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

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Abbreviations: MODIS, Moderate Resolution Imaging Spectroradiometer; PRODES, Program for the Estimation of Deforestation in the Brazilian Amazon; MT, Mato Grosso, INPE, Brazilian National Institute for Space Research; CONAB, National Food Supply Company of Brazil; EVI, Enhanced Vegetation Index; FGV, Getúlio Vargas Foundation; IBGE, Brazilian Institute of Geography and Statistics; BACEN, Brazilian Central Bank; MAPA, Brazilian Ministry of Agriculture; LPDAAC, Land Processes Distributed Active Archive Center; UNFCCC, United Nations Framework Convention on Climate Change

Abstract

From 2006-2010 deforestation in the Amazon frontier state of Mato Grosso decreased to 30% of its historical average (1996-2005) while agricultural production reached an all time high, achieving the oft-cited objective of increasing production while maintaining forest cover. 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 2001-2005 was entirely due to cropland expansion into previously cleared areas (74%) or forests (26%). From 2006-2010, 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 while deforestation continued to decline, suggesting that anti-deforestation measures may have influenced the agricultural sector. We found little evidence of leakage of soy expansion into cerrado in Mato Grosso or forests in neighboring Amazon states during the late 2000s, although leakage to more distant regions is possible. This study provides empirical evidence that reduced deforestation and increased agricultural production can occur simultaneously in tropical forest frontiers through productive use of already cleared lands. It remains uncertain whether government and industry-led policies can contain deforestation when market conditions again favor a boom in agricultural expansion.

Key-words: deforestation, land-use change, agriculture, soybean, intensification

Introduction

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 (1-3). As global demand for agricultural products grows to unprecedented levels, the supply of available land continues to shrink (4). 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 (2, 5-8). 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 (9, 10) via direct agricultural encroachment or displacement of other land uses (4, 11). To date, empirical examples that test these assertions are limited to national-scale analysis and scenarios (3, 4), 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 post-deforestation 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 1996-2005, converting an average of $16,600 \text{ km}^2\text{yr}^{-1}$ of forest (12). The underlying forces driving agricultural expansion in the region shifted dramatically in the last two decades (13, 14). Deforestation in the 1970s and 1980s was driven by a combination of government subsidies for Amazon development, investments in road infrastructure (15), unclear land tenure, and policies that promoted land speculation by rewarding deforesters with formal land titles (16). The last decade saw the removal of many policies that stimulated deforestation and an increasing influence of global markets on the Amazon economy (8, 17).

From 2006-2010 deforestation in the Amazon declined dramatically, particularly in MT. The state is situated in the agricultural frontier and occupies $900,000 \text{ km}^2$, divided between tropical forest (Amazon) and savanna/grassland (Cerrado) ecosystems (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 (18). From 2000-2005 it also led in deforestation, accounting for 40% of all Amazon deforestation. In the ensuing years deforestation in MT declined substantially, reaching an estimated 850 km^2 by 2010 (12) – just 11% of its historical average ($7,600 \text{ km}^2\text{yr}^{-1}$ from 1996-2005, 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.

While 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 (19) and indirectly by replacing existing cattle pastures, some of which moved into other forested regions (14). The replacement of extensive land uses (e.g. cattle pastures) with intensive production (e.g. soybeans) is often referred to as 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 (20). 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 2001-2010*. We analyze MODIS data to develop spatially and temporally explicit estimates of transitions from forest to pasture or cropland and from already cleared land (pasture, fallow) to cropland. This analysis extends our previous time series of land-use transitions (19) 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: 1) What land-use transitions – cropland expansion into forest, expansion

* Growing years span 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.

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? 2) Was declining deforestation from 2006-2010 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 from 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 (S2) and production increasing by 85% (Fig. 1), or 8 million tons (21). A third of that increase in area (~ 1 million ha) and production (~3 million tons) occurred in the Amazon forest biome, where planted area nearly tripled during the same period. Rising demand for soy was primarily related to export markets for animal fodder in Europe and Asia (14, 22). While 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 confirm those previously reported for 2001-2005 (19), with a clear peak in deforestation for soy (18.5%) in 2003. Minor differences in our results are likely due to changes in the MODIS data and differences in the details of our methodology (*Methods*).

The second half of the decade paints a very different picture. Soy planted area in MT contracted by nearly 1 million ha, while 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 (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 all deforestation events (by area) from 2001-2005 and 65% from 2006-2009 (S3). This is consistent with previous work showing that deforestation during this latter period occurred primarily at the edge of existing fields or pastures (23), 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 (S1), we spatially allocated annual data on municipal soy production and area planted (21) 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, S4). 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 years). As expected, the boom from 2001-2005 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 two years saw a recovery in production, mainly due to increases in yield (2008) and area planted (2009). During the latter half of the decade, cropland expansion in MT's forested region occurred primarily in previously cleared lands (pasture, fallow), which

accounted for 91% (318,000 ha) of expansion from 2006-2010 in contrast to 74% (800,000 ha) during the boom period (Fig. 4).

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 (17). 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 (14). This displacement effect is difficult to quantify, though it is clear that the two sectors are strongly interconnected (22). Recent studies suggest that soy expansion and intensification in MT during the early part of the decade displaced cattle ranching northward into Pará state (11, 24). 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 (17). Improvements in pasture management and phyto-sanitary measures aimed at keeping the herd free of foot and mouth disease may have been crucial to limiting indirect impacts of soy expansion, avoiding an estimated 6,000 to 10,000 km²yr⁻¹ of additional deforestation (17).

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, even before industry-led initiatives such as the “beef moratorium” (*Policy initiatives*). The increasing costs of expansion were concurrent with a move towards intensification, as many of the state’s cattle producers replaced extensive grazing (< 1 head of cattle per ha) with confinement of animals in feedlots for part of the growing period – a practice that grew by 286% from 2005-2008 (25). The use of confinement not only allows for local consumption of second-harvest crops (millet, sorghum, and corn) for cattle feed, but also improves beef production during the long dry season (25). Recent increases in the number of meat processing plants in MT have also facilitated increases in cattle production by doubling meat processing capacity and reducing transportation costs (25).

