divide Mato Grosso into six categories. These included: micro (properties <100 ha); small (100–250 ha); medium (250–1,000 ha); large (1,000–5,000 ha); mega (>5,000 ha); and other CAR (or LAU). Other CAR included all land that was registered in the CAR database, but which was contested, either owing to competing documents or owing to survey error on parcel boundaries. We then divided the rest of Mato Grosso into three additional categories. First, we classified areas pertaining to assentamentos, but which were not included in the CAR or LAU databases, as assentamentos. Properties in the assentamentos are generally less than 100 ha, and may be less than 30 ha. Second, we compiled all protected areas, including indigenous lands, as an eighth category (protected). Third, we classified all remaining areas, including urban areas and waterways, as 'no CAR'.

In total, assentamentos and micro and small properties account for approximately 6% of the state, or about 50,000 km²

Table 1 | Forest loss, by property type.

Category	Assentamento	Micro	Small	Medium	Large	Mega	Other	Protected	No CAR	Total
Total forest loss, 2001–2012 (km^2)										
Mato Grosso[GFC]	9,231	1,218	1,457	7,512	21,239	11,396	1,009	2,797	27,315	83,173
	11%	1%	2%	9%	26%	14%	1%	3%	33%	(100%)
Cerrado[GFC]	1,220	248	254	1,963	5,778	2,794	256	616	6,878	20,006
	6%	1%	1%	10%	29%	14%	1%	3%	34%	(100%)
Amazon[GFC]	7,359	955	1,178	5,377	15,090	8,098	726	2,161	18,144	60,988
	12%	2%	2%	9%	25%	13%	1%	4%	30%	(100%)
Amazon[PRODES]	7,247	771	956	4,578	13,125	7,081	602	1,234	16,953	52,546
	14%	1%	2%	9%	25%	13%	1%	1%	32%	(100%)
Percentage of forest cover, 2000–2013										
Mato Grosso[GFC]										
2000	53%	40%	41%	49%	56%	53%	67%	80%	48%	56%
2013	30%	21%	27%	36%	46%	47%	60%	78%	41%	48%
Difference	(22%)	(19%)	(14%)	(13%)	(10%)	(6%)	(7%)	(2%)	(7%)	(8%)
Cerrado[GFC]										
2000	36%	36%	27%	29%	32%	31%	38%	56%	32%	35%
2013	28%	21%	21%	23%	27%	27%	33%	55%	28%	31%
Difference	(8%)	(15%)	(6%)	(6%)	(5%)	(4)	(5%)	(1%)	(5%)	(4%)
Amazon[GFC]										
2000	61%	42%	50%	66%	75%	69%	86%	93%	67%	73%
2013	31%	21%	30%	47%	60%	61%	76%	91%	53%	62%
Difference	(30%)	(19%)	(20%)	(19%)	(15%)	(8)	(10%)	(2%)	(14%)	(11%)
Amazon[PRODES]										
2000	56%	38%	42%	63%	74%	67%	84%	98%	64%	72%
2013	23%	20%	24%	44%	59%	60%	75%	96%	50%	61%
Difference	(23%)	(18%)	(16%)	(17%)	(15%)	(7%)	(9%)	(2%)	(14%)	(9%)

Calculations based on estimates of forest loss and remaining forest as indicated in the Global Forest Change (GFC; 2014) and PRODES data sets.

**Table 2 | Remaining forest cover and carbon, by property type.**

Category	Assentamento	Micro	Small	Medium	Large	Mega	Other	Protected	No CAR	Total
Remaining forest cover (km^2)										
Mato Grosso[GFC]	10,745	1,169	2,397	18,321	80,234	77,955	6,935	113,422	125,579	436,758
Cerrado[GFC]	3,062	274	675	5,437	19,396	14,653	1,347	28,658	39,171	112,673
Amazon[GFC]	7,406	870	1,669	12,422	59,144	56,018	5,231	84,651	72,281	299,692
Amazon[PRODES]	5,027	771	1,256	10,647	52,662	49,154	4,721	78,665	60,924	263,827
Remaining C in above-ground live biomass, by property type (Tg)										
Mato Grosso[GFC]										
Ref. 47	58	6	11	104	533	536	53	940	769	3,010
Ref. 48	85	8	19	166	804	811	74	1,335	1,211	4,541
Cerrado[GFC]										
Ref. 47	10	1	2	16	66	53	5	166	124	443
Ref. 48	24	2	5	44	171	131	13	306	340	1,034
Amazon[GFC]										
Ref. 47	47	5	9	87	459	447	46	774	569	2,442
Ref. 48	59	6	13	118	618	610	59	1,028	733	3,244
Amazon[PRODES]										
Ref. 47	30	3	7	75	411	393	41	718	488	2,164
Ref. 48	37	3	10	99	545	531	53	954	733	2,845

