DRIVERS AND CONSEQUENCES OF LAND USE CHANGE ACROSS THE BRAZILIAN CERRADO, 2000-2013

BY

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Cohn A, VanWey LK, **Spera SA**, Mustard JF (2016) Climate Variability Reduces Food Production by Diminishing Cropping Frequency and Area, *Nature Climate Change*

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Spera SA, Cohn A, Mustard J, Rudorff B, VanWey L, Risso J, Adami M (2014) Recent cropping frequency, expansion, and abandonment in Mato Grosso, Brazil had selective land characteristics. *Environmental Research Letters*, 9: 065010

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To my parents and sister,
for all their love, encouragement,
and tolerance of my particular brand of crazy

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INTRODUCTION

Food security and climate change are two pressing issues facing the global community. Brazil, home to abundant land that is both rich in carbon, water, and biodiversity and often cleared for agropastoral and renewable energy purposes, is the ideal location for studying these issues, especially with regard to socioeconomic and environmental tradeoffs. Much of the country's increasing role in the global marketplace is rooted in agricultural development and expansive and dynamic land transformations: today, Brazil is a top producer and exporter of orange juice, soy, sugarcane, coffee, chicken, corn, cotton, beef, and the list continues (FAS 2015).

The Amazon region has been the subject of much of the research concerning deforestation, agricultural expansion, and development in Brazil (see Davidson et al. 2012 for a review). The Cerrado biome, Brazil's two million km^2 tropical savanna, has been largely overlooked. The Cerrado is considered by some a 'sacrifice zone' of land traded off as a means to conserve the Amazon (Branstromm 2009, Oliveira and Hecht 2016). This work relies on remote sensing methodologies to perform three case studies across the Cerrado, and ultimately answers the question as to whether Brazil can feasibly continue its agricultural development without sacrificing the remainder of the biome.

The Cerrado is home to half of Brazil's agricultural area and 5% of the world's biodiversity (Klink and Machado 2005). Despite being considered a biodiversity hotspot, only 3% of this biome is legally protected and another 37 million ha are legally clearable under the Brazilian Forest Code (Soares-Filho et al. 2014, Françoco et al. 2015). To date, over half of the Cerrado has been deforested, primarily for agropastoral purposes, and the Brazilian government continues to incentivize agricultural expansion in the biome (MAPA 2015). Understanding the dynamics of agricultural development across the biome provides key insights into these agricultural and socioeconomic tradeoffs.

Remote sensing data and methodologies are fantastic tools for studying landscape scale processes across such a large geographic area. This thesis relies on remote sensing techniques to map annual land-use and land-cover change across the Cerrado, specifically large-scale row-crop crop agriculture, beginning with Brazil's 2001 growing season. The resulting novel datasets are then used to investigate the socioeconomic and environmental drivers and consequences of these land-use changes in Mato Grosso State, Goiás State, and the Matopiba region. Chapters 1 and 2 present the new remote sensing methodologies and the novel datasets.

In Chapter 1, we develop a new method for mapping annual agricultural land cover and then uses this methodology to investigate land-cover change dynamics in Mato Grosso between 2000 and 2013. First, we create a remote-sensing-based decision-tree algorithm that exploits the timing of critical phenology events specific to Mato Grosso. The algorithm uses 250 meter Moderate Resolution Imaging Spectroradiometer (MODIS) Enhanced Vegetation Index (EVI) data and maps annual row-crop agriculture across the state between August 2000 and July 2011. The algorithm, which is validated to a high degree of accuracy (93%), determines both the area of land in mechanized agriculture and the specific crop rotation of that agricultural land—a soy or cotton single-cropping rotation, or a soy-corn or soy-cotton double-cropping rotation. In

Chapter 2, we adjust and generalize the Mato-Grosso-focused remote-sensing methodology created in Chapter 1 so that it accurately maps row-crop agriculture across a majority of the Cerrado. We use these maps for Chapters 2, 3, and 4.

In Chapter 1, we ask whether the increasing rates of intensive agriculture and decreasing rates of annual deforestation in the Mato Grosso are the result of effective governance or land scarcity. We find that the aggregate amount of land in row-crop agriculture doubled from 3 to 6 million ha and the amount of land in double cropping increased six-fold from 0.46 million hectares to 2.9 million hectares between 2001 and 2011. Soy-corn double-cropping rotations account for 92% of double-cropped land in 2011. We also determine the biophysical characteristics associated with new agricultural areas and abandoned agricultural land. We analyze the pool of 'good' agricultural land in the state, and find that this pool of land declines throughout our study period. Thus, we conclude that Mato Grosso's decline in deforestation rates and increase in intensive double-cropping agriculture during the study period may be due, in part, to a scarcity of biophysically-suitable agricultural land.

We then move on to consider the drivers and constraints of the expansion of sugarcane agriculture in Goiás and the Federal District, and ask whether this expansion has affect food production in the region. In Goiás and the Federal District, sugarcane area increased six-fold from 142,000 to 847,000 ha between 2003 and 2013. We find that global and national demand is related to overall sugarcane expansion within the state; the crop is not constrained by biophysical parameters; and infrastructure, institutions, and local actors affect where land is converted to sugarcane. We also find that although food (soy and cattle) production has not yet been affected by sugarcane expansion, given the locations of planned roads, railroads, and sugarcane mills, it may be in the future. Here, then, we suggest incentivizing policies that support converting degraded pastures to sugarcane and increasing cattle stocking rates both to preserve the remainder of the Cerrado in the state and to not encroach on land currently used for food production.

Because itensive cropping systems may engender substantial environmental impacts, we explore one dimension of these impacts in Chapter 2. In this chapter, we ask whether recent land-use changes in the states of Maranhão, Tocantins, Piauí, and Bahia—the Matopiba region—have affected the regional water balance. We couple our Cerrado-wide annual agriculture datasets with an analysis of satellite-derived MODIS evapotranspiration (ET) data to determine the effects of land-use change on the water cycle in the northeastern Cerrado. Between 2003 and 2013, 1.5 million hectares of indigenous Cerrado vegetation were deforested and replaced with cropland (often soybeans) in the Matopiba region. This conversion to cropland resulted in 14 km^3 less water returned back to the atmosphere in 2013 alone. Our results demonstrate that croplands have the greatest evapotranspiration losses during the dry season as compared to natural Cerrado vegetation. Our results also highlight the benefits of intensive agriculture: double-cropping rotations behave more similarly to natural vegetation in terms of annual evapotranspiration rates than do single-cropping rotations. We conclude by suggesting incentivizing intensive agriculture throughout the region.

Chapter 4 contextualizes the results of the first three chapters and asks whether Brazil can continue to increase agricultural production without having the Cerrado remain a 'sacrifice zone' (Branstromm 2009). We use our Cerrado-based agricultural case-studies to demonstrate how incentivizing intensive agricultural practices and improving degraded pasture may be a means by which Brazil can increase agricultural production, provide socioeconomic benefits to the surrounding communites, minimize effects of agricultural expansion on the regional water balance, all while conserving the remainder of the Cerrado.

REFERENCES

Branstromm C (2009) South America's Neoliberal Agricultural Frontiers: Places of Environmental Sacrifice or Conservation Opportunity. *AMBIO: A Journal of the Human Environment* **38(3)**, 141-149.

Davidson EA, de Araujo AC, Artaxo P, Balch JK, Brown IF, Bustamante MMC, Coe MT, DeFries RS, Keller M, Longo M, Munger JW, Schroeder W, Soares-Filho B, Souza CM, Wofsy SC (2012) The Amazon basin in transition. *Nature* **481**, 321-328.

DeFries RS, Herold M, Verchot L, Macedo MN, Shimabukuro Y (2013) Export-oriented deforestation in Mato Grosso: Harbinger or exception for other tropical forests? *Philosophical Transactions of the Royal Society-Biology* **368**, 20120173.

Françoso RD, et al. (2015) Habitat loss and the effectiveness of protected areas in the Cerrado Biodiversity Hotspot. *Natureza & Conservação* **13**, 35–40.

Klink CA, Machado RB (2005) Conservation of the Brazilian cerrado. *Conservation Biology* **19(3)**, 707-713.

MAPA (Ministério da Agricultura, Pecuária e Abastecimento) (2015) Projeções do Agronegócio: Brasil 2014/15 a 2024/25 Projeçoes de Longo Prazo.

Mather A (1992) The forest transition. Area 24, 367-379.

Meyfroidt P, Rudel TK, Lambin EF (2010) Forest transitions, trade, and the global displacement of land use. *PNAS* **107(49)**, 20917-20922.

Nepstad D, McGrath D, Stickler C, Alencar A, Azevedo A, Swette B, Bezerra T, DiGiano M, Shimada J, da Motta RS, Armijo E, Castell L, brando P, Hansen MC, McGrath-Horn M, Carvalho O,, Hess L (2014) Slowing Amazon deforestation through public policy interventions in beef and soy supply chains. *Science* **344(6188)**, 1118-1123.

Oliveira G, Hecht S (2016) Sacred groves, sacrifice zones and soy production: globalization, intensification and neo-nature in South America. *The Journal of Peasant Studies* **43(2)**, 251-285.

Soares-Filho B, Rajao R, Macedo M, Carneiro A, Costa W, Coe M, Rodrigues H, Alencar A (2014) Cracking Brazil's Forest Code. *Science* **344**, 363-364.

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CHAPTER 1

Recent cropping frequency, expansion, and abandonment in Mato Grosso, Brazil had selective land characteristics

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ABSTRACT

This letter uses satellite remote sensing to examine patterns of cropland expansion, cropland abandonment, and changing cropping frequency in Mato Grosso, Brazil from 2001 to 2011. During this period, Mato Grosso emerged as a globally important center of agricultural production. In 2001, 3.3 million hectares of mechanized agriculture were cultivated in Mato Grosso, of which 500,000 hectares had two commercial crops per growing season (double-cropping). By 2011, Mato Grosso had 5.8 million hectares of mechanized agriculture, of which 2.9 million hectares were double cropped. We found these agricultural changes to be selective with respect to land attributes —significant differences ($p < 0.001$) existed between the land attributes of agriculture versus nonagriculture, single cropping versus double cropping, and expansion versus abandonment. Many of the land attributes (elevation, slope, maximum temperature, minimum temperature, initial soy transport costs, and soil) that were associated with an increased likelihood of expansion were associated with a decreased likelihood of abandonment ($p < 0.001$). While land similar to agriculture and double cropping in 2001 was much more likely to be developed for agriculture than all other land, new cropland shifted to hotter, drier, lower locations that were more isolated from agricultural infrastructure ($p < 0.001$). The scarcity of high quality remaining agricultural land available for agricultural expansion in Mato Grosso could be contributing to the slowdown in agricultural expansion observed there over 2006 to 2011. Land use policy analyses should control for land scarcity constraints on agricultural expansion.

Keywords: agricultural expansion, agricultural abandonment, land suitability, Brazil, remote sensing

1. INTRODUCTION

Tropical agricultural expansion, harvest frequency, and intensification (hereafter agricultural development) are growing phenomena (Rudel et al. 2009) with important implications for global economic development, food security, deforestation, and environmental quality (Foley et al. 2005, Angelsen 2010, Ray and Foley 2013, VanWey et al. 2013). Governance of tropical agricultural development is a high priority for conservation and development, but it is inhibited by a dearth of evidence on the characteristics of tropical lands where agricultural development has occurred and can be projected to occur. In new agricultural regions such as Mato Grosso, the evidence gap is particularly dire and creates uncertainty concerning the area of remaining land suitable for agricultural development (hereafter the land reserve) and the efficacy of policies to control deforestation or encourage particular agricultural management practices.

Here we investigate the characteristics of land selected for agricultural development as compared to neighboring lands in Mato Grosso over the period 2001 to 2011. Ricardo's rent theory posits that, 'the most fertile and most favourably situated land will be first cultivated' (Ricardo 1891, p 49). If Ricardo is correct, then we can expect significant differences in the characteristics of land selected for agricultural development and lands left undeveloped. Quantifying the relative influence of particular land characteristics requires: (1) identifying the land characteristics to investigate, (2) determining the representation of the land characteristics variables, and (3) choosing the appropriate spatio-temporal scale of analysis.

We investigate land characteristics that are invariant and effectively invariant (elevation, soil type, slope, soy transportation costs at the start of the study period), slow-changing factors (local climatic conditions), and more dynamic processes (protected areas, land reserve). We take several approaches in the representation of land characteristics variables. We (1) test for significant differences between individual land characteristics across agricultural management classifications, (2) investigate trends in the reserve of land with land characteristics similar to existing agriculture, and (3) perform logistic regressions to examine the influence of each land characteristic on the probability that land is used for each of a set of agricultural activities.

Mato Grosso (7.23°–17.87° S and 50.57°–61.52° W) is a 900,000 km^2 state in central Brazil comprising portions of three of the government-designated biomes of Brazil: the Amazon (480,000 km^2), Cerrado (360,000 km^2), and Pantanal (60,000 km^2). The natural land cover includes dense forest, primarily in the Amazon biome, biologically diverse woody savannahs primarily in the Cerrado biome, and biodiverse wetlands primarily in the Pantanal Biome (Figure 1).

Mato Grosso grows over 8% of global soybeans (FAO 2013). The region has benefited from the development of new soybean varieties that have overcome previous constraints on tropical production—acidic, aluminum-rich soils and short photoperiods (Sephar 1995, Fearnside 2005). Mato Grosso also has Brazil's largest cattle herd and produces 50% of the country's cotton (Brazilian Agricultural Ministry 2013).

Across South America, agricultural expansion and deforestation are often spatially and temporally correlated, and Mato Grosso has been an important center of the phenomenon (Gasparri et al. 2013). Annual deforestation in Mato Grosso peaked in 2004 when over 1.1 million hectares were deforested (Brazilian National Institute for Space Research 2013). Between 2004 and 2011, deforestation rates in Mato Grosso declined 94% (Brazilian National Institute for Space Research 2013). Years of soybean expansion and deforestation in Mato Grosso have tended to coincide (Morton et al. 2006), but it is rare for soybeans to expand directly onto cleared land. It is more common for soybean production to expand on cattle pasture and for cattle pasture to expand onto recently cleared land. Although this relationship has not been demonstrated to be causal, it has been argued that by replacing cattle ranching, soy production displaces cattle ranching to the forest frontier (Barona et al. 2010, Arima et al. 2011). However, from 2006 to 2012, increased output on existing agricultural lands became a more important component of increased agricultural production than expansion onto new lands (Macedo et al. 2012).

Mato Grosso's agricultural development and deforestation have been linked to the rise of soy and beef exports to China, the European Union, and the Middle East (Fearnside 2001, Kaimowitz et al. 2004, Naylor et al. 2005, Nepstad et al. 2006). Heightened soy expansion, deforestation, and exports were observed in periods in the early 2000s when the Brazilian currency, the real, was weak relative to the US dollar and when world agricultural commodity prices were high (Richards et al. 2012). The Soy Moratorium, a 2006 agreement in which leading soybean companies pledged not to export soy cultivated on land deforested in the Amazon biome after 2006, may have helped to reduce deforestation (Macedo et al. 2012, DeFries et al. 2013). Controls on credit for deforesting areas and satellite monitoring for intervening in illegal deforestation may also have helped slow deforestation (Assunção et al. 2012, Assunção et al. 2013).

However, it is also possible that land clearing in Mato Grosso has ebbed and cropping frequency has increased in part for the reason that Boserup (1965) argues—that little suitable land remains in the region for agricultural development. In order to investigate whether scarcity of high quality land is affecting agricultural development in Mato Grosso, it is necessary to first assess the characteristics of agricultural expansion, abandonment, and management in the state over time.

This letter leverages a recently developed dataset of agricultural land use in Mato Grosso, Brazil over the period 2001 to 2011 to investigate the association between agricultural development and land suitability in a region undergoing rapid agricultural change. For each year of the study period, the dataset identifies the extent of large-scale mechanized agriculture, the extent of double cropping in the region, the areas of newly created cropland and double cropping, and the areas where mechanized agriculture and double cropping were abandoned. First, we investigate the characteristics of mechanized agricultural lands versus the rest of the state and the characteristics of double cropped lands versus all agricultural lands. Then, we identify which land characteristics have the strongest association with mechanized agriculture and double cropping.

We also investigate whether newly created mechanized agriculture occurs on land with similar characteristics to the agriculture that existed in the state at the start of the study period, arguably the most suitable land. We investigate whether the reserve of high quality land for agriculture has measurably dwindled. We conclude by examining whether abandoned lands have similar characteristics to lands on which expansion occurs.

2. METHODS

We developed maps of changes in agricultural management and prepared maps of key attributes of all land in Mato Grosso over the 2001–2011 period. Land attributes investigated were selected based, in part, on previous studies investigating the region's agriculture and include soils, climate, land use, topography, and transportation costs (Jasinski et al. 2005). We performed analyses to: (a) quantify trends in agricultural development in the state; (b) investigate differences in the characteristics of land under different uses at the start of the study period; (c) determine whether the land attributes investigated were associated with agricultural development (when controlling for soils and protected areas); and (d) determine whether, over the course of the study period, land with qualities similar to agricultural land at the start of the period had greater likelihood of development.

Data

Agricultural land cover mapping

Previous research has successfully used moderate resolution imaging spectoradiometer (MODIS) vegetation index (VI) time series to classify land cover types in Mato Grosso (Galford et al. 2008, Morton et al. 2008, Arvor et al. 2012, Brown et al. 2013) and to monitor the planting of soy on deforested land (Rudorff et al. 2011, 2012). We developed and validated the first 250 m resolution maps of mechanized agricultural land cover and management in Mato Grosso over the period 2001–2011. We are also first to demarcate the area of single cropped soybeans, the area of single cropped cotton, the soy-cotton rotation, and the soy-corn rotation across the entire state and study period. Because we are using 250 m resolution satellite data, these maps do not capture areas of smallholder farming.

We created MODIS Enhanced VI 16-day 250 m resolution annual time series over Mato Grosso for the eleven growing seasons between August 2001 and July 2011. We analyzed these data pixel-by-pixel with a decision-tree algorithm to determine both the area of cropland per growing season and the specific rotations of that cropland. Crop-specific growing season lengths and maximum EVI thresholds were used to classify mechanized agriculture into one of five crop rotation classes: soy, cotton, soy-corn, soy-cotton, and irrigated. All thresholds and parameters were determined using 99 points of training data collected in Mato Grosso in March 2011, general phenological patterns and thresholds described in Galford et al. (2008) and Arvor et al. (2011), and published regional crop calendars (United States Department of Agriculture Foreign Agricultural Service 2012).

We randomly sampled points within 1 km of roads in Mato Grosso (an area constituting 18% of the state and known to be the location of a large fraction of mechanized agriculture) to choose 600 new points for validation of each of the 11 annual agricultural land-cover maps. For each point, Landsat images depicting bands 4 (0.84 μm) as red, 5 (1.65 μm) as green, and 3 (0.66 μm) as blue were compiled and analyzed. Landsat images from the mid-to-late growing season highlight unique crop canopy reflectance signatures. A complete discussion of the decision-tree algorithm—including specific parameters and thresholds, validation, and accuracy assessment—can be found in the supporting online material. We present results for annual mechanized agricultural extent, C_t, and annual double cropping extent, DC_t, where *t* is each of the 11 growing seasons between 2001 and 2011. The notations used throughout the paper are summarized in Table 1.

Land reserve identification

Annual mechanized agriculture land reserve (CR) and double cropping land reserve (DCR) for the period 2003–2011 were identified. The agricultural land reserve, CR_t, is the area of all land in Mato Grosso that can potentially be converted to agriculture because it is not yet used for agriculture. Using a two-year rule, the land reserve is defined as all land that was not mechanized agriculture in either year $t - 1$ or year $t - 2$. The double cropping land reserve, DCR_t, is the area of all land with the potential to be converted to double cropping. The double cropping land reserve, then, is defined as all land that was not double cropping in year $t - 1$ or year $t - 2$. Therefore DCR_t is the sum of CR_t and all land in single cropping. This approach overestimates the land that is likely to be converted to agriculture or to double cropping by including land that is inaccessible due to remoteness or institutional barriers (such as policies preventing deforestation). Thus, our estimates of scarcity will be conservative estimates.

New cropland identification

Annual maps were developed of new mechanized agriculture (NC) and new double cropping (NDC) for the period 2003 to 2011. The new cropland class, NC_t, is the subset of all land classified as mechanized agriculture in year, t, that was not mechanized agriculture in year $t - 1$ or year $t - 2$. The new double-cropping class, NDC_t, is the subset of all land classified as double cropping in year, t, that was not double cropping in year $t - 1$ or year $t - 2$. This approach overestimates the area of new cropland by including land that may have been cropland greater than two years before year t. However, it more accurately captures dynamic changes than an approach classifying a pixel as cropland in perpetuity once it has been used for agriculture in any year.

Abandoned cropland (AC) identification.

Annual mechanized agriculture AC and abandoned double cropping (ADC) for the period 2002 to 2010 were identified. Again, the two-year rule was implemented: AC_t, is all land that was mechanized agriculture in year $t - 1$, but not in years t or $t + 1$. Abandoned double-cropped land, ADC_t, is all land that was double cropped in year $t - 1$, but not in years t or $t + 1$. This approach may overestimate the area of abandoned land by including land that is returned to agriculture after year $t + 1$. All analyses were repeated using a five-year abandonment rule and a nine-year abandonment rule to test the sensitivity of our results. While the total abandoned area identified changed under the different rules, the land characteristics of the abandonment were stable. See Tables S8–S13.

Suitability maps

Slope and elevation maps

NASA's Shuttle Radar Topography Missions (SRTM) data were used to create a 90 m digital elevation map (DEM) of Mato Grosso. A slope map of the same resolution was derived from the DEM using ENVI software and the application of a seven-kernel smoothing window to account for anomalously high slopes created as a result of forest edges and variable canopy heights (Van Zyl 2001).

Average temperature maps

Annual minimum and maximum Climate Research Unit V 3.21 temperature data at 50 km resolution for 1980–2000 were downloaded from the British Atmospheric Data Centre database, and averaged over this time period (New et al. 2002).

Average precipitation and soil moisture maps

Gridded 50 km long-term means from monthly (1981–2010) Climate Prediction Center soil moisture and Global Precipitation Climatology Centre data were downloaded from NOAA/ OAR/ERL Physical Sciences Division website (Fan and van den Dool 2004).

Soybean transportation costs map

A model was developed estimating the least cost of transporting soybeans from any location in Mato Grosso to processing facilities in the state at the start of the study period. The costs are expressed in year 2000 US. Dollars per ton and are computed for each 1 km grid cell in Mato Grosso. A raster map of land cover and of road, river, and rail transportation networks was created and used to develop a friction raster depicting the cost per meter of traversing each surface type. Costs were adapted from travel times in Farrow et al. (2011), were modeled using data on Brazilian agricultural logistics (de Castro et al. 1999, Bowman et al. 2011, University of São Paulo-ESALQ System of Freight Information 2012) and were adjusted for slope and elevation (Wagtendonk and Benedict 1980). Next, locations where soybeans are purchased and traded were mapped (Brazilian Institute of Geography and Statistics 2013). Finally, we used the cost-distance feature of ArcMap 10.0 Spatial Analyst to compute the least-cost path from each grid cell on the map to the soybean market points.

Protected areas

Shapefiles of Brazil's protected areas and indigenous reserves were downloaded from the World Database on Protected Areas (IUCN and UNEP-WCMC 2014). The dataset maps indigenous reserves and the year of their creation over 1958–2010 and protected areas over 1978–2006. For our analysis, for each year from 2001 to 2011, we created maps of indigenous reserves and protected areas to date. Soils. We classified soils based on a 1 km, 19 class soil map produced by the Brazilian Agricultural Research Corporation and the Brazilian Institute of Geography and Statistics (Brazilian Agricultural Research Corporation 2014). The 19 classes in the map are aggregate groups of similar soil types in the Brazilian soil classification system. Of the 19 soil classes in the mapping, ten are present in Mato Grasso (SFigure 12). We reclassified the Mato Grosso soils into two categories: upland soils suitable for agriculture (deep quartz-rich soils, soils 'podzolicos', latosols, and terra roxa) and all other soils (cambisols, hydromorphic laterites, hard laterites, gley soils, lithic soils, and water). These other soils are mainly present in wetland areas. Nearly all mechanized agriculture in Mato Grosso is cultivated on the upland soils suitable for agriculture (SFigure 13).

Analysis

Each suitability map and land-cover map was projected to WGS 84 UTM South American Zone 21, set to the extent of a 1255 km by 1187 km rectangle inscribing Mato Grosso, and resampled to match the resolution of the MODIS data. We converted the rasters to integer ascii files, exported them to Stata 12 SE and assigned a unique gridcode to each cell. We calculated descriptive statistics for each year of land cover maps CR_t, DCR_t, NC_t, NDC_t, AC_t, and ADC_t. Several analyses were performed: (1) we used t-tests to identify statistically significant differences in the distribution of land attributes of nine land use categories; (2) we computed the amount of agricultural land reserve and double cropping land reserve in each year that fell within 1/2 standard deviation, 3/4 standard deviation, 1 standard deviation, and 2 standard deviations of mean values for 2001 agriculture and mean values for 2001 double cropping for all seven land attributes simultaneously; and (3) we performed logistic regressions to assess the explanatory power of land attributes for the location of the stocks, increments, and decrements of mechanized agriculture and double cropping. The land characteristics employed as explanatory variables in the regressions were continuous variables for: average annual maximum temperature, average annual minimum temperature, average annual soil moisture, average annual precipitation, elevation, slope, and soy logistics costs in the year 2000; and binary variables for the presence of indigenous reserves, the presence of protected areas, and the presence of good soils. The dependent variables investigated were: (a) CR_t and DCR_t (from 2001 to 2011) over Mato Grosso; (b) NC_t and NDC_t (from 2003 to 2011) over CR_t and DCR_t respectively, and (c) AC_t and ADC_t (2002 to 2010) over C_t and DC_t respectively. In the logistic regressions performed, '1' denoted the pixels classified in each land classification and '0' denoted the remainder of the population at risk of transition—(i.e. the subset of the state that had the chance to transition into each land cover type, but did not. Thus, for new mechanized agriculture in 2003, '1' s were the area of agriculture in 2003 that was not agriculture in 2001 or 2002). '0's are the area that was not mechanized agriculture in 2003 that was also not mechanized agriculture in 2001 or 2002. Areas that were agriculture in either 2001 or 2002 were excluded because they had no possibility of becoming new agriculture in 2003. For 2002 abandonment, '1' denotes pixels that were not mechanized agriculture in 2002, were agriculture in 2001, and do not go on to become agriculture in 2003. Regressions on total agricultural area examined the probability that any pixel in the state could become mechanized agriculture.

