Correction

SUSTAINABILITY SCIENCE, ENVIRONMENTAL SCIENCES

Correction for "Actor-specific contributions to the deforestation slowdown in the Brazilian Amazon," by Javier Godar, Toby A. Gardner, E. Jorge Tizado, and Pablo Pacheco, which appeared in issue 43, October 28, 2014, of *Proc Natl Acad Sci USA* (111:15591–15596; first published October 13, 2014; 10.1073/pnas.1322825111).

The authors note that the following text published incorrectly: in the Abstract, lines 14–15, "63% decrease between 2005 and 2011" should instead appear as "63% of the level observed in 2005 by 2011"; also in the Abstract, lines 17–18, "88% between 2009 and 2011" should instead appear as "24% between 2004 and 2011"; in the Significance Statement, line 11, "from a peak in 2005" should instead appear as "of the level observed in 2005"; and on page 15593, right column, first full paragraph, lines 15–16, "dropped by a maximum of 63% between 2005 and 2011" should instead appear as "had declined by 2011 to 63% of the level observed in 2005." These errors do not affect the conclusions of the article.

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CORRECTION

Actor-specific contributions to the deforestation slowdown in the Brazilian Amazon

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Annual deforestation rates in the Brazilian Amazon fell by 77% between 2004 and 2011, yet have stabilized since 2009 at 5,000–7,000 km². We provide the first submunicipality assessment, to our knowledge, of actor-specific contributions to the deforestation slowdown by linking agricultural census and remote-sensing data on deforestation and forest degradation. Almost half (36,158 km²) of the deforestation between 2004 and 2011 occurred in areas dominated by larger properties (>500 ha), whereas only 12% (9,720 km²) occurred in areas dominated by smallholder properties (<100 ha). In addition, forests in areas dominated by smallholders tend to be less fragmented and less degraded. However, although annual deforestation rates fell during this period by 68–85% for all actors, the contribution of the largest landholders (>2,500 ha) to annual deforestation decreased over time (63% decrease between 2005 and 2011), whereas that of smallholders went up by a similar amount (69%) during the same period. In addition, the deforestation share attributable to remote areas increased by 88% between 2009 and 2011. These observations are consistent across the Brazilian Amazon, regardless of geographical differences in actor dominance or socioenvironmental context. Our findings suggest that deforestation policies to date, which have been particularly focused on command and control measures on larger properties in deforestation hotspots, may be increasingly limited in their effectiveness and fail to address all actors equally. Further reductions in deforestation are likely to be increasingly costly and require actor-tailored approaches, including better monitoring to detect small-scale deforestation and a shift toward more incentive-based conservation policies.

deforestation policy | Amazon | sustainable development | forest degradation | land use

By 2012, some 749,987 km² of forest, or about 20% of the original forest extent of the Brazilian Legal Amazon (BLA), had been cleared (1). Large areas of the remaining forests have been severely degraded and fragmented by logging, fire, and overhunting (2). The combined effects of deforestation and forest degradation threaten the maintenance of critical ecosystem services, including carbon storage and sequestration and the conservation of hydrological cycles, as well as the protection of globally significant biodiversity (2, 3). Much of the land already cleared for farming is poorly used (4), and despite the economic growth often associated with converting forests to farmland, many inhabitants of the Amazon continue to live in poverty (5).