Market trends

From 2001-2009 deforestation for soy was weakly correlated with the profitability per 60 kg sack of soy (S5a, Adj-R²=0.31, p<0.1, n=9), defined as the difference between the variable costs of production and the price received by producers in MT (Fig. 3). This relationship becomes stronger if we consider only the years prior to 2008 (S5a, Adj-R²=0.57, p<0.05, n=7), suggesting that high profitability was a strong incentive for soy expansion into forested areas during the boom period and that decreases in deforestation for soy from 2003-2007 were at least partially due to declines in profitability. Decreased profitability in the latter half of the decade was associated with a global crash in commodity markets and increases in the variable costs (26) of soy production (e.g. seeds and fertilizers), which may have temporarily removed incentives for expansion. Despite the recovery of soy prices after 2007, deforestation for soy did not increase as in the early part of the decade (23). Rather, expansion of soy during this period occurred almost exclusively on previously cleared lands (Fig. 4).

The boom in soy and cattle expansion began shortly after a rapid devaluation of the Real, creating market conditions that favored commodity exports (14). The Brazilian Real became

considerably stronger in the latter half of the decade, which may have contributed to decreased deforestation by influencing the profitability of soy and cattle exports. In the absence of consistent historical data on MT cattle profitability, we used the exchange rate as a proxy for market incentives for cattle expansion. Throughout the study period, the exchange rate (Reais per Euro) was significantly correlated with total deforestation ($\text{Adj-R}^2 = 0.86$, $p < 0.0001$, $n=10$) and deforestation for pasture (S5b, $\text{Adj-R}^2 = 0.81$, $p < 0.001$, $n=9$). Although based on a limited number of years, these trends support the notion that global markets are important forces in the Amazon economy and potentially key drivers of land-use change. They may also help to explain why deforestation decreased simultaneously throughout the Amazon and across both the cattle and soy sectors of the agricultural economy.

Policy initiatives

While 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, which introduced regular satellite-based monitoring of deforestation (27-29). 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 (30). 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 (8, 29). 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 (8, 31).

Two agroindustry-led initiatives to reduce deforestation accompanied the government-led enforcement initiatives described above. The first was a 2006 “soy moratorium” (32), which excluded all soy cultivated in areas deforested after that date from the supply chains of major exporters (31). 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 (14, 22).

The land-use transitions observed during the post-boom period – and the case of 2009 in particular – suggest that when market conditions favored expansion producers expanded into previously cleared areas rather than forest areas (S4, Fig. 4). 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 2006-2010 (i.e. no new cropland). In fact, our MODIS estimates indicate that there was a steady increase in cumulative area planted after 2005 (S6a) 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 PRODES data on the year of clearing (12) indicates that this shift was not simply due to a glut of land cleared during the boom period (8). Rather, about two-thirds of non-forest areas converted to soy during this period were cleared prior to 2000 (50% prior to 1997) and the remaining third was cleared from 2001-2005 (Fig. 4).

Leakage

One potential byproduct 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 (4) 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 (11). Our analysis of leakage is spatially constrained to the frontier states of MT, Pará, and Rondônia, a region that accounted for the majority (> 80%) of Amazon deforestation throughout the 2000s. First, we used our satellite-derived data on cropland area and the MT vegetation map (S1) to assess whether decreased deforestation in the post-boom 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 (S6) and may even indicate a slight contraction in soy area planted in cerrado regions over the last two years.

At a coarse scale, annual deforestation in Pará and Rondônia (12) decreased considerably after 2005 (S7) and do not suggest substantial leakage (direct and indirect) from MT in the short term. The fact that we did not observe clear evidence of leakage into the Cerrado or increased deforestation in neighboring states does not preclude lagged effects, whereby recent land use dynamics result in future leakage, or eliminate the possibility that leakage may already be underway in more distant regions. Previous studies have linked soybean expansion in MT to indirect land-use changes in Pará (24), Rondônia, and Amazonas (11) based on municipality-level agricultural statistics. Given that annual deforestation rates in Pará decreased more slowly than in other Amazon states, it is possible that this leakage has simply slowed due to weak markets. However, there are a multitude of other factors that potentially influence deforestation in distant frontiers, including differences in governance (33), enforcement capacity, patterns of agrarian reform, and land speculation. If applied to a larger region, the methods presented here could provide a more spatially-explicit understanding of the land-use transitions in these 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. These complex processes are an important area of study and merit further evaluation.

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 2006-2010. 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 to 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 (5, 9, 13), given a sufficient supply of previously cleared land and incentives that encourage productive use of that land instead of expansion into forests. While 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 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 trade-offs 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 (34) due to logging (35) and fire (36), which 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 the strength of the Real and increases in the variable cost of soy production, both of which decreased profitability relative to the first half of the decade. These trends were 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 increased 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 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 less suitable for cropland, neither of which is captured by the data presented here. Over the last decade, expansion into previously cleared lands and intensification of agricultural production (20) may also have mitigated potential leakage into other regions (17). However, the prospect of a near-term increase in soy expansion into forested areas in Pará is plausible, given the recent construction of a new port to export soy from Santarém and paving of the BR-163 highway connecting it to MT. There is already evidence of recent soy expansion into cerrado areas further east and northeast in the country, particularly in the states of Bahia, Maranhão, Piauí, and Tocantins (21), although it is unclear if these trends are linked to leakage from the southern Amazon.

