Supporting information for

Actor specific contributions to the deforestation slowdown in the Brazilian Amazon

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This document provides supplementary information (SI) to support and further explain the data and analyses presented in the manuscript “Actor-specific contributions to the deforestation slowdown in the Brazilian Amazon”. The SI is divided into five main sections: 1) Assessment of the spatial patterns of actor dominance in the Brazilian Legal Amazon (BLA) based on property size, 2) Deforestation, land-use and demographic data, 3) Sensitivity analyses of actor-specific deforestation contributions, 4) Landscape configuration metrics, and 5) Targeting of government embargos and fines on larger properties. The sensitivity analyses section assesses the potential of five factors to influence the generality and robustness of our results on actor-specific deforestation contributions, namely: the choice of actor-dominance threshold to classify census tracts; differences in deforestation dynamics between both states and biomes; the distinction between smallholder dominated areas that do or do not have agrarian reform settlements, and the potential for bias due to mismatches between property boundaries and census tract boundaries. Taken together the results of these analyses suggest that our findings of changing actor-specific deforestation contributions during the slowdown period 2004-2011 reflect consistent differences in actor-specific deforestation behavior.

1. Assessment of spatial patterns of actor dominance in the Brazilian Legal Amazon based on property size

Landholders occupying the BLA can be classified with respect to a wide array of criteria (1). For the purposes of our analysis we focused on property size because it is widely recognized as the single most important proxy of differences in land-use amongst rural Amazonian landholders (e.g. Fig. S1). The Brazilian Government uses an area-based rule to differentiate actors for a variety of regulations and public policies by defining so-called fiscal modules. Although the size of a fiscal module varies slightly between municipalities in rural areas of the BLA to account for variability in production and market conditions (between 50-100 ha), more than half (56%) of the municipalities have a module of between 70-80 ha according to the Brazilian Geographical and Statistical Institute (IBGE). Distinguishing actors based on property size also confers an additional advantage of facilitating comparisons with previous studies of deforestation patterns in the Amazon (2, 3).

Actor dominance was calculated using the property size distribution reported at the census tract (CT) level in the 2006 IBGE Agricultural Census. As such we used an analysis of property size dominance for 2006 to draw inferences about property size dominance for the entire 2004-2011 period of analysis. This is an unavoidable shortcoming of the available data but we believe that the assumption is robust given the relative short time span of our study period, and that the 2006 survey data can provide a meaningful representation of the spatial heterogeneity in the size distribution of rural properties in the Amazon.

The Brazilian agricultural census provides information on economic, social and environmental characteristics of properties involved in some form of agriculture, including forestry and aquaculture, for all municipalities in Brazil. The census is conducted approximately once every decade. Each Brazilian municipality is divided into census tracts (with approximately 300,000 in total and available for download[*]), the boundaries of which are defined according to the workload and logistical difficulties facing IBGE surveyors. Survey data are not available for approximately 30% of the BLA, mostly corresponding to a relatively small number of large CTs situated in very scarcely populated areas, often coincident with reserves and indigenous lands (see Figure 1). Overall the survey accounted for 871,559 properties, which covered 1,163,904 km^2, or about one-fourth of the total BLA area.

Census tract-level information is available on public request from IBGE. Census data at the scale of individual census tracts offer the finest-scale assessment of associations between deforestation patterns and socio-economic variables that is possible to achieve to date, and represents a significant improvement over analyses conducted at the scale of municipalities (4). For example if our classification approach is applied at the municipal level, the largest Amazonian municipality (Altamira, 159,695 km^2) would be classified as dominated by very large landholders (54.5% of the area of all municipal surveyed properties), when in fact much of Altamira is made up of indigenous and conservation areas. By contrast, our analysis at the level of the census-tract identifies that, out of the total of 213 CTs that make up Altamira, 146 correspond to remote or urban areas, 22 are dominated by smallholders and only 17 are dominated by very large landholders.

[*] http://downloads.ibge.gov.br/downloads_geociencias.htm

IBGE provides the number of properties belonging to 18 different property size classes for each rural CT. For calculating the area occupied by each class, instead of assuming that a surveyed property would have the size of the central value of the class size to which it belongs, we used the data on average property size per class at state level[†] (the finest-scale available) to calculate the area occupied by the properties of a given property size class in each CT. We reclassified these data into four groups, such that: i) “smallholders” equate to properties of up to 100 ha – a classification commonly adopted by other researchers (5-10); ii) “medium” sized properties are between 100 and 500 ha; iii) “large” sized properties are between 500 and 2500 ha; and iv) “very large” sized properties are greater than 2500 ha. Classes are exclusive, with properties that are exactly the same size as a class boundary being allocated to the smaller size class.

Actor dominance for individual CTs was determined based on the size class that represented more than 50% of the area of all sampled properties in each CT. Where no actor type accounted for at least half of the sampled area the two most dominant consecutive property size-classes were used, resulting in three additional mixed-property size classes (“small and medium”, “medium and large” and “large and very large”). The simple majority criterion of 50% to define dominance in a given CT was adopted after first testing a range of thresholds. A 50% threshold to describe actor dominance has been used in another recent study on deforestation in the Brazilian Amazon (4). More stringent thresholds have the effect of increasing the proportion of CTs with mixed size classes, limiting our ability to characterize actor dominance across a large area of the BLA. That said, the main conclusions of our analysis are robust to choice of dominance threshold, with qualitatively very similar results even when using a very conservative 90% threshold (see section 3.1 below). We also assessed potential biases due to mismatches between property and census tract boundaries by assessing the spatial coverage of sampled properties and the size distribution of adjacent CTs (see section 3.5 below).

† http://www.ibge.gov.br/home/estatistica/economia/agropecuaria/censoagro/2006_segunda_apuracao/default_tab_uf_xls.shtm

2. Deforestation, land-use, demographic and property size data

Annual deforestation was mapped using PRODES data for the 2004-2011 period, and pre-slowdown data from 2001 was included to determine deforestation rates before the slowdown[‡]. It was not possible to look at deforestation rates prior to 2001 because PRODES maps covering the whole Brazilian Legal Amazon (BLA) are only available since this date. For the images in the period 2005-2011 INPE provides geo-referenced raster images for each state. Using the software GRASS GIS all images were mosaiced and subsetted by the BLA boundaries available at IBGE. Information between 2002 and 2003 was incomplete with entire scenes missing and/or excessive amount of unknown areas due to cloud cover, and thus were not included. The maps for 2001 and 2004 required special treatment because the only available information is in vector format. For these two years a topology clean was performed for each Landsat scene used in the PRODES project, and all scenes were then subsequently merged. The codes describing land use were recoded for consistency with the codes of the 2005-2011 raster images (classes forest, deforestation, water, non-forest, unknown). The resultant vector map was rasterized to match the spatial resolution of the other years in the study period (120 m).

The resulting BLA maps presented a varying amount of unclassified areas (mostly due to cloud cover). For all years these areas were filled up where possible with information from the map of the immediately previous year. To eliminate sources of uncertainty in multi-temporal comparisons the largest contiguous unknown area in the 2001 mosaic (accounting for 6.3% of the BLA, mostly in the states of Tocantins and Maranhão) image was masked from the analysis for all years. Information on land-cover and land-use change was extracted for each census tract (CT) using the r.statistics module of GRASS GIS. By crossing land cover data with the actor dominance in each CT (see below) we could obtain data on land-use change for each actor type in the period 2004-2011, and calculate the average deforestation rate of each actor prior to the deforestation slowdown in the 2001-2004 period (e.g. Figure S4).

The deforestation estimates used in our analyses, by crossing LULC data and actor dominance, are very similar to those calculated by INPE since they are based on PRODES maps produced by INPE.

[‡] http://www.dpi.inpe.br/prodesdigital/dadosn/

However they are not identical because of methodological discrepancies in estimating annual deforestation. These are related to our use of land-use mosaics for the whole BLA to obtain the deforestation rates between all studied dates and for areas dominated by different actors. By contrast, INPE´s approach is based on information from individual LANDSAT scenes which are often obtained on different dates. This means that INPE´s deforestation rates take into account the date discrepancy of each Landsat scene against a fixed baseline date; the first of August for each year[§].

Furthermore, while INPE estimates land-cover in unknown areas from percentages of land use in the part of the same LANDSAT image that is classified, we excluded those areas from the analysis for all dates after filling unknown areas with information from the image in the previous year. This approach was chosen because our goal was not to estimate deforestation rates for the BLA (since INPE estimations are reliable for this purpose), but to compare the deforestation performance and dynamics of different actors. As such we assumed that classifying unknown areas based on the land-cover composition of the rest of the Landsat scene they belong to would decrease the accuracy of our analysis. The combination of all these discrepancies leads to a sum of deforestation rates between 2004 and 2011 differing by only 2.36% from those of INPE. However, for the sake of clarity and consistency in presenting annual rates of deforestation and avoided deforestation per actor type, we extrapolated the deforestation rates and land cover shares obtained with our method to those provided by INPE[**].

For the DEGRAD maps a simple rasterization was required. All geographical datasets were re-projected when necessary to a common spatial reference (GCS_SAD69). At the time of our analyses only data for the period 2007-2010 was available.