The BLA has experienced a dramatic slowdown in annual deforestation rates in the last decade, with a decrease of 83.5% by 2012, the lowest year on record, decreasing from a peak of 27,772 km² in 2004 (1). This slowdown has been driven by a combination of policy interventions, private sector initiatives, and market conditions (6). In 2004, in response to rising deforestation levels, the Brazilian federal government launched an interministerial process, the Action Plan for the Protection and Control of Deforestation in the Amazon (PPCDAm), encompassing a diverse set of policy interventions with three broad lines of action: land tenure regularization and the creation of new reserves (with about 500,000 km² of new reserves being created between 2004 and 2011) (7); increased land use monitoring and enforcement (supported by Brazil's world-leading deforestation monitoring system) (8); and the promotion of more sustainable agricultural production systems (9, 10). This process, in turn, gave rise to a number of linked policy interventions, including the Critical Municipalities Program, which suspended access to agricultural credit and markets for the 36 most-deforesting municipalities (6). These government efforts to curb deforestation, particularly through command-and-control measures, are widely recognized as having played a key role in reducing deforestation (8, 11). That said, other regional initiatives and changes have also played important roles. These include the soy and beef moratoria of 2006 and 2009, driven by intense campaigning from nongovernmental actors; increased private sector engagement in responsible land-use practices (6); and market changes, including oscillations in the price of agricultural commodities and a periodic weakening of the dollar (8). However, since 2009, deforestation rates have stabilized at 5,000–7,000 km², and there was a relative annual increase in deforestation (+28%) in 2013 for the first time since 2008. Although annual rates of deforestation are still among the lowest levels recorded since monitoring began in 1988, the decline in deforestation reductions calls into question the continued effectiveness of current policy measures. Set against the national target of an 80% reduction (on a 1996–2005 baseline) by 2020, Brazil still needs to reduce annual deforestation rates to 3,800 km² from the more than 5,000 km² cleared in 2013 (8). Moreover, although deforestation rates have fallen, rates of forest degradation from selective logging, fire, and fragmentation have remained high or

Significance

The Brazilian Amazon is at a critical juncture after the recent stabilization of deforestation rates. Identifying opportunities for continued deforestation reductions requires an understanding of the contribution of different actors to overall deforestation. We provide the first such assessment, to our knowledge, that reports on two headline findings. First, between 2004 and 2011, areas dominated by properties larger than 500 ha accounted for 48% of the deforestation compared with only 12% for smallholders (<100 ha). Second, the deforestation share attributed to the largest properties (≥2,500 ha) declined by 63% from a peak in 2005, whereas that of smallholders increased by 69%. Further reductions in deforestation are likely to require a shift toward more incentive-based policies that are tailored toward different actors.

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are increasing in many areas, threatening the ecological functioning and integrity of many remaining areas of forest (12).

To achieve further reductions in deforestation and forest degradation, it is vital to have an in-depth understanding of the relative contributions of different types of actors to total deforestation and forest degradation, as well as how such contributions have changed during the deforestation slowdown period. Agricultural frontier expansion in the Amazon is a dynamic process in which land-use decisions are shaped by factors that are often specific to different actor groups. These actor differences include the availability of assets, cultural backgrounds, household life cycles, access to markets and technologies, and power relationships (13). Improving our understanding of the link between different actor groups and patterns of deforestation and forest degradation can help identify possible improvements in existing forest conservation and regional sustainable development policies.

To date, two approaches have been used to understand the contribution of different actors to deforestation in the Amazon. First, actor contributions to deforestation have been assessed by linking data on land use change with data on land tenure on the scale of individual properties. However, this work has been restricted to relatively small geographical areas (14–16), and the findings are hard to generalize. Second, regional assessments have been conducted for the entire BLA by combining agricultural census data and remote sensing analyses aggregated at the scale of municipalities (13, 17), or by using the size of deforested patches as a proxy for the spatial distribution of deforestation activities of different actor groups (18, 19). Although these approaches address the entire BLA, they deal with relatively large geographic units. Thus, both approaches are limited in their ability to provide a reliable assessment of actor-specific contributions to deforestation for such a highly heterogeneous socioecological system as the Brazilian Amazon, which comprises more than 5 million km^2 and a diverse array of land-users (20).

Here, we provide the first submunicipality scale assessment to our knowledge of actor-specific contributions to deforestation and forest degradation for the BLA during the slowdown period from 2004 to 2011. Similar to previous studies, we combine Brazilian government agricultural census and remote sensing data, but we do so at the scale of individual census tracts (CTs). Thus, our analysis draws on survey data from 13,303 CTs, comprising 3.5 million km^2 (69.9% of the BLA), instead of only 771 municipalities for the same area. Specifically, we quantify the absolute contribution of different actor types to total deforestation between 2004 and 2011, as well as their contribution to avoided deforestation relative to the mean deforestation rate observed during the official Brazilian government baseline period of 1996–2005; changes in the absolute and relative contribution of different actors to deforestation during the slowdown period; and actor-specific differences in levels of forest fragmentation and degradation. Actors are defined on the basis of differences in the size of dominant properties within each CT. CTs that lack census information on property size distributions because of their geographic isolation and low population density are classified as remote areas. We interpret these findings in the context of the ongoing decline in deforestation rates across the BLA and the challenges of further reducing deforestation while also promoting sustainable social and economic development.