Remaining forest cover is based on the percentage of forest cover on non-deforested areas, as classified in the Global Forest Change (GFC; 2014) and PRODES data sets. Remaining carbon was calculated on the basis of the total above-ground live biomass in remaining forest areas. Estimates of above-ground live biomass area based on biomass maps produced in refs 47,48.

(Fig. 1). Medium-size properties amounted to an additional 6% (50,000 km^2). Thirty-seven per cent of the state, or 340,000 km^2 of the registered areas, pertained to properties larger than 1,000 ha. Of the remainder, 11,000 km^2 were included as Other CAR; 145,000 km^2 as protected, and approximately 300,000 km^2 as No CAR.
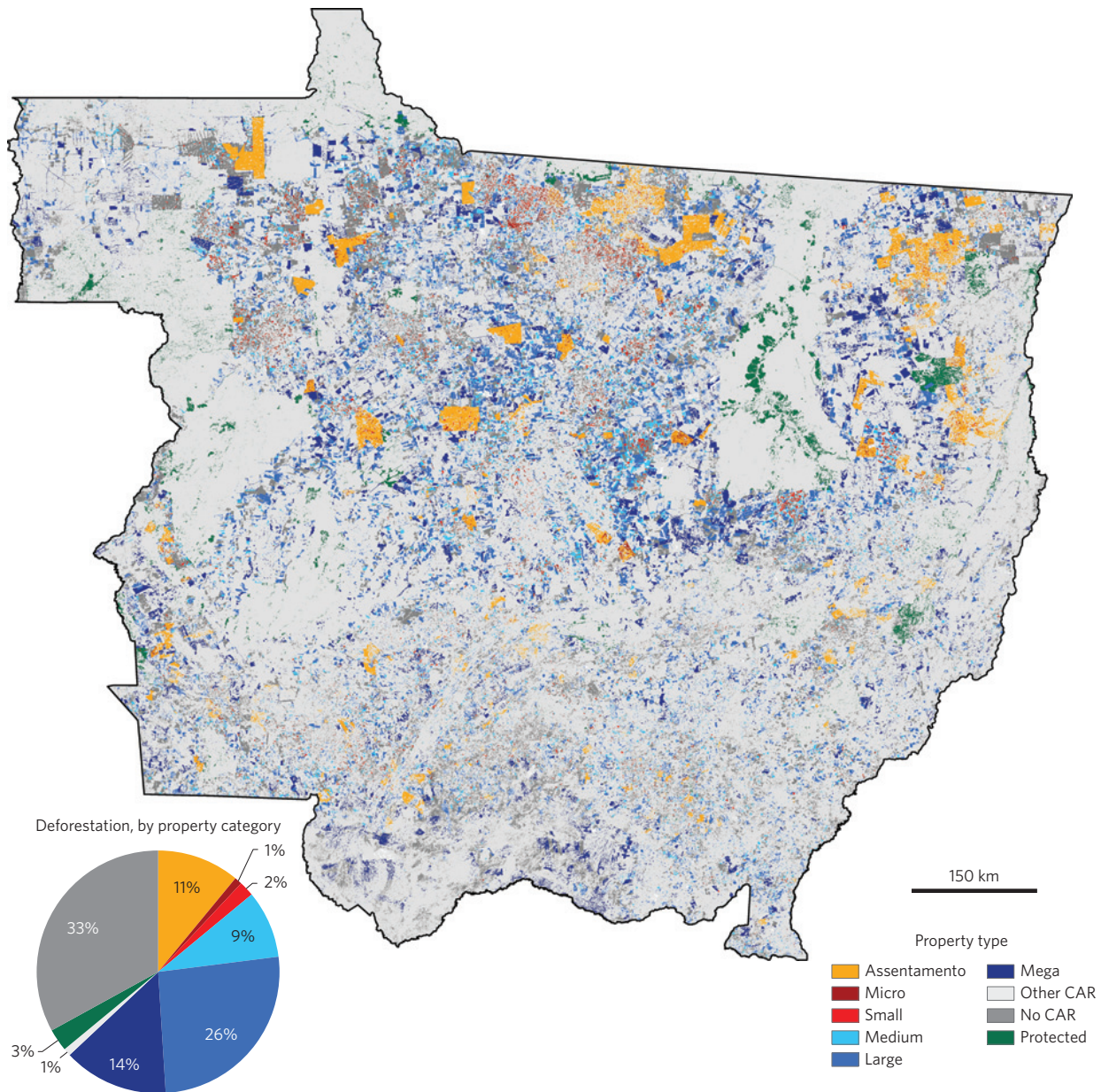
Figure 2 | Deforestation (2001–2012), by property size category. Over the past decade, deforestation in Mato Grosso was largely concentrated in the northern half of the state. Of deforestation on properties that are registered in the CAR system, most took place on properties larger than 1,000 ha (shown in medium and dark blues); however, small properties and assentamento projects account for a disproportionate share of the state's forest loss during this period. Deforestation in assentamento areas was also highly concentrated. See main text for definitions of each property type.

