Decoupling of deforestation and soy production in the southern Amazon during the late 2000s

Marcia N. Macedo[a], Ruth S. DeFries[a,1], Douglas C. Morton[b], Claudia M. Stickler[c], Gillian L. Galford[d], and Yosio E. Shimabukuro[e]

[a]Department of Ecology, Evolution, and Environmental Biology, Columbia University, New York, NY 10027; [b]Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, MD 20771; [c]Instituto de Pesquisa Ambiental da Amazônia, DF 71.503-505 Brasília, Brazil; [d]Woods Hole Research Center, Falmouth, MA 02540-1644; and [e]Divisão de Sensoriamento Remoto, Instituto Nacional de Pesquisas Espaciais, SP 12227-010 São José dos Campos, Brazil

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From 2006 to 2010, deforestation in the Amazon frontier state of Mato Grosso decreased to 30% of its historical average (1996–2005) whereas agricultural production reached an all-time high. This study combines satellite data with government deforestation and production statistics to assess land-use transitions and potential market and policy drivers associated with these trends. In the forested region of the state, increased soy production from 2001 to 2005 was entirely due to cropland expansion into previously cleared pasture areas (74%) or forests (26%). From 2006 to 2010, 78% of production increases were due to expansion (22% to yield increases), with 91% on previously cleared land. Cropland expansion fell from 10 to 2% of deforestation between the two periods, with pasture expansion accounting for most remaining deforestation. Declining deforestation coincided with a collapse of commodity markets and implementation of policy measures to reduce deforestation. Soybean profitability has since increased to pre-2006 levels whereas deforestation continued to decline, suggesting that antideforestation measures may have influenced the agricultural sector. We found little evidence of direct leakage of soy expansion into cerrado in Mato Grosso during the late 2000s, although indirect land-use changes and leakage to more distant regions are possible. This study provides evidence that reduced deforestation and increased agricultural production can occur simultaneously in tropical forest frontiers, provided that land is available and policies promote the efficient use of already-cleared lands (intensification) while restricting deforestation. It remains uncertain whether government- and industry-led policies can contain deforestation if future market conditions favor another boom in agricultural expansion.

agriculture | land sparing | extensification | Brazilian Amazon

Global markets for commodities such as oil palm and soybeans are increasingly replacing local demand as the primary driver of tropical forest conversion for agriculture (1, 2). As global demand for food, fiber, and biofuels grows to unprecedented levels, the supply of available land continues to shrink (3). Most of this land is concentrated in tropical forest regions, fueling debate about how to reconcile the need for agricultural production with forest conservation and maintenance of ecosystem services such as carbon storage, climate regulation, and biodiversity conservation. Many argue that intensification and the productive use of already-cleared lands is a pathway to meeting these objectives (1, 4–7). Others conclude that intensification itself does not reduce pressure on forests and that, in the absence of effective conservation policies, increased yields can stimulate additional deforestation (8, 9) via direct agricultural encroachment or displacement of other land uses (3, 10). To date, empirical examples that test these assertions have been limited to national-scale analysis and scenarios (2, 3), with few concrete cases where increased production and forest conservation occurred simultaneously. Here we combine satellite data with government statistics on deforestation and production to track forest clearing and postdeforestation land uses during a decade of historic agricultural expansion in the state of Mato Grosso (MT), Brazil. The resulting dataset enables a spatially explicit analysis of trends in production and deforestation, whether and where intensification and reduced deforestation occurred simultaneously, and the accompanying market and policy context.

The Amazon's "arc of deforestation" has been the world's most active deforestation frontier in recent decades. The frontier states of MT, Rondônia, and Pará accounted for 85% of all Amazon deforestation from 1996 to 2005, converting an average of 16,600 $km^2 \cdot y^{-1}$ of forest (11). The underlying forces driving agricultural expansion in the region shifted dramatically in the last two decades (12, 13). Deforestation in the 1970s and 1980s was driven by a combination of government subsidies for Amazon development, investments in road infrastructure, unclear land tenure, and policies that promoted land speculation by rewarding deforesters with formal land titles (14). The last decade saw the removal of many policies that stimulated deforestation and an increasing influence of global markets on the Amazon economy (7, 15).