Results

Actor Dominance and Characterization. Large-scale landholders (with properties >500 ha) dominate CTs across much of the southern and southeastern BLA, whereas smallholder properties (<100 ha) are much more prevalent in the western, northern, and northeastern regions (Fig. 1). Despite smallholder properties occupying only 12.9% of the area of private land surveyed by the Brazilian government in the BLA, they make up 81.1% of the total number of properties and dominate 46.6% of all CTs, which together cover 20.1% of the BLA area (*SI Appendix*, Table S1). In contrast, properties of very large landholders (>2,500 ha) account for 43.9% of the total area of private land surveyed but only make up 0.9% of the total number of properties and dominate just 11.4% of all CTs, accounting for 18.6% of the BLA area. The distribution of existing areas of forest among CTs is strongly associated with patterns of actor dominance. Overall, there is more forest in CTs dominated by smallholders (*SI Appendix*, Table S2), which is expected, given that they have traditionally dominated areas close to the forest frontier (21). In absolute terms 779,468 km^2, or 24.0% of the total forest area in the BLA, can be found in CTs dominated by smallholders, whereas only 13.2%, 5.6%, and 11.9% of the total remaining forest can be found in CTs dominated by medium, large, and very large landholders. Unsurprisingly, remote areas account for the highest proportion of forests in the BLA (38.6%). In relative terms, the proportion of remaining forest in CTs of a given actor class decreases with the size of the dominant property, as CTs dominated by small and medium-sized properties are made up by between 77.0% and 73.7% forest

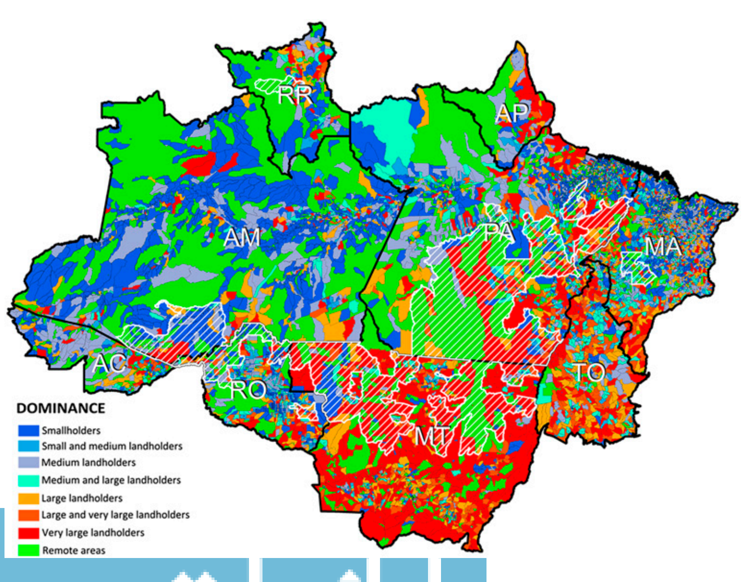

Fig. 1. Actor dominance by census tract in the BLA. The white dashed polygons correspond to municipalities under prioritization and increased monitoring included in the federal government Critical Municipalities List. Only 14.4% of the total deforestation and 30.1% of the total area was not accounted for in terms of actor dominance. AC, acre; AM, Amazonas; AP, Amapá; MA, Maranhão; MT, Mato Grosso; PA, Pará; RO, Rondônia; RR, Roraima; TO, Tocantins.

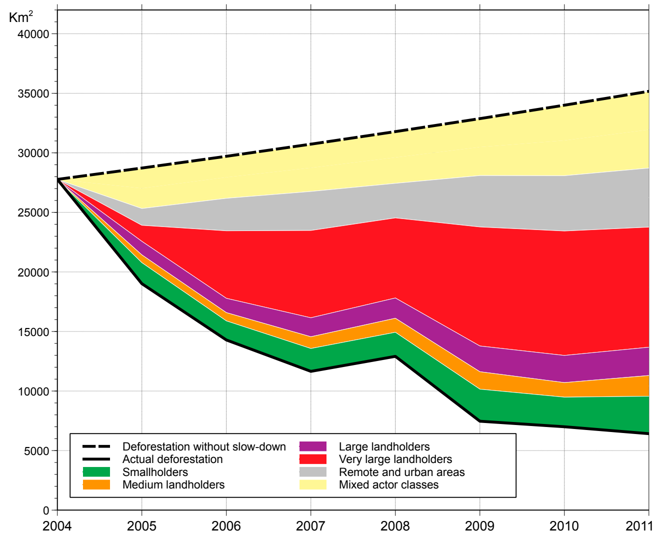

Fig. 2. Avoided deforestation per actor type in the BLA during the slowdown period (i.e., expected deforestation if rates remained at preslowdown 1996–2005 levels, less observed deforestation).