We overlaid the property classifications over the continuous surface of forest cover and deforestation as indicated in the GFC data product and PRODES data[7]. (The GFC provides complete coverage of the state, whereas the PRODES covers only areas in the Amazon biome.) Combined, these data offer a new perspective on deforestation and remaining forest cover. More importantly, they provide conclusive evidence, at an unprecedented level of detail, scale and scope, that small properties and assentamentos account for a disproportionate share of deforestation; but that large properties account for the larger proportion, overall, of forest loss in Mato Grosso; and that most remaining forest cover on private properties is located on either large or very large properties.

Forest loss (2001–2012)

Between 2001 and 2012, according to the GFC data set, more than 83,000 km² of forest were lost in Mato Grosso (see Table 1 and

Fig. 2). Approximately one-third of these clearings took place in unregistered areas (shown as No CAR); a tenth of the forest loss took place in unregistered properties in the assentamentos; and a tiny fraction took place in protected areas. Slightly more than half of the forest loss took place on private properties registered with a CAR or LAU. Most of this took place on properties larger than 250 ha, and most on properties larger than 1,000 ha. Barely 2,500 km² of the state's forest loss, or less than areas cleared in protected areas, were cleared from micro or small-scale properties.

Most of Mato Grosso's recent forest loss occurred in the biomass-rich Amazon biome. In total, of the approximately 83,000 km² of forest cleared (according to the GFC data product) in Mato Grosso, 60,000 km² were in the Amazon region. Most forest loss in the Amazon also took place on large properties. When considering only areas in the Amazon biome, we estimated that 38% of forest loss occurred on properties larger than 1,000 ha. In contrast,
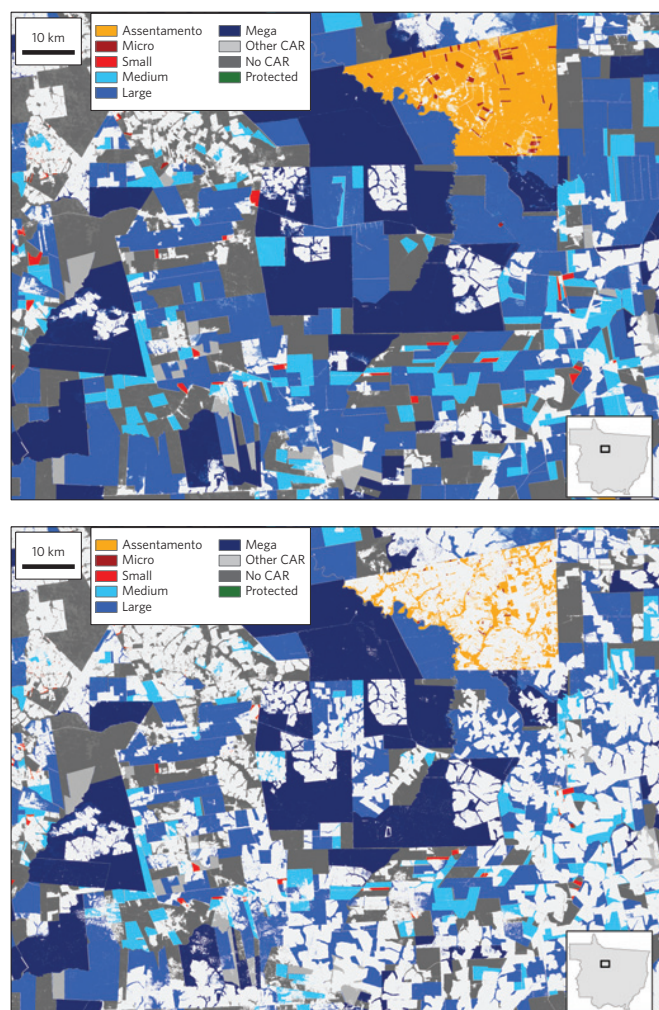
Figure 3 | Remaining forest cover, by property category: 2000 and 2012.
Close-up of GFC forest areas (coloured by property type) in northern Mato Grosso in 2000 and 2012 suggests that most remaining forests in this area pertain to large properties. Forest areas in the assentamento area at the top of the images (shown in yellow) were nearly entirely removed during this period.