From 2006 to 2010, deforestation in the Amazon declined dramatically, particularly in MT. The state is situated in the agricultural frontier and occupies 900,000 km^2, divided between tropical forest (Amazon) and savanna/grassland (Cerrado) ecosystems (Fig. S1). MT is Brazil's leader in soy and beef production, responsible for 31% of the nation's soy production and over 13% of its cattle herd in 2009 (16). From 2000 to 2005 it also led in deforestation, accounting for 40% of deforestation in the Brazilian Amazon. In the ensuing years, deforestation in MT declined substantially, reaching an estimated 850 km^2 by 2010 (11)—just 11% of its historical average (7,600 $km^2 \cdot y^{-1}$ from 1996 to 2005; Fig. 1). These declines in deforestation coincided with fluctuations in commodity markets and the implementation of several high-profile policy initiatives aimed at restricting credit for deforesters, improving monitoring and enforcement, and excluding deforesters from the supply chains of major exporters.

Although expansion of cattle ranching continues to be the primary proximate driver of deforestation, the expansion of mechanized agriculture (croplands) altered deforestation dynamics, both directly by increasing conversion of forests for soy cultivation (17) and indirectly by replacing existing cattle pastures, some of which moved into other forested regions (13). The replacement of extensive land uses (e.g., cattle pastures) with intensive production (e.g., soybeans) is often referred to as

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[1]To whom correspondence should be addressed. E-mail: rd2402@columbia.edu.

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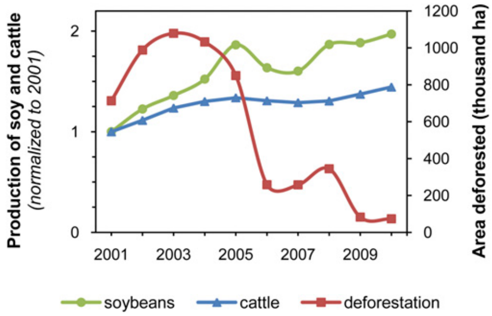

Fig. 1. Deforestation in Mato Grosso (11), tons of soy produced (19), and number of heads of cattle produced (16) from 2001 to 2010. Production was normalized to 2001. Production increases correspond to an area increase of 3 million ha for cropland (soy) and 10 million ha for pasture (assuming one head of cattle per ha).

"intensification," whereas the replacement of natural vegetation (e.g., forest or cerrado) with extensive land uses is termed "extensification." This terminology is complicated by the case of direct conversion of natural vegetation for intensive agriculture, which incorporates some elements of both. In lieu of this terminology, we distinguish among cropland expansion into already-cleared lands, cropland expansion into forests, and pasture expansion into forests.

As deforestation in MT decreased after 2005, soy production in the state continued its upward trend (Fig. 1), following a dip in 2006 and 2007 when commodity prices dropped precipitously. This decoupling of soy production from deforestation is a departure from trends during the first half of the decade, when deforestation tracked changes in soy and cattle production (18). Whereas the first half of the decade contradicts the hypothesis that intensification inevitably leads to land sparing, the latter half suggests that in certain contexts it can. This study combines satellite and field data with Brazilian government data on deforestation and production to quantify land-use transitions in the forested region of MT from 2001 to 2010. (Growing years span the period from August in the year of planting through July in the year of harvest. Unless otherwise specified, the years of analysis refer to growing years and are labeled by the harvest year.) We analyze Moderate Resolution Imaging Spectroradiometer (MODIS) data to develop spatially and temporally explicit estimates of transitions from forest to pasture or cropland and from already-cleared land (primarily pasture) to cropland. This analysis extends our previous time series of land-use transitions (17) and allows us to examine the changing dynamics associated with substantial declines in deforestation in the latter half of the decade. We focus on two central questions: (*i*) What land-use transitions—cropland expansion into forest, expansion into already-cleared lands, or changes in yields—occurred during the 2000s? How do trends vary between the first and second halves of the decade? (*ii*) Was declining deforestation from 2006 to 2010 associated with fluctuations in commodity markets, policy interventions, or both?