cover compared with only 39.5% for CTs dominated by very large landholders (*SI Appendix*, Fig. S1 and Table S2).

Total Actor-Specific Deforestation and Avoided Deforestation. Areas dominated by smallholder properties accounted for 13.9% (104,266 km^2) of the total accumulated deforestation by 2011, equivalent to 2.1% of the 5.05 million km^2 of the BLA. In contrast, CTs dominated by large and very large properties (>500 ha) accounted for 47.7% (356,554 km^2) of accumulated deforestation (*SI Appendix*, Table S3).

In total, an estimated 144,249 km^2 of additional deforestation would have occurred in the BLA by 2011 if the annual deforestation rates had remained the same as the average rate from 1996–2005 (the baseline period used by the Brazilian government to monitor deforestation performance; Fig. 2 and *SI Appendix*, Fig. S3 and Table S4). Set against this baseline, by far the largest amount of avoided deforestation between 2004 and 2011 occurred in areas dominated by actors with properties larger than 500 ha, making up 80,062 km^2 (or 55.5%) of the total area of forest that would otherwise have been cleared. By way of comparison, areas dominated by very large landholders (>2,500 ha) are associated with 51,589 km^2 (or 35.8%) of the total avoided deforestation between 2004 and 2011, whereas remote areas account for 24,246 km^2 (16.8%) and CTs dominated by smallholders (<100 ha) account for only 15,633 km^2 (10.8%). Although the small contribution from smallholder-dominated areas is not surprising, given the much larger initial deforestation rates in CTs dominated by larger properties, it amounts to some 1,820 km^2 less than expected from their actual share of total deforestation for the same period (12.1%; *SI Appendix*, Table S3).

Changes in Relative Actor-Specific Contributions to the Deforestation Slowdown. Deforestation rates in the BLA have exhibited a marked decline since 2004 (*SI Appendix*, Fig. S2 and Table S3), with recent years experiencing the lowest rates since record-keeping began in 1988 (*SI Appendix*, Fig. S3). Overall, the largest reduction occurred between 2004 and 2006, followed by a period between 2006 and 2008 during which annual deforestation rates remained at around 11,000–14,000 km^2/year, before stabilizing at 5,000–7,000 km^2/year starting in 2009 (Fig. 3*A* and *SI Appendix*, Fig. S2 and Table S3). However, the deforestation performance of actors during the slowdown period (2004–2011) has not been consistent for all actors, with annual deforestation rates falling much more in CTs dominated by large (80.3% drop, going from 2,223 km^2 to 437 km^2) and very large (81.0% drop, going from 9,373 km^2 to 1,785 km^2) properties than in CTs dominated by small- (73.0% drop, going from 3,158 km^2 to 854 km^2) and medium- (64.8% drop, going from 1,902 km^2 to 670 km^2) sized properties (*SI Appendix*, Table S3).

A similar pattern of actor-specific differences in deforestation contributions emerges when looking at the relative contribution of areas dominated by each actor to total deforestation for a given period (i.e., their deforestation "share"). Viewed in this way, smallholders contributed 12.1% (12,789 km^2) of total deforestation between 2004 and 2011 compared with 31.0% (33,041 km^2) for very large landholders and 20.1% (21,466 km^2) for remote areas (*SI Appendix*, Table S3). Considering the full slowdown period, CTs dominated by very large properties exhibited a marked decrease in their share of annual deforestation from what were initially very high levels, with a concomitant increase for CTs dominated by smallholders, and to a lesser extent for CTs dominated by medium-sized properties (Fig. 3 *B* and *C*). In fact, the contribution to annual deforestation for areas dominated by very large properties dropped by a maximum of 63% between 2005 and 2011, whereas that of smallholders increased by 69% for the same period. This trend of falling deforestation contributions from areas dominated by larger properties, set against rising deforestation contributions for areas dominated by smallholders, intensified after 2008, with smallholder-dominated areas becoming the single biggest contributors (among our actor-size classes, and excluding remote areas) to annual deforestation in the BLA in 2010 (Fig. 3*B*).