To estimate property size distributions for each CT we extracted information from the Brazilian agricultural census of 2006 for 37,289 CTs samples within the BLA, and classified them into three types: i) 13,303 CTs with sample data available on the size distribution of private properties. They

[§] http://www.obt.inpe.br/prodes/metodologia.pdf
[**] Obtained from http://www.dpi.inpe.br/prodesdigital/prodesmunicipal.php

cover 69.9% of the BLA area, 30.7% of the total 2010 BLA population of 25.47 million people and 85.7% of the area deforested by 2011. Actor dominance was calculated only in those CTs which provided the basis for all further analyses on actor-specific differences in deforestation and forest condition; ii) 5028 CTs in remote and sparsely populated rural areas where IBGE did not collect information on the property size distribution, and thus it was not possible to quantify actor dominance – though changes in deforestation and forest condition in these areas were assessed for comparison against actor-dominated areas. They account for 29.9% of the area, 7.0% of the population and 14.3% of the deforestation by 2011; and iii) 18,958 CTs in urban sectors, which account for 62.2% of the population, but for only 0.2% of the BLA area and a negligible percentage of deforestation. Census data was made spatially-explicit and integrated in a GIS environment using GRASS GIS.

To assess the population density of different agricultural CTs we used the Brazilian Population Census of 2010, the only population census produced within the study period we considered. However the CT boundaries of the agrarian census and the population census are not identical for all cases. To maximize fidelity in matching agrarian and population census data we calculated the centroids of all CTs from the population census boundaries, and associated the population of each CT to its respective centroid in a GIS environment. Next, we linked the actor dominance in each CT polygon with the population data of the overlapping centroid for each polygon. While many of the CT boundaries are identical in both censuses, this approach ensured that any discrepancies were further minimized. Although the population figures are not central to the results of the paper, they highlight the key fact that, in absolute terms, smallholders dominate the rural population of the Brazilian Amazon. Information from the IBGE agricultural census and demographic census was then made spatially explicit through merge and join operations based on common official CT descriptors.

3. Sensitivity analyses of actor specific deforestation contributions

3.1 Choice of dominance threshold used to classify census tracts based on the distribution of property sizes

In the absence of detailed spatially-explicit property data for the BLA, our approach assumes that classifying CTs in terms of actor dominance based on property size provides an adequate representation of the deforestation dynamics of actors for each CT. As such the choice of dominance threshold could have an important influence on the inferences made about different actor contributions to overall patterns of deforestation. However, we found that the actor-specific contributions to deforestation are qualitatively similar when using different dominance thresholds. The most robust demonstration of this can be seen when setting a 90% threshold to assign dominance of individual CTs. As seen in Fig. S4, which displays the same type of analysis as Figure 3 in the manuscript, the results of CTs with a 90% dominance threshold closely mirror those of the CTs with a simple (50%) threshold. In other words, CTs dominated by very large landholders show a marked decrease in their share of annual deforestation whilst smallholders show a concomitant increase (especially in the more recent years). Annual deforestation rates decrease for all actors, but the decrease is more marked for very large landholders than for smallholders. Patterns of forest degradation dynamics also follow a very similar pattern (Fig. S4).

3.2 Spatial heterogeneity in actor-specific deforestation dynamics between different states of the BLA

Our analysis draws conclusions about actor-specific contributions to deforestation for the entire BLA. However it could be argued that contributions of a given actor may differ in different areas, such as in states where the frontier is already consolidated versus states where agricultural expansion is currently more intense. Moreover, some states are strongly dominated by specific types of actors (e.g. much of Mato Grosso is dominated by large landholdings, see Figure 1), which may bias conclusions about the deforestation dynamics of specific actors across the entire BLA. To assess this we compared the percentage share of annual deforestation for CTs dominated by each actor type between the six major states of the Amazon (Pará, Mato Grosso, Rondônia, Amazonas, Acre, and Roraima – accounting for 93.0% of total deforestation between 2004-2011), mirroring the analysis presented in Figure 3b (see Figure S5). Despite systematic differences in the land-use and actor make-up of each state (e.g. Mato Grosso being dominated by large-landholdings and soy producers; Pará and Rondônia being dominated by many more smaller properties and cattle producers) the overall pattern is the same, with a contrasting decrease in the % deforestation contribution by CTs dominated by large properties and increase in the % deforestation contribution by CTs dominated by smallholders. This is observed by comparing the very similar slopes of the linear regression functions of small and very large landholders in Figure S5. In all cases smallholders have a positive slope while very large landholders show a decreasing tendency (negative slope). Indeed, despite representing starkly different realities the % deforestation contribution by smallholders increased between 2004 and 2011 for the 5 largest of the 6 states (Pará 14%, Mato Grosso 44%, Rondônia 21%, Amazonas 8%, and Roraima 57%), whilst Acre showed no consistent trend.

3.3 Spatial heterogeneity in actor-specific deforestation dynamics between the Amazon and Cerrado biomes within the BLA

In accordance with the majority of scholars studying the Brazilian Amazon, and the convention used by the Brazilian Government, we have defined our study region following the boundaries of the Brazilian Legal Amazon (BLA), which is composed of two different biomes – the Amazon and the Cerrado. While the Amazonian biome covers more than four fifths of the BLA, the Cerrado occupies more than half of the state of Mato Grosso, which along with Pará is one of the most deforesting states in the Brazilian Amazon and the focus of the current expansion of large-scale mechanized farming. To test if actor-specific deforestation dynamics observed for the entire BLA are similar for forests in each of the two biomes we used the official biome boundaries provided by the Ministry of the Environment to directly compare annual deforestation rates and contributions (Figure S6). Overall, we found that the pattern of deforestation amongst CTs dominated by different sized properties in the Cerrado biome is very similar to that observed for the Amazon biome, with areas dominated by very large and large landholders decreasing their deforestation rates much more than areas dominated by small and medium landholders or remote areas. A larger year-to-year variability is observed in the Cerrado, especially among the smaller landholders, which is a consequence of the smaller size of the Cerrado sample of CTs, coupled with the fact that the proportion of smallholder CTs is considerably smaller there than in the wider Amazon. The overall relative decrease of deforestation in CTs dominated by very large landholders and increase in smallholder dominated CTs is nearly identical in both biomes, as seen by comparing the slopes of the linear regression of their respective deforestation dynamics in Figure S6.

3.4 Distinction of deforestation contributions between smallholder dominated census tracts that are comprised of agrarian reform settlements, and those that are not

Agrarian reform settlements, established by the Brazilian government agrarian reform agency INCRA host a large number of smallholders in the BLA and are often viewed as hotspots of deforestation activity. It is therefore important to know whether our findings are general to all smallholder dominated areas, or if they are being driven by the behavior of landholders in INCRA settlements in particular.

We observed that smallholder dominated CTs that have any overlap of INCRA settlements within their borders account for 30.8% of the total smallholder CTs (1910 out of 6193 census tracts), and have a mean percentage of accumulated deforestation (2004-2011) of 59.7±36.5 compared to 56.6±43.0 for all smallholder dominated CTs. Figure S7 shows that both types of smallholder dominated CTs follow the same general deforestation pattern over time, with an increase in their contribution to annual deforestation rates with respect to 2004, and a smaller year-to-year decrease in their annual deforestation rates when compared to changes observed for larger actors. That said, and contrary to popular expectation, the smallholder dominated CTs with settlements did not exhibit a greater relative increase in their contribution to total annual deforestation (or a smaller concomitant decrease in their annual deforestation rate) than smallholder CTs without INCRA settlements (Figure S7). Instead, the opposite was true, with smallholder dominated CTs that lack settlements showing a greater relative increase in their contribution to annual deforestation. We can only speculate as to the reasons for this difference, such as a potentially higher visibility of deforestation activity in settlement areas, more focused enforcement and agricultural extension activities, but other factors may also be responsible.

3.5 Potential biases in actor-specific deforestation contributions due to mismatches between property and census tract boundaries

The agrarian census attributes information about farms that span CTs to the CT in which the headquarters of the farm are located[††]. This introduces the potential for mismatches between how CTs are classified with regards to the distribution of actors, and the actors that are

[††] http://www.ibge.gov.br/home/estatistica/economia/agropecuaria/censoagro/2006/notatecnica.pdf

responsible for deforestation activity within the CT. This problem is of particular concern for large properties that are more likely to span more than one CT. In the absence of available data on property boundaries for most of the BLA, we assessed the potential for overlap and mismatch errors to influence our results.

First, we calculated the percentage of the total area of each CT that is occupied by properties of each actor type, showing that for the majority of CTs the area occupied by the sampled properties is low, ranging from only 8% for smallholders to 59% for the largest (>2500 ha) properties (Table S1). The number of properties spanning more than one CT is therefore generally low. Second, we note that any bias in the classification of CT dominance from properties that overlap CT boundaries is only a problem (regarding the interpretation of our results) if overlapping properties span CTs dominated by different actor types. To assess the potential for overlap between differently classified CTs we conducted an adjacent polygons analysis in a GIS environment which determined that 48.5% of the CTs dominated by the largest landholders (> 2500 ha, i.e. the properties most likely to span CT boundaries) are adjacent to CTs dominated by the same sized actor, whilst 64.5% of their neighbors are either large or very large landholders (i.e. > 500 ha). The same pattern of spatial aggregation of properties sizes can be seen for smallholders, where 60% of CTs dominated by smallholder properties are adjacent to CTs also dominated by smallholders. This demonstrates that even if there are cases of properties overlapping some CT boundaries, the deforestation contributions of these properties would still be mostly attributed to large actors, providing reassurance that the CT dominance layer can provide us with an accurate assessment of actor-specific land-use dynamics.