smaller properties and all assentamentos, combined, accounted for less than 16% of the state's forest loss (Table 1).

Figs 3 and 4 shows that this substantial contribution of the largest properties to deforestation persists through the study period, with farms over 1,000 ha accounting for approximately 60% of deforestation on properties of known sizes in all years. The relative proportion of forest loss on private properties larger than 250 ha was highest from 2002–2004, but has since remained stable at approximately 70% per year (of all forest loss on properties registered in the CAR or LAU databases, or in assentamento areas). Within the Amazon biome, their role is slightly lower and depends on the data source; but even here these largest properties account for 40–60% of deforestation on properties of known sizes in any year. The PRODES data product shows declining, although still substantial, proportions of annual deforestation attributable to properties over 1,000 ha, whereas the GFC data suggest no decline in the representation of the largest properties.

This is not to suggest, however, that smaller properties have not had a significant role as a driver of forest loss in Mato Grosso over the past decade. Together, small properties and assentamentos cleared more than 9,000 km² of forest, and cleared significantly larger percentages of their properties than their larger counterparts

(see Table 1 and Figs 3 and 4). Nevertheless, medium, large and macro properties have consistently been responsible for most of the state's forest loss for each year since 2000 (Fig. 4 and Supplementary Tables 1–4).

Forest and carbon stocks remaining in 2013

In 2013, Mato Grosso possessed approximately 437,000 km² of forest cover, equating to between 3 and 4.5 Pg of carbon (depending on the estimate) stored in above-ground live biomass. Most of these forests and carbon stocks are located in the Amazon biome. Approximately 30% of the forests are protected, which leaves about two-thirds of the state's forest cover, or more than 200,000 km² of the Amazon forest (and the 1.6–2.2 Pg of carbon therein), in private hands. In Table 2 we break down remaining forest cover and carbon according to the types of property on which they are located. We also illustrate this distribution in Fig. 5 and Supplementary Fig. 1, where we map Mato Grosso's remaining forest cover and carbon reserves according to property category. We find that of the non-protected areas registered in the CAR or LAU databases or included as assentamentos, most of the state's forest cover, or nearly 150,000 km² of forest, are located on large or mega-scale properties (for example, over 1,000 ha). In contrast, only a tiny fraction, or less than 14,000 km² of the state's forest cover (including only 10,000 km² in the Amazon biome), is located in small properties or in assentamento areas.

Given the distribution of remaining forest by property size, and the differences in biomass across the biomes, we estimate that most of the state's privately owned carbon reserves are also held on large properties. Overall, nearly 80% of the state's carbon reserves registered in the CAR and LAU databases, or in assentamento areas, are located in properties larger than 1,000 ha. Only 6% are located in assentamento areas, or on properties less than 250 ha.

Targeting forest policy

Brazil's newest plan to protect the Amazon PPCDAM III (Plan for the Control of Deforestation in the Amazon III) suggests that government enforcement, having made gains in reducing forest loss among large landholdings, should turn towards reducing deforestation in smallholder farms[25]. This plan is in many respects supported by recent work showing that small farms account for a potentially increasing share of forest loss in the Amazon, and are often deforested at higher rates[6]. PPCDAM III also explicitly highlights the importance of examining whether payments for ecosystem services might serve as a viable means for reducing forest loss. This policy instrument draws also on recent discussions and policy-focused academic papers that suggest that payments for ecosystem services, specifically payments for avoided deforestation on small farms, might be a way to not only reduce deforestation, but also serve as a mechanism for poverty alleviation[26–28].