Results and Discussion

Trends in Soy Production. Land-use transitions differed dramatically between the periods 2001–2005 and 2006–2010 (Fig. 2). The first period corresponded to a boom in cropland (primarily soy) expansion, with the area planted in soy doubling from 3 to 6 million ha (Fig. S2) and production increasing by 85% (Fig. 1), or 8 million tons (19). A third of that increase in area (~1 million ha) and production (~3 million tons) occurred in the Amazon forest biome, where planted area more than tripled during the same period (Fig. S3) (19). Rising demand for soy was primarily related to export markets for animal fodder in Europe and Asia (13, 20). Although the majority of soy expansion replaced cattle pastures, an average of 12% of the area in large clearings (>25 ha) each year was directly converted from forest to cropland (Fig. 3). Our results support those previously reported for 2001–2005 (17), with a clear peak in deforestation for soy (18.5%) in 2003.

The second half of the decade paints a very different picture. Soy-planted area in MT contracted by nearly 1 million ha, and commodity prices crashed in 2006 and 2007. The area planted in soy increased each year since, but by 2010 still had not recovered to the highest levels recorded in 2005 (Fig. S2). After its peak in 2003, our analysis indicates that the percentage of large-scale (>25 ha) deforestation due to soy expansion decreased steadily, reaching 1% in 2009 (Fig. 3). The number of large clearings decreased markedly during the second half of the study period, representing an average of 85% of the deforested area from 2001 to 2005 and 65% from 2006 to 2009 (Fig. S4). This is consistent

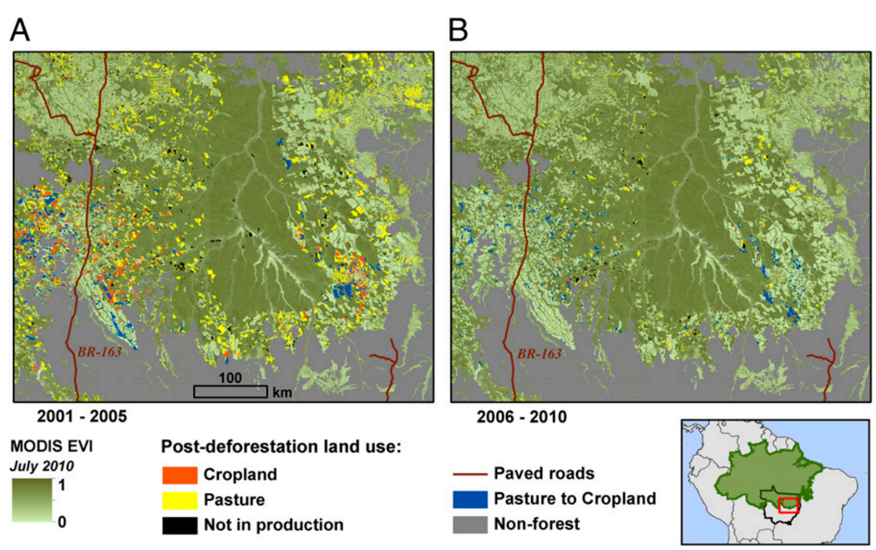

Fig. 2. (*A* and *B*, enlargements of the area boxed in red) Postdeforestation land uses in a subset of the study region from 2001 to 2005 (*A*) and 2006 to 2010 (*B*). Deforestation areas >25 ha were derived from the PRODES dataset (11), and land use from analysis of the MODIS EVI time series. The Brazilian Amazon forest biome is shaded in green (*Lower Right*).

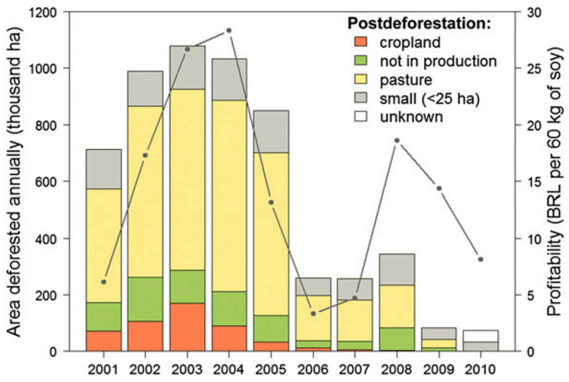

Fig. 3. Deforestation in Mato Grosso from 2001 to 2010. Postdeforestation land uses for large (>25 ha) clearings were derived from the PRODES dataset (11) and the MODIS EVI time series. Profitability was calculated from state-level data on price received for soy (38) and the cost of production (25), in Brazilian Reais (BRL). Soy profitability was correlated with cropland deforestation until 2007 ($R^2 = 0.64$, $n = 7$).

with previous work showing that deforestation during this latter period occurred primarily at the edge of existing fields or pastures (21), rather than through new large-scale expansion into forests. Despite overall reductions in deforestation and a temporary contraction in area planted, the forested region of MT saw a net increase in annual production of 750,000 tons between the 2005 and 2009 harvests (Fig. 4), roughly 25% of the increase observed in the first half of the decade.