3. RESULTS

Agricultural area expanded and cropping frequency increased

In 2001, total agriculture, C_{2001}, was 3.3 million hectares (Figures 2 and 3). Of this, roughly 500,000 hectares were double cropped, DC_{2001}. Of the 5.8 million hectares of C_{2011}, 2.9 million hectares were double cropped (DC_{2011}). Single cropped soybean production accounted for 53% of C_t from 2001 to 2011, while soy-corn rotations accounted for 37%. Over the period 2003–2011, 6 million hectares of cropland were created from forest, pasture, or Cerrado, while 6.4 million hectares of NDC were brought into cultivation. This indicates that, over the period, NDC was more likely to persist than new single cropping. Agricultural land is significantly different from nonagricultural land In 2001, just under 5% of Mato Grosso was mechanized agriculture. Of this agriculture, roughly 12% was double cropped. Relative to the rest of the state, land in agriculture was significantly higher in elevation, lower in slope, and had lower logistics costs for soybeans ($p < 0.001$). Mean minimum temperature and mean maximum temperature were lower for agricultural lands ($p < 0.001$). Mean annual precipitation and mean annual soil moisture were higher ($p < 0.001$). Double cropping in 2001 had similar characteristics to the rest of 2001 mechanized agriculture, except that the slope of these lands was somewhat lower. Mean and standard deviations of the attributes of each of the land cover types can be found in Table 2.

The selective land characteristics of agricultural expansion

Over the study period, the attributes of new cropland created were far more similar to base-year cropland than to the attributes of the rest of the state. However, steady trends in the attributes of new cropland were evident. Cropland created in 2011 was significantly hotter, at lower elevations, drier, farther from markets, and more steeply sloped than cropland created in 2003 ($p < 0.001$ for each attribute). Newly double-cropped land in 2011 was also significantly different from newly double-cropped land in 2003 ($p < 0.001$ for each attribute), but that difference was less pronounced than the difference between 2001 mechanized agriculture and newly mechanized agriculture in 2011. Figure 5 and table 2 provide synopses of these trends. The average hectare of C_{2001} had an elevation of 535 m, and a slope of 1°. By contrast, NC_{2011} averaged an elevation of 354 m and slope of 2.2°. From C_{2001} to NC_{2011}, precipitation decreased from 1811 mm to 1700 mm, soil moisture height dropped from 5493 mm to 5247 mm, and average annual maximum temperature increased from 32 °C to 32.3 °C. The average hectare of DC_{2001} had an elevation of 520 m, and a slope of 1°. By contrast, NDC_{2011} averaged an elevation of 435 m and slope of 1.4°. From DC_{2001} to NDC_{2011}, the precipitation mean increased slightly from 1780 mm to 1811 mm, soil moisture height dropped from 5460 mm to 5355 mm, and average annual maximum temperature increased from 32.1 °C to 32.2 °C (Table 2, Figure 4).

The selective land characteristics of agricultural abandonment

As shown in Table 2 and Figure 4, in comparison to 2001 mechanized agriculture, agriculture abandoned in 2002 was lower, drier, hotter, on steeper slopes, and had higher logistics costs. By 2010, the profile of abandonment had shifted even further toward lower, more sloped, drier, and higher initial logistics costs than of that in 2002 ($p < 0.001$). In comparison to 2001 double cropping, double cropping abandoned in 2002 was higher, more sloped, drier, hotter, and had slightly higher initial logistics costs. ADC in 2010 continued on lands that were even more sloped, and had lower soil moisture, and higher initial logistics costs than those abandoned in 2002 ($p < 0.001$).

Sensitivity of agricultural abandonment classification

For the 2002–2006 period, over half of the cropland that was abandoned for two years remained abandoned for at least another three years, while 36% remained abandoned throughout the study period. Only approximately 32% of double cropping abandoned for two years remained so for the following three years, while 17% remained abandoned through 2011. Our definition of abandonment allows for double cropping to be 'abandoned' to single cropping. Thus, much of the variability captured in sensitivity tests shown in Table 3 may be farmers rotating single cropping and double cropping through their fields.

Agricultural dynamics are correlated with specific land characteristics

Logistic regressions were performed to examine whether the land attributes investigated are associated with the incidence of C_t, DC_t, NC_t, NDC_t AC_t, and ADC_t. The regressions controlled for soil type and the presence of indigenous reserves or other protected areas. Of the seven land attributes investigated, all were significant in explaining land use location, expansion, and abandonment probabilities. The sign of the coefficients of each attribute was the same for agricultural extent, double cropping extent, agricultural expansion, and double cropping expansion. The sign of coefficients for agricultural abandonment and double cropping abandonment were the reverse of the sign for the coefficients of all other land types (see Table 3). In some regressions, soil moisture and precipitation were not significantly associated with land uses. The directions of the coefficients for agricultural abandonment and double cropping abandonment for the five-year rule and nine-year rule were the same as for the two-year rule. The magnitudes differed slightly, but not systematically. A comparison of these regressions can be found in Table 13 of the SOM.

The pool of high quality land is decreasing

Very little of the 2003 land reserve, CR_{2003}, was similar in all seven attributes to 2001 agriculture, C_{2001}, and very little of double cropping land reserve, DCR_{2003}, was similar to 2001 double cropping, DC_{2001}. Just 14% of CR_{2003} was within two standard deviations (2σ) of the characteristics of C_{2001} for all seven continuous land attributes investigated. For DCR_{2003}, just 14% was within 2σ of the mean attributes of DC_{2001}. Though constituting a small share of the land reserve, these areas went on to play a disproportionately important role in agricultural expansion. 32% of new cropland, NC_t, occurred on these lands and 53% of new double cropped land, NDC_t, occurred on these lands. In addition, land within 1σ of attribute means for C_{2001} was three times more likely to be developed than land between 1σ and 2σ. Considering all seven land attributes jointly suggests a much stronger case for the potential emergence of land reserve scarcity than examining scarcity attribute by attribute. The area of CR_{2011} within 1σ of 2001 declined 22% from CR_{2003}, while DCR_{2011} within $3/4\sigma$ declined 32% from DCR_{2003}. Nevertheless, the majority of CR_{2003} and DCR_{2003} remain within 2σ of Q_{2001} and DC_{2001} respectively (Figure 5).

4. DISCUSSION AND CONCLUDING REMARKS

Our investigation of Mato Grosso, Brazil from 2001 to 2011 provides firm evidence that agricultural expansion, abandonment, and harvest frequency were selective with respect to elevation, slope, maximum temperature, minimum temperature, and the soy logistics costs at the start of the study period ($p < 0.001$). Nonetheless, new agriculture and new double cropping in 2011 had come to have significantly different land characteristics than new agriculture and new double cropping had in 2003. The characteristics of new double cropping changed less than new single cropping. Thus the selectivity for double-cropped land was more pronounced than the selectivity for single cropped land. This discrepancy is perhaps due to the more stringent agronomic requirements associated with double cropping. However, double cropping was also less likely to be abandoned than single cropping. Perhaps double cropped farms tend to be more economically and institutionally resilient to production shocks than single cropped farms.

Over the decade, land characteristics of agricultural expansion inched further from the characteristics of the first lands developed and closer to the characteristics of previously abandoned lands. Recent areas of expansion were more likely to be abandoned than early areas of expansion. A scarcity of available suitable land may be prompting farmers to experiment with agriculture on a variety of lands. Through a process of expansion and abandonment, agriculture may eventually become concentrated on the most favorable of these.

Meanwhile, we also demonstrate a substantial decline in the area of land reserve with characteristics similar to the initial agricultural land. If Ricardian rent theory is correct that agricultural expansion will occur first on the highest quality lands and later on the lower quality lands, then this decline also means a reduction in the availability of quality land reserve. A growing shortage of quality land reserve may explain the slowdown in agricultural expansion over the latter half of the study period.

Thus a growing scarcity of high quality land available for agricultural expansion may be influencing patterns of agricultural development in Mato Grosso. Other explanations such as deforestation governance (DeFries et al. 2013) and the potentially underestimated utility of cattle ranching (Bowman et al. 2011) are unlikely to be associated with such strong and patterned trends in land characteristics of agricultural extent, expansion, and abandonment.

Land scarcity effects have important ramifications for the design and assessment of a variety of land use policies. One such policy is the Low Carbon Agriculture program, an effort by the Federal Government of Brazil that seeks to promote the conversion of pastureland to cropland in Brazil (Stabile et al. 2012). Future analyses could investigate whether low land quality of existing pastures is impeding conversion. Conversion of pasture may also be impeded if the utility of extensive cattle ranching is higher than some estimates suggest (Cohn et al. 2011).

Evaluation of policies to prevent deforestation can benefit from assessment of the influence of land quality on deforestation outcomes. Policies in Brazil seek to prevent deforestation through mechanisms such as satellite monitoring of deforestation, municipalities black-listed from selling agricultural products, government credit limitations, and voluntary agreements to prevent soy and beef sales from recently deforested land (Nepstad et al. 2009, Soares-Filho et al. 2010, Newton et al. 2013). It is possible that some of these policies have helped to 'decouple' agriculture expansion and deforestation in Mato Grosso (Macedo et al. 2012). But it is also possible that the decoupling is a consequence of a scarcity of available land worth deforesting for agricultural development (Soares-Filho et al. 2006). An investigation of the attributes of deforested versus forested lands is foundational for evaluating the efficacy of deforestation policies.

AUTHOR CONTRIBUTIONS

SAS, ASC, LKV, and JFM designed the research; SAS, and ASC performed the research; SAS, ASC, LKV, and JFM analyzed the data; SAS, ASC, LKV, and JFM wrote the paper; SAS, ASC, JR, BFR, and MA contributed reagents.

REFERENCES

Angelsen A (2010) Policies for reduced deforestation and their impact on agricultural production. Proc. Natl Acad. Sci. USA 107, 19639–44.

Arima E Y, Richards P, Walker R and Caldas M M (2011) Statistical confirmation of indirect land use change in the Brazilian Amazon. Environ. Res. Lett. 6, 024010.

Arvor D, Jonathan M, Penello Meirelles M S, Dubreuil V and Durieux L (2011) Classification of MODIS EVI time series for crop mapping in the state of Mato Grosso, Brazil. Int. J. Remote Sens. 32, 7847–71.

Arvor D, Meirelles M, Dubreuil V, Begue A and Shimabukuro Y E (2012) Analyzing the agricultural transition in Mato Grosso, Brazil, using satellite-derived indices. Appl. Geogr. 32, 702–13.

Assunção J, Gandour C C and Rocha R (2012) Deforestation Slowdown in the Legal Amazon: Prices or Policies? (Rio de Janeiro, Brazil: Climate Policy Initiative)

Assunção J, Gandour C C, Rocha R and Rocha R (2013) Does Credit Affect Deforestation? Evidence from a Rural Credit Policy in the Brazilian Amazon. (Rio de Janeiro, Brazil: Climate Policy Initiative).

Barona E, Ramankutty N, Hyman G and Coomes O T (2010) The role of pasture and soybean in deforestation of the Brazilian Amazon. Environ. Res. Lett. 5, 024002.

Boserup E (1965) The condition of agricultural growth. The Economics of Agrarian Change under Population Pressure (London: Allan and Urwin).

Bowman M S, Soares-Filho B S, Merry F D, Nepstad D C, Rodrigues H and Almeida O T (2011) Persistence of cattle ranching in the brazilian amazon: a spatial analysis of the rationale for beef production. Land Use Policy 29, 558–68.

Brazilian Agricultural Ministry (2013) Sixth National Harvest Accompanyment, March 2013. Retrieved 5 September 2013, from http://conab.gov.br/conteudos.php?a=1028

Brazilian Agricultural Research Corporation (2014) Soils Maps of Brazil (19 Class). EOS EarthData Catalogue Retrieved 14 January 2014, from http://eos-earthdata.sr.unh.edu/data/ data8.jsp

Brazilian Institute of Geography and Statistics (2013) Municipality agricultural data report (PAM) IBGE System of Automatic Data Access Retrieved 5 September 2013, from http://sidra.ibge.gov. br/bda/acervo/acervo2.asp

Brazilian National Institute for Space Research (2013) Projeto PRODES—Monitoramento da Floresta Amazônica Brasileira por Satélite. Retrieved 5 September 2013, from http://obt.inpe. br/prodes/index.php

Brown J C, Kastens J H, Coutinho A C, de Castro Victoria D and Bishop C R (2013) Classifying multiyear agricultural land use data from Mato Grosso using time-series MODIS vegetation index data. Remote Sens. Environ. 130, 39–50..

Cohn A, Bowman M, Zilberman D and O'Neill K (2011) The viability of cattle ranching intensification in Brazil as a strategy to spare land and mitigate greenhouse gas emissions. Working paper ♯11 (Copenhagen: CGIAR Program on Climate Change, Agriculture, and Food Security) p 43.

de Castro N, Carris L and Rodrigues B (1999) Custos de transporte ea estrutura espacial do comércio interestadual brasileiro. Pesquisa e Planejamento Econômico 29, 3.

DeFries R, Herold M, Verchot L, Macedo M N and Shimabukuro Y (2013_ Export-oriented deforestation in Mato Grosso: harbinger or exception for other tropical forests? Phil. Trans. R. Soc. 368, 1619.

Fan Y and van den Dool H (2004) Climate Prediction Center global monthly soil moisture data set at 0.5 resolution for 1948 to present J. Geophys. Res.: Atmos. (1984–2012) 109 (D10).

FAO 2013 FAOSTAT Online Database. from http://faostat.fao.org/

Farrow A, Risinamhodzi K, Zingore S and Delve R J (2011) Spatially targeting the distribution of agricultural input stocks in Malawi. Agric. Syst. 104, 694–702.

Fearnside P M (2001) Soybean cultivation as a threat to the environment in Brazil. Environ. Conserv. 28, 23–38.

Fearnside P M (2005) Deforestation in Brazilian Amazonia: history, rates, and consequences. Conserv. Biol. 19 680–8 Foley J A et al 2005 Global consequences of land use Science 309, 570–4..

Galford G L, Mustard J F, Melillo J, Gendrin A, Cerri C C and Cerri C E (2008) Wavelet analysis of MODIS time series to detect expansion and intensification of row-crop agriculture in Brazil. Remote Sens. Environ. 112, 576–87.

Gasparri N I, Grau H R and Gutiérrez Angonese J (2013) Linkages between soybean and neotropical deforestation: coupling and transient decoupling dynamics in a multi-decadal analysis Glob. Environ. Change 23 1605–14 IUCN and UNEP-WCMC 2014 World Database on Protected Areas. Retrieved 1 January 2014, from http://protectedplanet.net/

Jasinski E, Morton D, DeFries R, Shimabukuro Y, Anderson L and Hansen M (2005) Physical landscape correlates of the expansion of mechanized agriculture in Mato Grosso, Brazil. Earth Interact. 9, 1–18.

Kaimowitz D, Mertens B, Wunder S and Pacheco P (2004) Hamburger connection fuels Amazon destruction. Technical Report Retrieved 21 March 2006, from http://cifor.cgiar.org/ publications/pdf

Klink C A and Machado R B (2005) Conservation of the Brazilian Cerrado. Conserv. Biol. 19, 707–13.

Lambin E et al. (2013) Estimating the world’s potentially available cropland using a bottom-up approach. Glob. Environ. Change 23, 892–901.

Macedo M N, DeFries R S, Morton D C and Stickler C M Galford G L and Shimabukuro Y E (2012) Decoupling of deforestation and soy production in the southern Amazon during the late 2000s. Proc. Natl Acad. Sci. 109, 1341–6..

Morton D, Defries R, Randerson J, Giglio L, Schroeder W and van Der Werf G (2008) Agricultural intensification increases deforestation fire activity in Amazonia. Glob. Change Biol. 14, 2262–75.

Morton D et al. (2006) Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. Proc. Natl Acad. Sci. USA 103, 14637–41.

Naylor R et al. (2005) Agriculture: losing the links between livestock and land. Science 310, 1621–2.

Nepstad D et al. (2009) The end of deforestation in the Brazilian Amazon. Science 326, 1350–1.

Nepstad D, Stickler C M and Almeida O T (2006) Globalization of the amazon soy and beef industries: opportunities for conservation. Conserv. Biol. 20, 1595–603.

New M, Lister D, Hulme M and Makin I (2002) A high-resolution data set of surface climate over global land areas. Clim. Res. 21, 1–25.

Newton P, Agrawal A and Wollenberg L (2013) Enhancing the sustainability of commodity supply chains in tropical forest and agricultural landscapes. Glob. Env. Change 23, 1761–2.

Ray D K and Foley J A (2013) Increasing global crop harvest frequency: recent trends and future directions Environ. Res. Lett. 8, 44041–50.

Ricardo D (1891) Principles of Political Economy and Taxation (London, UK: G Bell and Sons).

Richards P D, Myers R J, Swinton S M and Walker R T (2012) Exchange rates, soybean supply response, and deforestation in South America. Glob. Environ. Change 22, 454–62.

Rudel T K, Defries R, Asner G P and Laurance W F (2009) Changing drivers of deforestation and new opportunities for conservation Conserv. Biol. 23, 1396–405.

Rudorff B F et al. (2011) The soy moratorium in the Amazon biome monitored by remote sensing images. Remote Sens. 3, 185–202.

Rudorff B F et al. (2012) Remote sensing images to detect soy plantations in the amazon biome—the Soy Moratorium Initiative Sustainability 4, 1074–88.

Sephar C R (1995) Impact of strategic genes on agricultural development in the Brazilian tropical savannahs. Field Crop. Res. 41, 141–6.

Soares-Filho B et al. (2010) Role of Brazilian Amazon protected areas in climate change mitigation. Proc. Natl Acad. Sci. 107, 10821–6.

Soares-Filho B S et al. (2006) Modelling conservation in the Amazon basin. Nature 440, 520–3.

Stabile M C C, Nepstad D and Azevedo A (2012) Brazil's 'Low Carbon Agriculture Program': Barriers to Implementation. (Brasilia, Brazil: Amazon Environmental Research Institute)

United States Department of Agriculture Foreign Agricultural Service (2012) Record soybean and corn Area expected for Brazil's upcoming 2012/13 season Commodity Intelligence Report Retrieved 5 September 2013, from http://pecad.fas. usda.gov/highlights/2012/08/Sinop_Brazil/

University of São Paulo-ESALQ System of Freight Information (2012) Soybean Logistics Costs from Farm to Port. Retrieved 2 July 2012, from http://sifreca.esalq.usp.br/sifreca/ en/index.php

VanWey L K, Spera S, de Sa R, Mahr D and Mustard J F (2013) Socioeconomic development and agricultural intensification in Mato Grosso Phil. Trans. R. Soc. 368, 1619.

Van Zyl J J (2001) The shuttle radar topography mission (SRTM): a breakthrough in remote sensing of topography. Acta Astronaut. 48, 559–65.

Wagtendonk J W and Benedict J M (1980) Travel time variation on backcountry trails J. Leis. Res. 12, 100–6.

TABLES

Table 1. Paper notation

Land cover type	Paper notation
Cropland 2001	C_{2001}
Agricultural land reserve 2003	CR_{2003}
New cropland 2003	NC_{2003}
New cropland 2011	NC_{2011}
Double cropping 2001	DC_{2001}
Double cropping land reserve 2003	DCR_{2003}
New double cropping 2003	NDC_{2003}
New double cropping 2011	NDC_{2011}
Mato Grosso	MT
Abandoned cropland 2002	AC_{2002}
Abandoned cropland 2010	AC_{2010}
Abandoned double cropping 2002	ADC_{2002}
Abandoned double cropping 2010	ADC_{2010}

Table 2. ***Attributes of select land uses*. Table 2 contains mean values and standard deviations of the attributes of the select land cover types. T-tests were also performed comparing land attributes of column 1 with columns 2–4 and 9–11, and comparing column 5 with columns 6–8, 9, and 12–13. Each t-test was statistically significant. Two-tailed *P*-values were <0.001 for each t-test performed.**

	C_{2001}	CR_{2003}	NC_{2003}	NC_{2011}	DC_{2001}	DCR_{2003}	NDC_{2003}	NDC_{2011}	MT	AC_{2002}	AC_{2010}	ADC_{2002}	ADC_{2010}
Area (km^2)	33,745	859,320	6,564	3,494	4,619	889,540	6,173	2,809	904,520	2,423	4,938	1,462	6,852
Elevation (m)	535	327	469	354	520	333	499	435	336	434	433	536	468
	[127]	[134]	[150]	[147]	[137]	[139]	[130]	[126]	[141]	[149]	[149]	[148]	[127]
Slope (degrees)	1.03	2.27	1.39	2.21	0.989	2.23	1	1.36	2.22	1.5	1.61	1.17	1.24
	[0.68]	[2.19]	[1.02]	[0.19]	[0.728]	[0.16]	[0.71]	[1.01]	[2.16]	[1.23]	[1.08]	[1.01]	[0.72]
Precipitation (mm yr^{-1})	1810	1760	1760	1700	1780	1770	1810	1810	1170	1800	1760	1770	1810
	[151]	[268]	[177]	[245]	[132]	[265]	[141]	[151]	[267]	[216]	[182]	[155]	[145]
Soil moisture (mm yr^{-1})	5490	5320	5370	5250	5460	5330	5460	5340	5340	5400	5390	5450	5430
	[216]	[430]	[299]	[411]	[197]	[426]	[213]	[253]	[427]	[319]	[302]	[231]	[249]
Minimum temperature (°C)	19.2	19.7	19.3	19.8	19.2	19.7	19.2	19.4	19.9	19.5	19.4	19.2	19.3
	[0.470]	[0.670]	[0.580]	[0.680]	[0.440]	[0.670]	[0.430]	[0.530]	[0.680]	[0.560]	[0.570]	[0.510]	[0.520]
Maximum temperature (°C)	32	32.2	32.1	32.3	32.1	32.2	32.1	32.2	32.3	32.2	32.1	32.4	32.6
	[0.540]	[0.590]	[0.570]	[0.600]	[0.550]	[0.590]	[0.500]	[0.500]	[0.600]	[0.520]	[0.560]	[0.550]	[0.530]
Soy cost distance ($)	46.5	74.6	57.8	63.9	47	73.8	54.1	70.7	73.5	56.1	63.6	47.1	62.3
	[17.2]	[35.0]	[22.8]	[29.8]	[15.8]	[34.8]	[18.0]	[30.2]	[34.8]	[21.9]	[26.8]	[18.2]	[24.0]

*standard deviations in brackets

Table 3. ***Land abandonment classification sensitivity test.*** **We examined the sensitivity of land abondonment area to the duration of abandonment. The two columns at left show the proportion of agriculture and double cropping abandoned for two years that persisted for at least five years. The two columns at right show the proportion agriculture abandoned for two years that persisted for nine years. Because our most recent land use data are from 2011, five-year abandonment tallies were limited to the 2002–2006 period and the nine-year abandonment could only be calculated for the year 2002.**

Remaining proportion of two year abandonment				
	After five years		After nine years	
	AC_t	ADC_t	AC_t	ADC_t
2002	49.6%	37.6%	36.4%	17.2%
2003	51.1%	30.1%		
2004	58.8%	25.8%		
2005	59.8%	31.6%		
2006	49.5%	35.8%		

Table 4. ***Relationships between land characteristics and land transitions*****. Pluses with asterisks indicate positive correlations ($p < 0.001$) across all years investigated. Pluses without asterisks indicate positive correlations across all years, but with some years statistically insignificant. Minuses indicate negative correlations ($p < 0.001$) across all years. Minuses without asterisks indicate negative correlations across all years, but with some years statistically insignificant. 'M's indicate cases where both negative and positive correlations were observed across the study period. Full results of all of the regressions performed are reported in the SOM.**

	C_t	DC_t	NC_t	NDC_t	AC_t	ADC_t
Maximum temperature	+*	+*	+*	+*	–*	–*
Minimum temperature	–*	–*	–*	–*	+*	+*
Precipitation	+*	m	m	–*	m	+*
Soil moisture	–*	–*	+	+*	m	m
Soy transport cost	–*	–*	–*	–*	+	+*
Elevation	+*	+*	+*	+*	–*	–*
Slope	–*	–*	–*	–*	+*	+*
Upland soils	+*	+*	+*	+*	–*	–
Protected areas	–*	–*	–*	–*	+*	m
Indigenous reserves	–*	–*	–*	–*	+*	m

FIGURE CAPTIONS

Figure 1. *Mato Grosso, Brazil and its agriculture*. (a) Mato Grosso State is completely within the Legal Amazon boundary (hatched lines). Mato Grosso is comprised of portions of three biomes, the Amazon (Amz), Cerrado (Cer) and Pantanal (Pntl). Other Brazilian biomes include the Caatinga (Caa), Mata Atlantica (M Atl) and Pampa (Pmp). (b) Cropland abandoned between 2002 and 2010 is highlighted in cyan, and the extent of mechanized agriculture in 2011 in white. (c) Double-cropped land abandoned between 2002 and 2010 is pink and 2011 double cropping is white. (d) Agricultural expansion in western Mato Grosso. Since land must lie fallow for just two years to be classified as abandoned agriculture, it is possible for some new agriculture to appear on old agricultural lands. (e) Agricultural expansion is blue and mechanized agriculture in 2001 is white. (f) The expansion of double-cropped agriculture is orange and 2001 double cropping is white.

Figure 2. *Maps of mechanized agriculture in Mato Grosso for the* 2001 (*left*) *and* 2011 (*right*) *crop years*. Between 2001 and 2011, total cropland area in Mato Grosso increased 75% from 3.3 million ha to 5.8 million ha. The amount of double cropped land increased six-fold from 0.5 million hectares of land 2001 to 2.9 million hectares in 2011, with soy-corn double cropping rotation accounting for 92% of double-cropped land in 2011.

Figure 3. *Cropping frequency, expansion and abandonment*. Cropland expanded from 3.9 million hectares of cropland in 2003 to 5.8 million hectares by 2011. However, during the period, over 6 million hectares of cropland were created from the forests, pastures, and savannas of the state and an additional 5 million hectares of single cropping were

converted to double cropping. Another 3.7 million hectares of cropland were two-year-rule abandoned between 2002 and 2010. There is no discernible trend in the rate of cropland creation or abandonment over the period, but increased cropland abandonment since 2005 has helped limit the increase in total cropland area in recent years. Single cropping and double cropping comprise the total cropland pool. New double cropping is not a subset of new cropland. New double cropping is areas in which no double cropping occurred in the previous two years, whereas new agriculture is in which there was no agriculture in the previous two years. Thus, new double cropping may or may not also be new cropland, but new cropland might not be new double cropping.