The present analysis challenges that narrative, at least for Mato Grosso. Our results certainly show that small farms continued to contribute non-negligible amounts of deforestation, and have higher deforestation rates. However, high rates of forest loss on small properties may result in significantly lower impact carbon emissions than lower rates of forest loss over a broader area. This is largely true for relatively small and large properties in Mato Grosso. Smaller properties certainly exhibit higher rates of clearing, yet it is the larger properties that today possess most of the state's remaining forest. Policy instruments should continue to focus on the largest landowners. If environmental interests do seek to implement a plan for payments for avoided deforestation they will need to recognize that, for such a plan to be successful, it would require significant cash transfers to already wealthy landowners.

The largest remaining forest tracts in Mato Grosso are concentrated in the possession of only a select subset of landowners. At present, fewer than 2,000 properties registered with SEMA are larger
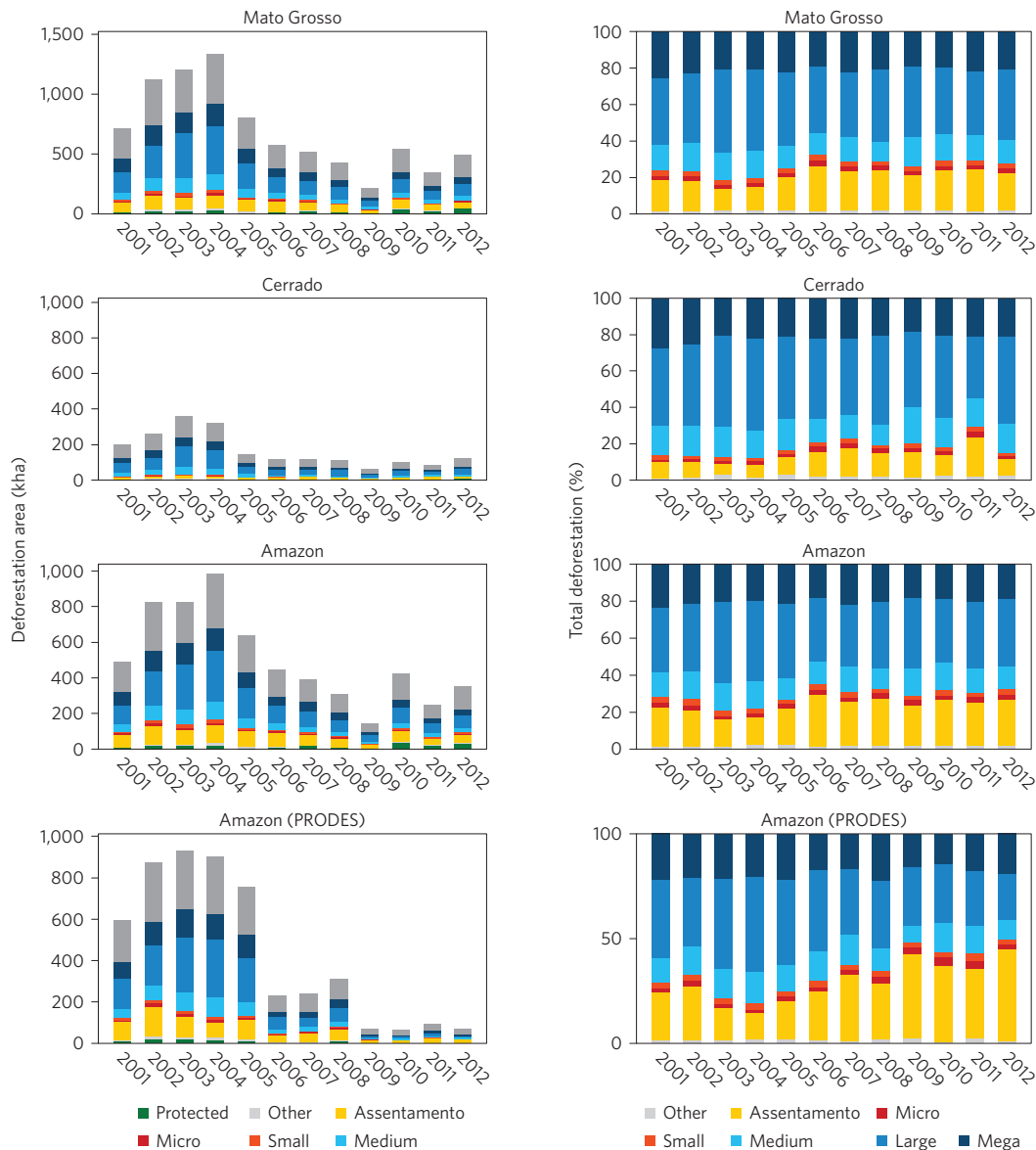
Figure 4 | Total and percentage of total deforestation by property category. Total deforestation (left panels) refers to total hectares (in thousands) of deforestation in Mato Grosso per year. Amazon and Cerrado refer to the total deforestation in each of these biomes. The upper three rows are based on the GFC deforestation data. The bottom row is based on Brazil's PRODES deforestation data set. The panels on the right showing percentage of total deforestation by year exclude protected areas and areas that are not registered in the CAR system.