Whether anti-deforestation policies can effectively contain deforestation when market conditions again favor a boom in agricultural expansion remains unknown. Reports of increased deforestation in MT during the first semester of 2011 have raised concerns that soaring commodity prices may soon reverse the recent reductions in deforestation. Regardless of the course of future deforestation in MT, the years from 2006-2010 are a concrete example of a period when deforestation declined and production increased, indicating that it is possible to simultaneously achieve forest conservation and agricultural production. The approach of tracking post-clearing land uses is pertinent to future work to understand the changing drivers of deforestation in this and other frontier regions.

Mato Grosso has considerable remaining forest land that is suitable for agricultural production (S8) and advances in infrastructure and technology will likely increase access to these and other Amazon forests (22). If Brazil is to build on its successes in reducing deforestation and continue the trend towards 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 like the UNFCCC REDD+ (Reduced Emissions from Deforestation and Degradation in Developing Countries) program (37) could help sustain lower deforestation rates by providing financial mechanisms to compensate actors for avoided deforestation. Although our results pertain to the specific context of MT in the last decade, the general observation that forest conservation and increased agricultural production can occur simultaneously applies to other tropical forest regions where already cleared land is available for intensification. Demands for export-oriented agricultural products will likely continue to exert pressure for expansion into forested regions (2) 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 for meeting these multiple objectives.

Methods

Data

Data on soy production and area planted came from the IBGE (21) and annual deforestation data from INPE (12). Data on the farm gate price of soy in MT came from FGV (38) and cost data from CONAB (26). Monthly data on Brazil's real foreign exchange rate came from BACEN (39), while export volumes and the destination of soybean exports from MT came from MAPA (40). The IBGE provided historical data on the Expanded Consumer Price Index (41) and 2007 municipal boundaries[†]. Collection 5 MODIS EVI data for the study area came from the LPDAAC[‡].

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 (19, 42). Given changes in the MODIS data (collection 4 to 5) and variation in the details of our methodology, we processed the entire 10-year time series for this analysis. First, we eliminated cloud-contaminated pixels and replaced missing data values using a spline

[†] Available at <http://www.ibge.gov.br/home/geociencias/geografia/>. Accessed on December 10, 2010.

[‡] Available at <http://mrtweb.cr.usgs.gov/>. Accessed on January 14, 2011.

interpolation in the time (z) dimension. For each growing year we calculated standard deviation, annual mean, dry season mean (July), wet season mean (Dec-Feb), and wet season maximum. Based on these metrics, we developed a decision tree classifier using 326 ground data points collected in 2006 (43) to classify cropland, forest, and pasture/cerrado for each year (S9). Finally, we filtered the classified time series using a three-year 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 (S10) 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 (44), which accounted for an increasing proportion of deforestation during the study period (23). As a result, we may underestimate deforestation for cropland, particularly towards the end of the time series. Nevertheless, most of the area in production occurs in clearings considerably larger than 25 ha (19), allowing us to characterize overall land-use trends.

Post-deforestation land use

To determine the post-deforestation 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 (19). First, we used the state vegetation map (S1) to mask out areas that were not historically forest. For each deforestation year (Sep-Aug), we selected large deforestation polygons (> 25 ha) and classified each according to the majority land use within its boundaries in the subsequent three years. Polygons identified as cropland in any of the following 3 years were classified as deforestation for cropland. Polygons identified as pasture in the 3 years after clearing were classified as deforestation for pasture. Polygons identified as forest in all 3 post-deforestation years 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 (19).

Planted area and production

We combined IBGE municipal boundaries and the potential vegetation map (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. In order to validate these results, we performed the same allocation using state level data on soy area and production. The latter approach did not change the results substantially (99% correlation) and we have reported results from the former analysis here.

Profitability and exchange rate

Initial analyses indicated that soy price did not explain variations in large-scale deforestation in MT from 2006-2010, leading us to examine fluctuations in the variable costs of production – those costs associated with planting, harvest, storage, and transport of a single soy crop. Our

analysis excluded fixed costs (e.g. depreciation of machinery), which are less likely to influence short term decisions (9). After using an expanded consumer price index (41) 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. Exchange rates between the Brazilian Real and EU Euro were already adjusted for inflation and indexed to 1994 (39).

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Figures

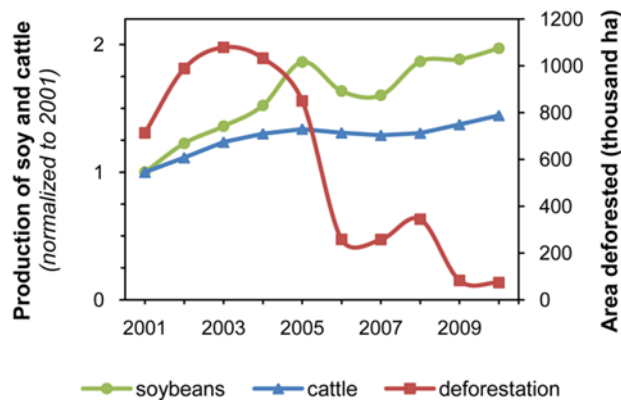


Figure 1: Deforestation in Mato Grosso (13), tons of soy produced (22), and number of heads of cattle produced (19) from 2001-2010. Production was normalized to 2001. Production increases correspond to an area increase of 3 million ha for cropland (soy) and 10 million ha for pasture (assuming one head of cattle per ha).