Our findings on the changing deforestation contributions over time of CTs dominated by different types of actor are robust to the choice of dominance threshold, with very similar results obtained using a dominance threshold of 90% (i.e., nearly complete dominance) compared with the 50% used for the main results presented here (*SI Appendix*, Fig. S4). In addition, actor-specific deforestation patterns during the slowdown period were found to be similar across all states of the BLA (*SI Appendix*, Fig. S5),

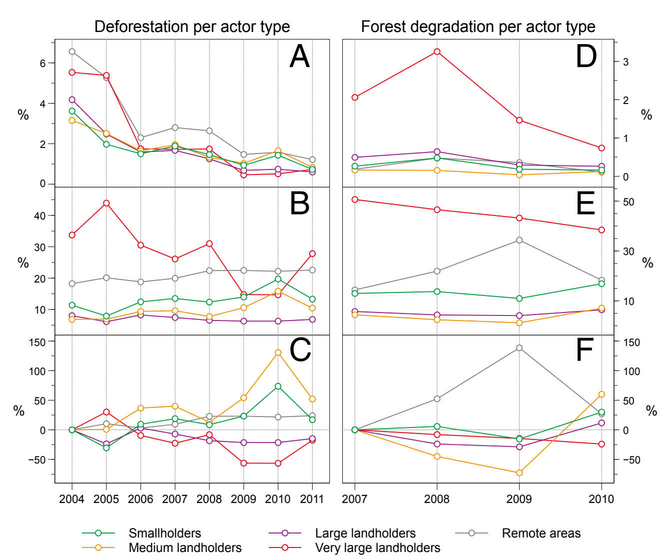

Fig. 3. Annual deforestation and degradation dynamics per type of actor in the BLA. (*A*) Annual rate of deforestation change. (*B*) Percentage share of annual deforestation. (*C*) Percentage share of annual deforestation relative to 2004 (baseline year). (*D*) Percentage forest degradation per hectare of forest. (*E*) Percentage share of annual degradation. (*F*) Percentage degradation share relative to 2007 (baseline year). For the sake of clarity, mixed-actor classes are not included.

as well as between the Amazon and Cerrado biomes of the BLA region (*SI Appendix*, Fig. S6). Moreover, we also found that the trajectory toward increased deforestation contributions in areas dominated by smallholders holds true irrespective of whether the smallholder-dominated areas contain an agrarian reform settlement or not (*SI Appendix*, Fig. S7).

Actor-Specific Differences in Landscape and Forest Condition. Comparing forest fragmentation metrics in 2011 among CTs dominated by different-sized properties shows that despite having a higher forest patch density than other actors (likely as a result of more forest fragmentation at the property level), forests in smallholder-dominated CTs are, on average, less fragmented and have a lower density of edges and a larger proportion of forest as core forest (*SI Appendix*, Table S5). Indeed, smallholder-dominated CTs had a forest edge density (1.9 m/ha) that was almost three times less than that observed for CTs dominated by very large landholders. The largest forest patches in smallholder-dominated CTs also tend to be larger than in CTs dominated by other actor types (an increase of between 3.8% and 24.0%). CTs in remote areas consistently presented the best measures of landscape condition, with lowest levels of edge density and consistently greater amounts of core forest (*SI Appendix*, Table S5). Similar differences were found when comparing CTs dominated by different actors between different Brazilian states of the BLA (*SI Appendix*, Fig. S8).