Figure 4. *Box-and-whisker plots of elevation, slope, soil moisture, precipitation, average maximum temperature, average minimum temperature, and soy transportation costs of all expansion of mechanized agriculture, expansion of double cropping, abandonment of mechanized agriculture, and abandonment of double cropping by year*. Pixels are classified as expansion of mechanized agriculture or double cropping in year t if they are classified as mechanized agriculture or double cropping in year t, but not in the previous two years. The gray boxes depict the characteristics of all agriculture and all double cropping in the state. Pixels are classified as agricultural abandonment or double cropping abandonment in year t if they are classified as agriculture or double cropping, respectively, in year $t-1$ but not classified as agriculture in years t or $t+1$. The line at the center of the boxes depicts the median, the ends depict the first and third quartiles, and the whiskers depict 1.5 times the interquartile range.

Figure 5. *Decline in area of available land similar to* 2001 *agriculture*. The characteristics of the land available in Mato Grosso (2003–2011) for mechanized agriculture and double cropping were compared to the characteristics of mechanized agriculture and double cropping in Mato Grosso in 2001. For example, the dark blue line represents the portion of land available for agricultural expansion that falls within zero to 1/2 standard deviations of the mean value of each the seven investigated land attributes of the 2001 agricultural area in the state. The red line represents the portion that is within 1/2 to 3/4 standard deviations from the mean values. The proportion of available land for double cropping declines more steeply despite constituting a larger area.

FIGURES

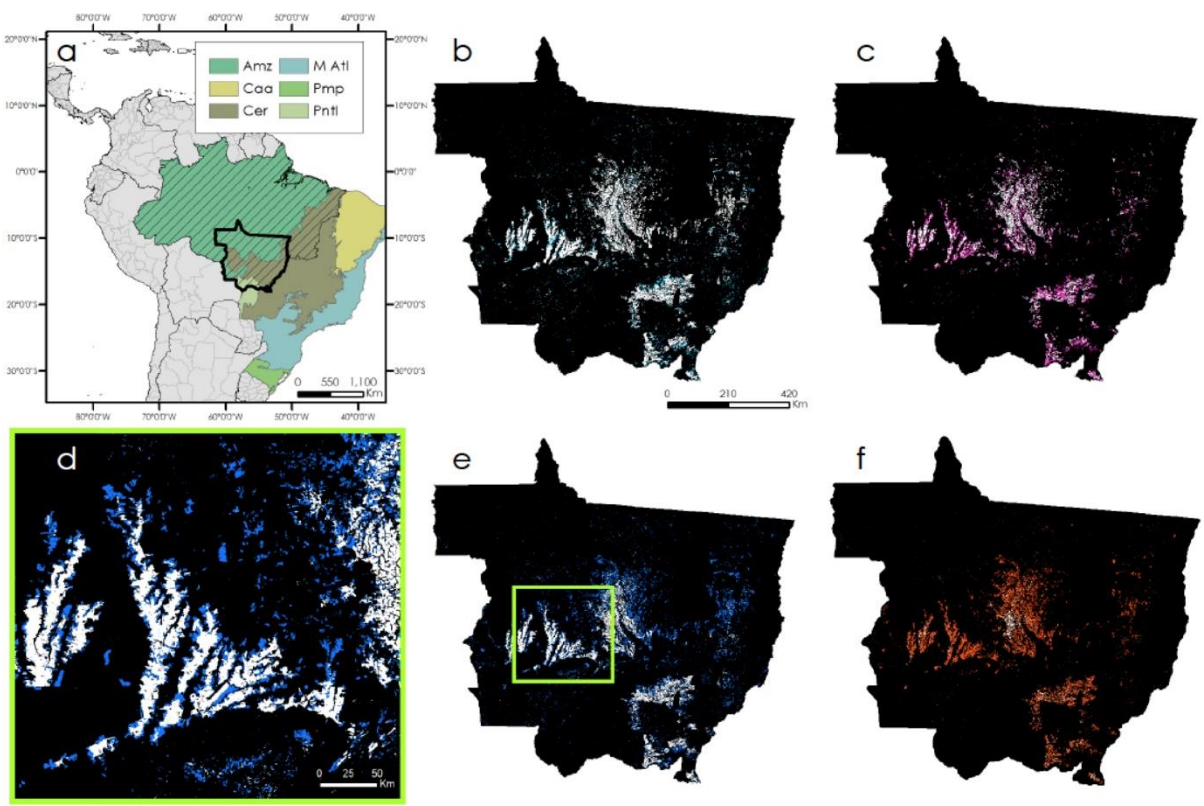

Figure 1

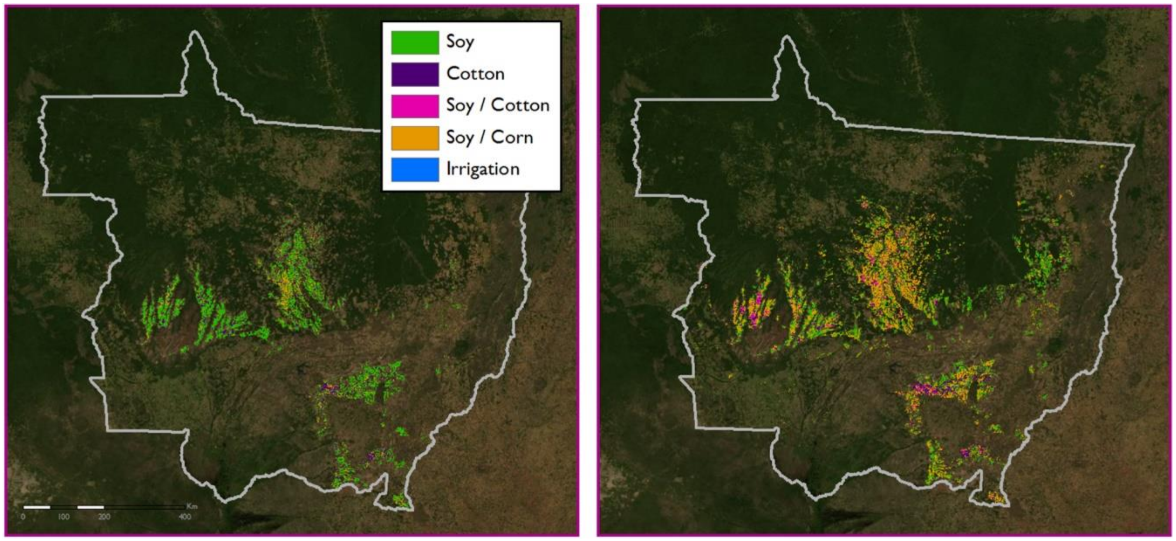

Figure 2

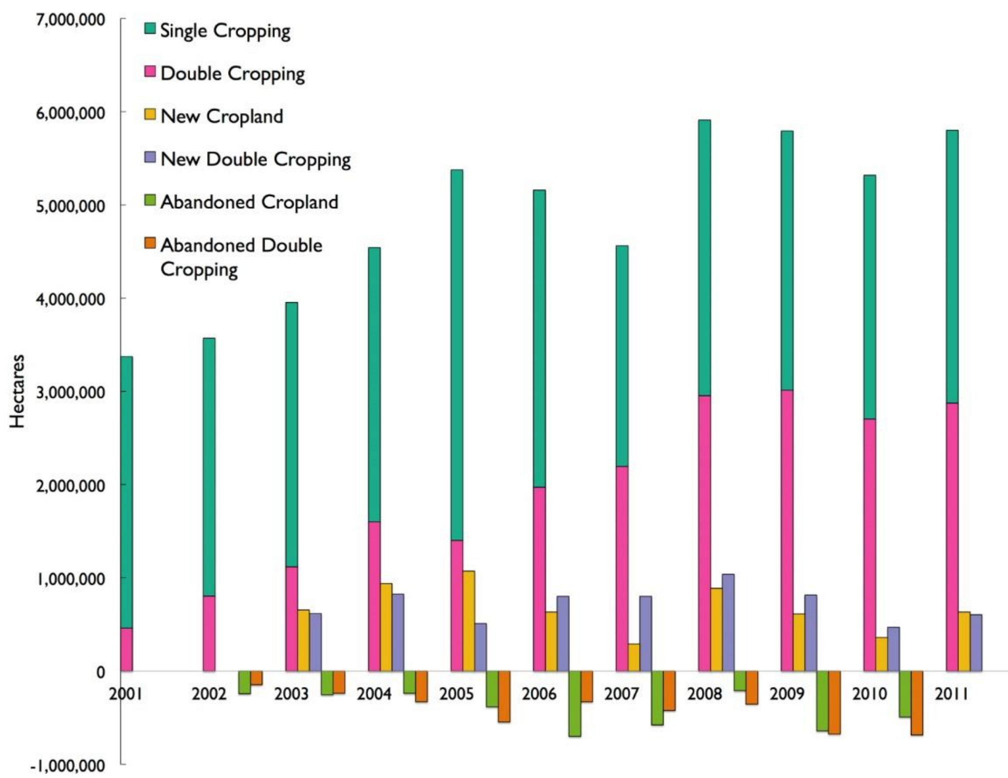

Figure 3

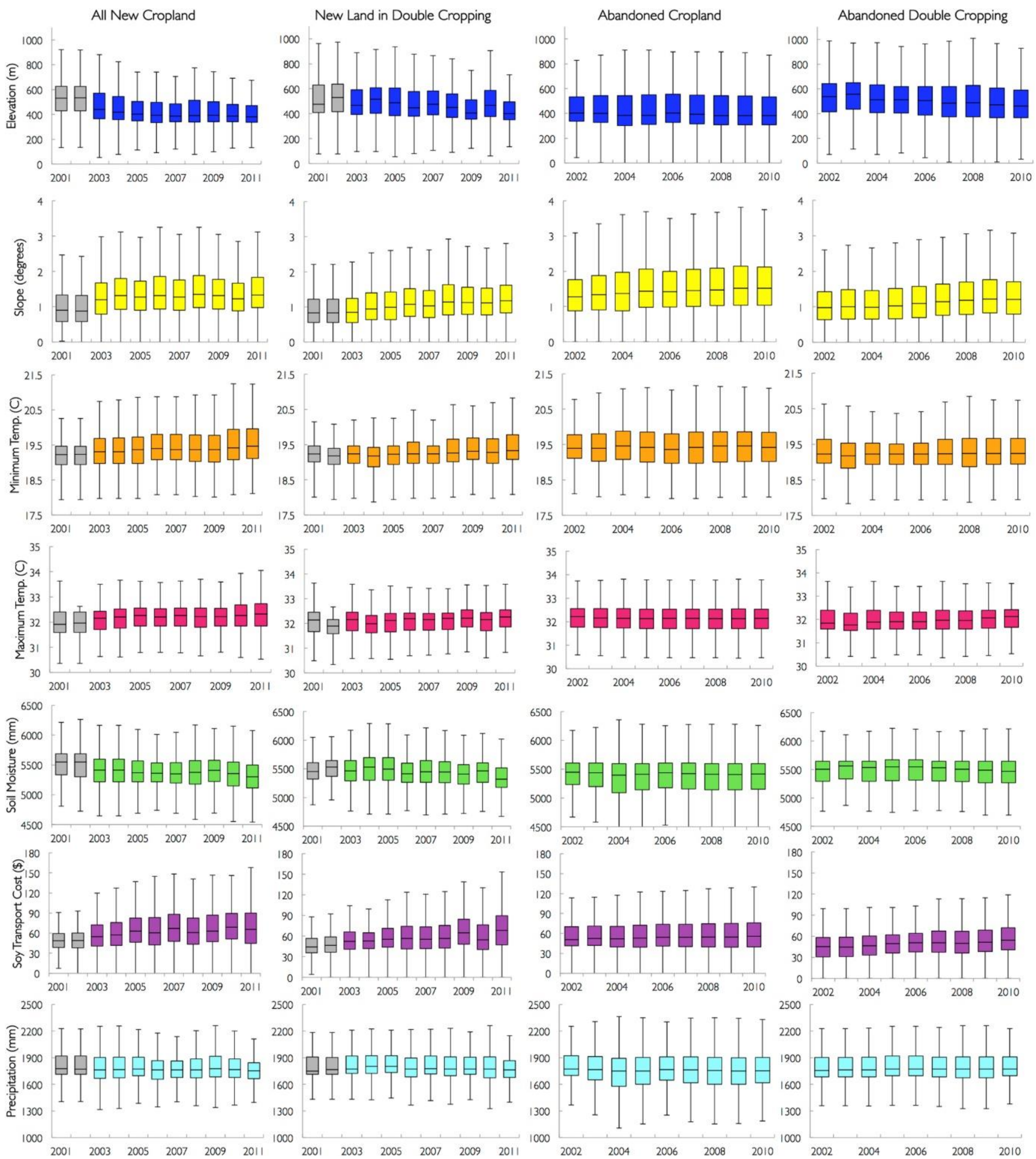
All New Cropland
New Land in Double Cropping
Abandoned Cropland
Abandoned Double Cropping
Elevation (m)
Slope (degrees)
Minimum Temp. (C)
Maximum Temp. (C)
Soil Moisture (mm)
Soy Transport Cost ($)
Precipitation (mm)

Figure 4

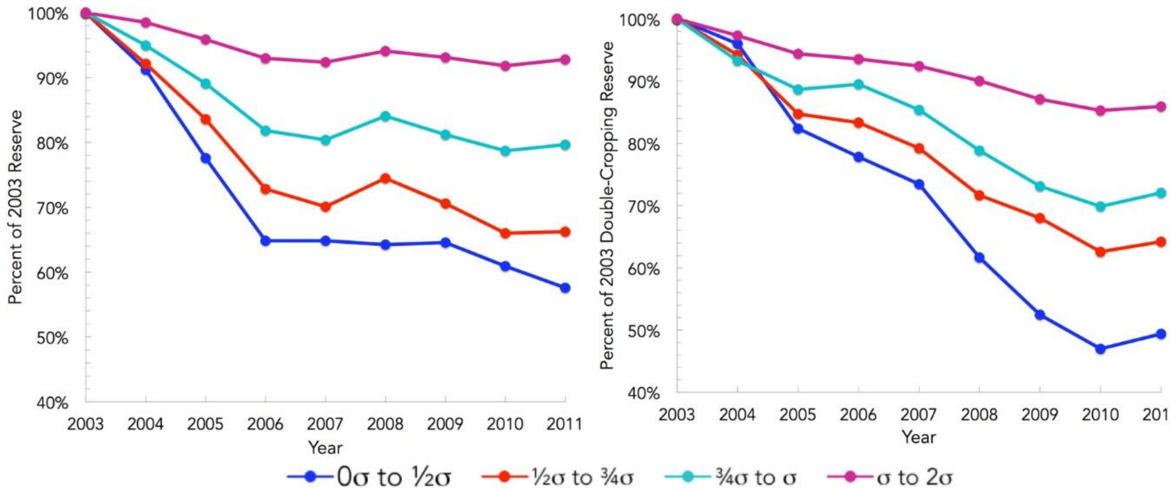
100%
90%
80%
70%
60%
50%
40%
Percent of 2003 Reserve
2003
2004
2005
2006
2007
2008
2009
2010
2011
Year
Percent of 2003 Double-Cropping Reserve
0σ to ½σ
½σ to ¾σ
¾σ to σ
σ to 2σ

Figure 5

SUPPLEMENTARY INFORMATION

Complete Methodology: Land Cover Classification

A. Data

All spatially-subsetted, georeferenced, 16-day, 250 m spatial resolution MODIS13Q1 data over Mato Grosso acquired between August 2000 and July 2011 were downloaded from the United States Geological Survey's Land Processes Distributed Active Archive Center. The data are composites of the highest quality observations of each pixel taken during a 16-day period. MODIS EVI, Day of Year (DOY) and VI Quality Assurance (QA) data were used in this crop classification. EVI was chosen over NDVI because NDVI saturates at lower leaf area indices than does EVI (Huete et al., 2002).

The EVI, DOY, and QA data were stacked sequentially, creating three image cubes consisting of 253 individual scenes resulting in an eleven-year-long time series for each pixel in the scene. Once these image cubes were created, pixels with EVI values below -2.0 and those whose QA data was less than or equal to "lowest quality" were replaced with temporally linearly interpolated values.

A crop year in Mato Grosso was defined to begin at Day 225 of the previous year and to end at Day 209 of the growing year itself. Thus the 2001crop year consists of 23 MODIS EVI scenes composited every 16 days beginning August 12, 2000 and ending July 27, 2001.

B. Decision Tree Classification Algorithm

Each pixel's resulting 2000-2011 time series was analyzed with a decision-tree algorithm written in Interactive Data Language (IDL) to determine both the area of cropland per growing season and the specific rotation of that cropland: a soy or cotton single-commercial-crop rotation or a soy-corn or soy-cotton double-commercial-crop rotation.

The decision tree uses crop-specific growing season lengths and maximum EVI thresholds to classify mechanized agriculture areas into one of four crop rotation classes: soy, cotton, soy-corn, and soy-cotton. The parameters of this classification are outlined in SOM Table 1. All thresholds and parameters were determined using basic statistics and trial-and-error on training data collected in Mato Grosso in March 2011 for the 2010-2011 crop year (99 total points: 10 non-mechanized agriculture, 89 in annual agriculture rotations), general phenological patterns and thresholds described in Galford et al. (2008), Arvor et al. (2011), and published crop calendars (United States Department of Agriculture Foreign Agricultural Service, 2012).

C. Characteristics of Mechanized Agriculture

The phenology of cropland has a distinctive rising and falling shape associated with the sowing and harvesting of crops. We classified a pixel as mechanized agriculture if its time series had a standard deviation greater than 0.21, or if it had a standard deviation greater than 0.16 and the time series had a distinct EVI peak between 50 and 150 days long (SOM Table 1). This second condition avoids false positive classifications of pasture or cerrado as cropland. To calculate these peaks, the algorithm finds the temporally closest observations to the maximum EVI observation that are lower than the average of the maximum and minimum EVI observations. The lengths of time—in days—between these observations are calculated using the corresponding pixel-specific

DOY values. If the width of this derived peak is not between 50 and 150 days, the pixel is not classified as mechanized agriculture.

D. Specific Crop Rotations

Annual cropping systems are the predominant form of mechanized agriculture in Mato Grosso. Single cropping is the conventional system, in which only one commercial crop (soy or cotton) is cultivated during the crop year. Double cropping typically involves the cultivation of a short-cycle soy variety during the first half of the crop year and followed by the cultivation of a second commercial crop (often corn or cotton and occasionally soy). Because nearly all the mechanized agriculture in Mato Grosso is rainfed, the short-cycle soy varieties are essential for the planting of a second commercial crop during the wet season. Soy is typically sown between late September and November (United States Department of Agriculture Foreign Agricultural Service, 2012). Mato Grosso's farmers can only begin to plant soy on September 15 – the official end of the 90-day "Free Host Period" which is employed to deter the spread of Asian soybean rust. If soy is the only commercial crop being sown, the growing season typically spans October to March (United States Department of Agriculture Foreign Agricultural Service, 2012). If corn is planted as a second crop, it is often sown in late January-February (immediately following soy harvesting) and harvested in late May and June (United States Department of Agriculture Foreign Agricultural Service, 2012). Second crop cotton is typically sown in January (United States Department of Agriculture Foreign Agricultural Service, 2012). If cotton is the only commercial crop planted, it is sown in late December-January, and is harvested in late June or early July

(United States Department of Agriculture Foreign Agricultural Service, 2012). Because corn is an erectophile and cotton and soy are planophiles, the latter crop's canopies often reach higher maximum EVI values during the growing season at full crop development (Dorigo et al., 2007).

For pixels classified as cropland, a second stage of the classification algorithm is employed to classify crop rotation based on the growing season length and maximum EVI. To determine the dates of green up and harvest, the time series is divided into two overlapping sections—EVI values that were compiled between DOY 225 (mid-August) and DOY 81 (late March of the following calendar year but same crop year) and those between DOY 353 (late December) and DOY 209 (late July of the following year). The algorithm identifies rapid increases and decreases in the EVI time series, specifically a Δ EVI greater than 0.4, corresponding to times of green up and harvest. The dates of these events for each pixel are then recorded. These pixel-specific dates are then used to calculate the lengths of the crop cycles for that growing season. If a green up date or a harvest date is not located for the first crop, the green up date of the second crop is used as the date of harvest for the first crop. Conversely if no green up date is identified in the second half of the time series, the date of the first crop's harvesting would be used as the second crop's green up date.

Because no smoothing algorithm is applied to the MODIS data, using maximum EVI values sometimes confused our training data classifications of a cover crop as corn, or corn as cotton. Thus, rather than use the maximum EVI value in each time segment, we chose to calculate the average of the second- and third-highest EVI values in each time series and use this as a corrected maximum.

We use phenological thresholds (SOM Table 1) based on analysis of the training data to perform the crop cover classification. The lowest 'corrected maximum' EVI value needed for classification as a soy or cotton crop is 0.6, while the lowest 'corrected maximum' EVI value for corn is 0.45. The growing season length for classification as soy and corn ranges from 78 days to 155 days. The growing season length for classification as cotton ranges from 116 to 240 days, but only appears during the second half of the growing season. While these growing season durations seem longer than appropriate, these extended lengths are necessary due to the methods by which MODIS derives its EVI data. The MOD13Q1 EVI product is a composite of the highest quality observations of each pixel taken during every 16-day compositing period. If a soy crop is harvested on January 1, the highest quality observation taken over that soy field may have been taken on January 16, seemingly adding 15 days to its growing season. Thus, we added a temporal buffer before and after the growing season to address this possibility when calculating crop cycle lengths. The algorithm, then, works pixel by pixel through a series of conditions to determine if the land cover of a given pixel's time series shows a soy, soy-non-commercial crop, cotton, non-commercial crop-cotton, soy-corn or soy-cotton pattern, and classifies the pixel as such.

Lastly, the algorithm also highlights irrigated cropland. To determine if a pixel represents irrigated agriculture, the pixel's time series must have a standard deviation that qualifies it as mechanize agriculture. Because irrigated land allows for the cultivation of crops through the dry season, unlike other annual crop rotations with characteristic low EVI values throughout the dry season, irrigated land shows high EVI values during these times. Thus, to be classified as such, a pixel must have the standard deviation characteristic of mechanized agriculture and a first or last growing season EVI pixel value greater than 0.5. Cotton, corn (for seed), and beans are the crops most commonly grown with central pivot-irrigation Mato Grosso. The algorithm, however, does not differentiate between irrigated crop types.

	Soy	Cotton	Soy/Corn	Soy/Cotton	Irrigated
σ of EVI Time Series > 0.21	x	x	x	x	x
First/Last EVI Time Series Value < 0.5					x
Occurs First During First Half of Crop Year	x		x	x	
Occurs During Second Half of Crop Year		x	x	x	
Minimum EVI "Maximum" ≥ 0.6	x	x	x	x	
Minimum EVI "Maximum" 0.45 < x < 0.6			x		
Growing Season Length: 78-155 days	x		x	x	

Growing Season Length: 116-240 days		x		x	

Table S1. *Characteristics used to classify crop rotations. All other pixels were aggregated to 'other' class containing forest, cerrado, pasture, sugarcane and rice.*

If algorithm cannot determine when the start or end of a growing season occurs from the EVI time series, it cannot perform the rest of the crop classification analysis. In these instances, the crop type determination is dependent on the EVI-corrected maxima thresholds discussed above and outlined in SOM Table 1.

E. Post-Classification Nosie Filter

A conservative noise reduction mode filter is applied to minimize any 'salt and pepper' effect, e.g. one cotton pixel in the middle of a soy-corn field. A 3-pixel-by-3-pixel moving kernel window filters through the resulting crop year classifications and modifies the middle kernel cell if all of its surrounding cells are classified as the same land cover. This conservative mode filter amounted to a correction of approximately 0.5% of all pixels within the Mato Grosso scene over the eleven crop years.

In summary, the algorithm analyzes each pixel independently to determine if the land cover present as non-mechanized agriculture or mechanized agriculture. Each pixel classified as mechanized agriculture is further refined based on the phenology dynamics as a single- or double-crop rotation, and which principal crops (soy, corn, cotton, cover) comprise that crop rotation.

F. Verification and Validation

The results were validated with a web-tool developed at the National Institute of Space Research in Brazil (INPE) (Freitas, 2011). More details about applications of this web-tool can be found outlined in Adami et al. (2012), at http://www.dsr.inpe.br/laf/series/en/about.html, and outlined below.

A purposive sampling of 600 new points distributed through Mato Grosso State was chosen for validation. Because mechanized agriculture is known to occur in close proximity to roads, we used ArcGIS 10.0 software to choose pseudo-randomly located validation points within 1 km of the road network shapefile downloaded from Mato Grosso's Secretary of State Planning and General Coordination (Mato Grosso State Secretary of Planning, 2013). The proximity of the validation points to roads was also important in facilitating ground truth validation activities. At least one false color composite of Landsat bands 4 (0.84 μm as red), 5 (1.65 μm as green), and 3 (0.66 μm as blue) was compiled for each of the 600 points for each growing season between 2001 and 2011. False color Landsat images highlight the unique shades of orange-red characteristic of forest, cerrado, pasture, soy, corn, cotton and cover crops with the aforementioned 4(red)-5(green)-3(blue) band combination (Figure 1). The 30 m resolution data are ideal for recognizing the different crop covers identified with MODIS, thus allowing for validation of the land-cover class at each point for each crop year. The tool's Landsat images were analyzed for each point for each crop year to determine that pixel's specific land-cover. The utility of having a spatial and temporal spread of validation points is integral to ensuring the robustness of the algorithm's processes.

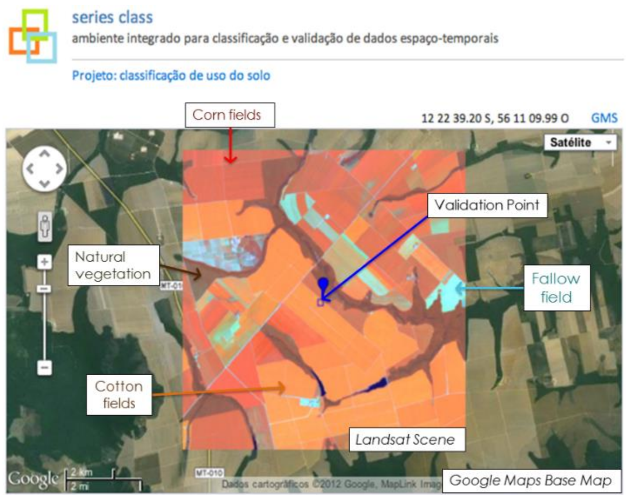

Figure S1. A screenshot of the validation webtool interface to demonstrate the ability to use Landsat imagery when field sizes are large.