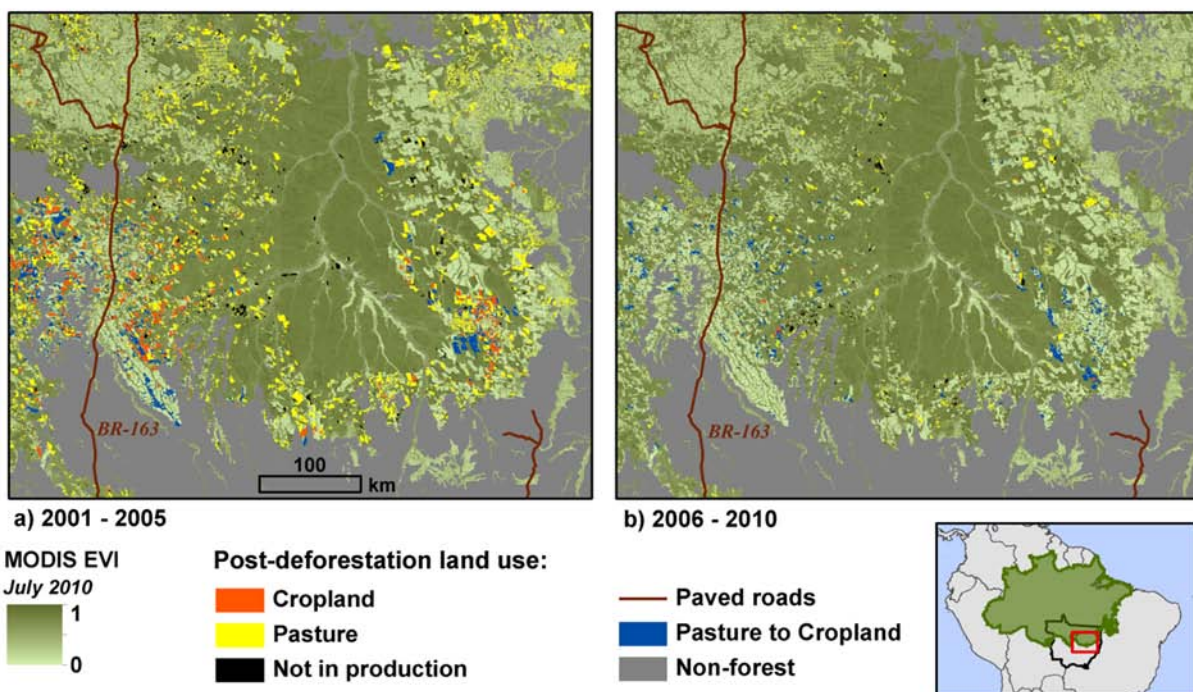


Figure 2: Post-deforestation land uses in a subset of the study region (*inset*) from 2001-2005 (a) and 2006-2010 (b). Deforestation areas >25 ha were derived from the PRODES dataset (13) and land use from analysis of the MODIS EVI time series. The Brazilian Amazon forest biome is shaded in green (*inset*).

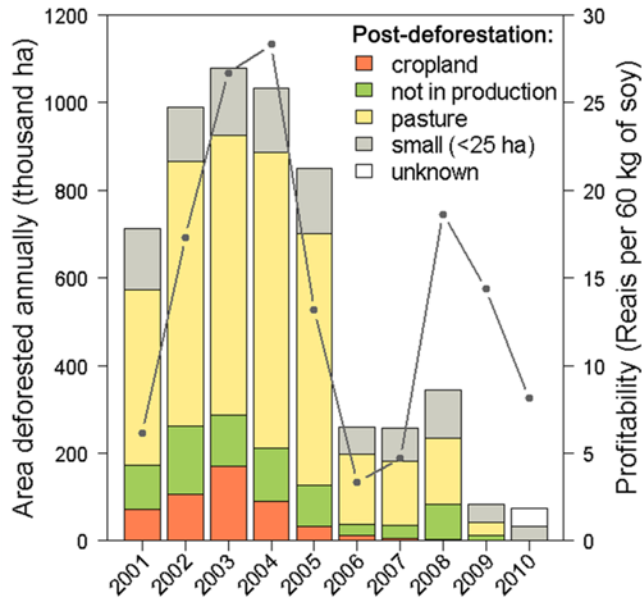


Figure 3: Deforestation in Mato Grosso from 2001-2010. Post-deforestation land uses for large (>25 ha) clearings were derived from the PRODES dataset (13) and the MODIS EVI time series. Profitability was calculated from state level data on price received for soy (42) and cost of production (28). Soy profitability was correlated with cropland deforestation until 2007 ($Adj-R^2 = 0.57$, $p < 0.05$, $n = 7$).