4. Landscape configuration metrics

Landscape metrics were obtained for each census tract using a moving windows analysis in FRAGSTATS 4.1 (Table S5 and Fig. S8). The results were aggregated for CTs dominated by each actor type by calculating the median value of a given landscape metric for the entire CT. We selected well-known landscape configuration metrics, including: patch density (PD), edge density (ED), landscape shape index (LSI), largest patch index (LPI) and core area index (CAI). Other metrics were tested but were discarded after showing high correlation with selected measures in a principal components analysis. The relevance of these indices for assessing ecologically meaningful differences in fragmentation processes has been suggested by several studies (7, 11, 12). Edge depths of 1, 3, 10 and 25 pixels were calculated (1 pixel corresponds to 120 m), in order to account for fragmentation processes at various scales, although choice of edge depth did not alter the observed differences in patterns between the CTs dominated by different actors.

PD and ED are measurements of forest fragmentation that are calculated on a per unit area basis to facilitate comparisons between CTs of different sizes. While PD reflects the number of patches regardless of their spatial configuration, ED complements the assessment of fragmentation by estimating the edge or perimeter of forest in contact with non-forest features. These areas are subject to degradation and edge effects, which erode the ecological integrity of forest areas close to edges. LSI a simple measure of forest aggregation, with LSI values close to unity indicating a high degree of forest compactness into one single patch. LPI measures forest dominance, with values close to 100 indicating that the largest forest patch comprises 100% of the CT. CA is a measure of both habitat loss and fragmentation, with values ranging from 0 to 100. Values close to 100 indicate that each part of the forest is further than a specified distance from the forest edge, and is therefore buffered from edge effects. CA is a measure of forest integrity, estimating the proportion of forest at risk from degradation due to edge effects.

Landscape and forest fragmentation indices are presented for the entire BLA in the main manuscript and separately for each Amazonian state in Fig. S8 - showing geographic consistency in overall relative patterns. For example, similar to the results obtained at the scale of the entire BLA, smallholder dominated areas in all states present a lower forest edge density and landscape shape index than areas dominated by all other actors, as well as a higher largest patch and core area index (Table S5).

5. Targeting of government embargos on larger properties

In order to assess the extent to which command and control approaches target different-sized properties, we used data from the list of embargoed areas published by the Brazilian Institute of

Environment and Renewable Natural Resources (IBAMA)[‡‡], as seen in Table S6. The embargo is an administrative action that penalizes the environmental offender by blocking the possibility of selling the land, securing bank loans and inhibiting the sale of products from the embargoed areas. Embargoes are not reverted until the property owner officially rectifies all violations of Brazilian law.

Although the IBAMA list reports the area of the notified embargo and not the area of the whole property where the infraction occurred, we assumed that embargos affecting more than 100 ha cannot correspond to smallholder properties in accordance with our definition of smallholders, except if the embargo refers to agrarian reform settlements created by the National Institute for Colonization and Agrarian Reform (INCRA). However those embargoes are clearly defined by IBAMA as affecting agrarian reform settlements. INCRA settlements are comprised of small-scale farmers in properties that are almost always smaller than 100 ha. Thus our analysis is likely to overestimate embargoes in smallholder properties because embargos affecting less than 100 ha can still be linked to properties larger than 100 ha.

6. References

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[‡‡] https://servicos.ibama.gov.br/ctf/publico/areasembargadas/ConsultaPublicaAreasEmbargadas.php

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SI Figures and Tables

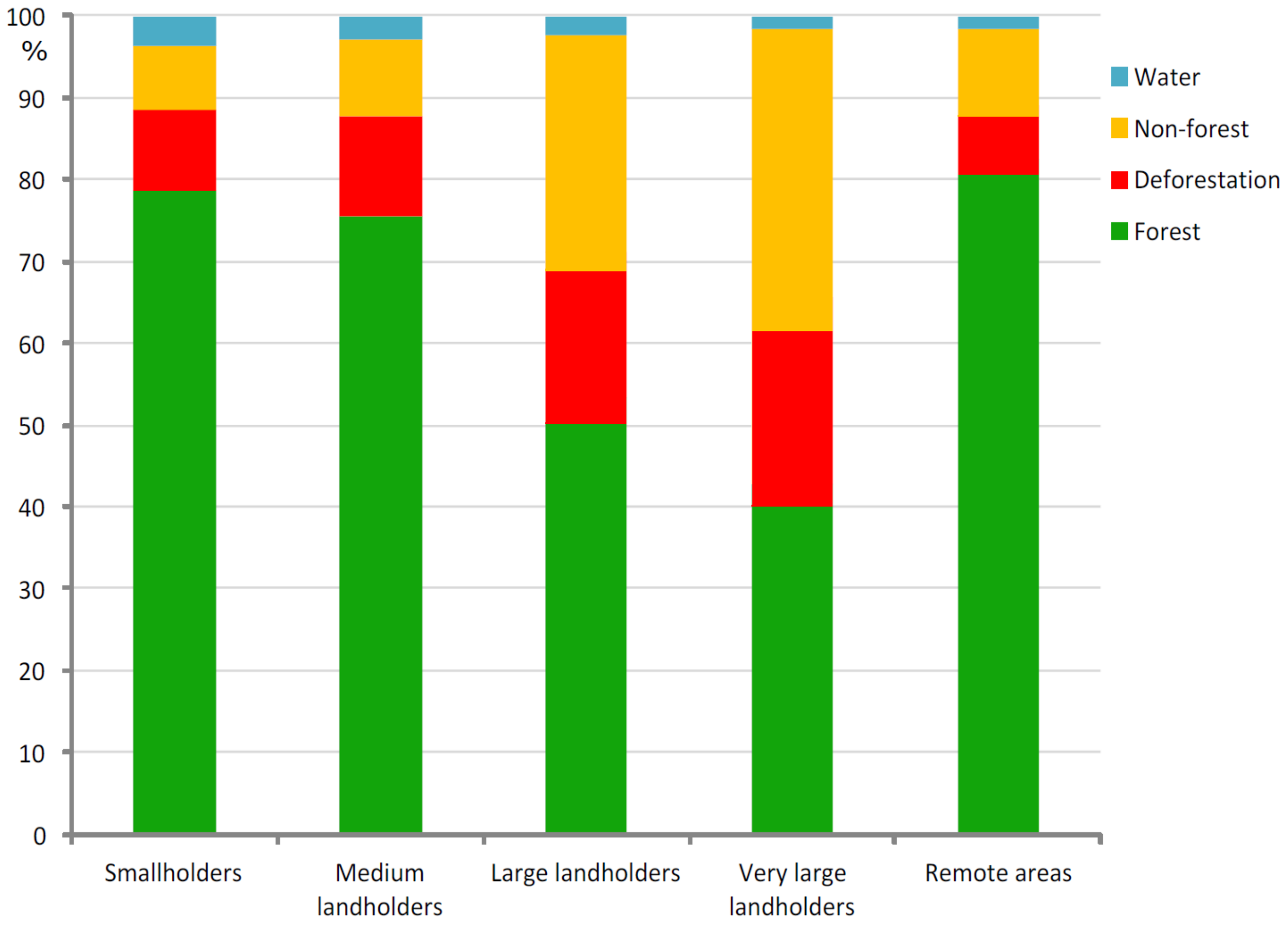

Figure S1: Land use composition per type of actor in the Brazilian Legal Amazon, year 2011. Mixed-actor classes were not included for the sake of clarity. The classes correspond to those of INPE PRODES. Source: Authors´ elaboration based on property size dominance from IBGE agricultural census and PRODES data from INPE.