When looking at forest degradation within remaining areas of forest, we observed that degradation per hectare of forest [as defined by the Brazilian National Institute For Space Research (INPE) DEGRAD program (22)] between 2007 and 2010 was much higher in CTs dominated by very large properties (an average of 1.9% per year) compared with CTs dominated by small, medium, and large landholders (0.3%, 0.1%, and 0.4%, respectively; Fig. 3*D*). As a consequence, CTs dominated by very large landholders accounted for 46.2% of all forest degradation recorded during this period (Fig. 3*E*) compared with 13.5% and 19.9% of the total degradation recorded in CTs dominated by smallholder and remote areas, respectively. That said, CTs dominated by very large properties have steadily decreased their share of annual forest degradation from 50.6% to 38.4%, in contrast to remote areas and smallholder-dominated CTs, in which degradation has increased in relative terms (Fig. 3*E*). As a consequence, only the very large landholders presented a smaller share of annual degradation in 2010 than was initially seen in 2007 (Fig. 3*F*).

Discussion

Absolute and Relative Contributions to Total Deforestation and the Deforestation Slowdown. Our analysis demonstrates that CTs dominated by properties larger than 500 ha make up the majority (55.6%) of accumulated deforestation in areas characterized as being dominated by any actor group, totaling 356,554 km^2 (compared with 47.7% if remote areas are included). In contrast, only 16.3% (104,266 km^2) of the accumulated deforestation was attributed to CTs dominated by smallholders. This finding is consistent with estimates reported by Pacheco (13), who found, from looking at clearances within landholdings surveyed by the Brazilian Institute of Geography and Statistics (IBGE), that the contribution of smallholders to total deforestation was about 14.8% in 1995/1996 and 16.1% in 2006. In contrast, earlier work using a variety of other methods and data estimated much higher deforestation contributions by smallholders. For example, Homma (23) estimated that half of the deforestation in the Amazon was caused by smallholder shifting cultivation farming systems, whereas Fearnside (24) suggested that 30% of deforestation was attributable to smallholders in 1990, and Faminow (25) argued that the figure was closer to 75%. The most likely reason for these strikingly different conclusions is the use of coarser-grained analyses, including highly aggregated information on land tenure, as the basis for comparing patterns of actor dominance with deforestation (*SI Appendix*, section 1).

Our analysis further demonstrates that although areas dominated by larger landowners (>500 ha) continue to be responsible for the bulk of deforestation, annual deforestation in these areas has declined disproportionately compared with rates observed in areas dominated by other actors. The result is that in recent years, smallholder-dominated areas have started to contribute less in both relative and absolute terms to the deforestation slowdown (Figs. 2 and 3). The possibility of an increase in the deforestation share of smallholders has been suggested recently by Rosa and colleagues (18). However, these authors used deforestation patch size as a proxy for actor type, which may be misleading in areas in which large properties encompass multiple deforestation patches (26), smallholder deforestation patches are contiguous, and smaller-scale deforestation activities are not linked to farming (e.g., mining operations).

Actor-Specific Differences in Landscape and Forest Condition. Although earlier studies have found that smallholders tend to deforest a larger proportion of their properties (16, 27), we found that smallholder-dominated CTs have proportionately more forest cover than CTs dominated by larger properties, and they also have forests that tend to be both less fragmented (relatively fewer edges and more core forest) and less degraded. This suggests that for similar-sized areas, such forests are arguably in better ecological condition (28, 29) and are less prone to fire and other edge-related degradation processes (30, 31).

Our finding of better forest condition in smallholder-dominated landscapes is partly explained by the fact that smallholders tend to dominate more forested frontier regions, whereas areas dominated by larger properties are more concentrated in older and more consolidated areas that have better infrastructure and better connections to markets. However, the fact that we observed similar differences in forest condition between areas dominated by different actors for all Amazonian states (*SI Appendix*, Fig. S8) suggests they do reflect consistent differences in actor-specific land-use patterns (16, 32). Increased forest fragmentation and degradation in areas dominated by larger (and often wealthier) properties may also be explained by the larger number of private roads in these landscapes compared with those areas dominated by smallholders, who commonly depend on public roads. Owners of larger properties are also often better equipped to extract economically valuable timber from their forests. The better condition of forests in smallholder-dominated landscapes may also be explained by their dependence on small-scale diversified, fallow-based farming systems, which do not require the clearance of large areas of forest and retain large areas of secondary forest in the landscape that act as a buffer to edge effects (16, 33).

Implications for Conservation and Development in the Amazon. No other tropical region has experienced reductions in deforestation comparable to those observed in the Brazilian Amazon in recent years. Our key finding, that larger properties have made a disproportionate contribution to the deforestation slowdown, whereas the relative contributions of smallholders and remote areas have increased in recent years, aligns with the conclusions of other assessments that both government and private sector interventions have played an important role in curbing deforestation (6, 8, 10, 11, 30). There are at least two interrelated reasons for this interpretation.