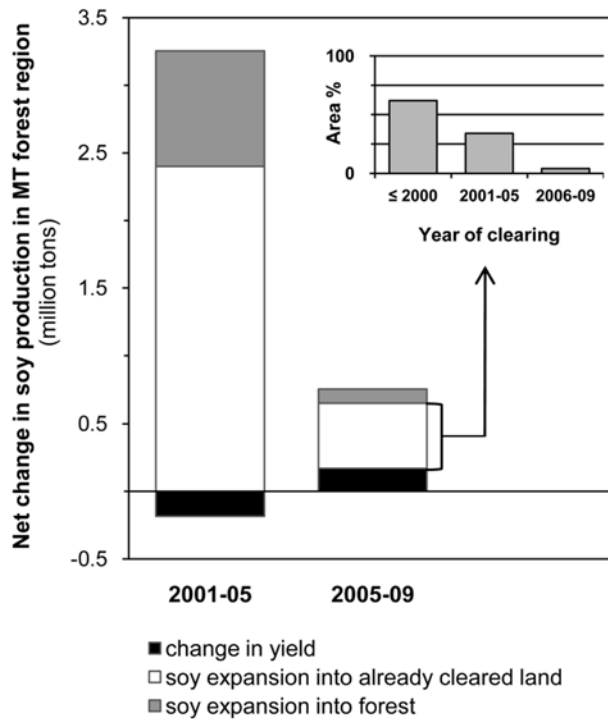
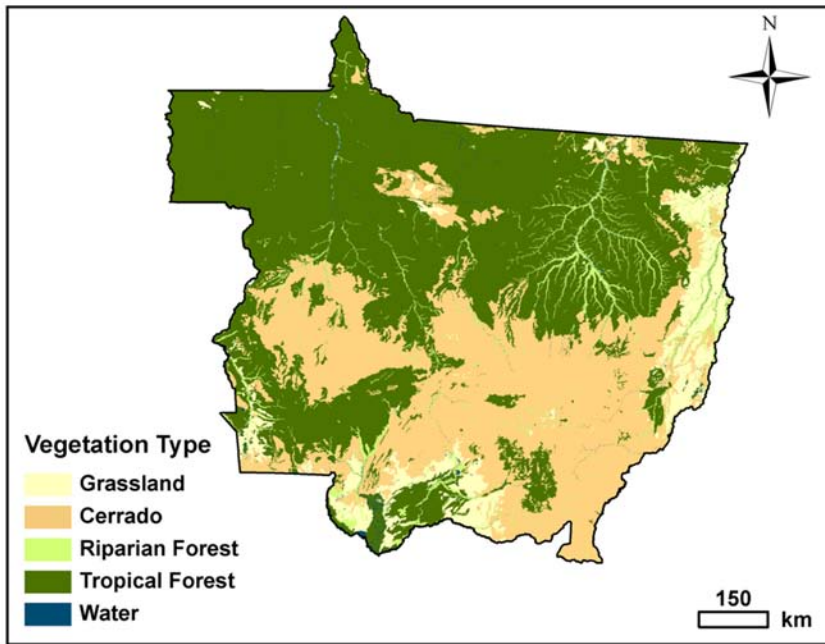
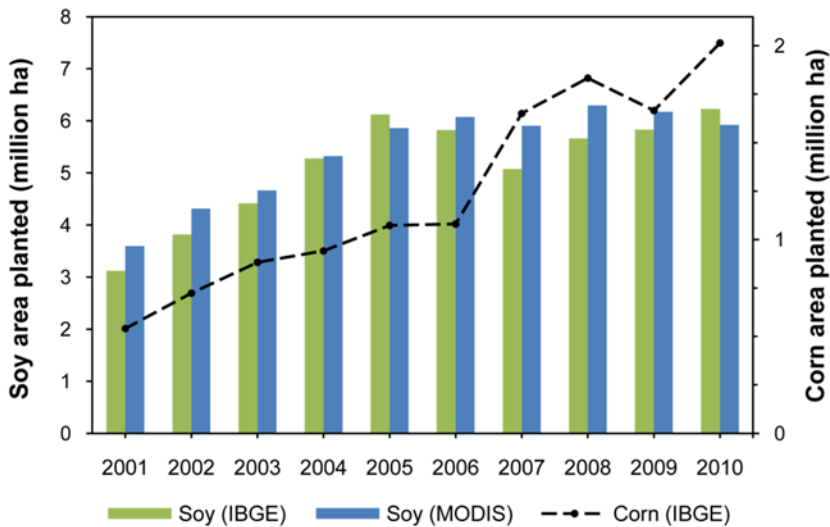


Figure 4: Attribution of net changes in soy production in the forested region of Mato Grosso (MT) to yield, expansion into forest, and expansion into previously cleared (pasture or fallow) land. From 2001-2005 increases in production were due entirely to expansion into forest (26%) and already cleared land (74%). From 2005-2009 increases in yield accounted for 22% of production increases and most cropland expansion (91%) occurred into already cleared land. Approximately two-thirds of this land was cleared prior to 2000, while the remaining third was cleared primarily from 2001-2005. These results were based on IBGE municipal agricultural data (22) and PRODES deforestation data (13), spatially allocated using the MODIS time series.

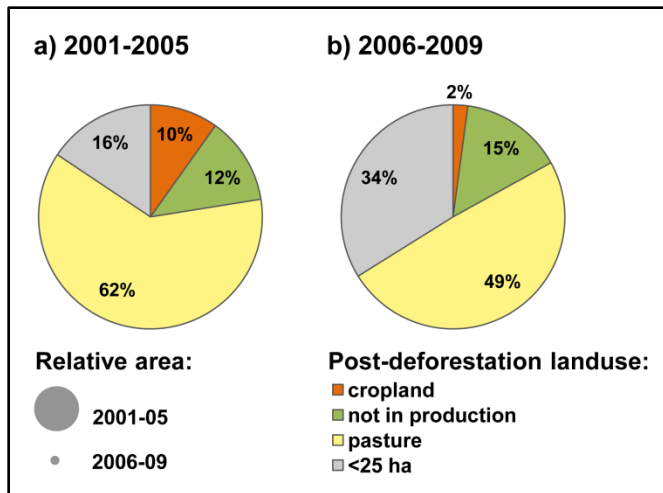
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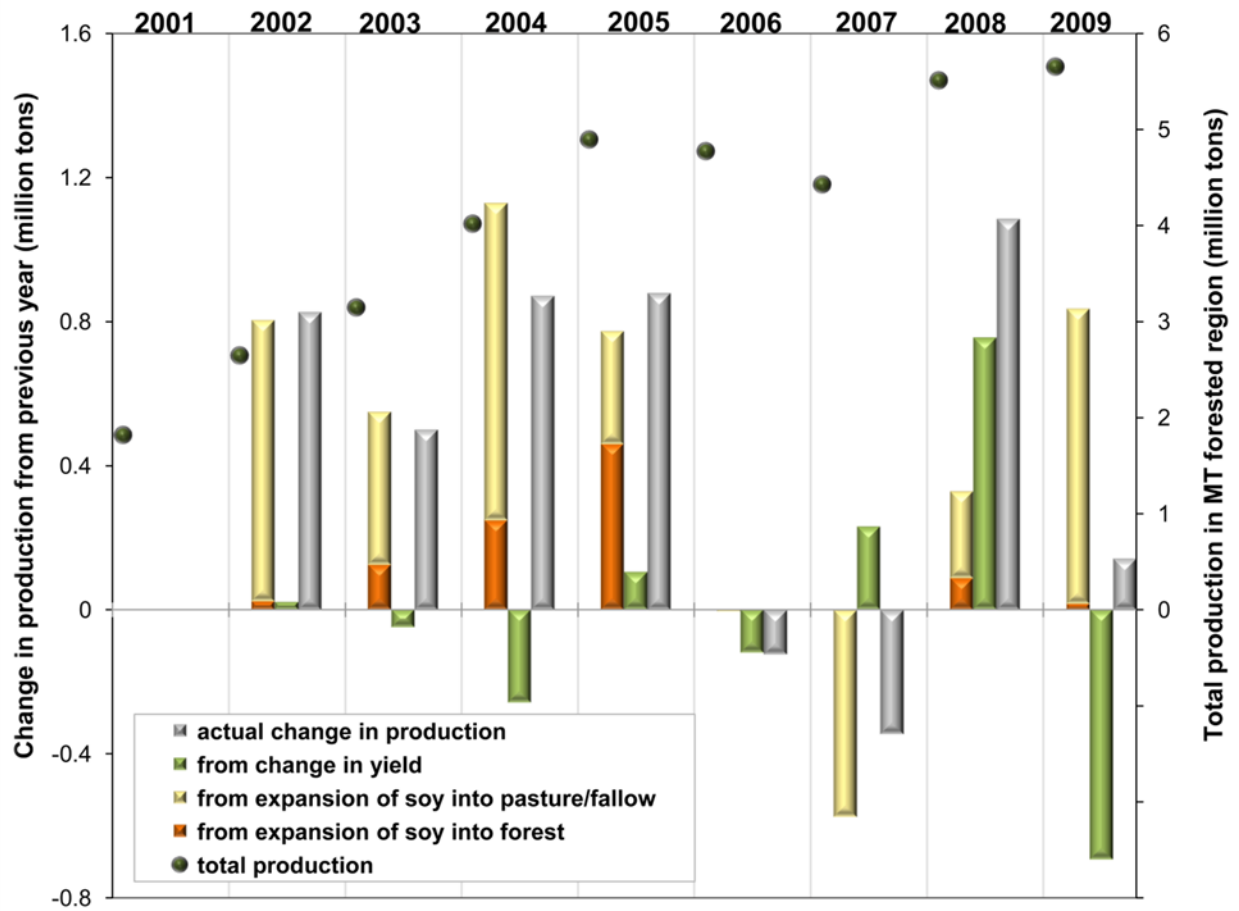
S1: Potential vegetation in the state of Mato Grosso. The state is divided between Cerrado (savannah woodlands and grasslands) and Amazon (tropical forest) ecosystems (1).