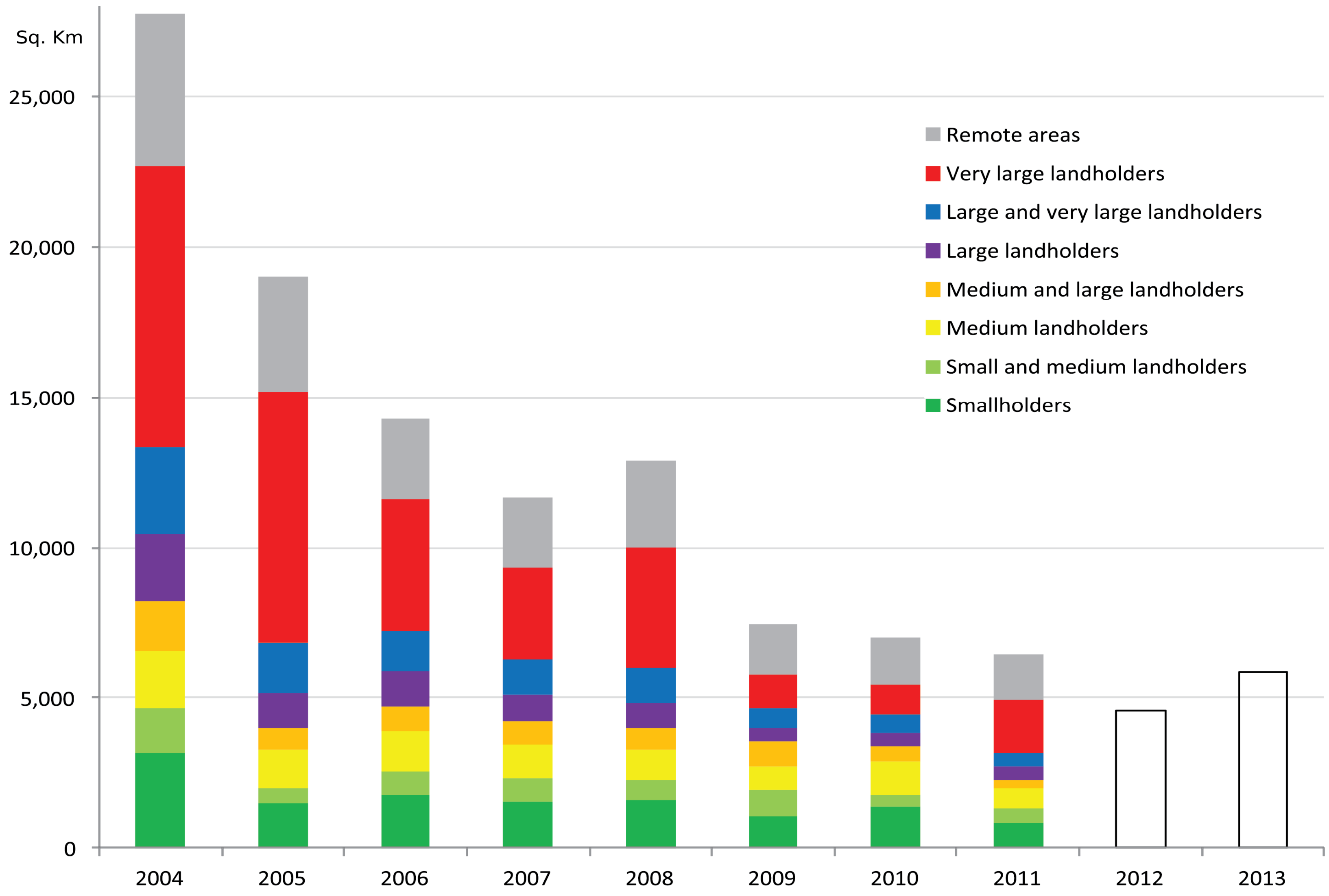

Figure S2: Share of annual deforestation per actor type during the deforestation slowdown in the Brazilian Legal Amazon 2004-2011. Stacked columns represent total annual deforestation rates in the BLA, as calculated by INPE. Data for 2013 is a preliminary estimation of INPE PRODES. All figures in km^2.

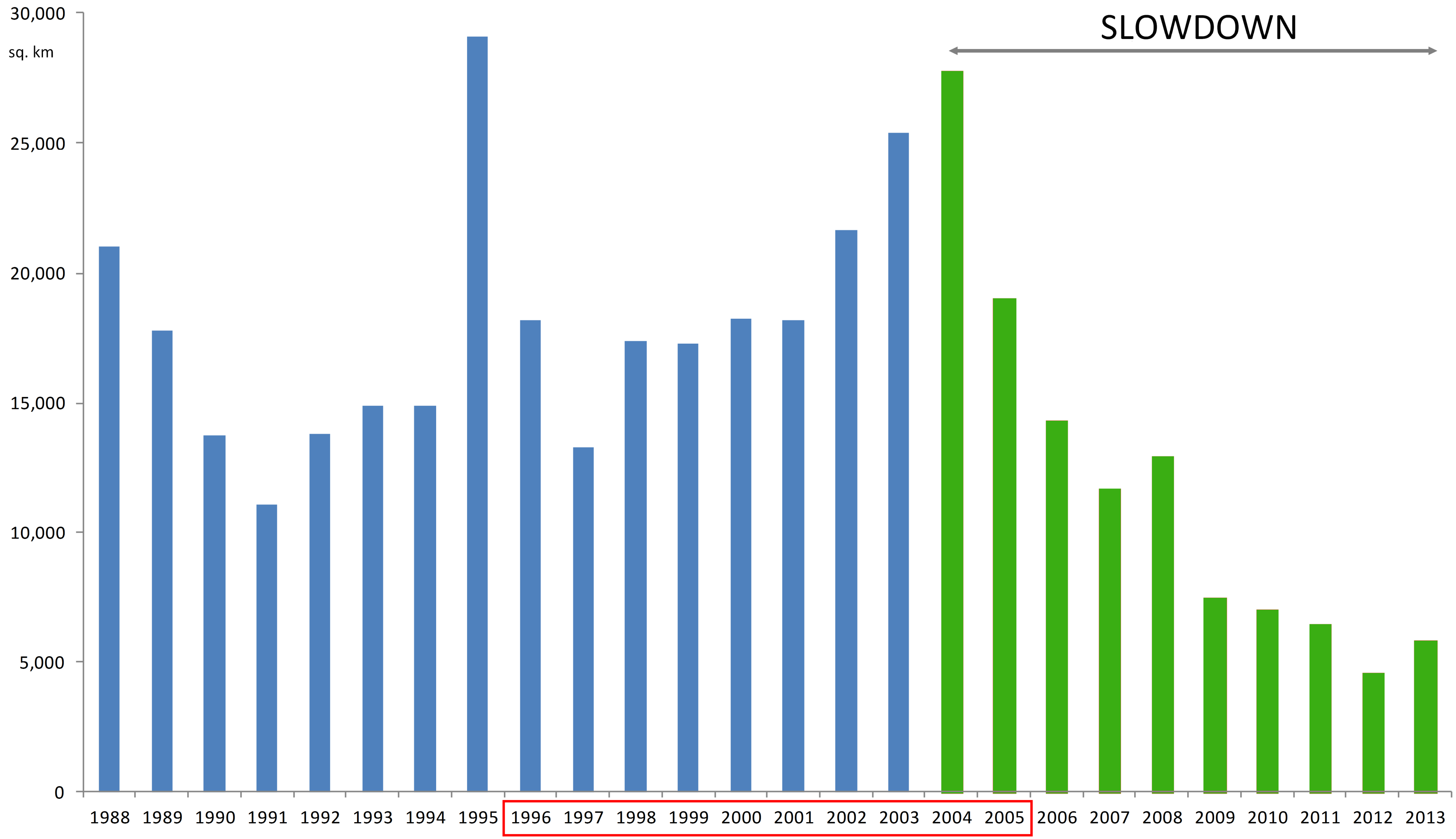

Figure S3: Annual deforestation in the Brazilian Legal Amazon (km^2), 1988-2013. Years marked in red correspond to the period the Brazilian government uses as a reference baseline for deforestation targets. The period of deforestation slowdown that forms the basis of this study is illustrated in green. Source: INPE PRODES.