Ideally the validation method would apply to all 600 points throughout all eleven crop years for a total of 6600 potential validation points. However, obtaining cloud free images over Mato Grosso during the season is extremely difficult. As a result, the only Landsat image associated with a particular point and growing season may not have been taken during the best crop identification window, making it impossible to accurately determine the land cover for some validation points. A point was only considered for validation if a Landsat image was if crop-type, and thus growing season rotation, could be distinguished. Furthermore, we excluded mixed pixels (MODIS validation points that covered two different land cover classes at Landsat resolution) from the validation analysis, but address their classifications below. Of the potential 6600 validation points, 2945 met our criteria as points to validate the algorithm's output.

As shown in Table 2, of the excluded validation points, 38% had no usable Landsat data due to missing data, cloud cover, or the date the image was taken; 52% were mixed pixels in which a MODIS pixel encompassed two land cover types; 3% were pixels that represented rice or sugarcane crops, both of which were classified as other in our analysis; and 7% were left unclassifiable. Of the pixels with no usable Landsat images, 53% were classified through the MODIS analysis as soy-corn land cover rotation; 46% as a soy-cover crop rotation; and 1% were as a soy-cotton rotation. Of the 7% of pixels in which the land cover could not be determined from the Landsat data; 60% were classified as other; 21% as a soy-cover crop rotation; 11% as soy-corn rotation; and 8% as a cotton rotation. These 235 unclassifiable pixels represent less than 4% of the total number of web-tool points and require fieldwork for verification and validation.

No usable Landsat	1387
Mixed pixels	1888
Rice or sugarcane	127
Unknown	253
Total	***3655***

Table S2. *Pixels not used in validation*

Every excluded mixed-pixel validation point was reanalyzed to estimate the aggregate effect on total area calculated. Of the 1901 mixed pixels, 97% were correctly classified as one of the two land covers contained within the pixel. Of the 97%, 25% were forest- or cerrado-crop boundaries that were classified as other; and the last 3% were randomly classified. The area attributed to may exhibit a slight positive bias. The classification of some mixed pixels at forest/crop edges would be troublesome if Mato Grosso were home to myriad patches of smallholder agriculture and thus create an abundance of non-crop/crop edges. However, because more than 85% of Mato Grosso's mechanized agricultural farms range are larger than 500 ha (Brazilian Institute of

Geography and Statistics, 2013a), and the land-cover land-use change occurs at such a large scale, these pixels should not significantly affect aggregate area estimates.

G. Accuracy

We classified 11 years of MODIS data with a high degree of accuracy. Mechanized agricultural land was separated from pasture, cerrado, and forest with an overall accuracy of 98% (Table 3). The algorithm successfully separated unique crop rotations with an overall accuracy of 93% and a k_{hat} of 0.90 (Table 3).

Classification	*Ground Cover Validation Data*			
	Mechanized Ag.	*Other*	*Row Total*	***User's Accuracy***
Mechanized Ag.	1608	16	1624	0.99
Other	49	1272	1321	0.96
Column Total	1657	1288	2945	
Producer's Accuracy	0.97	0.99		

Overall Accuracy = 98%

Classification	*Ground Cover Validation Data*							
	Soy	*Cotton*	*Soy/Corn*	*Soy/Cotton*	*Other*	*Irrigated*	Row Total	***User's Accuracy***
Soy	752	10	34	1	12	1	810	0.93
Cotton	10	165	4	1	0	0	180	0.92
Soy/Corn	41	3	502	4	4	3	557	0.90
Soy/Cotton	3	2	11	40	0	3	59	0.68
Pasture/Cerrado/Forest	38	3	2	0	1272	6	1321	0.96
Irrigated	0	0	0	0	0	18	18	1.00
Column Total	844	183	553	46	1288	31	2945	
Producer's Accuracy	0.89	0.90	0.91	0.87	0.99	0.58		

Overall Accuracy = 93% ***K_{hat} =.90***

Table S3. *Confusion matrices. Other contains forest, pasture, and cerrado.*

The land covers and uses associated with a relatively high error were 'irrigated land' and the soy-cotton rotation. The irrigated land class spanned a range of classifications, due to the irregular growing year phenology. Error associated with the soy-cotton rotation is related to the small number of validation points and conflation with soy-corn areas in the southeastern half of Mato Grosso.

We compared our classification of mechanized agriculture to statistics on the area of soy, corn, and cotton production statistics reported in the Municipality Agricultural Research (PAM) reports produced by the Brazilian Institute of Geography and Statistics (IBGE) (2013b). PAM agricultural production statistics are based on estimates by local experts. Averaged over the ten crop years, the soy algorithm results were in 86% of the area of the PAM, with a high of 96% of the area in the 2001 crop year and a low of 79% of the area in the 2004 crop year. Corn harvested area results were 32% higher than reported government statistics with a maximum of 70% higher than the area reported in the 2006 crop year. There was only one crop year, 2000/2001, where our corn harvested area estimate was lower than that reported by the IBGE. The average area of cotton estimated was never more than 9% higher than PAM statistics over the period 2000 to 2010.

Our approach has a number of limitations. There was decision tree confusion distinguishing between soy-cotton and soy-corn rotations in the southeastern half of Mato Grosso. There, the short and late wet season results in similar growing season phenologies for corn and cotton. We also obtained the fewest validation points for the soy-cotton class.

Although the algorithm can differentiate central-pivot irrigation areas, it cannot identify crops planted in these irrigation circles. However, irrigated areas comprised less than 1% of the land in mechanized agriculture in Mato Grosso.

As Brown et al. (2013) highlight, other soy-commercial crop rotations, such as soy-sunflower, soy-sorghum, soy-soy, and soy-beans are present on the landscape. Because sunflower, sorghum and beans comprised less than 0.3%, 1.6%, and 0.93% of the total land in annual crops in Mato Grosso between 2000 and 2011 respectively (Brazilian Institute of Geography and Statistics, 2013b), they were not considered in our algorithm. Rice, which comprised almost 6% total land in annual agriculture over the eleven-year period (Brazilian Institute of Geography and Statistics, 2013c), was also not considered. Beans are often cultivated using pivot irrigation, which allows for the ability to plant three harvests per crop year, and our algorithm's irrigation results may be used as a proxy for bean-crop land cover.

Sugarcane was also not classified in our analysis. As of 2012, 290,000 hectares of sugarcane were cultivated in Mato Grosso, an increase of 83% over the 160,000 hectares cultivated in 2003, but no change has been observed since 2008 (Rudorff et al., 2010). Non-commercial cover crops such as millet, which often precede or succeed single crop soy or cotton rotations, were lumped into the single cropping class. Although not validated, using single cropped fields with commercial cover crops as a proxy for no-till management regimes, and single cropped fields with no cover crop as a proxy for till management regimes, in both 2001 and 2011, approximately 60% of single cropped field pixels presented an obvious cover crop.

Our algorithm was written to discriminate between crops that comprise 89% of the IBGE's reported total aggregated cultivated land area in Mato Grosso. The aforementioned crops of rice, sugarcane, beans, sorghum, and sunflower comprise much of the remaining 11%. Based on our validation points, both rice and sugarcane (7.75% of Mato Grosso's area in agriculture and less than 1% of Mato Grosso's total land cover) were consistently classified as 'other' due to the short growing season and low maximum EVI associated with rice and the similarity of sugarcane's phenology to pasture. While this misclassification causes us to slightly underestimate mechanized agricultural are, it does not affect our specific crop type accuracies.

Mixed pixels were classified as one land cover type. Pixels with a mixture of forests and crops were classified as other, biasing downward the area of mechanized agriculture. Pixels with a mixture of soy and corn were classified as soy/corn, biasing downward the area soy and the area of corn. However, the methodology succeeds in its goal to capture majority of agricultural development in Mato Grosso

Complete Methodology and Results: Logistic Regressions

A. Data

A1. Agri-climatic attribute maps

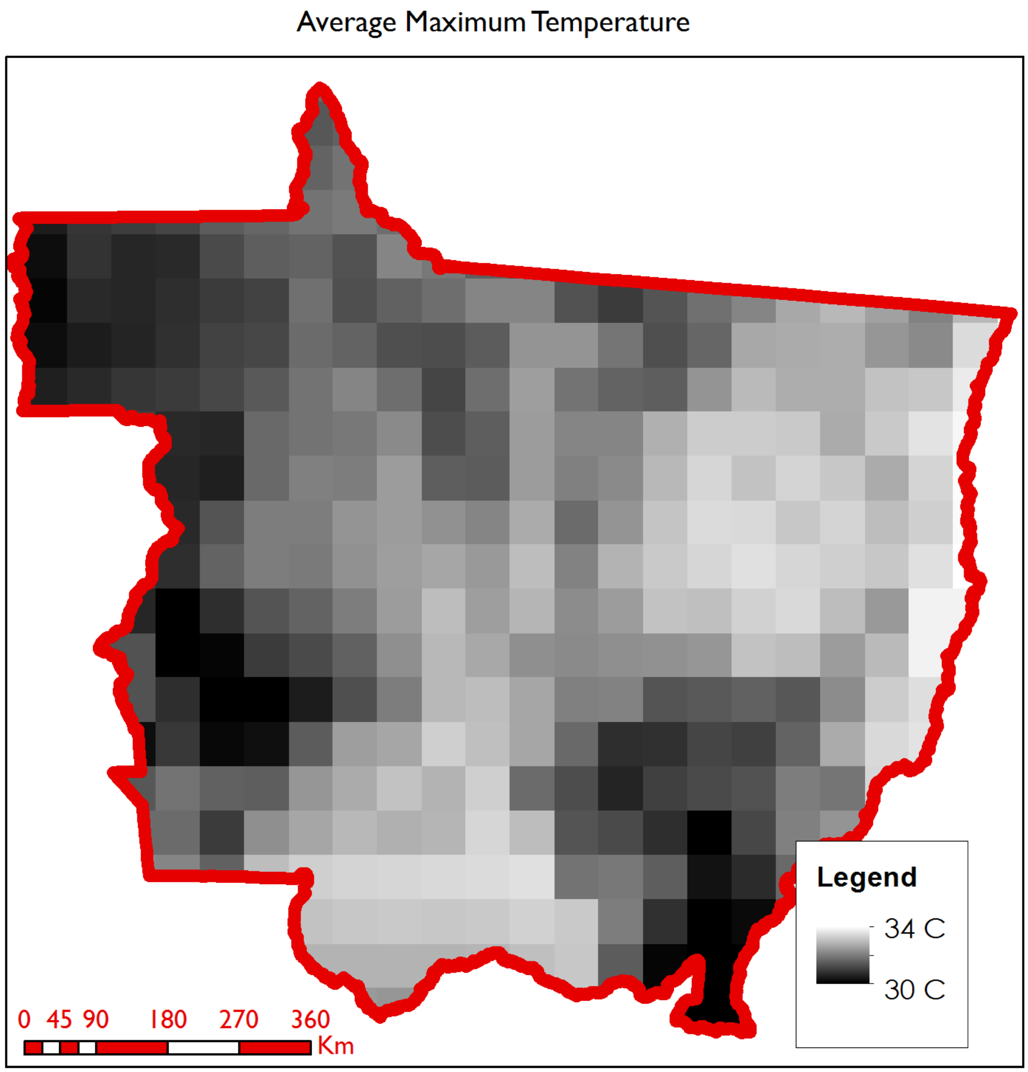

Figure S2. Climate Research Unit (CRU) Average Maximum Temperature across Mato Grosso from 1980 to 2000 (New, Lister, Hulme, & Makin, 2002).

Average Minimum Temperature

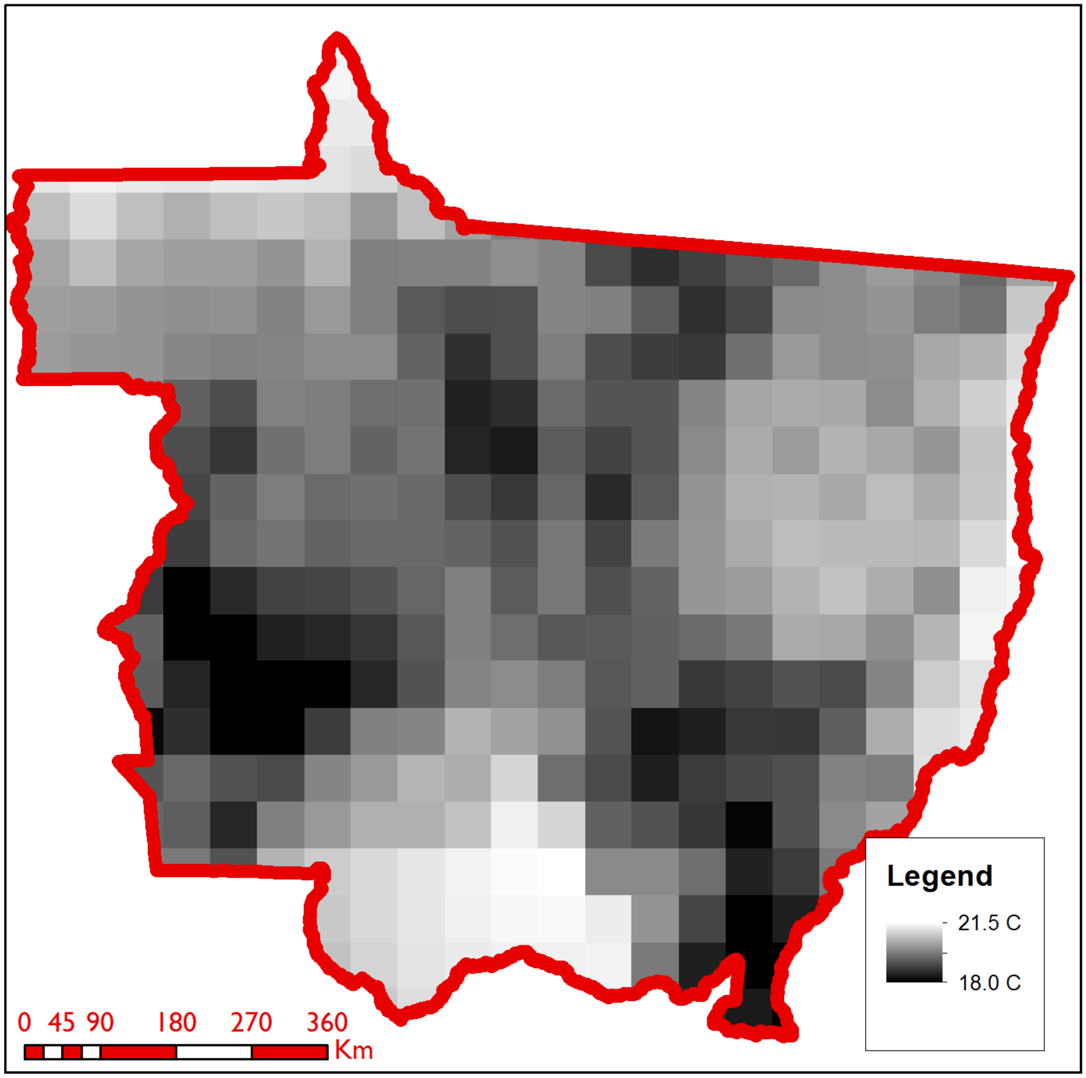

Figure S3. Climate Research Unit (CRU) Average Minimum Temperature across Mato Grosso from 1980 to 2000 (New, et al., 2002).

Average Annual Precipitation

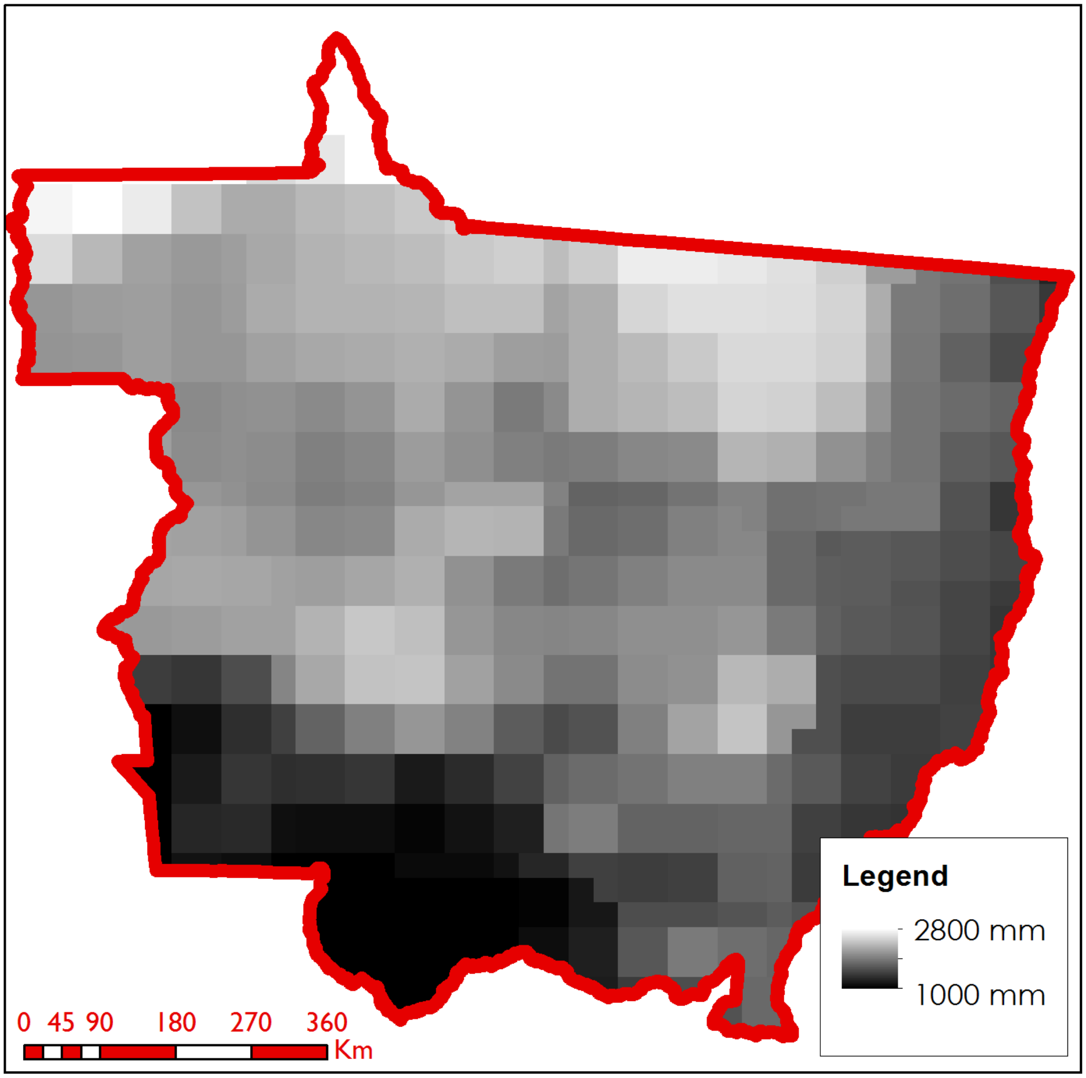

Figure S4: Climate Prediction Center (CPC) average annual precipitation across Mato Grosso from 1981 to 2010 (Fan & van den Dool, 2004).

Average Annual Soil Moisture

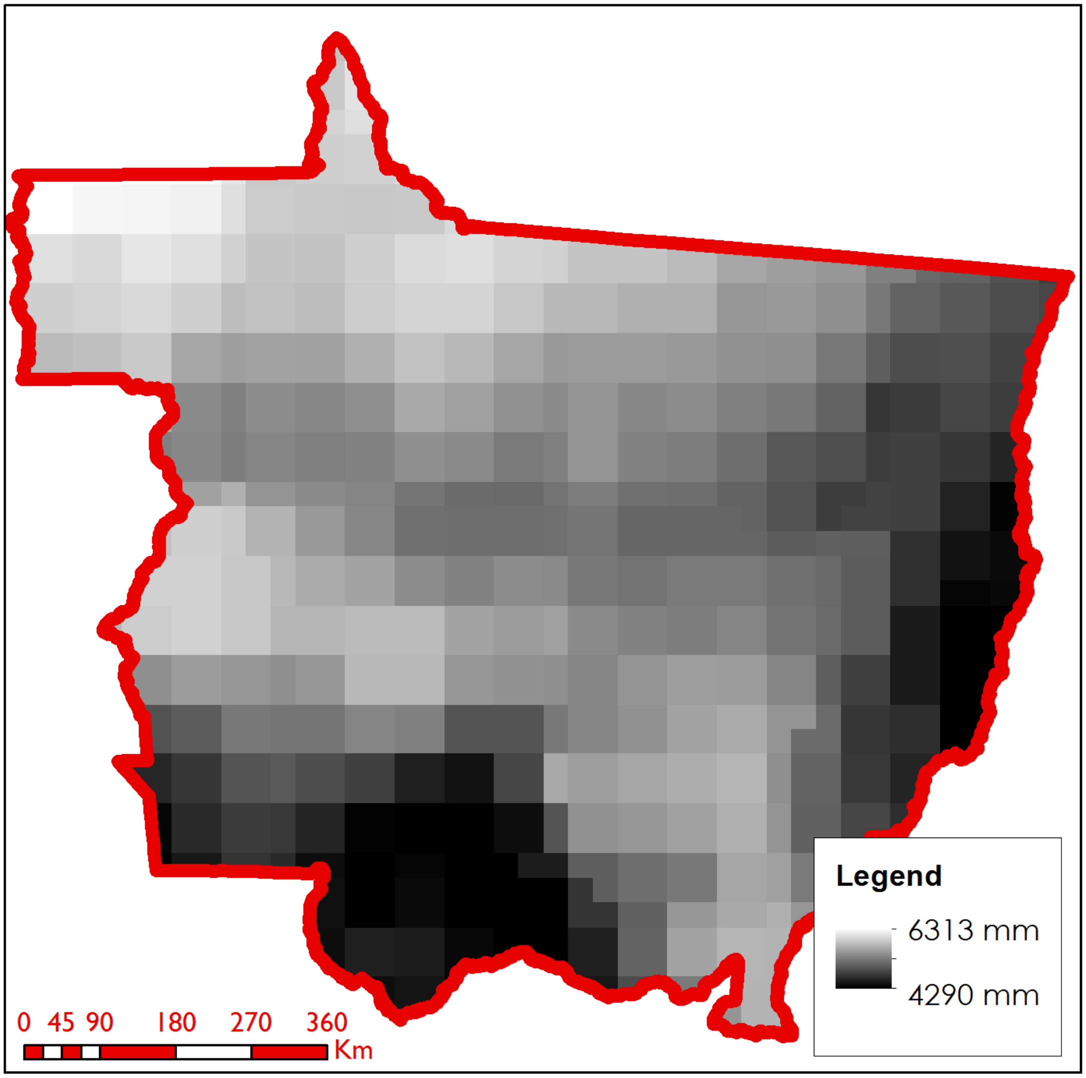

Figure S5. Climate Prediction Center (CPC) average annual soil moisture across Mato Grosso between 1981 and 2000 (Fan & van den Dool, 2004).

Elevation

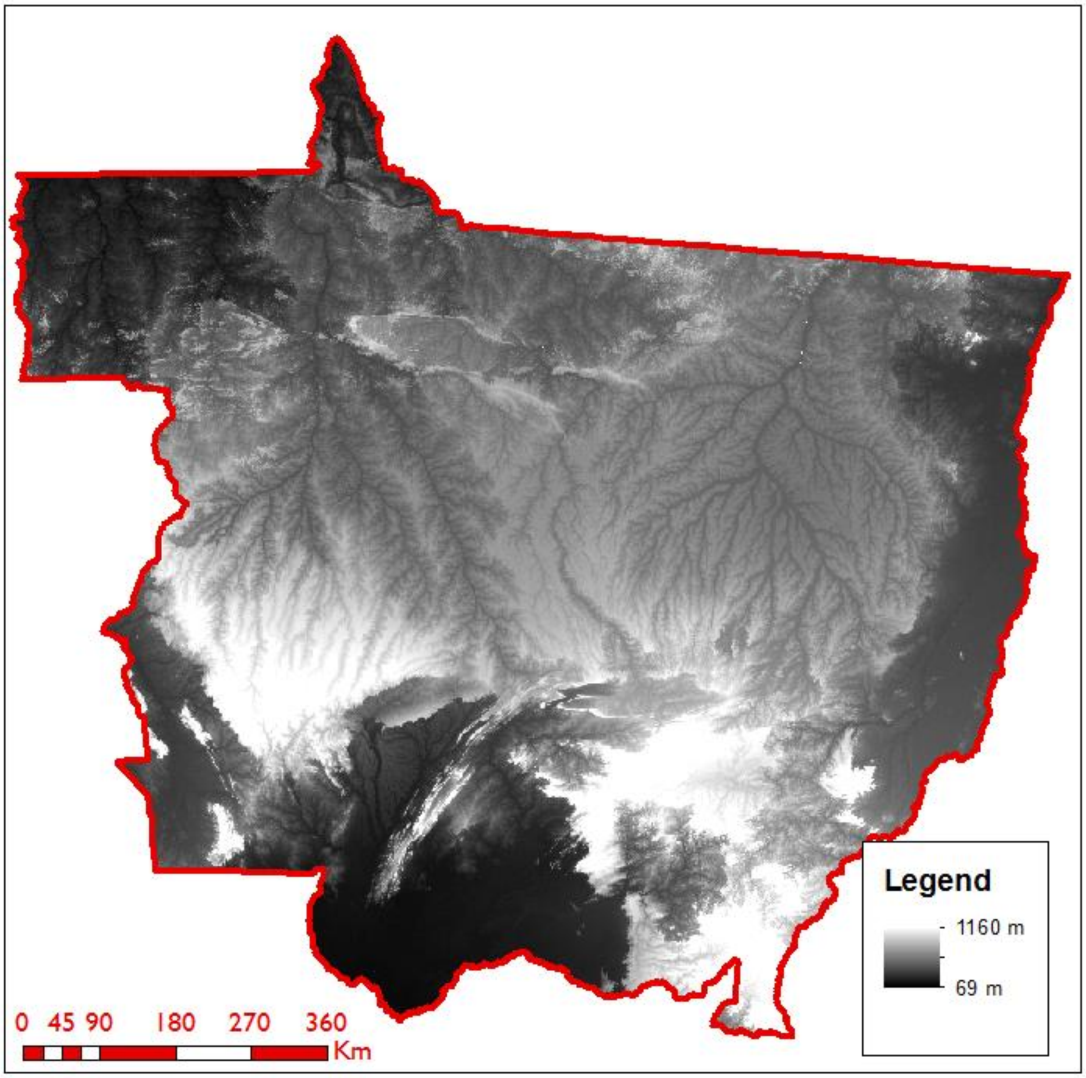

Figure S6. Shuttle Radar Topography Mission (SRTM) digital elevation map (Van Zyl, 2001).