Using our MODIS-derived soy distribution data and the state vegetation map (Fig. S1), we spatially allocated annual data on municipal soy production and area planted (19) by biome. The resulting land-use transition maps allowed us to examine whether annual changes in production within MT's forested region were due to deforestation, expansion into already-cleared areas, or changes in yield (Fig. 4 and Fig. S5). Short-term changes in yield may be influenced by several factors, including rainfall variability, emergence of crop diseases, changes in planting technology, and the time required to build up soil fertility (~2–3 y). As expected, the boom from 2001 to 2005 was largely due to cropland expansion, with increases in area planted accounting for steady increases in production. This pattern shifted noticeably in 2006 and 2007, when area planted and overall production decreased. The next 2 y saw a recovery in production attributable to increases in yield (2008) and area planted (2009). During the latter half of the decade, cropland expansion in MT's forested region occurred largely in previously cleared lands (primarily pasture), which accounted for 91% (318,000 ha) of expansion from 2006 to 2010, in contrast to 74% (800,000 ha) during the boom period (Fig. 4).

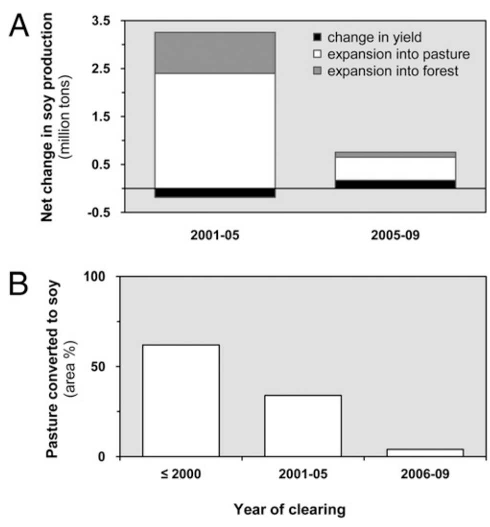

Fig. 4. Trends in soy expansion during the study period. (*A*) Attribution of net changes in soy production in the forested region of Mato Grosso to yield, expansion into forest, and expansion into previously cleared (primarily pasture) land. From 2001 to 2005, increases in production were due entirely to expansion into forest (26%) and pasture (74%). From 2005 to 2009, increases in yield accounted for 22% of production increases, and most (91%) cropland expansion occurred into pasture. (*B*) Of the pasture converted to soy from 2005 to 2009, about two-thirds represented old clearings deforested before 2000. These results are based on IBGE municipal agricultural data (19) and PRODES deforestation data (11), spatially allocated using the MODIS time series.

Trends in Pasture Expansion. As soy became more profitable in the region, the price of land increased, as did the opportunity cost of holding land for livestock production (15). During the boom period in soy expansion (2001–2005), the incentive for cattle producers was to sell their land at a profit and clear more land elsewhere (13). This displacement effect is difficult to quantify, although it is clear that the two sectors are strongly interconnected (20). Recent studies suggest that soy expansion and intensification in MT during the early part of the decade displaced cattle ranching northward into neighboring states (10, 22). This phenomenon may have been partially mitigated by improvements in livestock technology introduced in the center-west to keep up with the profitability of soy in the region (15). Improvements in pasture management and phyto-sanitary measures aimed at keeping the herd free of hoof-and-mouth disease may have been crucial to limiting indirect impacts of soy expansion, avoiding an estimated 6,000–10,000 $km^2 \cdot y^{-1}$ of additional deforestation (15).