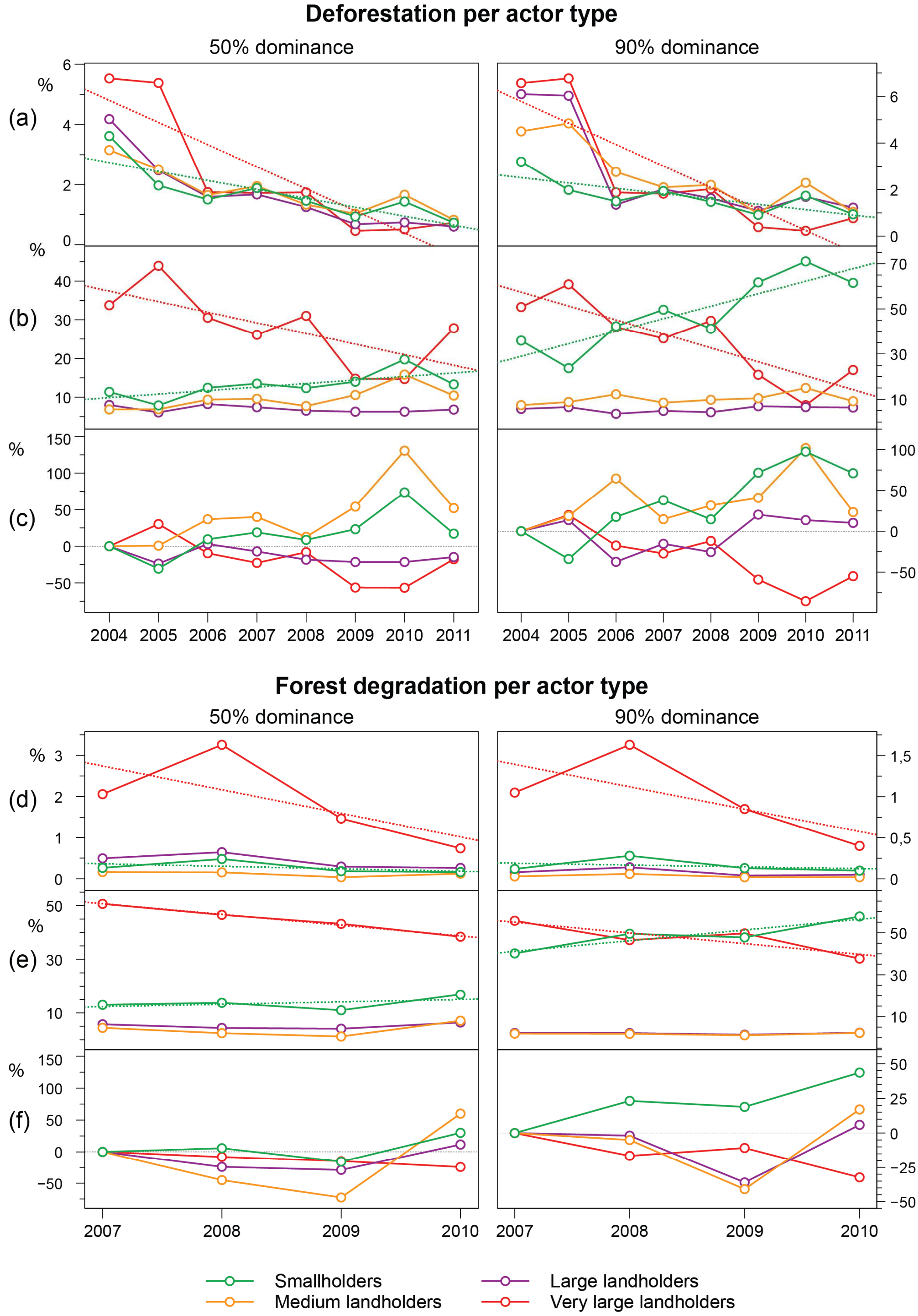

Figure S4: Sensitivity of temporal patterns of actor-specific deforestation dynamics to the choice of dominance threshold. CTs with an overwhelming single actor-specific dominance (90% area dominance threshold), were compared with the 50% threshold used in the main analysis to compare deforestation patterns with regards to: a) Annual rate of deforestation change, b) % share of annual deforestation, c) % share of annual deforestation relative to 2004 (baseline year), d) % forest degradation per ha of forest, e) % share of annual degradation, and f) % degradation share relative to 2007 (baseline year). For the sake of clarity mixed-actor classes were not included. The linear regression functions of the deforestation dynamics of smallholders (dashed green line) and very large landholders (dashed red line) are presented to facilitate comparison.

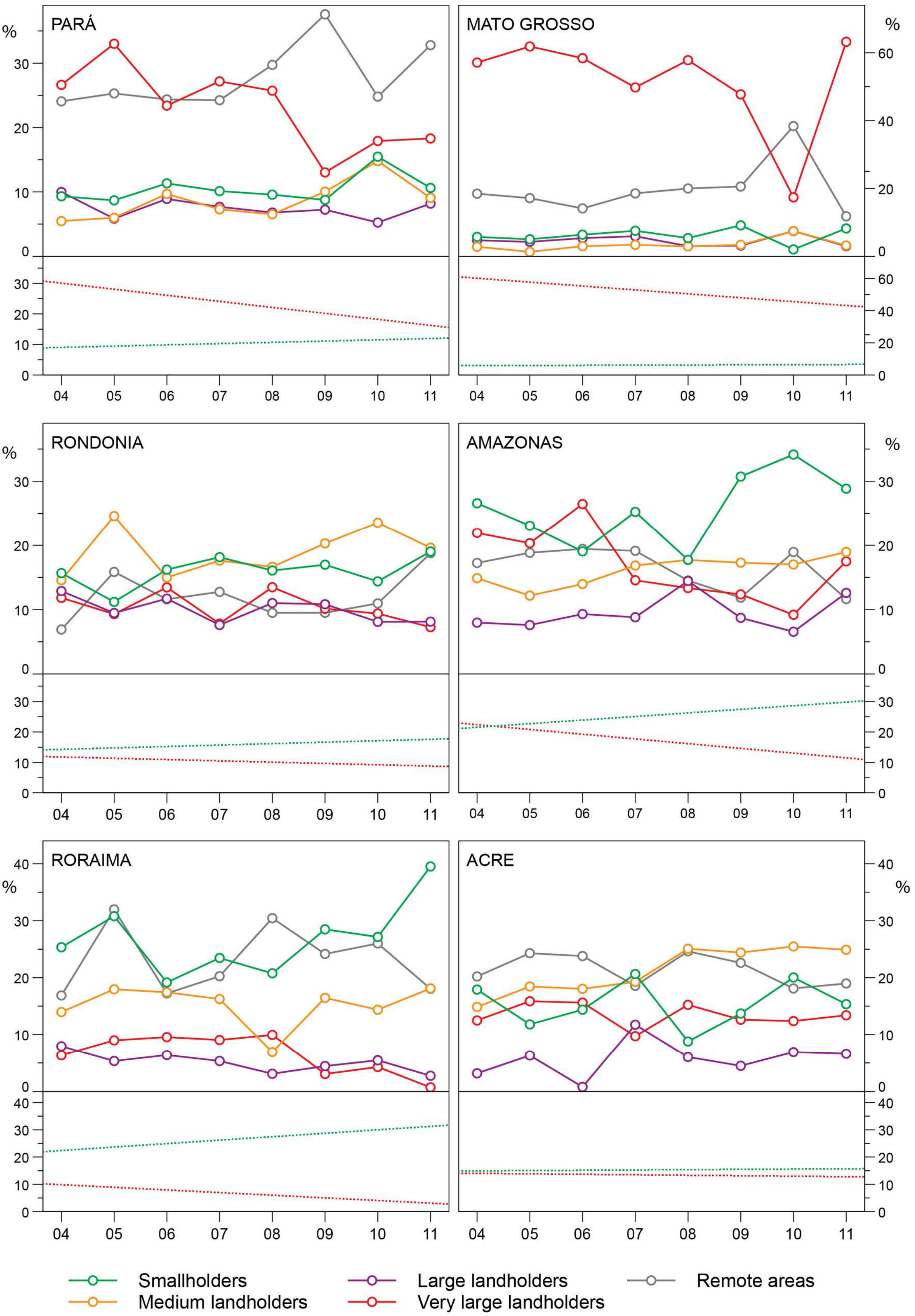

Figure S5. Actor-specific share of annual deforestation in the major states of the BLA. For the sake of clarity mixed-actor classes were not included. Below the subpanel of each state the linear regression functions of the deforestation dynamics of smallholders (dashed green line) and very large landholders (dashed red line) are presented to facilitate comparison.