than 5,000 ha. The number of people who control these properties, and the nearly 80,000 km² of forests that they cover, is likely to be significantly less, given that multiple parcels may be owned by a single individual, group or family. On their own, these owners of mega-scale properties possess the equivalent of more than 500 Tg of carbon in above-ground live biomass. They will face an ongoing tension in the coming years, as their incentives to clear their lands and remove the standing forests are weighed against state-imposed penalties, or in the case of legal deforestation, the bureaucracy that often stands as the last obstacle before forest clearing in the Amazon.

The future of the forest

Over the past decade Mato Grosso has grown tremendously on the strength of its agriculture and ranching sectors[29,30]. The soybean sector in particular generates a tremendous amount of foreign exchange for the Brazilian economy and has contributed to local growth in employment and GDP (gross domestic product)[31]. However, this past growth has not come without cost, and recent research has

stressed the impact of the state's agricultural growth on its forest cover, both directly and indirectly[32–37]. In the coming decades, there is also likely to be nowhere in Brazil where landowners will have a greater incentive to clear new lands, or where forest cover will be under greater pressure for development, than in Mato Grosso[38].

We estimate that private properties in Mato Grosso contain more than 2 Pg of carbon in above-ground live biomass, the equivalent of approximately one-half of the state's historical emissions[8]. As land values rise across Mato Grosso, or across the Amazon more broadly, landowners will face a still-greater incentive to clear their properties of their remaining forest cover. As policymakers consider avenues for preserving these carbon reserves in their natural land covers, we argue that they must continue to focus on the extensive tracts of forest cover located on the many large properties across the state. Maintaining these forest tracts will require maintaining the bureaucratic and legal obstacles that have served as their last line of protection. Similarly, more information is needed on the still extensive areas that remain under private

Remaining forest, by property category
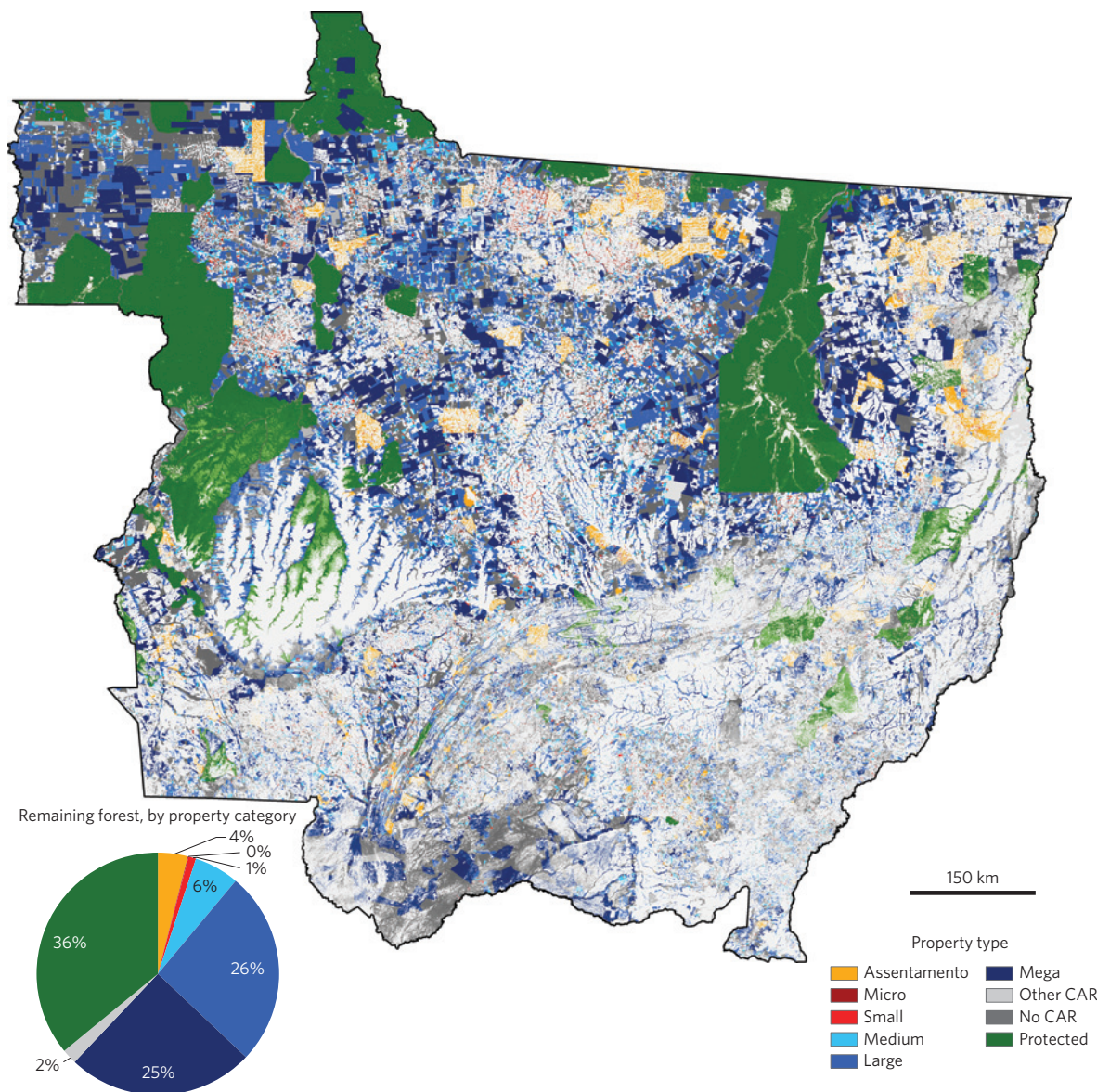
Figure 5 | Remaining forest cover in Mato Grosso, by property size category. 2012 forest cover, as measured in the GFC data. Darker shades indicate denser forest cover. Much of the remaining forest in the state pertains to large landholders. See main text for definitions of each property type.