Our MODIS-based analysis indicates that large-scale clearings of forest for pasture decreased rapidly after 2005, dropping over 70% from 2005 to 2006 alone (Fig. 3). These reductions in cattle expansion made the biggest contribution to deforestation reductions observed after 2005, suggesting that market signals and policy measures aimed at reducing illegal deforestation may have had a broad impact. The increasing costs of expansion were concurrent with a move toward intensification, as many of the state's cattle producers replaced extensive grazing (less than one head of cattle per ha) with confinement of animals in feedlots for part of the growing period—a practice that grew by 286% from 2005 to 2008 (23). Such intensification allows for local consumption of second-harvest crops (millet, sorghum, and corn) and potentially releases land for other agricultural uses.

Market Trends. From 2001 to 2009, deforestation for soy was weakly correlated with the profitability per 60-kg sack of soy (Fig. S6*A*; $R^2 = 0.39$, $n = 9$), defined as the difference between the variable costs of production and the price received by producers in MT (Fig. 3). The farm gate price of cattle showed virtually no correlation with deforestation for pasture (Fig. S6*B*; $R^2 = 0.04$, $n = 9$) during the same period. These relationships become considerably stronger if we consider only the years before 2008, with soybean profitability and cattle prices explaining significantly more of the variation in cropland deforestation (Fig. S6*A*; $R^2 = 0.64$, $n = 7$) and pasture deforestation (Fig. S6*B*; $R^2 = 0.89$, $n = 7$), respectively. Although based on a limited number of observations, these trends suggest that high profitability was a strong incentive for soy and cattle expansion into forested areas during the boom period and that decreases in deforestation from 2003 to 2007 were at least partially due to declines in profitability. This trend is supported by a recent econometric analysis for 783 municipalities, indicating that fluctuations in meat and soybean prices drove deforestation in the region from 2002 to 2007 (24). Decreased profitability in the latter half of the decade was associated with a global crash in commodity markets and increases in the variable costs (25) of soy production (e.g., seeds and fertilizers), which may have temporarily removed incentives for expansion. Despite the recovery of soy and cattle prices after 2007, deforestation did not increase as in the early part of the decade (21). Rather, expansion of soy during this period occurred almost exclusively on previously cleared (pasture) lands (Fig. 4). Expansion of cattle ranching also decreased during this period, presumably as a result of the market contraction and a move toward intensification in MT (23).

Policy Initiatives. Although profitability and macroeconomic trends almost certainly affect the short-term decision making of producers, it is difficult to isolate their impact from that of government- and industry-led policies introduced during the same period. In response to increasing deforestation in the mid-1990s and the decentralization of environmental regulatory powers, MT implemented an integrated system of environmental licensing and management that introduced regular satellite-based monitoring of deforestation (26–28). Despite implementation of this system, deforestation rates continued to climb. As they reached their peak in 2004, the federal government established a national plan to control deforestation in the Amazon, requiring states to develop and implement their own deforestation control programs (29). In an attempt to curtail corruption related to licensing for logging and clearing, the federal government implemented real-time monitoring of deforestation and carried out raids, which led to the imprisonment of employees in several state and federal agencies and reorganization of the MT state environmental agency (7, 28). Finally, in 2008 the federal government created a "black list" of municipalities with high deforestation rates, imposing a series of sanctions on producers in those municipalities, including eliminating subsidies, restricting credit, halting all (legal) deforestation, and issuing fines for illegal clearing and burning (7, 30).

Two agroindustry-led initiatives to reduce deforestation accompanied the government-led enforcement initiatives described above. The first was a 2006 "soy moratorium" (31), which excluded all soy cultivated in areas deforested after that date from the supply chains of major exporters (30). Prompted by pressure from international environmental organizations and demand from environmentally conscious consumers, it served as a model for a similar moratorium in the beef and leather industry, declared in 2009 by the four largest cattle producers and traders. These demand-driven disincentives to deforestation are relatively new forces in the region, complementing government enforcement measures and bolstering existing certification schemes to reward environmentally responsible production (13, 20).