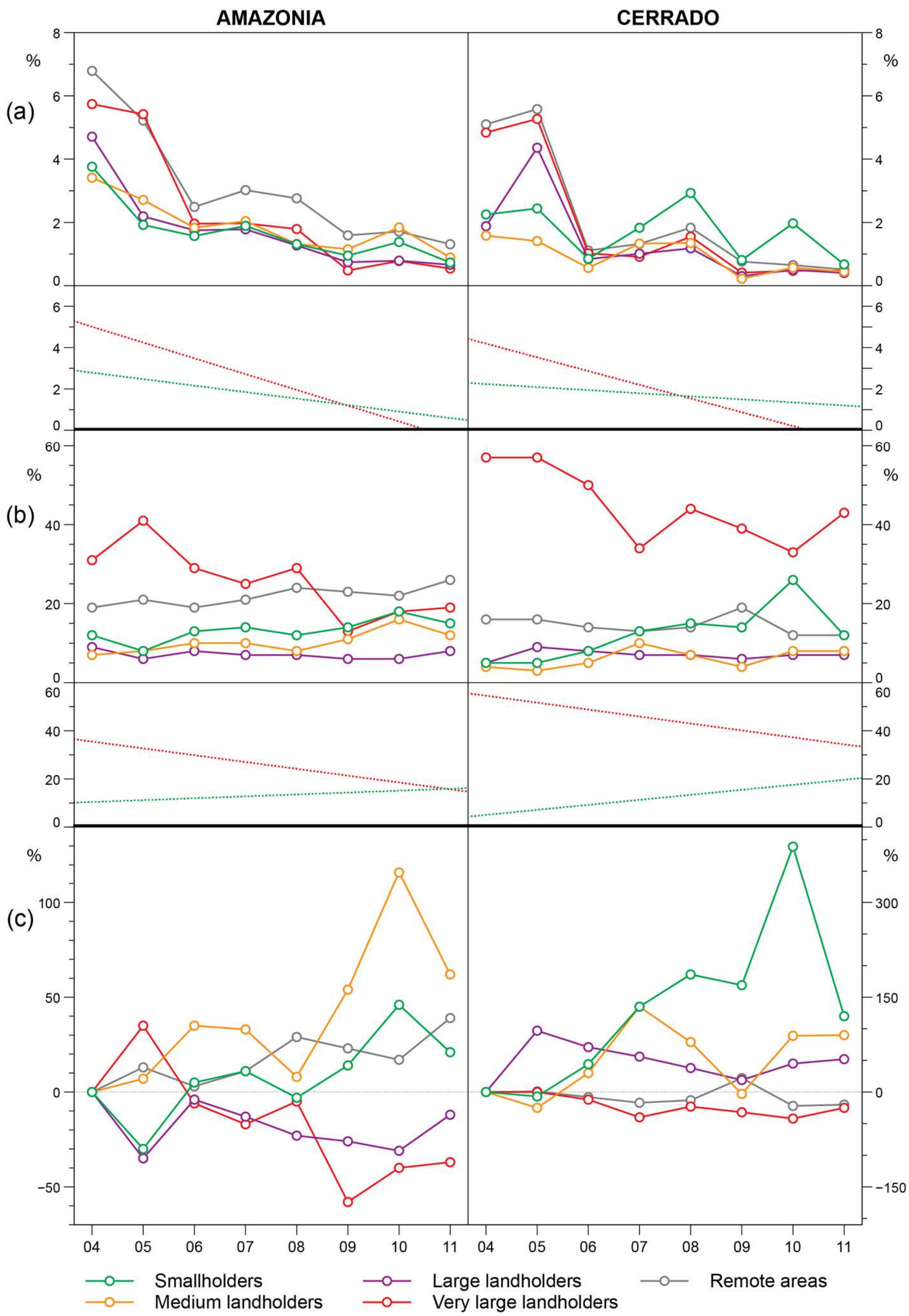

Figure S6. Actor-specific deforestation dynamics compared between the two main biomes of the BLA with respect to the annual rate of deforestation change (a), the % share of annual deforestation (b), and the % share of annual deforestation relative to 2004 (c). For the sake of clarity mixed-actor classes were not included. The lower subpanels in a) and b) represent the linear regression functions of the deforestation dynamics of smallholders (dashed green line) and very large landholders (dashed red line) to facilitate comparison. The biome boundaries were obtained from the Brazilian Ministry of Environment http://mapas.mma.gov.br/i3geo/datadownload.htm

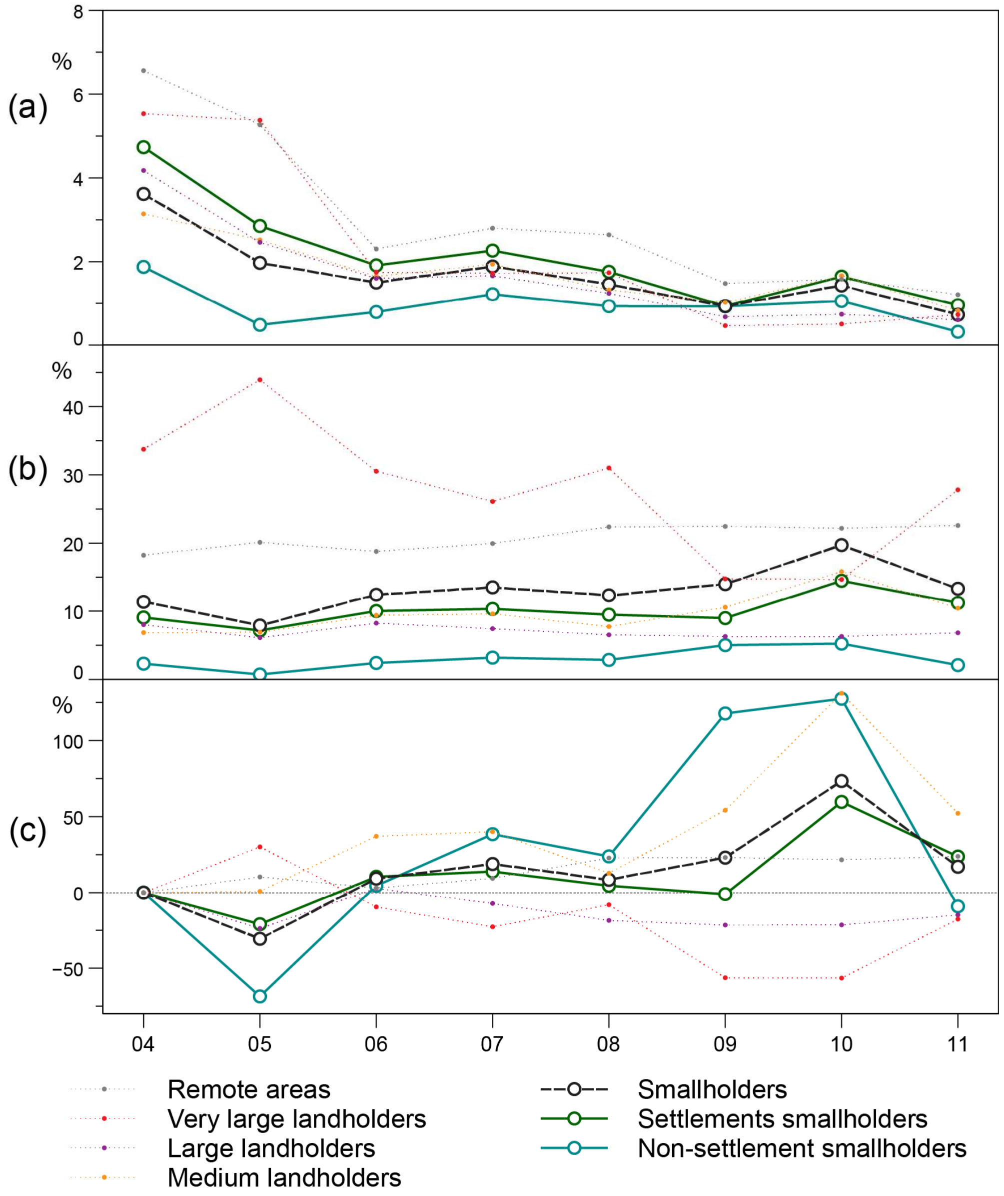

Figure S7. Deforestation contributions of smallholder dominated census tracts that are comprised of agrarian reform settlements and those that are not. The figure illustrates the annual rate of deforestation change (a), the % share of annual deforestation (b), and the % share of annual deforestation relative to 2004 (c). For the sake of clarity mixed-actor classes were not included.

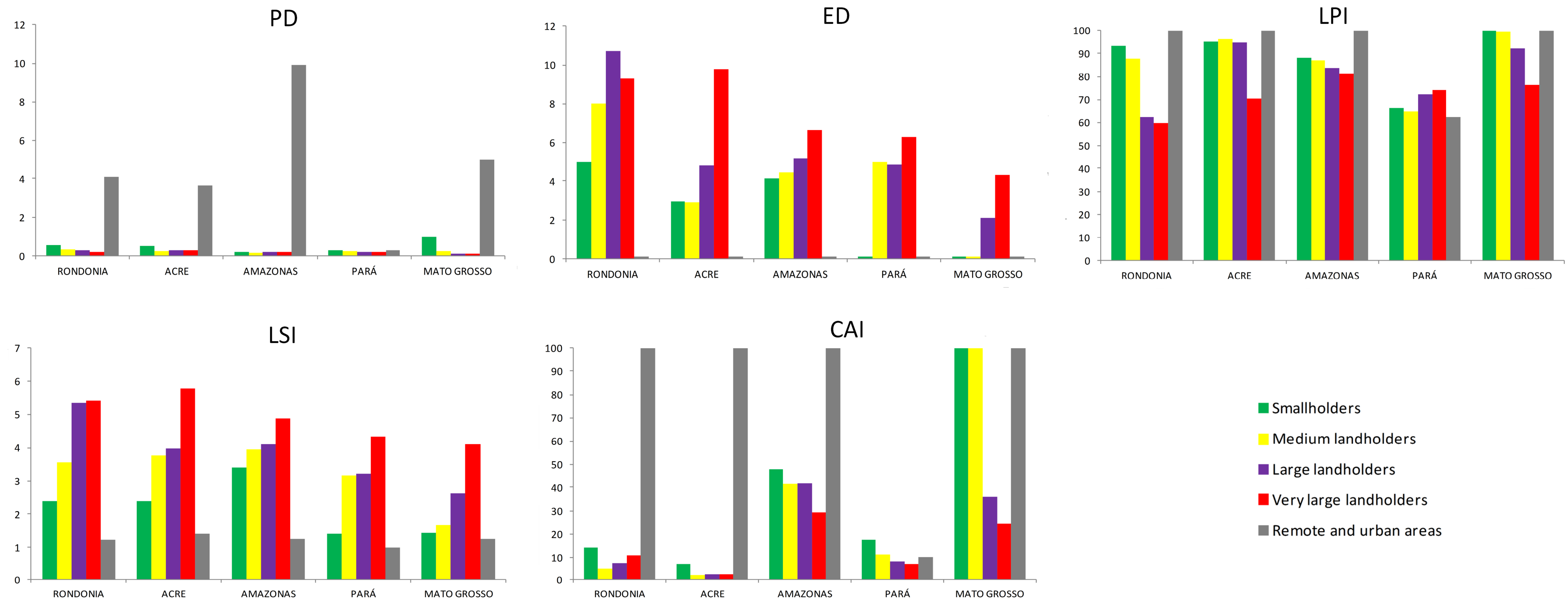

Figure S8: Average values for different landscape metrics calculated in census tracts dominated by different actor types per state in the Brazilian Legal Amazon, year 2011. Only the major Amazonian states are shown for the sake of clarity. PD: Patch density, number of forest patches divided by the total CT area in hectares; ED: Edge density, sum of the lengths of all forest edge segments in meters, divided by the total CT area in hectares; LSI: Landscape shape index, total length of forest edge in number of cell surfaces, divided by the minimum length of forest edge possible for a maximally aggregated forest, also given in terms of the number of cell surfaces; LPI: Largest patch index, percentage of the CT comprised by the largest forest patch; and CAI: Core area index, the percentage of the forest in a given CT that is core area. The forest core area is calculated as the amount of forest that lies further from the edge than a selected distance (edge depth). Here an edge depth of 3 pixels (480 m) is presented but similar results were found for edge depths of 1, 10 and 25 pixels. All metrics calculated per census tract using FRAGSTATS 4.1.