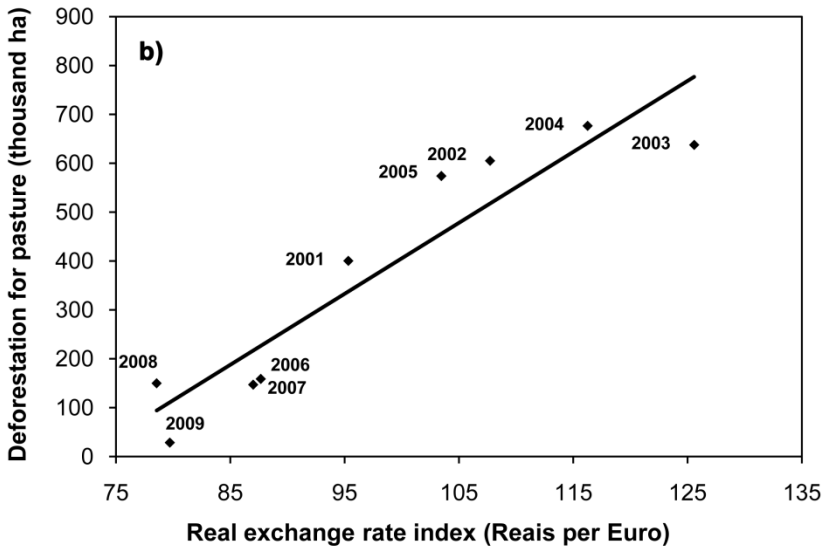
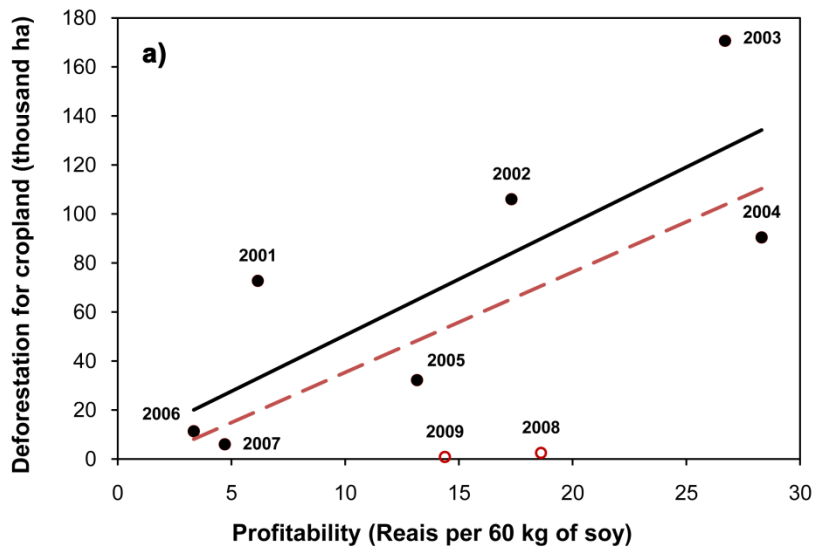
S2: Area planted in soy in Mato Grosso (bars) from MODIS-based estimates in this study and Brazilian government data (2). The datasets show relatively good agreement ($Adj-R^2 = 0.86$, $p < 0.0001$, $RMSE = 0.44$). Although soy is the most prevalent cash crop in the state, secondary row crops such as corn (dashed line), are also economically important (2).