ownership, but which are unaccounted for in the Mato Grosso's environmental registry.

Global land use change

No state in Brazil is more dominated by large properties than Mato Grosso. In 2006 (the year of Brazil's most recent agricultural census), more than 75% of Mato Grosso's agricultural and ranch areas was held in properties larger than 1,000 ha (ref. 39). This is significantly higher than the other Amazon states in Brazil, including Pará (50%), Amazonas (43%) and Rondônia (35%). Consequently, although we emphasize the importance of large properties to forest preservation in Mato Grosso, the relative importance of large farms and ranches may be less elsewhere in the Amazon. Whether large farms control most of the remaining forests in these states, however, remains unclear. As the rest of Brazil has lagged behind Mato Grosso in developing an environmental registry, it is impossible to accurately assess the relative control of small or large farms over these states' forest reserves. We thus hope that in the coming years, as more Amazon properties enter into the CAR system basin wide, future studies using the same methods used in this

analysis will better reveal the distribution of forest ownership across the basin.

We also recognize that Mato Grosso's structure of land ownership differs from structures of landownership in many of the other key forest global forest areas[40]. Yet in these areas, research has broadly documented trends towards private ownership. In China, where forests were once divided between state and community ownership[41], since 2003 control has incrementally shifted towards to individual ownership or long-term contracts[42,43]. Across sub-Saharan Africa, a similar trend has emerged, with forest ownership gradually transferring from community or state institutions to international investors, generally through long-term agricultural leases or mineral concessions[44,45]. A similar process has been carried out in Indonesia, where forests, once regarded as public goods, shifted first from centralized to local control in the late 1990s, and then from local control to logging or agricultural companies[46].

As more of the world's forests are shifted to private ownership, governments and environmental interests will increasingly need to work with these owners to secure their preservation. In the future, it will be vital that policymakers and environmental interests are able

to accurately identify the individuals or interests that control these resources and tailor their responses appropriately.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions

P.D.R. devised the study. P.D.R. and L.V. designed the experiments. P.D.R. conducted the experiments. P.D.R. and L.V. wrote the manuscript. All authors approved this manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to P.D.R.

Competing financial interests

The authors declare no competing financial interests.