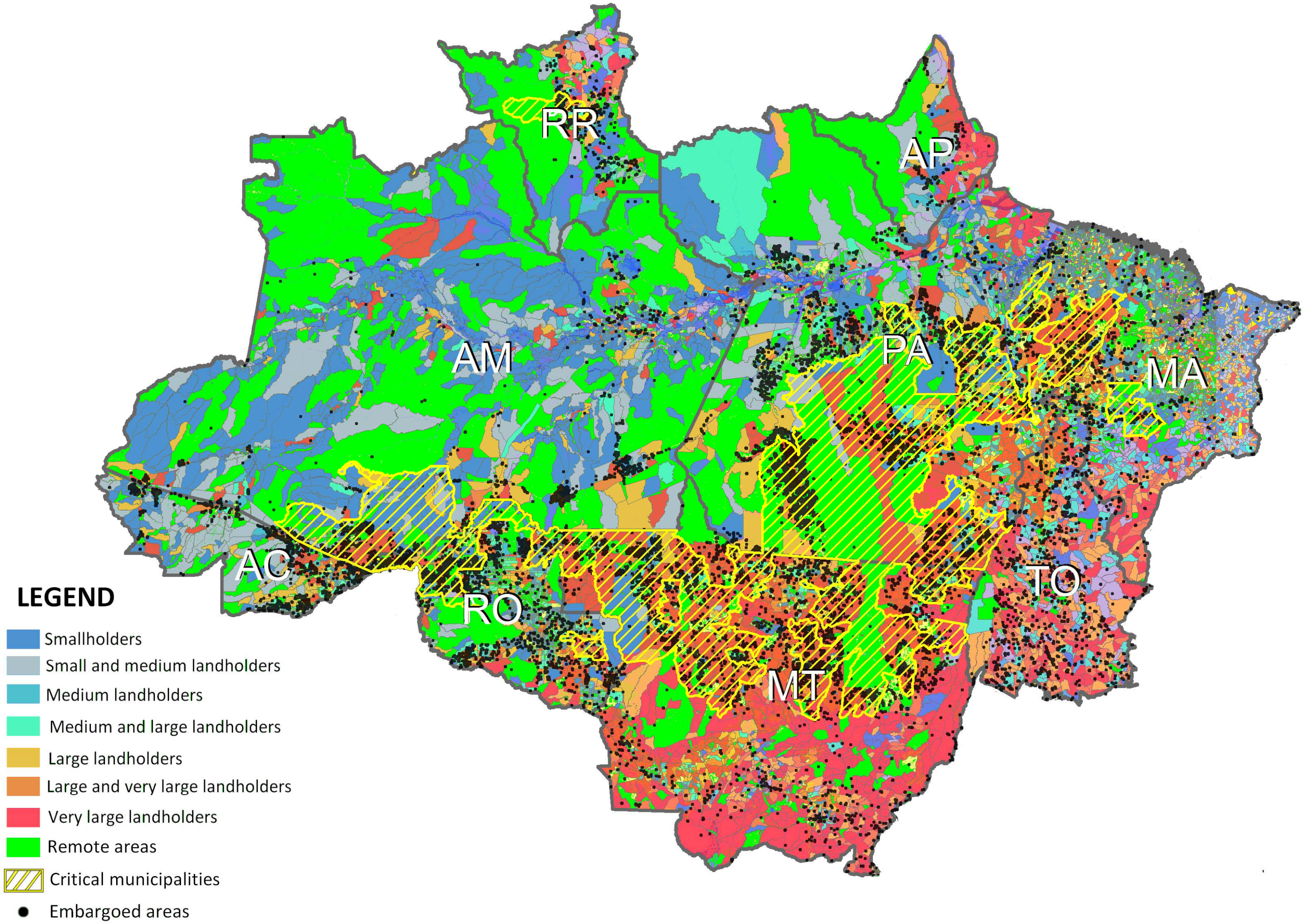

Figure S9: Location of embargoed areas between 2005 and 2013 in the Brazilian Legal Amazon (BLA). The background colors represent actor dominance by census tract in the BLA. The yellow dashed polygons correspond to municipalities under prioritization and monitoring status of the federal government Red List program (Critical Municipalities), where increased monitoring and law enforcement is focused. Source: IBAMA. Note: AC: Acre; AM: Amazonas; AP: Amapá; MA: Maranhão; MT: Mato Grosso; PA: Pará; RO: Rondônia; RR: Roraima; TO: Tocantins.

Table S1: Area dominance, occupation and population by actor type in the rural Brazilian Legal Amazon. Percentages calculated with respect to total amounts in the Brazilian Legal Amazon.

	Smallholders	Medium landholders	Large landholders	Very large landholders	Remote areas
Number of CTs dominated by each class of actor	6193 (46.6)	2483 (18.7)	1315 (9.9)	1511 (11.4)	0
Area dominated [a]	1014.4 (20.1)	600.6 (11.9)	388.6 (7.7)	938.7 (18.6)	1519.1 (30.1)
Number of properties	633,351 (81.1)	112,741 (14.4)	27,409 (3.5)	7248 (0.9)	-
Area covered by properties [a]	150.3 (12.9)	215.8 (18.5)	287.5 (24.7)	510.3 (43.9)	-
Average size of properties (ha)	23.7	191.4	1049.1	7040.7	-
Average CT occupation (%)	7.9	15.4	26.9	59.1	-
Median % CT occupation	19.4±19.2	54.4±45.6	51.3±36.1	80.5±19.5	-
Total population in rural sectors of rural areas [b]	4,382.0	748.4	196.0	69.0	1,788.9
Total population in urban sectors of rural areas [b]	2,152.2	215.7	47.6	18.2	0

[a] In thousands of km^2

[b] In thousands of people. Population was assigned to actor types in each sector proportionally to the amount of properties of a given property size range, not by allocating all the population of sector to the actor that dominates it. Total population in the BLA is 25.47 million inhabitants, of which 15.85 million lived in large cities (62.2%)

Smallholders: 0-100 ha; medium landholders: 100-500 ha; large landholders: 500-2500 ha; very large landholders: >2500 ha. Percentages with respect to the total presented in parentheses. Mixed-actor classes are not presented for the sake of clarity. Source: Authors' elaboration based on IBGE data at the census tract level from the demographic census 2010 and the agricultural census 2006.

Table S2: Distribution of main land uses in the Brazilian Legal Amazon for census tracts dominated by different actors in 2011. Land-use classes correspond to the PRODES classification.

	Land use area attributed to areas dominated by each actor type (km^2)				Share of main land uses in the BLA attributable to areas dominated by each actor type (%)				Land use composition for total area dominated by each actor type (%)			
	Deforestation	Forest	Non-forest	Water	Deforestation	Forest	Non-forest	Water	Deforestation	Forest	Non-forest	Water
Smallholders	104,266	779,468	91,554	36,806	13.94	24.03	9.79	33.60	10.30	77.02	9.05	3.64
Small and medium landholders	48,318	39,214	15,121	3,706	6.46	1.21	1.62	3.38	45.43	36.87	14.22	3.48
Medium landholders	72,104	427,697	63,388	17,001	9.64	13.19	6.78	15.52	12.43	73.72	10.93	2.93
Medium and large landholders	59,762	121,667	47,739	4,461	7.99	3.75	5.10	4.07	25.58	52.08	20.43	1.91
Large landholders	63,951	182,106	108,570	7,841	8.55	5.61	11.61	7.16	17.64	50.24	29.95	2.16
Large and very large landholders	74,946	55,058	81,572	1,370	10.02	1.70	8.72	1.25	35.19	25.86	38.31	0.64
Very large landholders	217,657	385,082	357,491	13,551	29.10	11.87	38.22	12.37	22.35	39.55	36.71	1.39
Remote areas	106,959	1,253,285	169,998	24,810	14.30	38.64	18.17	22.65	6.88	80.59	10.93	1.60
Total	747,962	3,243,579	935,437	109,550	100	100	100	100	n.a.	n.a.	n.a.	n.a.

Source: Authors´ elaboration based on property size dominance from IBGE agricultural census and PRODES data from INPE.