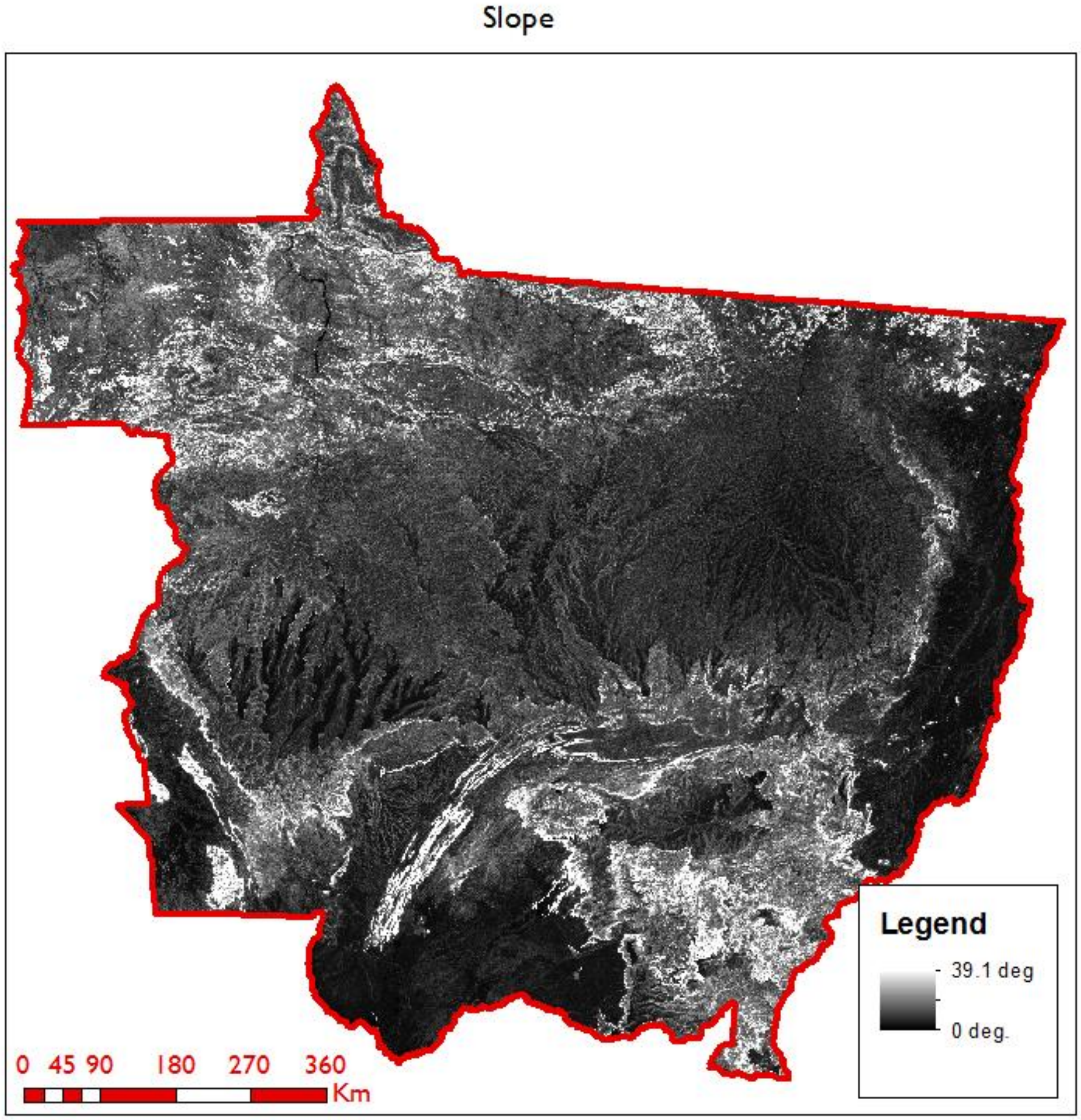

Figure S7. Shuttle Radar Topography Mission (SRTM) derived slope (Van Zyl, 2001).

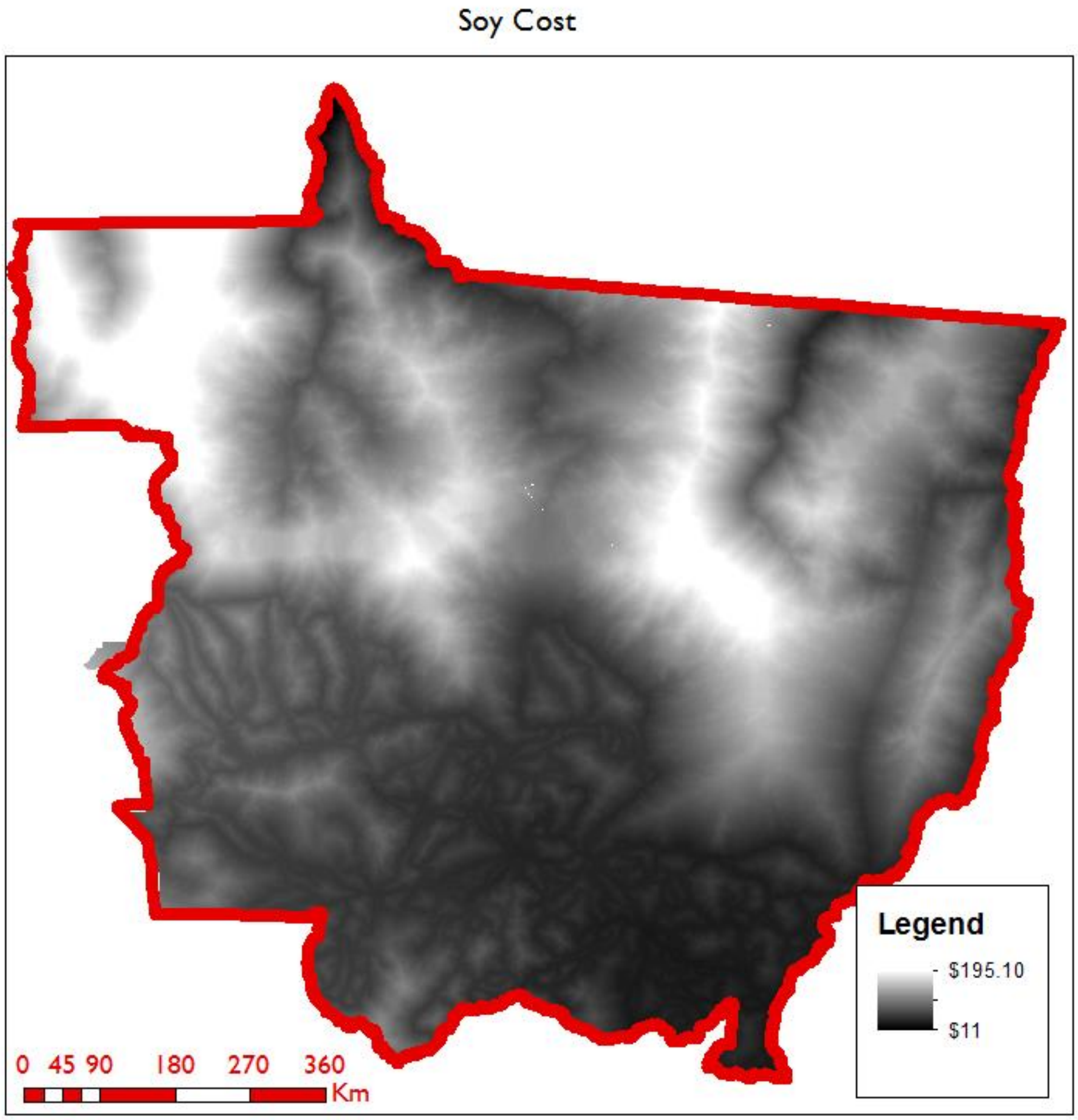

Figure S8. Soy logistics cost estimates map (in year 200 US Dollars).

A2. Agri-Climatic Attribute Correlation Matrix

	Precipitation	Soy Transport cost	Minimum temperature	Maximum temperature	Soil moisture	Slope	Elevation
Precipitation	1						
Soy Transport cost	0.422*	1					
Minimum temperature	-0.204*	0.00526*	1				
Maximum temperature	-0.311*	-0.142*	0.680*	1			
Soil moisture	0.804*	0.339*	-0.414*	-0.674*	1		
Slope	0.0720*	-0.0143*	-0.138*	-0.290*	0.215*	1	
Elevation	0.127*	-0.208*	-0.715*	-0.405*	0.254*	0.199*	1

* p<0.001

Table S4. *Correlation matrix of the seven agri-climatic variables investigated.*

A3. Agri-Climatic Attribute Histograms

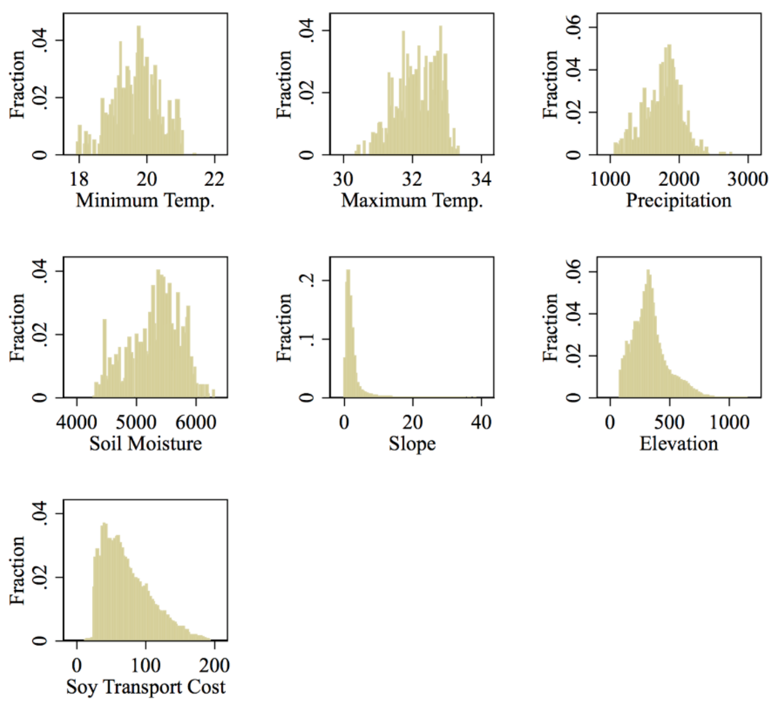

Figure S9: Histograms of land attributes investigated.

B. Protected Areas and Indigenous Reserves

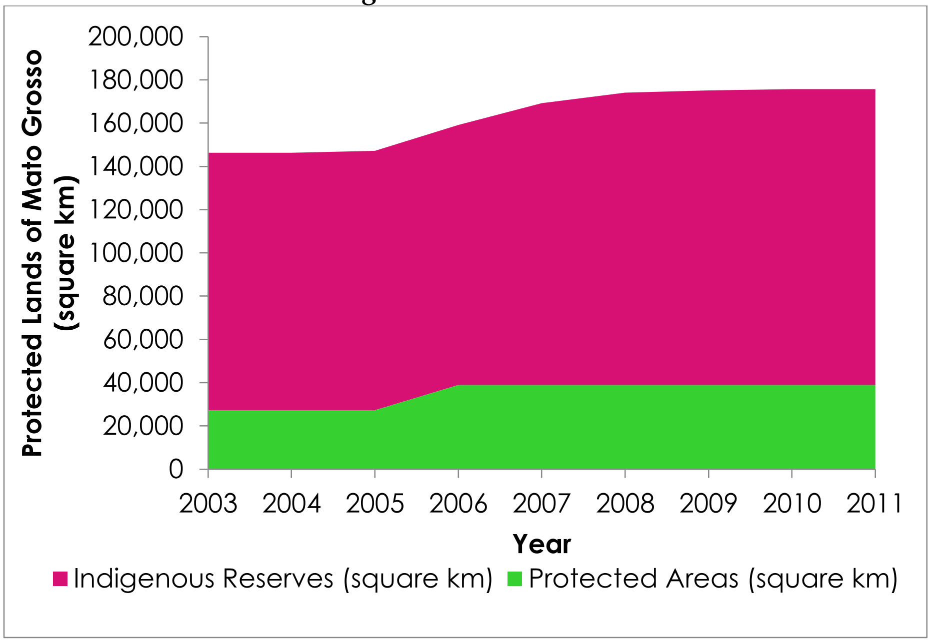

Figure S10: Cumulative area of protected areas and indigenous reserves over study period.

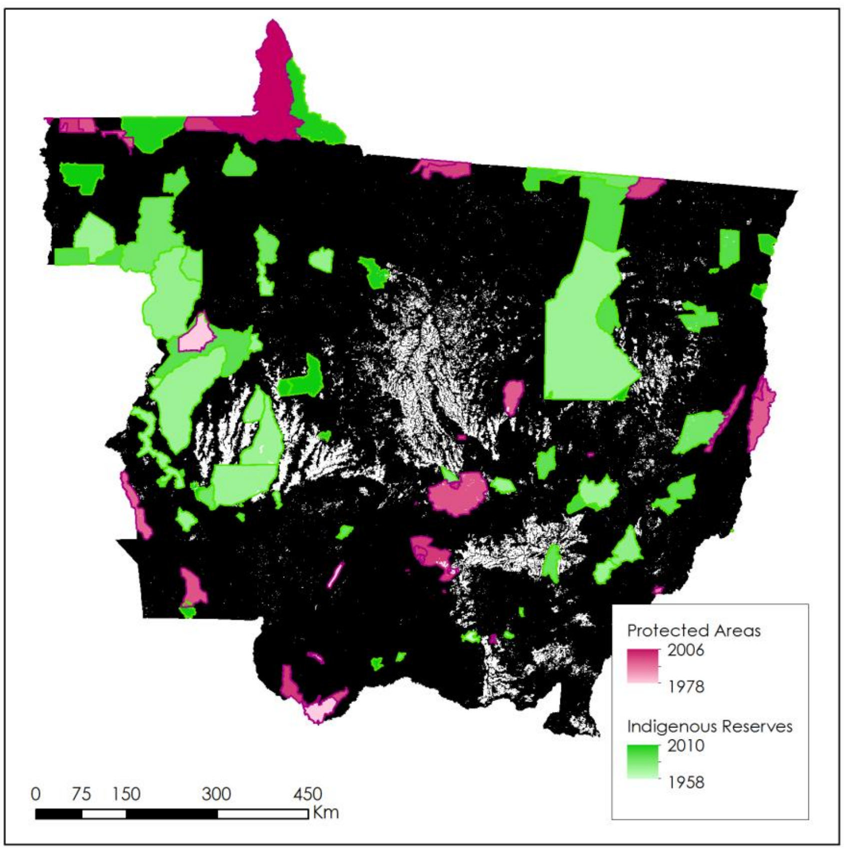

Figure S11. Map of protected areas and indigenous reserves by year of designation. (IUCN & UNEP 2014)

C. Soils

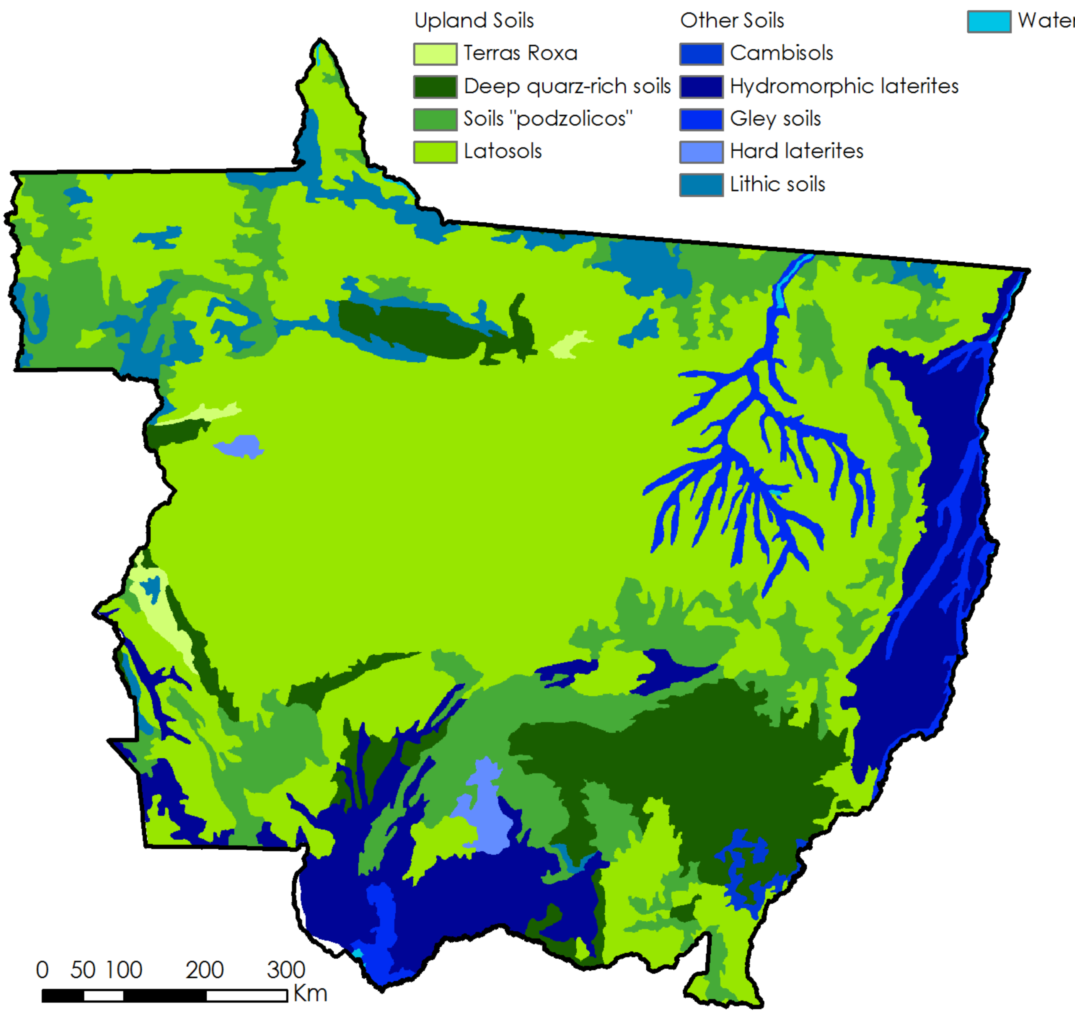

Figure S12. 1981 Embrapa soils map highlighting the Brazilian classification of soils and our categorization into 'upland soils' in green and all other soils, in blue.

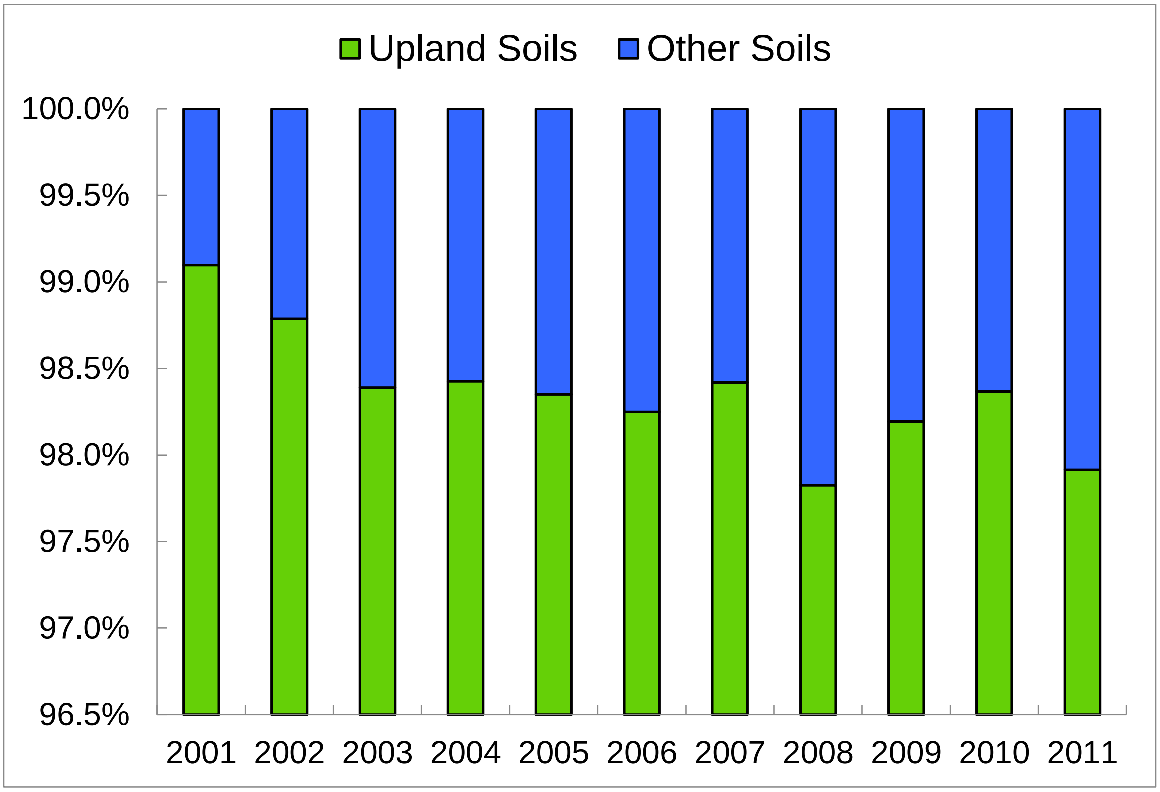

Figure S13. Breakdown of total agriculture on, preferred upland soils and other soil. 99% of agriculture was cultivated on preferred upland soil in 2001. In 2011, 98% of total agriculture was cultivated on upland soil.

D. Results Tables (Logistic Regressions and Transition Matrix)

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Min Temp.	0.0402*	0.163*	0.132*	0.107*	0.0900*	0.103*	0.0635*	0.0801*	0.0562*	0.0577*	0.0243*
	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)	(0.00)	(0.00)
Maximum Temp.	53.63*	17.48*	19.37*	25.19*	29.75*	26.26*	46.76*	35.75*	57.24*	56.97*	94.22*
	(6.42)	(0.40)	(0.43)	(3.29)	(0.57)	(0.50)	(0.99)	(4.19)	(7.07)	(1.16)	(2.41)
Soil Moisture	0.997*	1.000*	1.000*	1.00	1.000*	0.999*	0.999*	0.999*	0.999*	0.999*	0.998*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Precipitation	1.006*	1.010*	1.010*	1.010*	1.010*	1.010*	1.010*	1.010*	1.010*	1.011*	1.008*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Elevation	1.001*	1.002*	1.001*	1.001*	1.001*	1.001*	1.001*	1.001*	1.001*	1.001*	1.001*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Slope	0.169*	0.0863*	0.0853*	0.100*	0.108*	0.113*	0.1000*	0.117*	0.0990*	0.0955*	0.136*
	(0.01)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)
Soy Transport Cost	0.949*	0.964*	0.965*	0.969*	0.975*	0.977*	0.978*	0.980*	0.981*	0.983*	0.983*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Upland Soils	29.59*	7.398*	5.541*	5.611*	5.596*	6.010*	5.905*	5.634*	6.106*	6.122*	7.177*
	(11.45)	(0.27)	(0.17)	(0.98)	(0.14)	(0.15)	(0.17)	(0.82)	(0.98)	(0.16)	(0.30)
Indigenous Reserves	0.000878*	0.00138*	0.00106*	0.00167*	0.00199*	0.00407*	0.00202*	0.00493*	0.00457*	0.00560*	0.00710*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Protected Areas	0.0745*	0.0736*	0.0864*	0.116*	0.117*	0.157*	0.114*	0.127*	0.124*	0.125*	0.131*
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Area (km^2)	36,015	38,120	42,222	48,505	57,387	55,090	48,722	61,240	60,086	56,341	61,954
Land Reserve (km^2)	903,357	903,357	903,357	903,357	903,357	903,357	903,357	903,357	903,357	903,357	903,357
Pseudo R^2	0.538	0.515	0.511	0.490	0.475	0.457	0.475	0.452	0.476	0.476	0.462

* $p < 0.001$, Standard errors in parentheses

Table S4. Logistic Regression of Agricultural Extent: 2001 to 2011. Coefficients are reported as Odds Ratios (ORs). The ORs presented measure how much more likely the outcome land cover is to be found given a one unit increase in a predictor where all other predictors are at their means. Units for Minimum and Maximum Temperature are degrees Celsius. Units for Soil moisture and precipitation are millimeters, units for soy transportation cost is U.S.D. per ton soybeans, units for elevation are meters, and units for slope are degrees. All 15 soil classes in the state are represented as dummy variable controls. The presence of protected areas and indigenous reserves is indicates with binary variables.