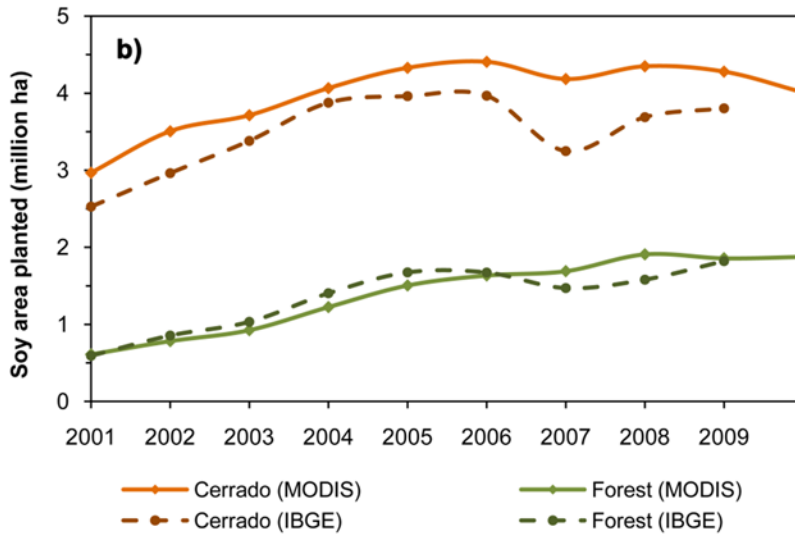
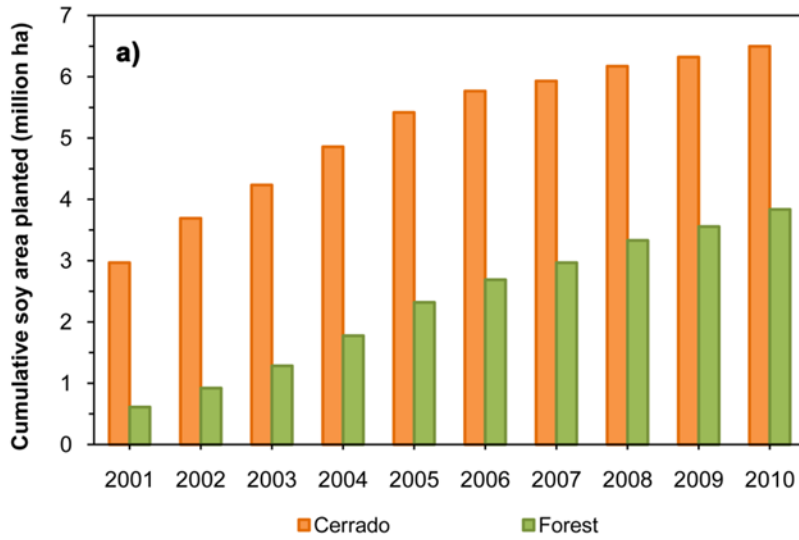
S3: Post-deforestation land uses in Mato Grosso for large-scale (> 25 ha) deforestation during the periods from 2001-2005 (a) and 2006-2009 (b). Total deforestation during the two time periods was 1.2 million ha and 0.23 million ha, respectively. Total soy production in forested municipalities was 16.5 million tons and 20.3 million tons, respectively (2). Data were derived from the PRODES dataset (3) and the MODIS EVI time series.



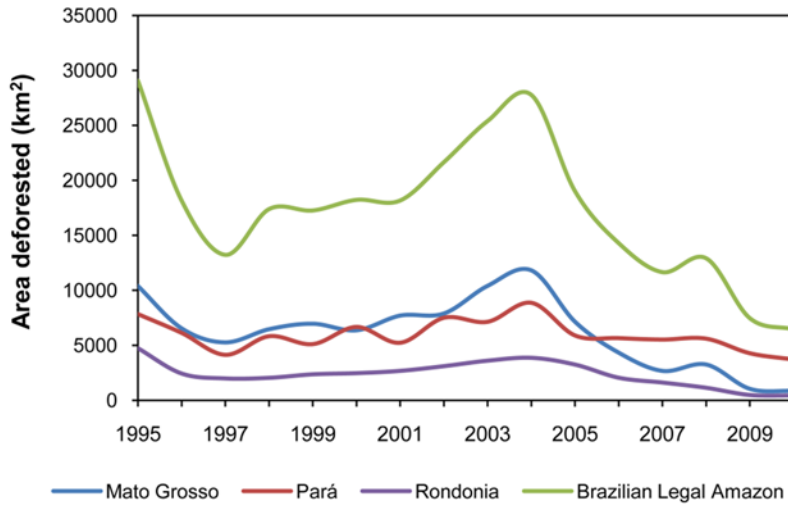
S4: Allocation of annual changes in soy production to yield, expansion into forest, and expansion into already cleared land in the forested region of Mato Grosso. Production and area data from the IBGE (2) were allocated to the forested region of the state using the MODIS time series.