First, larger properties have been more susceptible to fines and embargos by enforcement agencies, as individually they represent more rewarding (greater potential deforestation reductions), cheaper (per hectare), and more politically acceptable targets for deforestation control than smaller and poorer properties. Between 2004 and 2010 (i.e., after the onset of the slowdown), there was a 70-fold increase in the number of notices of legal violations issued by environmental agencies compared with the period between 2000 and 2004, and the majority of this increase in violations can be attributed to larger properties (10). In addition, more than 80% of the areas embargoed since 2005 are in properties larger than 100 ha (*SI Appendix*, Table S6). For similar reasons, private sector interventions have also disproportionately targeted larger properties, particularly those that are connected to national and international export markets, and most notably after the soy and cattle moratoria of 2006 and 2009 (6).

Second, the fact that the share of deforestation has increased in more remote areas is not unexpected, given the focus of both the government and the private sector on municipalities prioritized for monitoring and control measures by the federal government (i.e., the Critical Municipalities) (6, 34). These municipalities are for the most part dominated by larger properties (35) (Fig. 1), have received the majority of embargos to date (*SI Appendix*, Fig. S9), and have been the target of many nongovernment actors working to improve the sustainability of agricultural supply chains (6).

Despite the remarkable deforestation slowdown, the recent stabilization of deforestation rates [and 28% relative increase between 2012 and 2013 (1)] suggests that existing policies are likely to be increasingly limited in their effectiveness (36). As deforestation rates fall, the marginal costs of achieving further reductions in deforestation will continue to rise as a result of the increased technical difficulties of detecting small-scale clearings and the increased resources needed for on-the-ground enforcement in more, more remote, and smaller properties (7, 36). Between 2003 and 2011, the proportion of deforestation registered as occurring in patches larger than 25 ha [the patch size limit of the Real-Time System for Detection of Deforestation (DETER)] fell from 70% to 30% (37). Reconciling this observation with the fact that areas dominated by large properties still account for the majority of deforestation suggests larger landholders may have adapted their behavior to the clearance of smaller, incremental patches within the detection limits of the DETER system (38). Such a shift could perhaps help explain the significantly higher levels of forest degradation in areas dominated by larger landholdings (Fig. 3*E*), if small patches of deforestation are actually being picked up as degradation by the DEGRAD system. Testing this hypothesis would require more detailed analyses based on higher-resolution remote-sensing data.

There is an obvious need for continued and enhanced enforcement to tackle illegal deforestation, especially by larger landowners, who are still responsible for the bulk of forest clearance. However, it is hard to imagine how much of the remaining "residual" deforestation can be curbed through increased command-and-control-based approaches. Beyond the technical difficulties and increased costs, efforts to curb deforestation in areas dominated by smallholders are politically and socially problematic because many smallholders depend on clearing small areas of forest for their livelihoods and subsistence. Neither is it likely that deforestation rates could be reduced much further through the creation of more reserves. Aside from the obvious difficulties of appropriating increasingly consolidated private land for public reserves, government enthusiasm for further reserve creation has waned significantly in recent years (7), as evidenced by the recent downgrading of a large number of reserves (39).

To address this challenge, we suggest that a much greater emphasis be placed on investments and positive incentives for sustainable land-use practices, including on both forested and already-cleared land (36, 40). Such positive incentives are the focus of the third and current phase of the PPCDAm program (7) and are manifest in a wide range of initiatives including mechanisms for Reducing Emissions from Deforestation and Forest Degradation (REDD+) and carbon finance projects, the Green Settlements program from Brazil's National Institute for Colonization and Agrarian Reform, the ABC financial credit system for low-carbon agriculture, the Green Municipalities Program in the State of Pará, certification schemes, and voluntary farmer support programs (see ref. 6 for a detailed review). However, the challenge of reducing deforestation while fostering sustainable and inclusive rural development remains enormous and requires more intense and concerted efforts across multiple sectors.