The land-use transitions observed during the postboom period—and the case of 2009 in particular—suggest that when market conditions favored expansion, producers expanded into areas previously cleared for pasture rather than forest areas (Fig. 4 and Fig. S5). These patterns are consistent with the outcomes expected by many of the recent policy interventions, providing some support for the hypothesis that they have helped to suppress deforestation. An alternate explanation is that, even in the absence of policy reforms, the market-induced contraction in soy area planted provided sufficient fallow cropland to absorb soy expansion in the years following the market decline. Had this been the case, we would expect no increase in the cumulative area planted from 2006 to 2010 (i.e., no new cropland). In fact, our MODIS estimates indicate that there was a steady increase in cumulative area planted after 2005 (Fig. S7*A*) while deforestation was suppressed, suggesting a shift (proportionally) from soy expansion into forest to soy expansion into previously cleared lands during this period (Fig. 2). Combining our satellite analyses with Brazilian government data on the year of clearing (11) provides further evidence that this shift was not simply due to a glut of land cleared during the boom period (7). Rather, about two-thirds of nonforest areas converted to soy during this period were cleared before 2000 (50% before 1997), and the remaining third was cleared from 2001 to 2005 (Fig. 4*B*). Because MT had little mechanized crop production before 2000 (Fig. S3) (19), we assume that lands cleared before that date were originally cleared for pasture.

Leakage. One potential by-product of reductions in deforestation and cropland expansion in the forested region of MT is leakage into the state's cerrado or into forested areas of neighboring states. Theoretically, such leakage can occur at multiple scales (3) and could take the form of direct conversion of natural vegetation for cropland or indirect land-use changes associated with the displacement of cattle ranching (10). To examine direct leakage within MT, we used our satellite-derived data on cropland area and the MT vegetation map (Fig. S1) to assess whether decreased deforestation in the postboom period displaced soy expansion into the state's cerrado region. Based on patterns of soy area planted in each biome, we saw no evidence of an overall increase in soy expansion into the state's cerrado since 2005. Planted area in both biomes exhibited similar trends throughout the study period (Fig. S7). Moreover, an analysis of deforestation polygons in the MT cerrado (32) indicates that deforestation for cropland decreased from 2003 to 2006 and remained relatively low for the remainder of the decade (Fig. S8). These trends provide indirect evidence that reduced deforestation in the forest region did not provoke an immediate increase in clearing of cerrado for soy in the latter half of the decade.

Previous studies have linked soybean expansion in MT to the displacement of pastures into Pará (22), Rondônia, and Amazonas (10) based on municipality-level agricultural statistics. At the state level, annual deforestation rates in Pará and Rondônia (11) decreased considerably after 2005 (Fig. S9) and do not suggest substantial leakage (direct and indirect) from MT in the short term. However, small or isolated leakage effects may be masked by a number of other factors affecting deforestation at the state level, including changing markets, governance, enforcement capacity, agrarian reform, and land speculation. Prevention of leakage in the cattle sector is of particular concern, given the Brazilian government's commitment to decreasing deforestation- and land use-related carbon emissions (33). The present study focuses on the soybean sector because it played a catalytic role in increasing deforestation during the first half of the decade, but this is only part of the equation. Controlling deforestation over the long term will likely hinge on what happens in the cattle sector, where there are greater opportunities for gains in efficiency through intensification (33). The information presented here does not preclude lagged effects, whereby recent land-use dynamics result in future leakage, nor does it eliminate the possibility that leakage may be under way at finer scales or in more distant regions. Establishing that leakage is occurring from MT would require more in-depth analysis of the political context, migration patterns, and socioeconomic motivation of producers in those regions.

Conclusions

The combination of MODIS-derived land-use information with government agricultural and deforestation statistics allowed a spatially explicit analysis of land-use transitions associated with declining deforestation and increasing production in MT's forested region from 2006 to 2010. The analysis leads to three conclusions. First, after 2005 the increase in soy production was partially due to relatively high yields (e.g., 2008), but mainly to a proportional increase in soy expansion onto previously cleared land compared with the first half of the decade. The observed patterns provide evidence that it is possible to achieve the dual objectives of forest conservation and agricultural production (4, 8, 12) in contexts where there is a sufficient supply of previously cleared land and incentives that encourage productive use of that land instead of expansion into forests. Although this outcome is positive for forests and food production, there are likely additional synergies and tradeoffs inherent in the expansion of intensive production, even if constrained to previously cleared lands. On the one hand is the synergistic potential for improved farm-level management (e.g., no tillage, cover crops) to enhance crop productivity and soil carbon storage. On the other are potential tradeoffs with biodiversity loss, altered hydrological function, and runoff of agrochemicals. Furthermore, the observed decreases in deforestation do not guarantee that remaining forests are pristine, considering recent evidence that forest degradation in the region is increasing due to logging (34) and fire (35). This may diminish the benefits of reduced deforestation for climate and forest conservation.