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Minimum Temp.	0.0402*	0.0823*	0.0137*	0.0444*	0.0495*	0.0276*	0.0267*	0.0315*	0.0247*	0.0216*	0.0243*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Maximum Temp.	53.63*	26.39*	129.6*	38.64*	34.63*	74.49*	74.34*	64.84*	91.51*	107.6*	94.22*
	(6.42)	(1.09)	(18.17)	(1.21)	(1.12)	(2.16)	(2.12)	(9.98)	(14.39)	(18.19)	(2.41)
Soil Moisture	0.997*	0.997*	0.998*	0.999*	1.001*	0.998*	0.999*	0.999*	0.998*	0.998*	0.998*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Precipitation	1.006*	1.007*	1.006*	1.007*	0.999*	1.007*	1.008*	1.008*	1.008*	1.009*	1.008*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Elevation	1.001*	1.002*	1.001*	1.001*	1.007*	1.001*	1.001*	1.001*	1.001*	1.001*	1.001*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Slope	0.169*	0.155*	0.141*	0.154*	0.162*	0.154*	0.136*	0.152*	0.125*	0.114*	0.136*
	(0.01)	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)	(0.01)	(0.00)
Soy Transport Cost	0.949*	0.963*	0.966*	0.971*	0.970*	0.976*	0.975*	0.978*	0.982*	0.977*	0.983*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Upland Soils	29.59*	11.15*	6.901*	7.053*	6.769*	8.697*	11.83*	5.888*	11.18*	12.73*	7.177*
	(11.45)	(1.03)	(1.85)	(0.43)	(3.46)	(0.47)	(0.74)	(1.41)	(3.55)	(4.46)	(0.30)
Indigenous Reserves	0.00526*	0.00398*	0.00320*	0.00174*	0.00174*	0.00237*	0.00287*	0.00523*	0.00543*	0.00493*	0.00887*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Protected Areas	0.117*	0.201*	0.259*	0.263*	0.263*	0.334*	0.239*	0.211*	0.208*	0.233*	0.272*
	(0.02)	(0.02)	(0.03)	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.02)	(0.02)
Area (km^2)	4,911	8,560	11,898	17,022	14,901	20,965	23,342	31,409	32,038	28,759	30,559
Land Reserve (km^2)	903,357	903,357	903,357	903,357	903,357	903,357	903,357	903,357	903,357	903,357	903,357
Pseudo R^2	0.369	0.396	0.396	0.393	0.424	0.415	0.342	0.400	0.410	0.431	0.455

* $p < 0.001$, Standard errors in parentheses

Table S5. Logistic Regression of Double Cropping Extent: 2001 to 2011. Coefficients are reported as Odds Ratios (ORs). The ORs presented measure how much more likely the outcome land cover is to be found given a one unit increase in a predictor where all other predictors are at their means. Units for Minimum and Maximum Temperature are degrees Celsius. Units for Soil moisture and precipitation are millimeters, units for soy transportation cost is U.S.D. per ton soybeans, units for elevation are meters, and units for slope are degrees. All 15 soil classes in the state are represented as dummy variable controls. The presence of protected areas and indigenous reserves is indicates with binary variables

	2003	2004	2005	2006	2007	2008	2009	2010	2011
Minimum Temp.	0.170*	0.169*	0.122*	0.270*	0.181*	0.221*	0.231*	0.277*	0.283*
	(0.01)	(0.01)	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Maximum Temp.	9.481*	11.13*	17.12*	6.760*	11.51*	8.801*	8.480*	7.809*	8.712*
	(0.41)	(0.39)	(0.59)	(0.28)	(0.75)	(0.32)	(0.37)	(0.45)	(0.39)
Soil Moisture	1.00	1.00	1.00	0.999*	0.999*	1.000*	1.000*	0.999*	1.000*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Precipitation	1.007*	1.007*	1.007*	1.005*	1.006*	1.006*	1.006*	1.007*	1.007*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Elevation	1.000*	1.001*	1.000*	1.001*	1.001*	1.001*	1.001*	1.001*	1.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Slope	0.201*	0.269*	0.261*	0.309*	0.281*	0.362*	0.292*	0.244*	0.368*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.01)	(0.01)
Soy Transport Cost	0.979*	0.983*	0.988*	0.991*	0.995*	0.990*	0.994*	0.998*	0.996*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Upland Soils	2.598*	3.198*	3.711*	3.495*	2.945*	2.666*	3.110*	5.123*	3.559*
	(0.11)	(0.13)	(0.14)	(0.15)	(0.19)	(0.09)	(0.14)	(0.33)	(0.15)
Indigenous Reserves	0.00500*	0.0101*	0.0133*	0.0480*	0.0234*	0.0360*	0.0367*	0.0466*	0.0497*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Protected Areas	0.239*	0.247*	0.240*	0.318*	0.137*	0.183*	0.244*	0.261*	0.227*
	(0.02)	(0.02)	(0.02)	(0.03)	(0.03)	(0.02)	(0.02)	(0.03)	(0.02)
Area (km^2)	6,573	9,391	10,736	6,327	2,902	8,882	6,138	3,612	6,319
Land Reserve (km^2)	859,083	854,762	847,922	839,615	837,134	841,258	838,193	834,191	837,023
Pseudo R^2	0.220	0.202	0.197	0.134	0.140	0.147	0.147	0.147	0.132

* $p < 0.001$, Standard errors in parentheses

Table S6. Logistic Regression of New Cropland: 2003 to 2011. Coefficients are reported as Odds Ratios (ORs). The ORs presented measure how much more likely the outcome land cover is to be found given a one unit increase in a predictor where all other predictors are at their means. Units for Minimum and Maximum Temperature are degrees Celsius. Units for Soil moisture and precipitation are millimeters, units for soy transportation cost is U.S.D. per ton soybeans, units for elevation are meters, and units for slope are degrees. All 15 soil classes in the state are represented as dummy variable controls. The presence of protected areas and indigenous reserves is indicates with binary variables.

New Double Cropping

	2003	2004	2005	2006	2007	2008	2009	2010	2011
Minimum Temp.	0.0192*	0.0932*	0.109*	0.0646*	0.0678*	0.121*	0.0830*	0.198*	0.0986*
	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)
Maximum Temp.	80.42*	17.74*	16.18*	30.83*	29.81*	17.99*	32.63*	15.00*	23.12*
	(14.55)	(0.73)	(0.83)	(1.27)	(1.28)	(0.65)	(1.35)	(0.81)	(1.12)
Soil Moisture	0.999*	0.999*	0.999*	0.998*	0.999*	0.999*	0.998*	0.998*	0.999*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Precipitation	1.006*	1.007*	1.006*	1.007*	1.008*	1.007*	1.007*	1.009*	1.008*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Elevation	1.00	1.001*	1.002*	1.001*	1.001*	1.001*	1.002*	1.002*	1.001*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Slope	0.154*	0.180*	0.178*	0.188*	0.162*	0.196*	0.172*	0.133*	0.183*
	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Soy Transport Cost	0.972*	0.978*	0.984*	0.982*	0.981*	0.984*	0.990*	0.982*	0.989*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Upland Soils	7.514*	4.600*	5.159*	6.617*	8.693*	3.386*	5.513*	8.374*	4.621*
	(2.55)	(0.31)	(0.44)	(0.42)	(0.70)	(0.15)	(0.32)	(0.76)	(0.27)
Indigenous Reserves	0.00246*	0.00220*	0.00560*	0.00387*	0.00533*	0.0103*	0.0112*	0.0137*	0.0234*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Protected Areas	0.210*	0.245*	0.348*	0.281*	0.154*	0.206*	0.128*	0.171*	0.266*
	(0.03)	(0.03)	(0.04)	(0.03)	(0.02)	(0.02)	(0.02)	(0.02)	(0.03)
Area (km^2)	6171.91	7757.77	4311.68	6054.47	5092.22	6987.27	5009.37	2143.31	2808.61
Land Reserve (km^2)	889239.96	884531.55	878649.15	876837.56	874297.68	869570.43	863405.68	858787.51	860841.15
Pseudo R^2	0.347	0.331	0.287	0.285	0.330	0.283	0.270	0.325	0.249

* $p < 0.001$, Standard errors in parentheses

Table S7. Logistic Regression of New Double Cropping: 2003 to 2011. Coefficients are reported as Odds Ratios (ORs). The ORs presented measure how much more likely the outcome land cover is to be found given a one unit increase in a predictor where all other predictors are at their means. Units for Minimum and Maximum Temperature are degrees Celsius. Units for Soil moisture and precipitation are millimeters, units for soy transportation cost is U.S.D. per ton soybeans, units for elevation are meters, and units for slope are degrees. All 15 soil classes in the state are represented as dummy variable controls. The presence of protected areas and indigenous reserves is indicates with binary variables.

Abandoned Agriculture

	2002	2003	2004	2005	2006	2007	2008	2009	2010
Minimum Temp.	7.372*	5.659*	9.629*	6.006*	4.598*	6.451*	5.051*	7.886*	5.292*
	(3.09)	(0.38)	(4.28)	(0.32)	(0.19)	(0.29)	(2.27)	(0.34)	(0.24)
Maximum Temp.	0.180*	0.0930*	0.0441*	0.0666*	0.126*	0.0512*	0.25	0.0521*	0.0760*
	(0.08)	(0.01)	(0.02)	(0.00)	(0.01)	(0.00)	(0.12)	(0.00)	(0.00)
Soil Moisture	1.00	1.001*	1.00	1.001*	1.002*	1.002*	1.00	1.002*	1.001*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Precipitation	0.990*	0.991*	0.992*	0.993*	0.995*	0.992*	0.989*	0.993*	0.991*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Elevation	1.00	1.000*	1.00	0.999*	0.999*	0.999*	1.00	0.999*	1.000*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Slope	5.280*	4.496*	5.161*	4.697*	4.202*	3.990*	4.846*	5.235*	4.319*
	(1.09)	(0.13)	(1.11)	(0.12)	(0.08)	(0.08)	(1.06)	(0.11)	(0.10)
Soy Transport Cost	1.01	1.019*	1.025*	1.012*	1.007*	1.003*	1.01	1.003*	1.00
	(0.01)	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)
Upland Soils	0.29	0.288*	0.43	0.414*	0.532*	0.694*	0.512*	0.457*	0.486*
	(0.23)	(0.03)	(0.21)	(0.03)	(0.03)	(0.04)	(0.03)	(0.02)	(0.03)
Indigenous Reserves	8.327*	5.253*	4.715*	20.13*	3.650*	4.364*	2.728*	4.312*	10.98
	(2.58)	(1.21)	(0.81)	(2.61)	(0.49)	(0.60)	(0.33)	(0.59)	(11.49)
Protected Areas	5.458*	2.642*	1.872*	3.966*	2.461*	2.799*	2.69	7.25	7.88
	(1.36)	(0.43)	(0.24)	(0.45)	(0.30)	(0.40)	(10.13)	(7.77)	(9.21)
Area (km^2)	2,420	2,528	2,383	3,820	7,016	5,785	2,101	6,417	4,932
Potentially abandoned (km^2)	36,015	38,120	42,222	48,505	57,387	55,090	48,722	61,240	60,086
Pseudo R^2	0.263	0.222	0.279	0.202	0.140	0.187	0.269	0.225	0.173

* $p < 0.001$, Standard errors in parentheses

Table S8. Logistic Regression of Abandoned Cropland: 2002 to 2010. Coefficients are reported as Odds Ratios (ORs). The ORs presented measure how much more likely the outcome land cover is to be found given a one unit increase in a predictor where all other predictors are at their means. Units for Minimum and Maximum Temperature are degrees Celsius. Units for Soil moisture and precipitation are millimeters, units for soy transportation cost is U.S.D. per ton soybeans, units for elevation are meters, and units for slope are degrees. All 15 soil classes in the state are represented as dummy variable controls. The presence of protected areas and indigenous reserves is indicates with binary variables.

Abandoned Double Cropping

	2002	2003	2004	2005	2006	2007	2008	2009	2010
Minimum Temp.	16.93*	15.00*	7.783*	8.702*	8.618*	10.51*	7.659*	8.060*	7.753*
	(1.94)	(1.39)	(0.63)	(0.54)	(0.62)	(0.60)	(0.47)	(0.38)	(0.36)
Maximum Temp.	0.0475*	0.0733*	0.143*	0.0927*	0.104*	0.0827*	0.101*	0.0967*	0.133*
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.00)	(0.01)
Soil Moisture	1.002*	1.002*	1.001*	1.002*	1.002*	1.000*	1.002*	1.002*	1.002*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Precipitation	0.998*	0.999*	0.998*	0.997*	0.997*	0.997*	0.999*	0.997*	0.996*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Elevation	1.00	1.00	1.00	1.000*	1.001*	1.000*	1.000*	1.000*	1.000*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Slope	1.880*	2.112*	1.817*	2.225*	2.651*	2.040*	2.015*	2.694*	2.557*
	(0.09)	(0.07)	(0.05)	(0.05)	(0.08)	(0.05)	(0.05)	(0.05)	(0.05)
Soy Transport Cost	1.024*	1.017*	1.011*	1.005*	1.012*	1.014*	1.008*	1.004*	1.010*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Upland Soils	0.28	0.70	0.235*	0.326*	0.382*	0.579*	0.375*	0.294*	0.365*
	(0.14)	(0.13)	(0.05)	(0.05)	(0.06)	(0.07)	(0.05)	(0.02)	(0.03)
Indigenous Reserves	0.92	1.20	3.58	4.69	3.21	7.689*	1.70	3.391*	2.956*
	(0.57)	(0.70)	(1.88)	(2.97)	(1.45)	(2.93)	(0.54)	(0.71)	(0.57)
Protected Areas	0.85	0.256*	0.45	0.368*	0.80	1.47	1.40	0.96	0.58
	(0.38)	(0.09)	(0.12)	(0.08)	(0.15)	(0.21)	(0.23)	(0.14)	(0.11)
Area (km^2)	1,461	2,382	3,287	5,472	3,289	4,231	3,527	6,756	6,844
Potentially abandoned (km^2)	4,911	8,560	11,898	17,022	14,901	20,965	23,342	31,409	32,038
Pseudo R^2	0.096	0.088	0.051	0.073	0.092	0.085	0.063	0.101	0.086

* $p < 0.001$, Standard errors in parentheses

Table S9. Logistic Regression of Abandoned Double Cropping: 2002 to 2010. Coefficients are reported as Odds Ratios (ORs). The ORs presented measure how much more likely the outcome land cover is to be found given a one unit increase in a predictor where all other predictors are at their means. Units for Minimum and Maximum Temperature are degrees Celsius. Units for Soil moisture and precipitation are millimeters, units for soy transportation cost is U.S.D. per ton soybeans, units for elevation are meters, and units for slope are degrees. All 15 soil classes in the state are represented as dummy variable controls. The presence of protected areas and indigenous reserves is indicates with binary variables.

C. Supplementary References

Adami, M., Mello, M. P., Aguiar, D. A., Rudorff, B. F. T., & Souza, A. F. d. (2012). A Web Platform Development to Perform Thematic Accuracy Assessment of Sugarcane Mapping in South-Central Brazil. *Remote Sensing, 4*(12), 3201-3214.

Arvor, D., Jonathan, M., Penello Meirelles, M. S., Dubreuil, V., & Durieux, L. (2011). Classification of MODIS EVI time series for crop mapping in the state of Mato Grosso, Brazil. *International Journal of Remote Sensing, 32*(22), 7847-7871.

Brazilian Institute of Geography and Statistics. (2013a). 2006 Agricultural Census. *IBGE System of Automatic Data Access* Retrieved 9/5, 2013, from http://www.sidra.ibge.gov.br/bda/acervo/acervo2.asp

Brazilian Institute of Geography and Statistics. (2013b). Municipality Agricultural Data Report (PAM). *IBGE System of Automatic Data Access* Retrieved 9/5, 2013, from http://www.sidra.ibge.gov.br/bda/acervo/acervo2.asp

Brazilian Institute of Geography and Statistics. (2013c). Sistema IBGE de Recuperação Automática - SIDRA. Retrieved 9/5, 2013, from http://www.sidra.ibge.gov.br/bda/tabela/listabl.asp?z=t&o=11&i=P&c=1613

Brown, J. C., Kastens, J. H., Coutinho, A. C., Victoria, D. d. C., & Bishop, C. R. (2013). Classifying multiyear agricultural land use data from Mato Grosso using time-series MODIS vegetation index data. *Remote Sensing of Environment, 130*, 39-50.

Dorigo, W. A., Zurita-Milla, R., de Wit, A. J. W., Brazile, J., Singh, R., & Schaepman, M. E. (2007). A review on reflective remote sensing and data assimilation techniques for enhanced agroecosystem modeling. *International Journal of Applied Earth Observation and Geoinformation, 9*(2), 165-193.

Fan, Y., & van den Dool, H. (2004). Climate Prediction Center global monthly soil moisture data set at 0.5 resolution for 1948 to present. *Journal of Geophysical Research: Atmospheres (1984–2012), 109*(D10).

Freitas, R. M. (2011). Virtual laboratory of remote sensing time series: visualization of MODIS EVI2 data set over South America. *Journal of Computational Interdisciplinary Sciences, 2*(1).

Galford, G. L., Mustard, J. F., Melillo, J., Gendrin, A., Cerri, C. C., & Cerri, C. E. (2008). Wavelet analysis of MODIS time series to detect expansion and intensification of row-crop agriculture in Brazil. *Remote Sensing of Environment, 112*(2), 576-587.

Huete, A., Didan, K., Miura, T., Rodriguez, E. P., Gao, X., & Ferreira, L. G. (2002). Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment, 83*(1–2), 195-213.

Mato Grosso State Secretary of Planning. (2013). Road Network Map.   Retrieved 9/5, 2013, from http://www.siigeo.mt.gov.br/SIIGEO/flex/BasisTemplate.html

New, M., Lister, D., Hulme, M., & Makin, I. (2002). A high-resolution data set of surface climate over global land areas. *Climate research, 21*(1), 1-25.

Rudorff, B., Aguiar, D., Silva, W., Sugawara, L., Adami, M., & Moreira, M. (2010). Studies on the Rapid Expansion of Sugarcane for Ethanol Production in São Paulo State (Brazil) Using Landsat Data. *Remote Sensing, 2*(4), 1057-1076.

United States Department of Agriculture Foreign Agricultural Service. (2012). Record Soybean and Corn Area Expected for Brazil's Upcoming 2012/13 Season *Commodity Intelligence Report* Retrieved 9/5, 2013, from http://www.pecad.fas.usda.gov/highlights/2012/08/Sinop_Brazil/

Van Zyl, J. J. (2001). The Shuttle Radar Topography Mission (SRTM): a breakthrough in remote sensing of topography. *Acta Astronautica, 48*(5), 559-565.

CHAPTER 2

Land-Use Change Affects Water Recycling in Brazil's Last Agricultural Frontier

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ABSTRACT

Historically, conservation-oriented research and policy in Brazil have focused on Amazon deforestation, but a majority of Brazil's deforestation and agricultural expansion has occurred in the neighboring Cerrado biome, a biodiversity hotspot comprised of dry forests, woodland savannas, and grasslands. Resilience of rainfed agriculture in both biomes likely depends on water recycling in undisturbed Cerrado vegetation; yet little is known about how changes in land-use and land-cover affect regional climate feedbacks in the Cerrado. We used remote sensing techniques to map land-use change across the Cerrado from 2003-2013. During this period, cropland agriculture more than doubled in area from 1.2 to 2.5 million ha, with 74% of new croplands sourced from previously intact Cerrado vegetation. We find that these changes have decreased the amount of water recycled to the atmosphere via evapotranspiration (ET) each year. In 2013 alone, cropland areas recycled 14 km^3 less (-3%) water than if the land cover had been native Cerrado vegetation. ET from single-cropping systems (e.g., soybeans) is less than from natural vegetation in all years, except in the months of January and February, the height of the growing season. In double-cropping systems (e.g., soybeans followed by corn), ET is similar to or greater than natural vegetation throughout a majority of the wet season (December – May). As intensification and extensification of agricultural production continue in the region, the impacts on the water cycle and opportunities for mitigation warrant consideration. For example, if an environmental goal is to minimize impacts on the water cycle, double-

cropping (intensification) might be emphasized over extensification to maintain a landscape that behaves more akin to the natural system.

Keywords: Cerrado, evapotranspiration, land-use change, deforestation, Matopiba, agriculture, remote sensing

INTRODUCTION

Over the past four decades, the Cerrado has undergone a transition from a sparsely inhabited region with native dry forests, shrublands, and grasslands to an agricultural powerhouse. Increased deforestation governance in the Brazilian Amazon's tropical forest and land scarcity in older frontier regions have led both farmers, states, and the federal government to seek out new areas for development (Branstromm et al. 2008, Barretto et al. 2013, MAPA 2015a, Embrapa 2016). The northeast Cerrado has been developing as an agricultural frontier since the early 2000s, and on May 6, 2015, Brazilian Decree no. 8447 officially committed government support to developing the "Matopiba" region. Matopiba, Brazil's newest — and potentially final — agricultural frontier, is so named because its 337 municipalities span the states of Maranhão (MA), Tocantins (TO), southern Piauí (PI), and western Bahia (BA).

Over 90% of Matopiba lies within the Cerrado biome, and the states of Tocantins and Maranhão also reside within Brazil's Legal Amazon, a political designation of the Amazon watershed (Fig. 1). Unlike most of the Cerrado, Matopiba does not have a history of large-scale cattle ranching. As a result, cropland expansion in Matopiba is advancing primarily through clearing native vegetation rather than by using previously cleared pasturelands. Compared to the better-known Amazon, the Cerrado has less stringent environmental regulations that govern forested areas on private properties. The Brazilian Forest Code specifies conservation regulations according to vegetation types and location within legal boundaries. Landowners in the Amazon biome must set aside 80% of their property as a forested "legal reserve." Landowners in the Cerrado biome, however, must set aside a minimum of only 20% of their property as a legal reserve, unless their property falls within the Legal Amazon (Fig. 1), where the required legal reserve increases to 35%. Moreover, only 3% of the biome is legally sheltered by strictly protected areas (Françoso *et al.* 2015). Of the Cerrado's native vegetation, 40-55% has already been cleared (Klink & Machado 2005, Sano *et al.* 2010). Nearly half of Brazil's agro-pastoral land is cultivated in the Cerrado (IBGE 2015) with high rates of clearing in recent years, mostly in Matopiba (Fig. 2) (LAPIG 2015).

As Cerrado vegetation is cleared, fragmented, and replaced with croplands, the water balance is modified as water leaves the system through runoff and ground water rather than being recycled as evapotranspiration (ET). The Cerrado is characterized by distinct wet and dry seasons; nearly 90% of mean annual precipitation falls between October and April (Klink and Machado, 2005). Air masses moving westward over the Cerrado transport evapotranspired water over the Amazon Basin, where it contributes to rainfall (Spracklen *et al.* 2012). Large-scale deforestation of the Cerrado has the potential to reduce the amount of rainwater that reaches the Amazon (Malhado *et al.* 2011). Models suggest that deforestation of the Amazon and Cerrado may increase Cerrado dry season length by up to a month (Costa & Pires 2010, Yin *et al*. 2014).

Moreover, climate modeling experiments have shown that preserving remnant Cerrado is essential to climate stability in this region and in the Amazon downwind (Biggs *et al.* 2006, Malhado *et al,* 2010, Pires & Costa 2013, Coe *et al.* 2013). Feedbacks between land-cover changes and climate have the potential to reduce precipitation, increase precipitation variability, and ultimately threaten the sustainability of agricultural production in both the Cerrado and the Amazon (Nobre et al. 1991, Wang et al. 2008, Malhado *et al.* 2010, Butt et al. 2011, Spracklen et al. 2012, Lee *et al.* 2012, Oliveira *et al*. 2013, Knox *et al*. 2015).

Given the importance of land-cover changes to regional rainfall and future agricultural production, there is a need for accurate information about the spatial distribution of agropastoral lands, historic land-use transitions, and the different pools of land potentially available for further expansion and intensification (Lambin *et al.* 2000). In this study, we use remotely sensed datasets to map annual land-use and land-cover changes across the Cerrado from 2003-2013. Our results include the first documentation of the spatiotemporal distribution of row-crop agriculture across the Cerrado, including soy, corn, cotton, and sugarcane. We determine the impacts of agricultural conversion in Matopiba on regional ET, including the impacts of crop management choices, and discuss policy implications.

MATERIALS AND METHODS

Mapping Land-cover Change

Baseline Cerrado land cover was defined by the 2002 Project for the Conservation and Sustainable Use of Brazilian Biological Diversity (PROBIO) (MMA 2007; Sano *et al*.

2010), derived from 30 m resolution Landsat data. Its 15 land cover categories were condensed into five: Cerrado, pasture, agriculture, water, and other (urban and mining).

We used satellite remote sensing data to map annual land cover across Matopiba. The Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra satellite produces image composites at a high temporal frequency, allowing us to exploit phenological thresholds to discriminate among land covers. All MODIS (MOD13Q1) Enhanced Vegetation Index (EVI), day of year (DOY), and VI Quality 16-day, 250 m resolution data composited between August 2002 and July 2013 were used. We define a growing season as beginning in August and ending in July: the data used to analyze the 2003 growing season span August 1, 2002 – July 31, 2003. A published decision-tree algorithm (Spera *et al.* 2014) was modified to incorporate crop cycles and calendars for the states of Tocantins, Goiás, Maranhão, western Bahia, and southern Piauí (MAPA 2015b). The modified Spera et al. (2014) algorithm adds single-cropped corn as a crop class, as it is common in Matopiba. We identified expansion of agriculture and intensification by differentiating among (a) single-cropping (a single rotation of soy, corn, or cotton within one growing season); (b) double-cropping (a soy-corn or soy-cotton rotation within one growing season); and (c) irrigated agriculture. This algorithm uses metrics that include growing season EVI standard deviation, minima and maxima; it derives green-up and harvest dates to differentiate natural vegetation from croplands. Due to the 250 m spatial resolution of the data, we mapped only agricultural fields greater than 25 ha. Because 25 ha is below the average farm size of row crops in the region (Rally da Safra 2015), we consider our cropland estimates to be relatively conservative.

We mapped annual croplands across 45 million ha of Matopiba (Fig 1). Although our study region comprises only 65% of the legal Matopiba region, these 45 million ha account for 80% of the planted area of annual crops during our study period and 88% of the planted areas of soy, corn, and cotton in 2013 (IBGE, 2015). The results of our algorithm were validated using 883 validation points collected across the Cerrado over the study period using the Landsat data repository within Google Earth Engine. Compositing false-color Landsat 5 and 7 images (NIR Band 4 as red, SWIR1 Band 5 as green, red Band 3 as blue) from the growing season permitted visual identification and separation of corn, soy, cotton, pasture, and natural vegetation land covers (Spera et al. 2014). Across the study region, annual agriculture was distinguished from natural vegetation and pasture with 95% accuracy (STable 1), and crop types were separated with 87% accuracy (STable 2 and SFig. 2). Because pasture and sugarcane are difficult to separate using the phenological signal from a single growing season, we integrated previously published (spatially explicit) sugarcane data (Canasat: Rudorff *et al.* 2010) into our land-cover maps. Finally, we used annual spatial data of Cerrado deforestation from the Integrated Deforestation Warning System (SIAD) to determine the total area of natural vegetation cleared in the biome after 2002 (LAPIG 2015). See Supplementary Materials for additional details.

Evapotranspiration Analysis

The MODIS MOD16A2 data product (Mu et al. 2011) provided estimates of ET. Our analysis relied on the monthly one km resolution ET time series for the period covering August 2001 to July 2013, available from the University of Montana's Numerical Terradynamic Simulation Group (http://ntsg.umt.edu/project/mod16). The MODIS ET data product is an estimate of total plant transpiration, wet canopy evaporation, and soil evaporation derived from application of the Penman-Monteith equation (Mu et al. 2013). The derived product relies on NASA's Global Modeling and Assimilation Office daily meteorological reanalysis data, as well as the MODIS albedo leaf area index (LAI), the fraction of absorbed photosynthetically active radiation (fPAR), and land cover datasets (Mu et al. 2013).