Table S3: Accumulated deforestation and annual deforestation for areas dominated by different actor types and remote areas during the deforestation slowdown 2004-2011. Values reported in km^2 for both measures, and their respective percentages are calculated with respect to both the BLA and the areas surveyed by IBGE (which exclude remote areas). Deforestation rates were calculated by extrapolating deforestation shares per actor to the INPE PRODES official deforestation rates. For more details see SI Appendix section 2.

			2004	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Smallholders	Accumulated deforestation	Area (km^2)	94,862	96,713	98,087	99,610	101,238	102,140	103,466	104,266
		% of BLA	14.16	13.94	13.92	13.91	13.88	13.88	13.94	13.94
		% of area surveyed by IBGE	16.37	16.16	16.15	16.16	16.16	16.17	16.26	16.26
	Annual deforestation	Area (km^2)	3158	1501	1775	1574	1592	1044	1380	854
		Annual contribution (%)	11.37	7.89	12.42	13.51	12.33	13.99	19.72	13.3
		Rate of deforestation change (%)	3.62	1.97	1.50	1.89	1.46	0.93	1.43	0.73
Small and medium landholders	Accumulated deforestation	Area (km^2)	44,081	44,749	45,309	46,117	46,826	47,612	47,948	48,318
		% of BLA	6.58	6.45	6.43	6.44	6.42	6.47	6.46	6.46
		% of area surveyed by IBGE	7.61	7.47	7.46	7.48	7.47	7.53	7.53	7.54
	Annual deforestation	Area (km^2)	1499	485	791	768	681	883	392	452
		Annual contribution (%)	5.40	2.55	5.54	6.59	5.28	11.83	5.60	7.04
		Rate of deforestation change (%)	3.70	1.37	1.45	1.99	1.35	1.71	0.87	0.83
Medium landholders	Accumulated deforestation	Area (km^2)	64,916	66,603	67,576	68,674	69,728	70,424	71,551	72,104
		% of BLA	9.69	9.60	9.59	9.59	9.56	9.57	9.64	9.64
		% of area surveyed by IBGE	11.21	11.13	11.13	11.15	11.13	11.15	11.23	11.25
	Annual deforestation	Area (km^2)	1902	1314	1341	1118	997	788	1108	670
		Annual contribution (%)	6.85	6.91	9.38	9.60	7.72	10.56	15.82	10.43
		Rate of deforestation change (%)	3.14	2.52	1.65	1.94	1.33	1.02	1.67	0.83
Medium and large landholders	Accumulated deforestation	Area (km^2)	55,336	56,196	56,795	57,503	58,277	59,018	59,527	59,762
		% of BLA	8.26	8.10	8.06	8.03	7.99	8.02	8.02	7.99
		% of area surveyed by IBGE	9.54	9.39	9.35	9.33	9.30	9.34	9.35	9.32
	Annual deforestation	Area (km^2)	1676	696	831	773	722	836	529	287
		Annual contribution (%)	6.04	3.66	5.82	6.64	5.59	11.20	7.56	4.48
		Rate of deforestation change (%)	3.26	1.57	1.21	1.60	1.15	1.30	0.95	0.43
Large	Accumulated	Area (km^2)	58,686	60,151	61,023	61,871	62,799	63,139	63,535	63,951

landholders	deforestation	% of BLA	8.76	8.67	8.66	8.64	8.61	8.58	8.56	8.55
		% of area surveyed by IBGE	10.13	10.05	10.05	10.04	10.01	10.00	9.98	9.97
	Annual deforestation	Area (km^2)	2223	1160	1177	865	843	469	440	437
		Annual contribution (%)	8.01	6.10	8.24	7.43	6.53	6.28	6.28	6.82
		Rate of deforestation change (%)	4.18	2.46	1.60	1.66	1.24	0.68	0.74	0.61
Large and very large landholders	Accumulated deforestation	Area (km^2)	67,930	70,072	71,099	72,254	73,448	74,030	74,519	74,946
		% of BLA	10.14	10.10	10.09	10.09	10.07	10.06	10.04	10.02
		% of area surveyed by IBGE	11.73	11.71	11.70	11.72	11.72	11.72	11.71	11.70
	Annual deforestation	Area (km^2)	2879	1683	1325	1188	1181	665	573	484
		Annual contribution (%)	10.36	8.85	9.28	10.20	9.15	8.90	8.18	7.55
		Rate of deforestation change (%)	4.74	3.09	1.55	1.96	1.49	0.82	0.82	0.57
Very large landholders	Accumulated deforestation	Area (km^2)	193,609	204,041	207,378	210,247	214,364	215,319	216,062	217,657
		% of BLA	28.90	29.41	29.43	29.36	29.39	29.26	29.11	29.10
		% of area surveyed by IBGE	33.41	34.09	34.15	34.12	34.20	34.08	33.94	33.95
	Annual deforestation	Area (km^2)	9373	8350	4360	3041	4002	1102	1028	1785
		Annual contribution (%)	33.75	43.92	30.52	26.10	31.00	14.76	14.68	27.81
		Rate of deforestation change (%)	5.53	5.38	1.75	1.72	1.74	0.47	0.51	0.73
Remote areas	Accumulated deforestation	Area (km^2)	90,507	95,325	97,382	99,824	102,623	104,127	105,619	106,959
		% of BLA	13.51	13.74	13.82	13.94	14.07	14.15	14.23	14.30
		% of area surveyed by IBGE	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	Annual deforestation	Area (km^2)	5062	3825	2686	2323	2892	1678	1551	1449
		Annual contribution (%)	18.23	20.12	18.80	19.94	22.40	22.47	22.15	22.57
		Rate of deforestation change (%)	6.56	5.27	2.30	2.80	2.64	1.48	1.58	1.21

Table S4: Contribution of areas dominated by different actors to total avoided deforestation in the Brazilian Legal Amazon during the deforestation slowdown period 2004-2011. All figures in km^2. These data correspond to Figure 2.

	2004	2005	2006	2007	2008	2009	2010	2011
Smallholders	0	1765	1603	1920	2021	2693	2486	3145
Small and medium landholders	0	1066	813	891	1035	892	1444	1447
Medium landholders	0	653	694	986	1179	1463	1221	1739
Medium and large landholders	0	1038	962	1081	1196	1148	1523	1835
Large landholders	0	1139	1202	1595	1701	2163	2282	2378
Large and very large landholders	0	1295	1754	1997	2113	2743	2951	3161
Very large landholders	0	1344	5666	7330	6724	9993	10,448	10,084
Remote areas	0	1410	2732	3277	2903	4318	4645	4961
Actual deforestation	27,772	19,015	14,283	11,653	12,910	7462	7002	6419
Deforestation without slowdown	27,772	28,725	29,710	30,729	31,784	32,874	34,002	35,168

Table S5: Average values for different landscape metrics for census tracts dominated by different actor types in the Brazilian Legal Amazon for the year 2011.

Landscape metric	Smallholders	Medium landholders	Large landholders	Very large landholders	Remote areas
PD [a]	0.7 ± 0.6	0.4 ± 0.3	0.2 ± 0.2	0.1 ± 0.1	5.8 ± 4.1
ED [a]	1.9 ± 1.9	3.5 ± 3.5	4.3 ± 4.3	5.2 ± 3.4	0.0 ± 0.0
LSI [a]	1.7 ± 0.6	2.6 ± 1.3	3.1 ± 1.5	4.3 ± 2.0	1.2 ± 0.2
LPI [a]	96.8 ± 3.2	93.2 ± 6.8	88.5 ± 11.5	78.1 ± 18.6	100.0 ± 0.0
CAI [a]	97.0 ± 3.0	45.6 ± 43.0	34.2 ± 30.9	20.2 ± 15.6	100.0 ± 0.0

[a] Median ± median absolute deviation

PD: Patch density, number of forest patches divided by total CT area in hectares; ED: Edge density, sum of the lengths of all forest edge segments in meters, divided by the total CT area in hectares; LSI: Landscape shape index, total length of forest edge in number of cell surfaces, divided by the minimum length of forest edge possible for a maximally aggregated forest, also given in terms of the number of cell surfaces; LPI: Largest patch index, percentage of the CT comprised by the largest forest patch; CAI: Core area index, is the percentage of the forest in a given CT that is core area. The forest core area is calculated as the amount of forest that lies further from the edge than a selected distance (edge depth). Here an edge depth of 3 pixels (480 m) is presented but similar patterns were found for edge depths of 1, 10 and 25 pixels. All metrics calculated per census tract using FRAGSTATS 4.1. Mixed actor classes are not presented for the sake of clarity.

Table S6: Areas under embargo in the BLA during the period 2005-2013, per size and characteristics of the embargoed area.

Size of the embargoed area	Type	Number of properties/settlements	Area under embargo (ha)	Percentage of total embargoed area (%)
0-100 ha	Properties	7962	193,766	7.3
>100 ha	Settlements	17	274,869	10.3
	Properties	2416	2,200,329	82.4

Source: Authors´ elaboration based on a public consultation of embargoed areas, Brazilian Ministry of the Environment https://servicos.ibama.gov.br/ctf/publico/areasembargadas/ConsultaPublicaAreasEmbargadas.php. Only the properties/settlements where the embargoed area was specified where included.