Second, deforestation for cropland in MT remained low even when profitability favored soy expansion. In 2008, profitability peaked to levels comparable to those during the 2000–2005 boom, yet deforestation for soy continued to decrease (Fig. 3). These decreases may be partially explained by increases in the variable cost of soy production, which decreased profitability relative to the first half of the decade. These trends were also concurrent with the implementation of policies aimed at restricting credit for deforesters, improving monitoring and enforcement, and excluding deforesters from the supply chains of major exporters. Observed patterns suggest that they have had some success. However, the implementation of the policies mentioned here occurred at a time when market conditions already favored a slowing in deforestation. Whether this coincidence was strategic or serendipitous, it likely helped in achieving deforestation reductions during the late 2000s. Quantifying the relative influences of concurrent market drivers and policy interventions requires more detailed analyses of landholder responses to different incentives.

Finally, MT's reduction of deforestation after 2005 did not result in a net increase of soy expansion into the state's cerrado. Deforestation in Pará and Rondônia also declined, suggesting that the patterns observed in MT did not provoke a major net increase in clearing in adjacent Amazonian states during the study period. It is possible that the advancing wave of soy production into the Amazon has already exhausted suitable lands for agricultural production in MT's cerrado or that forested areas in neighboring states are unsuitable for large-scale crop production, neither of which is captured by the data presented here. Over the last decade, expansion into previously cleared lands and intensification of crop (18) and cattle production may also have mitigated potential leakage into other regions (15). Although the large supply of low-productivity pasture land presents an opportunity for gains in efficiency and mitigation of future leakage, this result is by no means guaranteed. There is already evidence of recent soy expansion into cerrado areas farther east and northeast in the country, particularly in the states of Bahia, Maranhão, Piauí, and Tocantins (19, 36), although it is unclear whether these trends reflect leakage from the southern Amazon.

The Brazilian government's investments in monitoring and enforcement of deforestation have created powerful disincentives for expansion into forest lands (24), complemented by voluntary industry initiatives. Although these efforts have had some success, our results suggest that preventing deforestation over the long term will require parallel efforts to modernize the cattle sector and create strong new policy incentives that promote efficient use of degraded lands. Recent efforts to model Brazil's low-carbon development alternatives indicate that the implementation of existing technologies to restore degraded lands and increase pasture productivity could free enough additional land to accommodate projected growth through 2030 (33), although achieving this would be challenging and require substantial private and public investments.

Mato Grosso has considerable remaining forest land that is suitable for agricultural production (Fig. S10), and advances in infrastructure and technology will likely increase access to these and other Amazonian forests (20). Reports of increased deforestation in MT during the first semester of 2011 have already raised concerns that soaring commodity prices and proposed changes to Brazil's forest code may soon reverse recent trends in deforestation. If Brazil is to build on its successes in reducing deforestation and continue the trend toward becoming one of the world's major food producers, it will require continued implementation of policies that conserve standing forests while directing agricultural expansion onto previously cleared lands. If successful, initiatives such as the Reduced Emissions from Deforestation and Degradation in Developing Countries (REDD+) program of the United Nations Framework Convention on Climate Change (37) and national efforts to promote low-carbon development could help sustain lower deforestation rates by providing mechanisms to compensate actors for avoiding deforestation and increasing productivity (7). Although our results pertain to the specific context of MT in the last decade, the approach of tracking postclearing land uses can yield insights into the changing drivers of deforestation in other tropical forest regions. Demands for export-oriented agricultural products will likely continue to exert pressure for expansion into forested regions (1) at the same time that carbon markets and consumer demand call for decreased deforestation. National, state, and local governments will need to consider context-specific strategies and policy incentives to balance these objectives.