Methods

Data sources and processing. We used seven data sets in this analysis. We first acquired data on property boundaries for the State of Mato Grosso from SEMA. Second, we downloaded data on forest loss and remaining forest cover from the Global Forest Change (GFC) data set, which provides a standardized, high-resolution map (1 arcsec) of annual forest loss from 2000 to 2012 (ref. 7). Third, we also used Brazil's National Institute of Space Research's Monitoring Deforestation in the Brazilian Amazon by Satellite Project (PRODES) data[49]. We note that although the PRODES data are widely used in studies of forest loss, they do not capture land use change outside the Amazon biome, a substantial portion of the state of Mato Grosso. We thus use the PRODES data as an alternative source for measuring deforestation for the portion of the state in the Amazon biome. Fourth, we downloaded data on the location of public agricultural settlements, or assentamentos, from the National Institute for Colonization and Agrarian Reform. Fifth and sixth, we downloaded data on protected areas and biomes from the Brazilian Ministry of the Environment. Finally, for our seventh and eighth data sets we used the Amazon Basin Aboveground Live Biomass Distribution Map (AGLB), produced in ref. 47 and the Pantropical National Level Carbon Stock Dataset (PCSD), from ref. 48. To ease comparison of the data sets, we projected each data layer into an Albers equal-area projection. We also standardized all of the raster data sets to the pixel size associated with the GFC data ($31.4546412\,m^2$, approximately 1 arcsec in Mato Grosso). Before analysing the CAR and LAU data sets we needed to complete several steps of processing.

First, several properties were duplicated in the databases. The duplications stem from a number of potential issues related to the licensing process. In some cases new owners may register their new property with a CAR or LAU after purchase, even if the previous owner had already obtained the documentation. Similarly, a landowner may have submitted a revised CAR, but the initial documentation remains in the system. Second, overlapping boundaries also posed an issue. As the CAR and the LAU are produced at the grass roots level (usually by a private technician, NGO (non-governmental organization) or by the farmer himself), and then only later compiled by SEMA, many of the properties slightly overlap. Unfortunately, it was impossible to distinguish the true property to which an overlapped area pertained. To account for these issues, we processed the data using the delete identical feature in ArcGIS, to remove duplicated features, and used ArcGIS's typology tools to identify any overlapping boundaries. We marked these latter areas as overlapping, and set these areas into their own category, namely 'Other CAR'. We then categorized Mato Grosso into the nine specified property categories, from assentamento to mega-scale properties. We also further subdivided the state according to the two largest biomes: the Cerrado and Amazon regions.

We used the PRODES data set for analysing forest cover and deforestation within the Amazon biome portions of Mato Grosso only. We did not include a separate biome for the Pantanal region.

Measuring forest cover and deforestation. The PRODES data provided straightforward classifications of forest loss and forest cover. We used these classifications to determine forest loss in 2000 and 2013, as well as annual deforestation by each property category. However, calculating total forest cover from the GFC data set, where forest cover is shown as a percentage, required an additional calculation. For the GFC data we multiplied each pixel according to its percentage of area in forest, and then by $31.4546412\,m^2$, to convert from arc seconds to square metres. Finally, to calculate remaining forest areas in the GFC data we subtracted areas classified as deforested from forest cover in 2000, and recalculated the forest area for 2013. For the PRODES data, we used remaining forest cover in 2013.

Measuring remaining above-ground carbon stocks. The PRODES data are produced as a binary forest–non-forest classification for each area, allowing us to mask out pixels that are non-forest and sum the biomass in those pixels classified as forest.

The GFC data product we used was the percentage of canopy cover, itself a measure of biomass; we therefore used an arbitrary decision rule to identify pixels in the GFC product as forest and then sum the biomass in those pixels. We used all pixels reported in the GFC product as having 1% or more forest cover.

We used the AGLB and PCSD carbon maps as our basis for estimating remaining carbon stocks. The AGLB data, however, are shown according to one of twelve classification categories, and range from 0 to more than 400 mg of biomass per hectare. Classification levels increase in 25–$50\,mg\,ha^{-1}$ increments. We classified each pixel according to the middle value (for example, all pixels estimated as having between 25 and $50\,mg\,ha^{-1}$ of biomass were classified as having $37.5\,mg\,ha^{-1}$). The PCSD data are continuous, and range from 0 to $411\,mg\,ha^{-1}$. The PCSD data generally indicated higher levels of biomass than the AGLB biomass map. To calculate remaining carbon we needed to convert we summed the values in the AGLB and PCSD data sets for all pixels classified as forest within each property size class, to estimate biomass by property size. Following recent research[50], we multiplied this estimate of total remaining biomass by 0.5 to convert biomass to carbon[51,52].

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