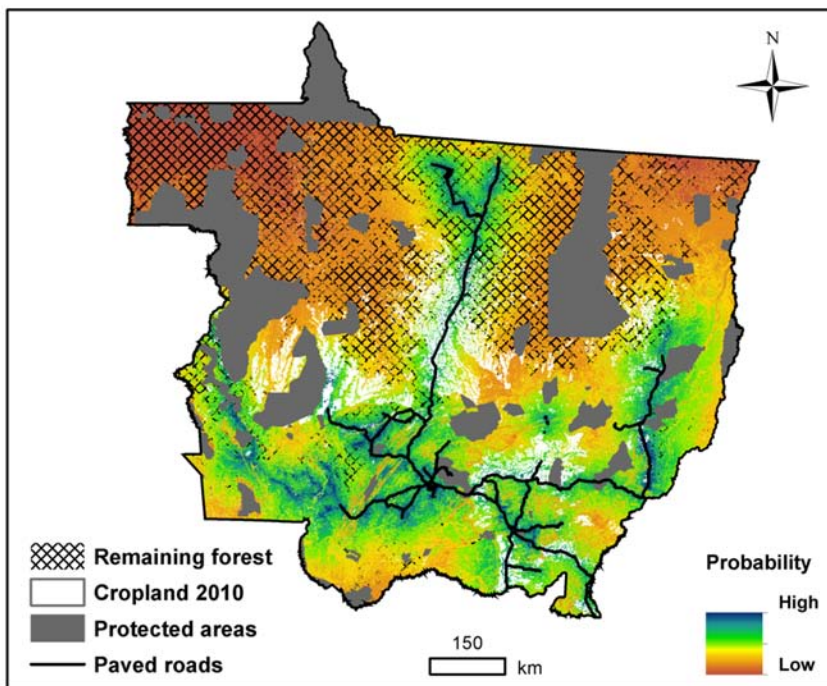
S5: Relationship of market and economic indicators with deforestation for cropland in Mato Grosso. **(a)** Correlation between profitability (4, 5) and deforestation for cropland from 2001-2009 (*red dashed line*, $Adj-R^2=0.31$, $p<0.1$, $n=9$) and 2001-2007 only (*black solid line*, $Adj-R^2=0.57$, $p<0.05$, $n=7$). **(b)** Correlation between deforestation for pasture and exchange rate from 2001-2009 ($Adj-R^2 = 0.81$, $p<0.001$, $n=9$). The real exchange rate index (1994 = 100) is expressed in Brazilian Reais per EU Euro (6).



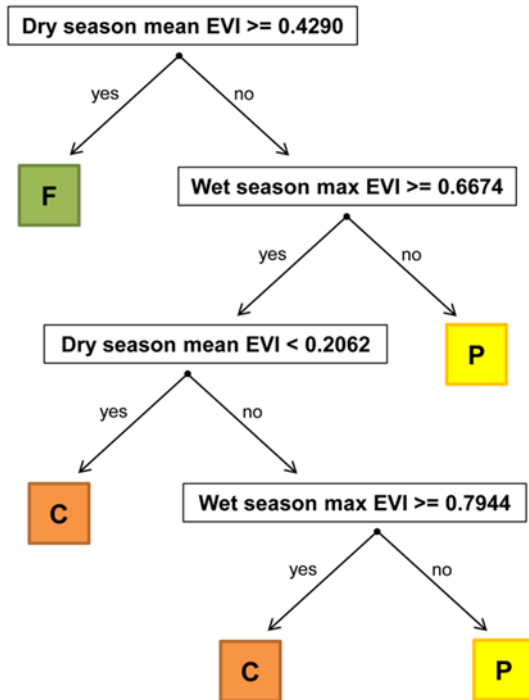
S6: Soy area planted in Mato Grosso's Cerrado (savannah woodlands and grasslands) and Amazon (tropical forest) biomes (S1). Cumulative area planted (a) is derived from the MODIS analysis, whereas the annual area planted (b) compares IBGE municipal data (2) and MODIS-based results.



S7: Annual deforestation in the Brazilian Legal Amazon from 1995-2010 (3). The states of Pará, Rondônia, and Mato Grosso accounted for the majority of deforestation during this time period.



S8: Relative probability of conversion to cropland. The probability is determined by slope, climate, soil properties, road infrastructure, and other factors (7). State and federal protected areas (gray) are masked out and remaining forest areas are cross-hatched.

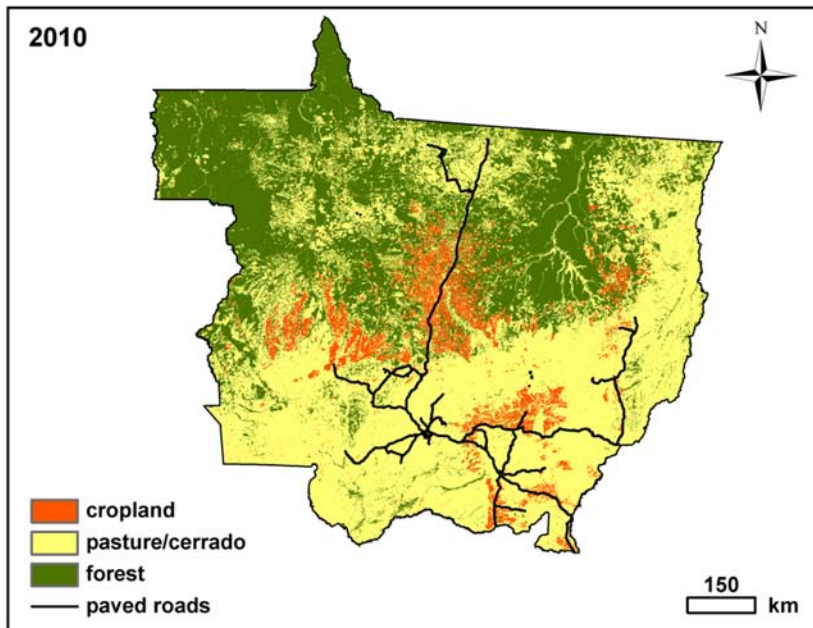


S9: Decision tree classifier based on the MODIS enhanced vegetation index (EVI). The resulting land use classes are cropland (C), pasture/cerrado (P), and forest (F). Thresholds were determined using field training data collected in July and August of 2006.

Table S1: Validation of decision tree using field data collected in July and August of 2010.

Classification outcome	Ground truth			Row total	User's accuracy
	Forest	Pasture	Cropland		
Forest	61	2	2	65	93.85%
Pasture	5	145	5	155	93.55%
Cropland	2	7	73	82	89.02%
Column total	68	154	80	302	
Producer's accuracy	89.71%	94.16%	91.25%		

Overall accuracy: 92.38%
Kappa coefficient: 0.8767



S10: Classification output for Mato Grosso in 2010. The resulting land use classes are cropland (C), pasture/cerrado (P), and forest (F). The decision tree was trained using 2006 field data. Similar maps were derived for each year from 2001 to 2010.

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