Methods

Data. Data on soy production and area planted came from the Brazilian Institute of Geography and Statistics (IBGE) (19), and annual deforestation data from the Brazilian National Institute for Space Research (INPE) (11). Data on the farm gate price of soy and cattle in MT came from The Getúlio Vargas Foundation (38, 39), and cost data from the National Food Supply Company of Brazil (25). The IBGE provided historical data on the expanded consumer price index (40) and 2007 municipal boundaries (http://www.ibge.gov.br/home/geociencias/geografia). Collection 5 MODIS enhanced vegetation index (EVI) data for the study area came from the Land Processes Distributed Active Archive Center (http://mrtweb.cr.usgs.gov).

Remote Sensing. We used the MODIS EVI product (MOD13Q1) to perform annual land-use classifications based on differences in vegetation phenology, an approach that is conceptually similar to that of previous studies (17, 41). Given changes in the MODIS data (collection 4–5) and variation in the details of our methodology, we processed the entire 10-y time series for this analysis. First, we eliminated cloud-contaminated pixels and replaced missing data values using a spline interpolation in the time (z) dimension. For each growing year, we calculated SD, annual mean, dry-season mean (July), wet-season mean (December–February), and wet-season maximum. Based on these metrics, we developed a decision tree classifier using 326 ground data points collected in 2006 (42) to classify cropland, forest, and pasture/cerrado for each year (Fig. S11). Finally, we filtered the classified time series using a 3-y filter to remove unlikely land-use transitions through time. This correction affected at least one observation in 13% of the pixels monitored (<2% of all observations).

The final land-use classification (Fig. S12) was validated using 317 data points collected in 2010 and distinguishes the three classes of interest with an overall accuracy of 92% (Table S1). Given the moderate resolution of MODIS data (250-m), we cannot reliably evaluate edge pixels or areas smaller than 25 ha (43), which accounted for an increasing proportion of deforestation during the study period (21). As a result, we may underestimate deforestation for cropland, particularly toward the end of the time series. Nevertheless, most of the area in production occurs in clearings considerably larger than 25 ha (17), allowing us to characterize overall land-use trends.

Postdeforestation Land Use. To determine postdeforestation land use, we combined INPE's high-resolution (30-m) deforestation data with our land-use classification, a method similar to that published by Morton and coauthors (17). First, we used the state vegetation map (Fig. S1) to mask out areas that were not historically forest. For each deforestation year (September and

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August), we selected large deforestation polygons (>25 ha) and classified each according to the majority land use within its boundaries in the subsequent 3 y. Polygons identified as cropland in any of the following 3 y were classified as deforestation for cropland. Polygons identified as pasture in the 3 y after clearing were classified as deforestation for pasture. Polygons identified as forest in all 3 postdeforestation y were classified as not in production, and likely include damaged forests that were never fully cleared (e.g., logged or burned), edge effects from adjacent forest cover, and regrowth (17). We used the same approach for analysis of cerrado deforestation polygons (32).

Planted Area and Production. We combined IBGE municipal boundaries and the potential vegetation map (Fig. S1) to allocate production and planted area data to the Cerrado and Amazon forest biomes. Municipalities with most of their area in one biome (>80%) were automatically assigned to that biome (~70% of municipalities). Remaining municipalities were evaluated according to the majority biome, municipal area, and cumulative area planted during the study period to identify cases where assignment to the majority biome could result in misallocation of croplands. In these cases, we used our annual land-use classification to determine the proportion of soy area located in each biome in a given year. This correction affected 10% of all municipalities and reduced errors that would have occurred had we assumed that mixed municipalities were in a single biome based on the majority vegetation type. Performing the same allocation using state-level data did not change the results substantially (r = 0.98), and we have reported municipality-level results here.

Market Trends. Our calculation of soy profitability is based on the variable costs of production—those costs associated with planting, harvest, storage, and transport of a single soy crop. Our analysis excludes fixed costs (e.g., depreciation of machinery), which are less likely to influence short-term decisions (8). After using an expanded consumer price index (40) to adjust price and cost data to the July 2010 Real, we calculated the difference between soy price and production costs. The resulting index estimated the profit per 60-kg sack of soybeans in each growing year. In the absence of comparable data on the cost of cattle production, we used inflation-adjusted data on the farm gate cattle price (39) to examine the relationship between markets and deforestation for cattle. To assess the influence of temporal autocorrelation on the statistical models, we compared parameter estimates from models with and without an autocorrelation error structure. Because including the autocorrelation structure did not change the results, we present only the estimates derived from ordinary least squares regression.

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