Comparative analyses were performed using ArcGIS 10.2. To compare ET over different land covers for each month in each year, we calculated the average ET over areas classified as croplands (by our algorithm) and Cerrado (by the 2002 PROBIO map), excluding areas that were cleared during out study period (as identified by SIAD).

We also tested the statistical significance of the relationship between crop management regime and monthly ET. We performed multivariate linear regressions at the 0.0625-degree grid cell resolution. Tropical Rainfall Measuring Mission data (TRMM 3B42 V7) were downloaded from the Goddard Distributed Active Archive Center and resampled to 0.0625 degrees. Climatic Research Unit monthly average temperature data (New *et al*. 2002), gridded at 0.5 degrees, were downloaded from http://www.cru.uae.ac.uk/cru/data/hrg/ and then resampled to 0.0625 degrees. We tested and accounted for spatial autocorrelation following the methods of Cohn et al.

(2016). Every variable exhibited spatial autocorrelation. Thus we determined the radius of correlation for each variable using semivariograms (SFig 10), and generated a neighborhood variable for each original variable. Monthly ET was regressed against precipitation, temperature, a precipitation-temperature interaction term, the fraction of single-cropping and double-cropping, and the ET, precipitation, temperature, and agriculture neighborhood variables in each 0.0625 degree grid cell. This was done for every month of our study period, using robust standard errors to account for heteroscedasticity. StataCorp's Stata Statistical Software 13 was used to perform these multivariate statistical analyses.

To determine the effects of land-use change on the regional water cycle, we estimated ET as if there had been no land-use changes since 2002. We compared the MODIS monthly composite ET values (ET_{LUC}) to hypothetical ET surfaces (ET_{NOLUC}). To obtain monthly ET_{NOLUC} surfaces, 50,000 points were randomly distributed across the study region using the Create Random Points tool of ArcGIS 10.2 to perform regularized spline interpolation with a weight of 10 and minimum of five neighbors. These 50,000 points were distributed across natural vegetation that had neither been converted to agriculture (as identified by our algorithm) nor cleared (as identified by SIAD). Each was required to be at least one km from any area that had undergone a land-change transition or from another interpolation point. We then interpolated those ET values across a one km raster grid for every month of each year. By using month-year values to create monthly ET_{NOLUC} surfaces, we controlled for interannual variability in weather, thus capturing the changes in ET due to land-use change alone. To calculate the monthly

ET due to all land-use change that occurred before August 2002, we subtracted the ET_{NOLUC} surface from the ET_{LUC} surface for each month between August 2001 and July 2002.

Uncertainty

The MODIS data show an increasing trend in ET through the region during our study period, whereas precipitation, temperature, and water storage level exhibited no such trend (SFig11). To rule out the possibility that this increasing trend was an artifact of the derived data product, we performed non-parametric Pettitt tests to determine if a significant change-point existed in the dataset (Pettitt 1980) (See SI). We also analyzed historical streamflow data downloaded from the Brazilian National Water Agency for rivers in our study region. Of the 18 rivers in our study region with daily streamflow data available during our study period, 14 showed decreasing trends in discharge (SFig 13). Decreasing river discharge would be consistent with increasing ET rates assuming no change in precipitation or water storage. Moreover, the eight-day ET data product has been validated using ET estimates from eddy flux towers at 232 watersheds worldwide (Mu et al. 2013). The MODIS land cover input has been cited as the largest source of error (Ruhoff et al. 2013); and the eight-day ET data consistently provide underestimates of ET (Ruhoff et al. 2013). However, the data show good agreement with measured ET when aggregated at monthly time scales (Ruhoff et al. 2013), lending confidence that the monthly MODIS ET data are robust enough for analysis of the ET dynamics from land-use change.

To test for the robustness of our interpolated surfaces, we compared the average ET between both surfaces in areas that had not experienced any land-use change over our study period. The resulting interpolated ET fields were in good agreement for locations that had not experienced change. The mean monthly ET of areas that experienced no land-use change in the original dataset was 714 mm. The mean reconstructed ET in areas of no land-use change differed from the original dataset by only 0.015 mm (less than 1%), with a standard deviation of 0.024 mm and a maximum difference of 0.24 mm (less than 1%) occurring in September of 2010.

We have excluded pasturelands from our analysis. Pasturelands are difficult to distinguish from Cerrado vegetation using moderate resolution satellite data because the two land covers exhibit similar phenologies. Moreover, pasture condition (e.g. degree of degradation) varies widely within the study area, which likely affects evapotranspiration. Spatially explicit pasture data that include pasture condition would enable a more detailed analysis.

RESULTS

Large-scale Land-use Change

In 2003, land cover in Matopiba was largely Cerrado (82%); less than 20% was cultivated (12% pasture, 5% cropland), while water, urban, and mining areas comprised 1% of the region. Between 2003 and 2013, aggregate cropland area almost doubled from 1.3 ha to 2.5 million ha (Table 1), and an additional one million ha had been converted and later left fallow or used for other purposes over the decade. During this period, row-crop agriculture was predominantly single-cropped (91%), with 61% of all agricultural land cultivated with single-cropped soybean rotation. Seventy-four percent of the 2.3 million ha converted to cropland during the study period was drawn from indigenous Cerrado vegetation, while the remaining areas were converted from previously cleared pasturelands (SFig 6). Within our study region, Piauí experienced the most rapid rate of expansion: total area in cropland almost quadrupled from 120,000 ha to nearly 450,000 ha. Maranhão's cropland area nearly doubled to 450,000 ha. Tocantins increased its area nearly threefold to 270,000 ha. And in western Bahia, the oldest established agricultural region among the four states, croplands expanded from 820,000 ha to 1.4 million ha. By 2013, nearly 375,000 ha of Matopiba were cultivated with an intensive double-cropping rotation (planting two crops in the same growing season), which represented an increase in this cultivation regime greater than eightfold (Table 1). Less than two percent of the cropland in Matopiba was irrigated and these areas were concentrated in Bahia and Tocantins (Table 1).

Evapotranspiration in Matopiba

Our analysis of the TRMM rainfall product shows that annual precipitation for the Matopiba region averaged 1460 mm yr^{-1} during our study period, and ranged from 1000 mm yr^{1} in western Bahia and Piauí to 2000 mm yr^{-1} in western Tocantins (SFig. 7). MODIS ET estimated annual ET rates that ranged from ~570 to ~1025 mm yr^{-1} and averaged ~790 mm yr^{-1}. These results fall within previously reported ranges of annual Cerrado ET and precipitation (Oliveira *et al.* 2014). ET over all lands that remained as intact Cerrado vegetation for the entirety of the study period averaged 904 mm yr^{-1}, while ET over single-cropping rotations averaged 661 mm yr^{-1}, and over double-cropping rotations the average was 805 mm yr^{-1}.

There was a general annual increase in ET from both Cerrado and row-crop land covers over the period of study (Fig. 3), which agrees with increasing trends over the region previously published (Zeng et al. 2012, Oliveira et al. 2014). During 2003, native vegetation transpired 800 mm of water per unit area, while croplands transpired approximately 510 mm (64% that of Cerrado). By 2013, native Cerrado ET was about 950 mm per unit area, while cropland ET rates were about 83% of that (800 mm). Although ET rates increased over both land covers, the annual increase in ET rate over cropland (38.6 mm yr^{-1}) was 11 mm yr^{-1} greater than that over natural vegetation (27.5 mm yr^{-1}) (Fig 3). The percentage difference in average ET between cropland and native Cerrado decreased over time, from -57% in 2003 to -18% in 2013 (Fig. 3).

ET differences between cropland and Cerrado were not evenly distributed throughout the year. ET rates over cropland during the dry season (May – September) were strongly negative (average ~60% lower than those over natural vegetation), with the biggest difference between these two land covers (-77%) occurring in September (Fig 4a). During the peak growing season in January and February when crops grow vigorously, ET occurred at similar (~100%) or slightly higher rates (~107%) over croplands (Fig. 4a). Consistent with previous research on soy fields in eastern Mato Grosso, our results demonstrate ET rates between row-crop agriculture are greatest (and negative) during the dry season, while there exist minimal differences during the wet season, (Lathuilliere *et al.* 2012, Oliveira *et al.* 2014, Panday *et al.* 2015).

Single-cropping and double-cropping rotations also have unique seasonal ET signals. Single-cropping rotations had ET rates similar to that of Cerrado only in January and February. Double-cropping rotations, however, had higher ET rates than single-cropping rotations for all months of the growing season (average 128%), and similar to higher ET rates than natural vegetation from January through May (Fig 4b), as a second crop extends transpiration. The relationships between cropping regime and ET rate are statistically significant across the growing season (Table 2, STables 3-14).

Differences in ET between cropland and Cerrado can be quantified volumetrically. Expansion of row-crop agriculture in Matopiba between 2003 and 2013 accounted for a loss of 3 km^3 of water. Comparison of ET_{LUC} and ET_{NOLUC} shows that in 2003, 11 km^3 more water would have been recycled into the atmosphere had no land-use change occurred (SFig. 8). By 2013, this figure increased to 14 km^3 (SFig. 8). The regions converted directly from Cerrado to cropland accounted for a 1.53 km^3 decrease in ET between 2003 and 2013. This equates to more than a seventh of the total change in ET due to pre-2003 land-use changes (Fig. 5).

DISCUSSION AND CONCLUDING REMARKS

Cropland area has expanded rapidly and continues to do so in Matopiba. Between 2003 and 2013, over 2.3 million ha of land were newly cultivated, and a majority were cleared from natural Cerrado. Among other environmental consequences, these large-scale land-cover changes have affected the water balance in the region.

Our results indicate significantly different seasonal trends in ET between natural vegetation and row-crop agriculture. We found that cropland ET (regardless of management regime) is similar to or greater during the growing season (January and February) when compared to the Cerrado's vegetation. This is contrary to the result found when ET over soy fields in the southern Amazon was compared to forest vegetation (Panday et al. 2015), and is consistent with the higher LAI and photosynthetic and transpiration rates of native Amazon forests compared to Cerrado land-cover types.

Both single- and double-cropping rotations, however, show decreased ET during the dry season and the transition to rainy season when compared to native vegetation. There is little to no rainfall during the dry months, and soil evaporation over fallow cropland is limited. The deep roots of Cerrado vegetation can acquire water below 10 m soil depth and permit continued deep-water access and transpiration throughout the dry season over this land cover (Oliveira et al. 2005, Garcia-Monteil et al., 2008; Costa and Pires 2010). Moreover, changes in the amount of water recycled back to the atmosphere are linearly related to changes in natural land cover ($R^2 = 0.81$); for every 1,000,000 ha of Cerrado converted to croplands, dry season ET is reduced by 1.7 km^3 (Fig 6). With the present climate, if cultivated area expanded by 2.7 million ha, as projected by the government (MAPA 2015a), we estimate an additional annual reduction of 4.59 km^3 (-13%) of water each year during the three dry season months alone.

Modeling exercises have shown that limiting transpiration can lead to increased precipitation variability (Lee et al. 2012), and that less evapotranspiration during the dry season can delay the onset of the rainy season (Costa and Pires 2010, Lee et al. 2012), thus shortening the long, stable wet season needed to double crop. Further, although deforested areas are prone to more active shallow atmospheric convection than intact forests, intact forests have greater overall convective available potential energy, and are the source for deeper clouds and rainfall (Wang et al. 2009). In the Amazon, between 24% and 56% of ET is recycled into precipitation (Elathir & Bras 1994, Costa & Foley 1999). For lack of Cerrado-specific estimates, and assuming the recycling rate is similar, our estimated 14 km^3 decrease in ET due to land-use changes could result in an annual rainfall reduction on the order of 8-16 mm m^{-2} (-3%) in Matopiba. It should be noted that it remains unclear how the obvious seasonal differences in ET between cropland and Cerrado (-150% during the dry season), compared to the decreasing annual differences in ET over the two land covers (only -18% in 2013) will affect the onset or stability of the rainy season in the region. Coupling the high-resolution annual land-cover data used in this study with climate modeling can provide a better understanding of the physical mechanisms and causal relationships that result in these environmental changes, and presents an avenue for future work.

Our results also indicate important interannual differences in land-cover and evapotranspiration dynamics in the Cerrado. The difference in the annual average ET between row-crop agriculture and natural vegetation decreased over the decade of observation from a difference of –57% (291 mm yr^{-1}) between crops and native vegetation in 2003 to a –18% difference (144 mm yr^{-1}) in 2013 (Fig. 3). This 39% decrease in ET between crops and native vegetation is in part due to an increase in double-cropping in the region. Double-cropping extends the growing season by three to four months compared to single cropping, and prolongs the period of high ET. If the 455 km^2 of land (3% of total cropland) that was double-cropped in 2003 had remained single-cropped, the difference between cropland and natural vegetation would have increased from -57% to -58% (296 mm yr^{-1}). Double-cropping rotations were accountable for a 2% increase in 2003. By 2013, double-cropping area had increased to 3723 km^2 (26.5% of total cropland). If these croplands had remained in a single-cropping rotation, the percent difference between cropland and natural vegetation would have increased from –18% to –24% (186 mm yr^{-1}). Thus, by 2013, double-cropping rotations reduced the percent difference between cropland and natural vegetation by 25%. Double-cropping, then, accounted for over half of the total decrease in ET differences between cropland and Cerrado between 2003 and 2013. If we assume that the remainder of this decreased difference is due to climate variability, these results indicate that management decisions are of the same order of magnitude as natural variability.

Our results demonstrate that widespread adoption of double cropping may be a way to minimize the impacts of deforestation on the hydrologic cycle. Again, using the mean annual ET rates as estimates, if the 2.5 million ha of cropland in Matopiba were all double cropped, annual ET over the region would decrease by only 11% compared to native Cerrado (from 22.5 km^3 if all areas were natural Cerrado to 20 km^3 with double cropping), whereas ET would decrease by 26% if all agricultural areas were single-cropped (to 16.5 km^3). Embrapa (the Brazilian Agricultural Research Corporation) has already developed a Matopiba-adapted soybean cultivar that matures in only 110 days, thereby helping facilitate the widespread cultivation of two crops (often soy followed by corn) in one growing season.

The Cerrado has been the focus of intensive agricultural expansion over the last four decades. This has resulted in extensive land-cover transformations and significant changes to the water cycle. Furthermore, only 7% of the Cerrado is legally protected and there are at least 40 million hectares of land available for legal deforestation (Soares-Filho et al. 2014), making continued exploitation of this region, rather than the much more protected Amazon, likely in the coming decades. Understanding how land-use changes affect the regional water balance and how management strategies such as intensification may mitigate some of those changes could prove crucial in developing policies that ensure sustainable agricultural development.

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REFERENCES

Biggs TW, Dunne T, Muroaka, T (2006) Transport of water, solutes, and nutrients from a hillslope, southwestern Brazilian Amazon. Hydrological Processes, 20, 2427-2547.

Branstromm C, et al. (2008) Land change in the Brazilian Savanna (Cerrado), 1986-2002: Comparative analysis and implications for land-use. Land Use Policy, 25, 579-595.

Butt N, De Oliveira PA, Costa MH (2011) Evidence that deforestation affects the onset of the rainy season in Rondonia, Brazil. Journal of Geophysical Research: Atmospheres, 116, D11.

Coe MT, Costa MH, Soares-Filho BS (2009) The influence of historical and potential future deforestation on the stream flow of the Amazon River – Land surface processes and atmospheric feedbacks. Journal of Hydrology, 369, 165–174.

Coe MT, Latrubesse EM, Ferreira ME, Amsler ML (2011) The effects of deforestation and climate variability on the streamflow of the Araguaia River, Brazil. Biogeochemistry, 105,119–131.

Coe MT, et al. (2013) Deforestation and climate feedbacks threaten the ecological integrity of south–southeastern Amazonia. Philosophical Transactions of the Royal Society of London B: Biological Sciences, 368, 20120155.

Cohn A, Gil JDB, Toledo C, Berger T (minor revisions requested) Patterns and processes of pasture to crop conversion in Brazil: Evidence from Mato Grosso State. Land Use Policy.

Costa MH, Foley JA (1999) Trends in the hydrologic cycle of the Amazon Basin. Journal of Geophysical Research, 104, 14189–14198.

Costa MH, Botta A, Cardille JA (2003) Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. Journal of Hydrology, 283, 206–217.

Costa MH, Pires GF (2010) Effects of Amazon and Central Brazil deforestation scenarios on the duration of the dry season in the arc of deforestation. International Journal of Climatology, 30, 1970–1979.

Davidson E.A. et al. (2012) The Amazon Basin in Transition. Nature, 481, 321-328.

Dias LCP, Macedo MN, Costa MT, Coe MT, Neill C (2015) Effects of land cover change on evapotranspiration and streamflow of small catchment in Upper Xingu River Basin, Central Brazil. Journal of Hydrology: Regional Studies 4, Part B, 108-122.

Eltahir E a. B, Bras RL (1994) Precipitation recycling in the Amazon basin. Quarterly Journal of the Royal Meteorological Soceity, 120, 861–880.

Embrapa (Brazilian Agricultural Research Corporation) (2015) MATOPIBA: Delimitacao, Caracterizacao, Desafios e Oportunidades para o Desenvolvimento – BAHIA
www.embrapa.br/gite/projectos/matopiba/matopiba.html

Embrapa (Brazilian Agricultural Research Corporation) (2016) Matopiba www.embrapa.br/en/tema-matopiba

Françoso RD, et al. (2015) Habitat loss and the effectiveness of protected areas in the Cerrado Biodiversity Hotspot. Natureza & Conservação, 13, 35–40.

Garcia-Montiel, DC, et al. (2008) Estimating seasonal changes in volumetric soil water content at landscape scales in a savanna ecosystem using two-dimensional resistivity profiling. Earth Interactions, 12, 1-25.

Hayhoe SJ, et al. (2011) Conversion to soy on the Amazonian agricultural frontier increases streamflow without affecting stormflow dynamics. Global Change Biology, 17, 1821–1833.

Hecht SB (2005) Soybeans, Development and Conservation on the Amazon Frontier. Development and Change, 36, 375-404.

Hoffmann WA, Jackson RB (2000) Vegetation–Climate Feedbacks in the Conversion of Tropical Savanna to Grassland. Journal of Climate 13, 1593–1602.

IBGE (Brazilian Institute of Geography and Statistics) (2015) Area Plantada/Colhida, http://www.sidra.ibge.gov/br/bda/agric

Klink CA, Machado RB (2005) Conservation of the Brazilian Cerrado. Conservation Biology, 19, 707–713.

Lambin E., Rounsevell MD., Geist H. (2000) Are agricultural land-use models able to predict changes in land-use intensity? Agriculture, Ecosystems & Environment, 82, 321–331.

LAPIG (Laboratóorio de Processamento de Imagens e Geoprocessamento) (2015) SIAD-Cerrado. www.lapig.iesa.ufg.br/lapig/index.php/produtos/lapig-maps

Lathuillière MJ, Johnson MS, Donner SD (2012) Water use by terrestrial ecosystems: temporal variability in rainforest and agricultural contributions to evapotranspiration in Mato Grosso, Brazil. Environmental Research Letters, 2, 024024.

Lee J.E., et al. (2012) Reduction of tropical land region precipitation variability via transpiration. Geophysical Research Letters, 39, L19704.

MAPA (Ministério da Agricultura, Pecuária e Abastecimento) (2015a) Projeções do Agronegócio: Brasil 2014/15 a 2024/25 Projeçoes de Longo Prazo.

MAPA (Ministério da Agricultura, Pecuária e Abastecimento) (2015b) Calendario de Plantio 2015.

Malhado ACM, Pires GF, Costa MH (2010) Cerrado Conservation is Essential to Protect the Amazon Rainforest. AMBIO, 39, 580–584.

MMA (Minesterio do Meio Ambiente) (2007) Projecto de Conservacao e Utilizacao Sustenavel da Diversidade Biologica http://mapaps.mma.gov.br.mapas/aplic/probop/datadownload.htm?/

Mu Q, Zhao M, Running S (2011) Improvements to a MODIS global terrestrial evapotranspiration algorithm. Remote Sensing of Environment, 2011, 1781-1800.

Mu Q, Zhao M, Running S (2013) Algorithm Theoretical Basis Document: MODIS Terrestrial Evapotranspiration (ET) Product (NASA MOD16A2/A3) Collection 5. Nasa Headquarters.

New M, Lister D, Hulme M, Makin I (2002) A high-resolution data set of surface climate over global land areas. Climate Research, 21, 1-25.

Nobre CA, Sellers PJ, Shukla J (1991) Amazonia deforestation and regional climate Change. Journal of Climate, 4, 957-988

Oliveira RS, Bezerra L, Davidson EA, Pinto F, Klink CA, Nepstad DC, Moreira A (2005) Deep root function in soil water dynamics in cerrado savannas of central Brazil. Functionary Ecology, 19, 574-581,

Oliveira LJC, Costa MH, Soares-Filho BS, Coe MT (2013) Large-scale expansion of agriculture in Amazonia may be a no-win scenario. Environmental Research Letters, 8, 024021.

Oliveira PTS, et al. (2014) Trends in water balance components across the Brazilian Cerrado. Water Resources Research, 50, 7100-7114.

Panday PK, Coe MT, Macedo MN, Lefebvre P, Castanho AD de A (2015) Deforestation offsets water balance changes due to climate variability in the Xingu River in eastern Amazonia. Journal of Hydrology, 523, 822–829.

Pires GF, Costa MH (2013) Deforestation causes different subregional effects on the Amazon bioclimatic equilibrium. Geophysical Research Letterrs, 40, 3618–3623.

Pongratz J, et al. (2006) The Impact of Land Cover Change on Surface Energy and Water Balance in Mato Grosso, Brazil. Earth Interactions, 10, 1–17.

Rally da Safra (2015) Resultados Rally da Safra 2015 www.rallydasafra.com.br/downloads

Richards P (2015)

Richards P, Pellegrina H, VanWey L, Spera S (2015) Soybean Development: The Impact of a Decade of Agricultural Change on Urban and Economic Growth in Mato Grosso, Brazil. PLoS ONE, 10, e0122510.

Rudorff, B. F. T., et al. (2010) Studies on the Rapid Expansion of Sugarcane for Ethanol Production in Sao Paulo State (Brazil) Using Landsat Data. Remote Sensing; 2, 1057-1076.

Ruhoff AL, Paz AR, Aragao LEOC, Mu Q, Malhi Y, Collischonn W, Rocha HR, Running W (2013) Assessment of the MODIS global evapotranspiration algorithm using eddy covariance measurements and hydrological modeling in the Rio Grande basin. Hydrological Sciences Journal, 58, 1-19.

Sano EE, Rosa R, Brito JLS, Ferreira LG (2010) Land cover mapping of the tropical savanna region in Brazil. Environmental Monitoring Assessement, 166, 113–124.

Soares-Filho B.S. et al. (2006) Modeling Conservation in the Amazon Basin. Nature 440, 520-523.

Spera SA, et al. (2014) Recent cropping frequency, expansion, and abandonment in Mato Grosso, Brazil had selective land characteristics. Environmental Research Letters, 9, 064010.

Spracklen DV, Arnold SR, Taylor CM (2012) Observations of increased tropical rainfall preceded by air passage over forests. Nature, 489, 282–285.

VanWey LK, Spera S, Sa R de, Mahr D, Mustard JF (2013) Socioeconomic development and agricultural intensification in Mato Grosso. Philosophical Transanctions of the Royal Society B, 368, 20120168.

Wang J, et al. (2009), Impact of deforestation in the Amazon basin on cloud climatology. PNAS 106, 3670-3674.

Yin D, Roderick ML, Leech G, Sun F, Huang Y (2014) The contribution of reduction in evaporative cooling to higher surface air temperatures during drought. Geophysical Research Letters, 44, 2014GL062039.

Zeng Z, et al. (2012) Global evapotranspiration over the past three decades: Estimation based on the water balance equation combined with empirical models. Environmental Research Letters, 7, 014026.

TABLES

Table 1. Area (ha) of croplands in Matopiba.

	2003			2013		
Matopiba	*Total row-crop agriculture (ha)*			*Total row-crop agriculture (ha)*		
	1,284,850			2,534,963		
	Single Cropping	*Double cropping*	*Irrigated*	*Single Cropping*	*Double Cropping*	*Irrigated*
	1,223,984	45,588	15,278	2,126,017	372,325	36,621

Table 2. Relationships between cropping frequency and monthly ET. Pluses or minuses with asterisks indicate significant ($p < 0.05$) positive or negative correlations between ET and cropping frequency across all years during the study period. Pluses or minuses without asterisks indicate significant ($p < 0.05$) positive or negative correlations across most but not all years. Blank cells indicate cases where both negative and positive correlations were observed across the study period. Regression results for all months and all years are presented in the Supplementary Material.

	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July
Single Cropping	—*	—*	—*	—*	—*	+	+*		—*	—	—*	—*
Double Cropping		—				+*	+	+	+*	+*	+	

FIGURE CAPTIONS

Figure 1. Map of large-scale, row-crop agriculture in Maranhão (MA), Tocantins (TO), southern Piauí (PI), and western Bahia (BA) in 2003 (left) and 2013. (Goiás State (GO) is also shown.) Inset: The Legal Amazon boundary is shaded dark green, the Cerrado biome is beige, the official Matopiba boundary is highlighted in red, and the rectangle defines our study area, which comprises over 450,000 km^2 and 65% of the total official Matopiba bounded area.

Figure 2. Deforestation in the Cerrado from 2003-2013 (LAPIG 2015). Bars indicate the area of land deforested each year in Matopiba (white) and throughout the Cerrado (black). Percentages are the share of Cerrado deforestation occurring in Matopiba each year.

Figure 3. Average annual ET (mm) of row-crop agriculture (orange; orange trendline slope = 38.6 mm yr^{-1}) and natural vegetation (green, green trend line slope = 27.5 mm yr^{-1}) in Matopiba from 2003 to 2013. The dotted black line is the percent difference (right Y-axis) of the annual mean ET between the two land cover classes.

Figure 4. Average monthly ET over land in row-crop agriculture and natural vegetation in Matopiba: a) the average ET over all row-crop agriculture; b) the average ET of single-cropping compared to double-cropping rotation.

Figure 5. Changes in monthly ET due to land-use change before August 2002 (white bars), the baseline year for this study, and the change in ET ($ET_{NOLUC} – ET_{LUC}$) due to conversion to croplands during our study period (black bars).

Figure 6. Relationship between aggregate land in new row-crop agriculture and dry season (June-Aug) ET losses. Each point represents a year in our study period.