Incentive-based mechanisms for improving environmental performance could deliver important socioenvironmental cobenefits for all actors (41) and provide a particularly welcome boost for smallholder farmers (who represent the vast majority of the Amazon population) to adopt alternative paths of rural development (5). The low levels of forest fragmentation and degradation observed in many areas dominated by smallholders further underscores the importance of supporting such measures. Concerted efforts are needed to more effectively adapt initiatives such as REDD+ and other experimental environmental compensation and payment schemes to differentiated local contexts and socioeconomic needs (42), as well as more innovative solutions that link development assistance and credit access to environmental performance and local development needs.

Although dampened by the 2013 increase in deforestation, there is a widespread expectation that Brazil will continue to reduce deforestation in the Amazon, and calls for zero net deforestation policies are commonplace (43). Our results serve to highlight the need for actor-specific approaches to address some of the major environmental, economic, and social difficulties that lie in the way of achieving this goal. One prominent example of such difficulties is the challenge facing smallholders in achieving compliance with Brazil's revised Forest Code, even considering the amnesty for areas cleared by them before 2008 (44). The differences in actor-specific deforestation and degradation dynamics revealed by our study suggest that to be both effective and fair, legal reserve limits and compliance requirements established in the Forest Code may need to be not only coupled with appropriate supporting and incentive measures but also more closely tailored to the responsibilities, capacities, and context associated with different actors, in contrast with a blanket obligation to protect and restore a minimum percentage of forest cover.

Even if deforestation rates in the Amazon can be further reduced against mounting pressures posed by increased global demand for farming commodities; the potential effects of new mining, hydropower, and road investments (45); a weakened Forest Code (44); and the recent downgrading of conservation areas (39), other concerns remain. These include the need for additional measures to avoid further degradation (e.g., from unsustainable logging) and to rehabilitate already-degraded areas; the risk of deforestation shifting to other biomes (46); and increases in fire and drought caused by changes within the Amazon (47), neighboring biomes (48), and the global climate.

Methods

Data. This study uses a spatially explicit and multitemporal approach, integrating environmental and socioeconomic databases at the level of individual CTs. The main databases used were the latest IBGE agricultural and demographic censuses and the deforestation and forest degradation maps developed by INPE through the Amazon Monitoring Program PRODES and the DEGRAD project. Actor dominance was calculated per CT, based on property-size distributions of the number of properties belonging to 18 different property size classes, which we reclassified into smallholder (<100 ha) and medium (100–500 ha), large (500–2,500 ha), and very large (>2,500 ha) property size classes. See *SI Appendix*, section 1 for detailed methods and data used.

Actor Deforestation and Forest Degradation. Actor dominance in each CT was crossed with INPE land cover maps. The two map layers used were PRODES deforestation maps from 2001 and each of the years between 2004 and 2011 (1), in which unknown areas, mostly resulting from cloud cover, were filled with the map from the immediately previous year; and maps from the DEGRAD project (22). DEGRAD detects severe canopy disturbances (from logging and fire) in standing forests.

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Actor-Specific Contributions to the Deforestation Slowdown. Deforestation rates for each actor type were calculated by aggregating the deforestation across all CTs dominated by that actor. CTs not surveyed by IBGE in remote or largely unpopulated areas constituted a new class named "remote areas," in which deforestation rates were also calculated. The deforestation rates calculated directly from the INPE maps were very similar to official estimates reported by INPE (1), but they were not identical because of methodological discrepancies (*SI Appendix*, section 2). However, actor shares of annual and accumulated deforestation were extrapolated to INPE's figures to facilitate comparison. The potential avoided deforestation during the slowdown was calculated by subtracting the projected deforestation if preslowdown (1996–2005) deforestation rates would have maintained and observed deforestation rates. The 1996–2005 baseline is the official decade used by the Brazilian government to assess deforestation reduction targets. We assumed the same deforestation rate for all actors before 2004 in order to focus only on differential deforestation trajectories during the slowdown period.

Actor-Specific Differences in Forest Condition. To analyze differences in patterns of forest cover, we used metrics describing forest edge, forest fragmentation, and amount of core forest (*SI Appendix*, section 4), which were applied in each CT using FRAGSTATS. Information from multitemporal DEGRAD maps was extracted in each CT and was aggregated by actor dominance for comparison. Forest fragmentation indices are presented for the entire BLA in the main manuscript, and separately for each Amazonian state in *SI Appendix*, Fig. S8, showing geographic consistency in overall patterns.

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