FIGURES

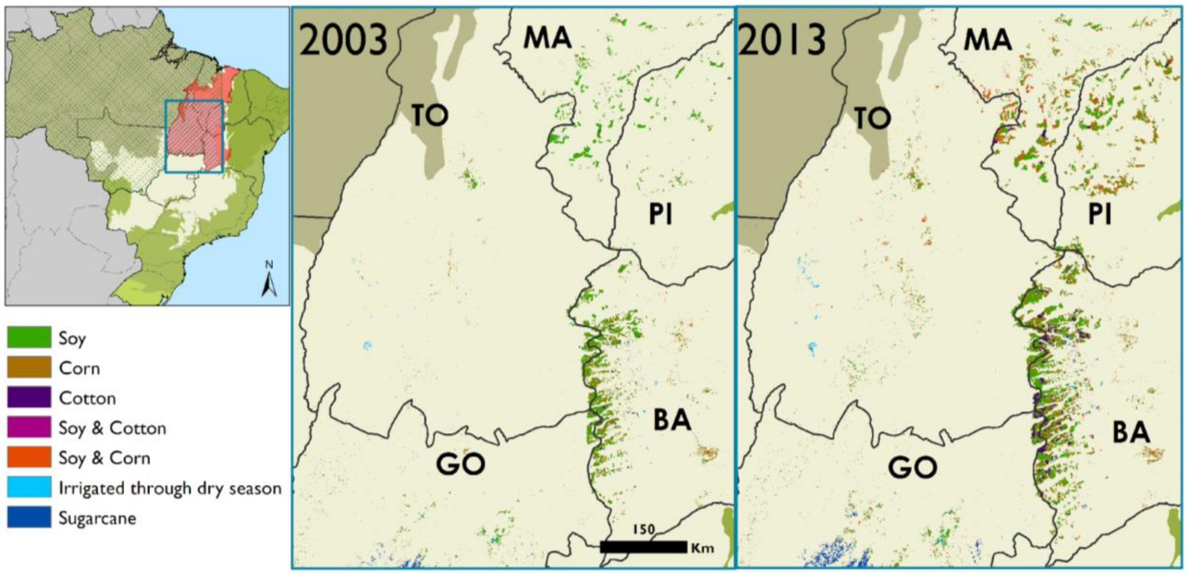


Figure 1

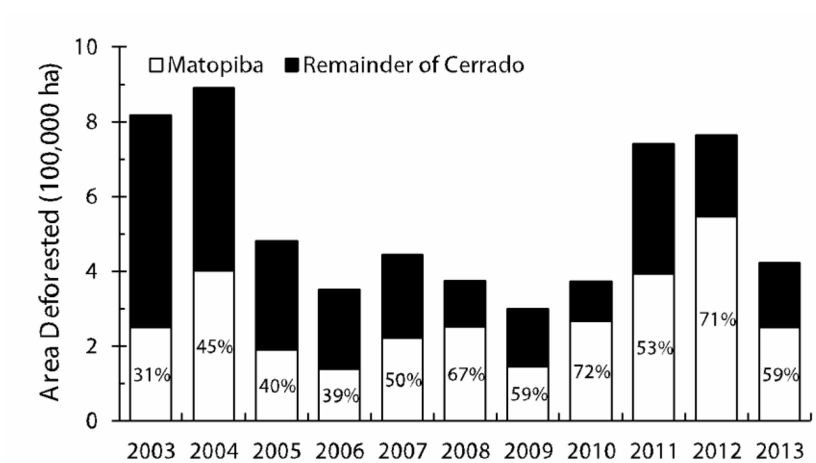


Figure 2

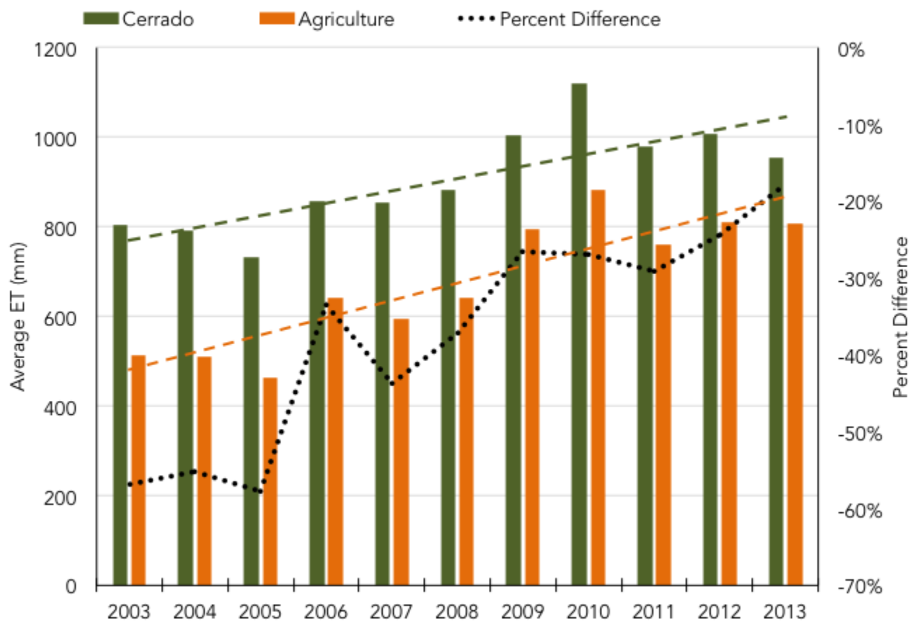
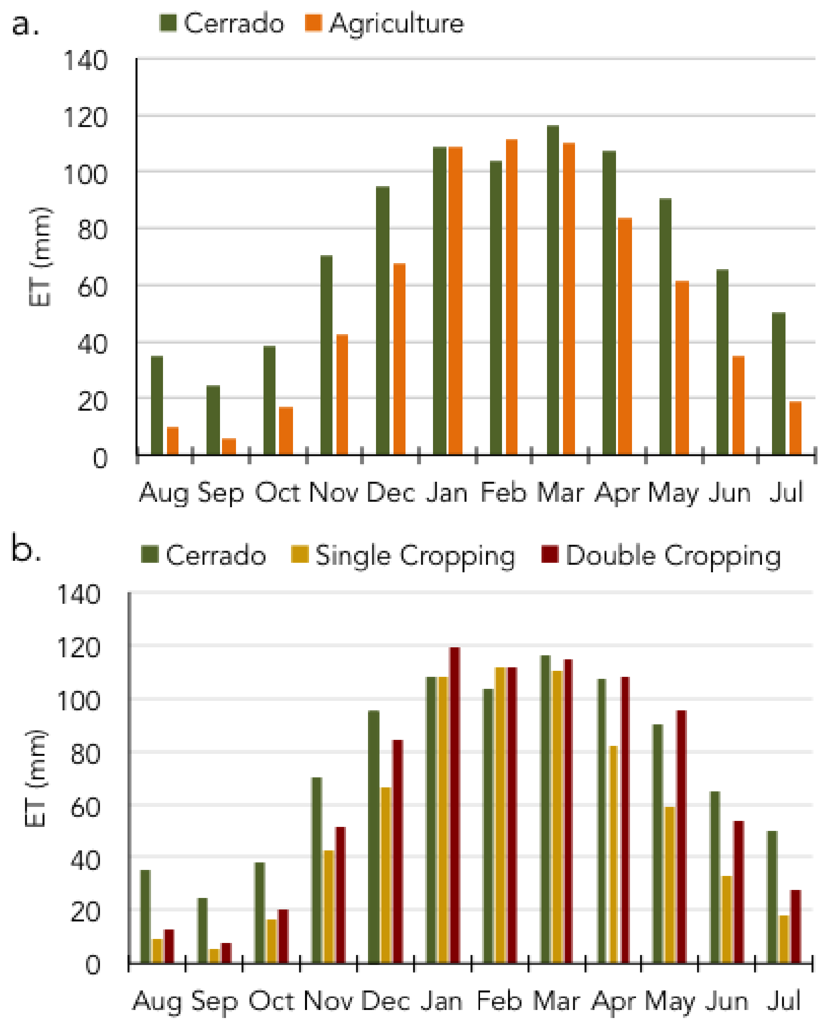

Cerrado
Agriculture
Percent Difference
Average ET (mm)
Percent Difference
1200
1000
800
600
400
200
0
0%
-10%
-20%
-30%
-40%
-50%
-60%
-70%
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013

Figure 3



a.
Cerrado
Agriculture
ET (mm)
140
120
100
80
60
40
20
0
Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul
b.
Cerrado
Single Cropping
Double Cropping
ET (mm)
140
120
100
80
60
40
20
0
Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul

Figure 4

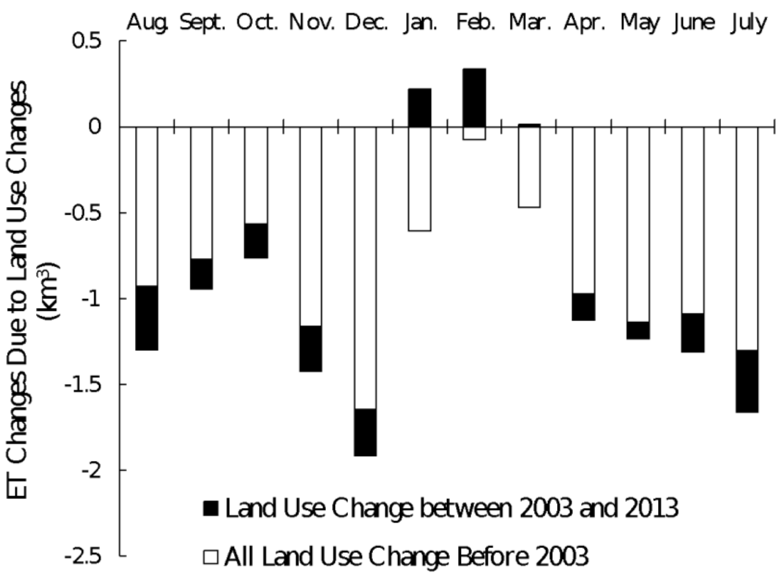


Figure 5

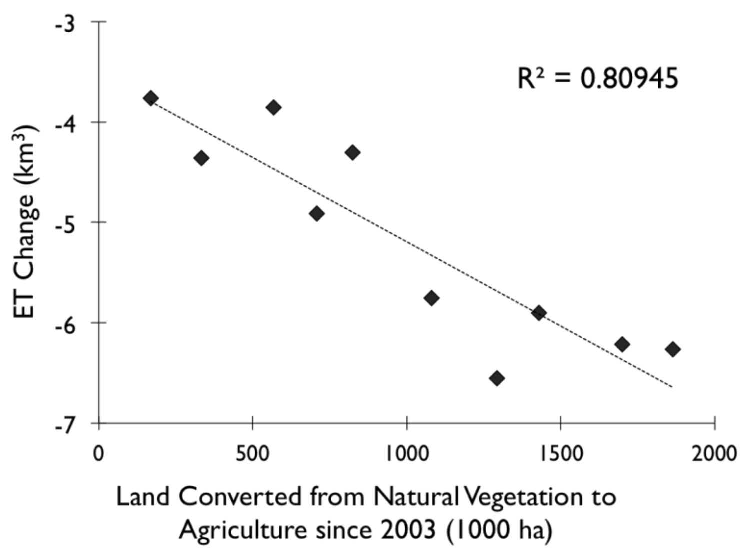
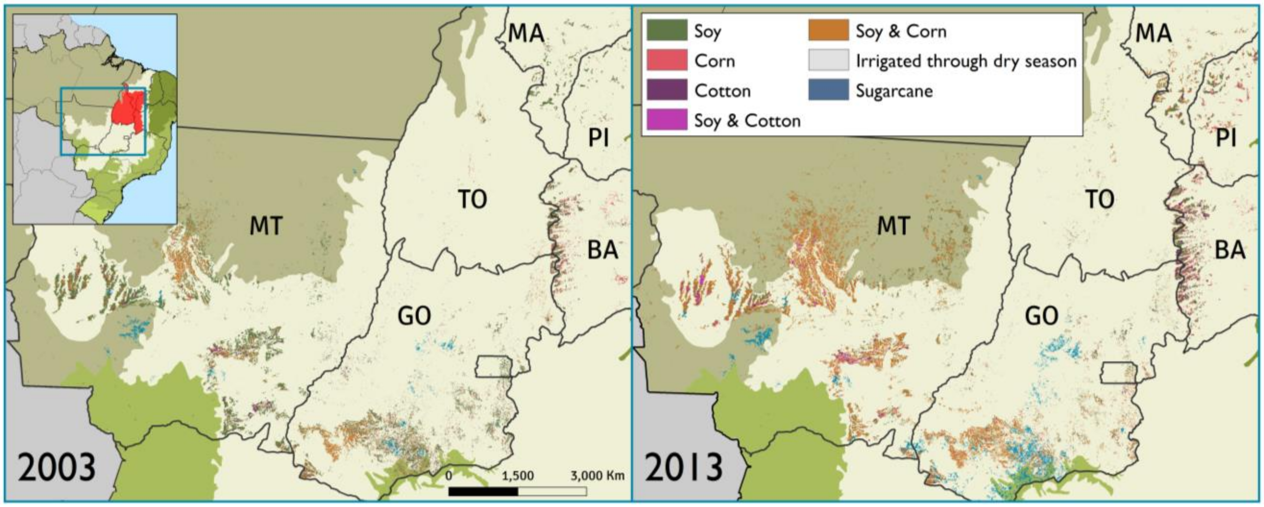


Figure 6

SUPPLEMENTARY MATERIAL



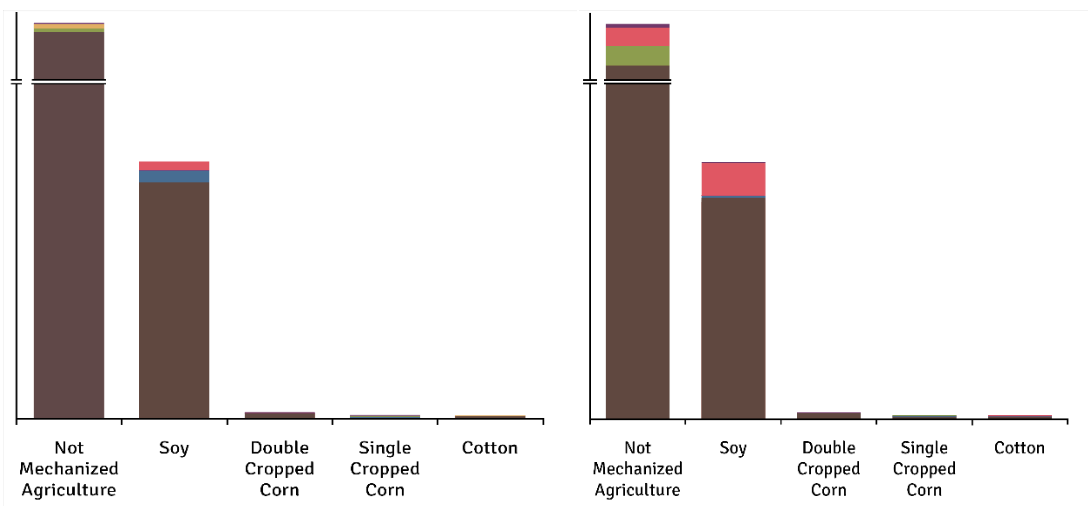
SFigure 1. Map of cropland agriculture in the Cerrado states of Mato Grosso (MT), Goiás (GO), Maranhão (MA), Piauí (PI), Tocantins (TO), and Bahia (BA) in 2003 and 2013. The map is derived from MODIS 250 m EVI data using an updated version of the methodology in Spera et al. (2014). Inset: The Cerrado biome is featured in ecru, and our region of interest, Mapitoba, is outlined in red.

STable1. Confusion Matrix

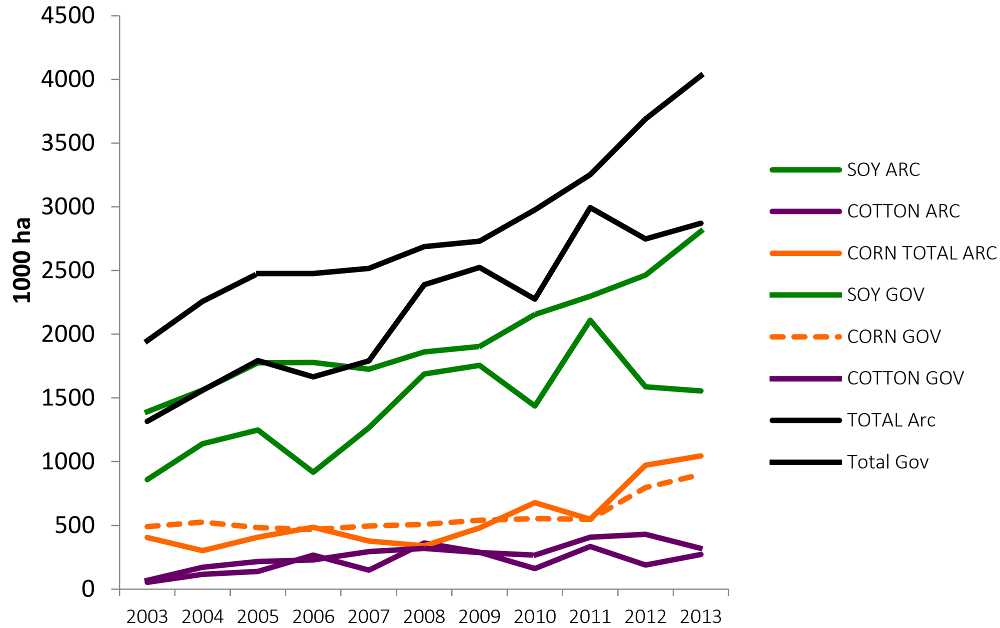
Classification	Reference Data			
	Row Crop Agriculture	Pasture/Cerrado/ Forest/Other	Row Total	User Accuracy
Row Crop Agriculture	552	7	559	98.7%
Pasture/Cerrado/Forest/Other	34	290	324	89.5%
Column Total	586	297	883	
Producer Accuracy	94.2%	97.6%		
Overall Accuracy	**95.4%**			

STable 2. Confusion Matrix with Crop Types Separated.

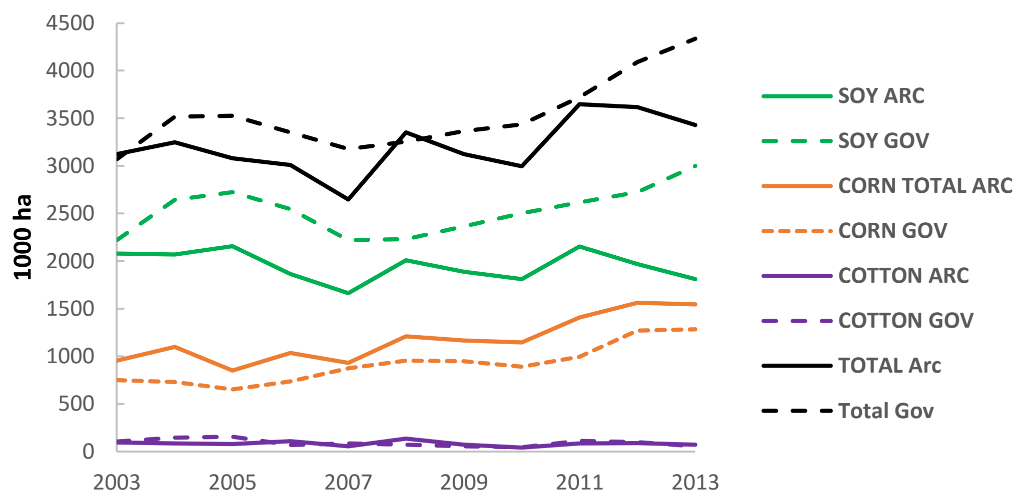
Classification	Soy	Single Cropped	Cotton	Double Cropped Corn	Other	Row Total	User Accuracy
	Reference Data						
Soy	318	47	1		3	369	86.20%
Single Cropped Corn	12	44			3	59	74.60%
Cotton		2	69	6	1	78	88.40%
Double Cropped Corn			3	50		53	94.30%
Other	16	15	3		290	324	89.50%
Column Total	346	108	76	56	297	883	
Producer Accuracy	91.90%	40.70%	90.80%	89.30%	97.60%		
Overall Accuracy	**87.30%**						



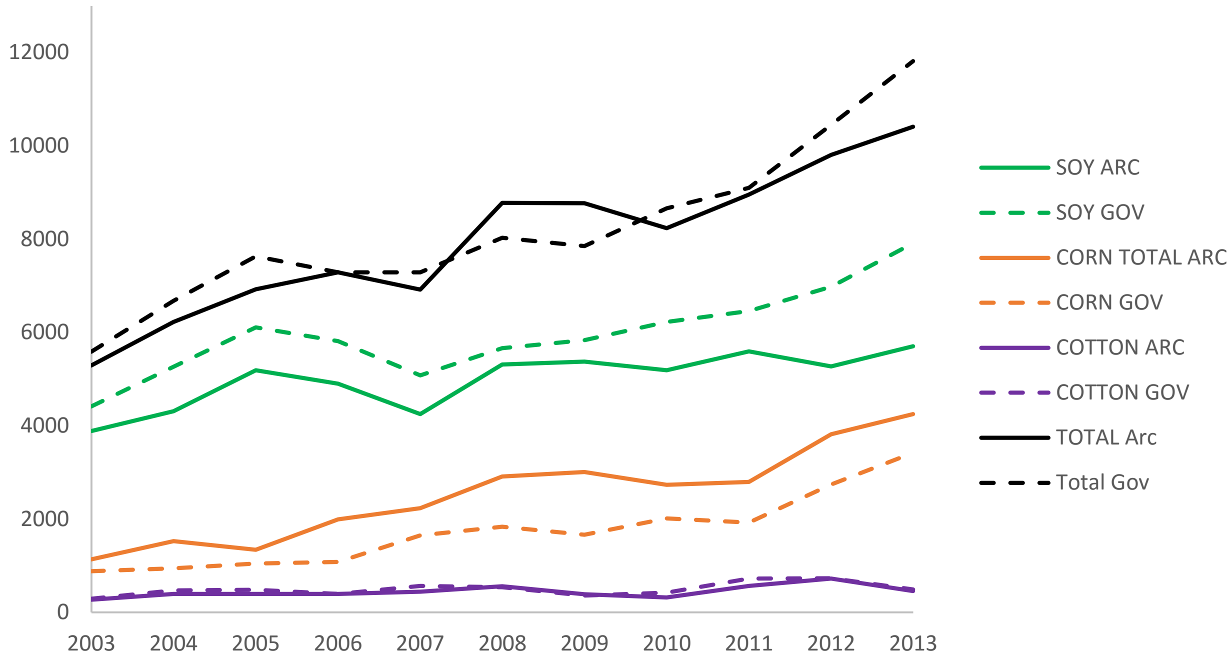
SFigure 2. Producer accuracy (left) and user accuracy (right). With the exception of the 'not mechanized agriculture' class, the heights of the bars correspond to the total area encompassed by each land cover type over the study period. The area that is not mechanized agriculture is too large relative to crop classes to create a bar of the proper scale, requiring a y-axis break. Brown represents areas that were accurately classified. Misclassifications as 'not mechanized agriculture' are blue, soy – green, single-cropped corn – red, cotton – purple, double cropped corn – yellow.



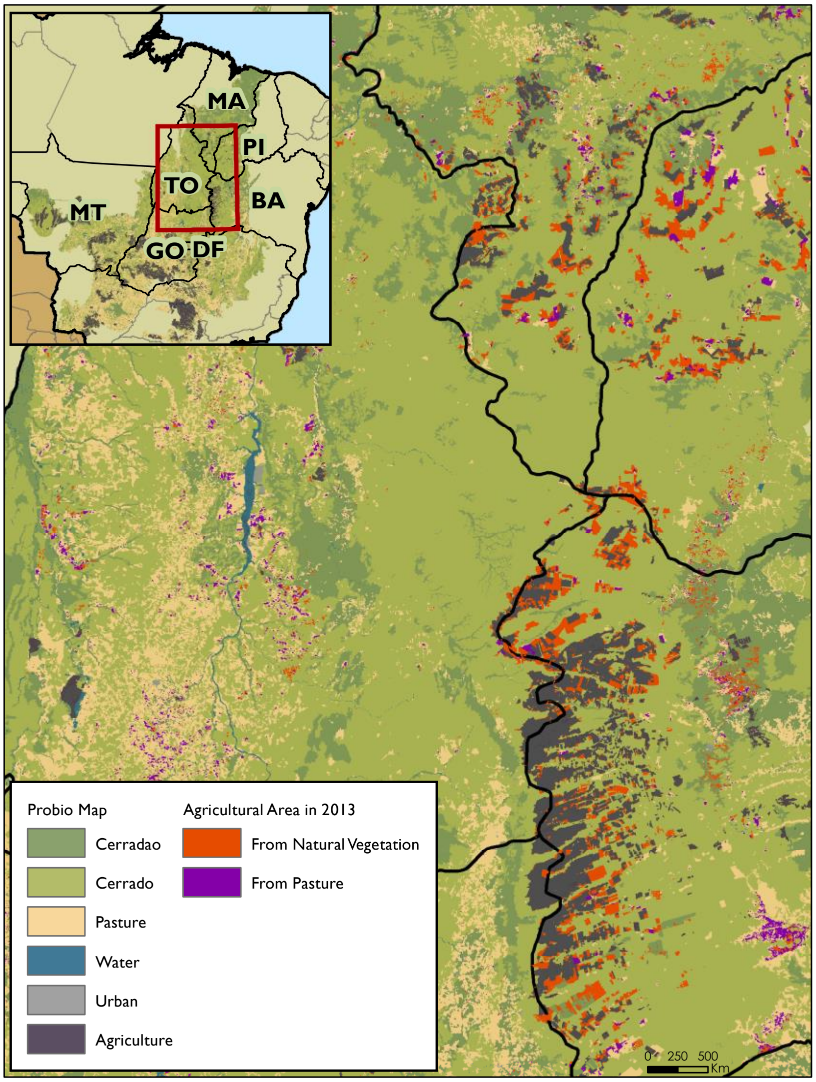
SFigure 3. Comparison of government reported cropland area (soy – green, corn – orange, cotton – purple, total – black) across Matopiba (dotted lines, referred in legend to as GOV) to mapped agricultural area using the modified Spera et al. (2014) algorithm (solid lines, referred in legend to as ARC). Canasat did not map sugarcane in this region during our study period.



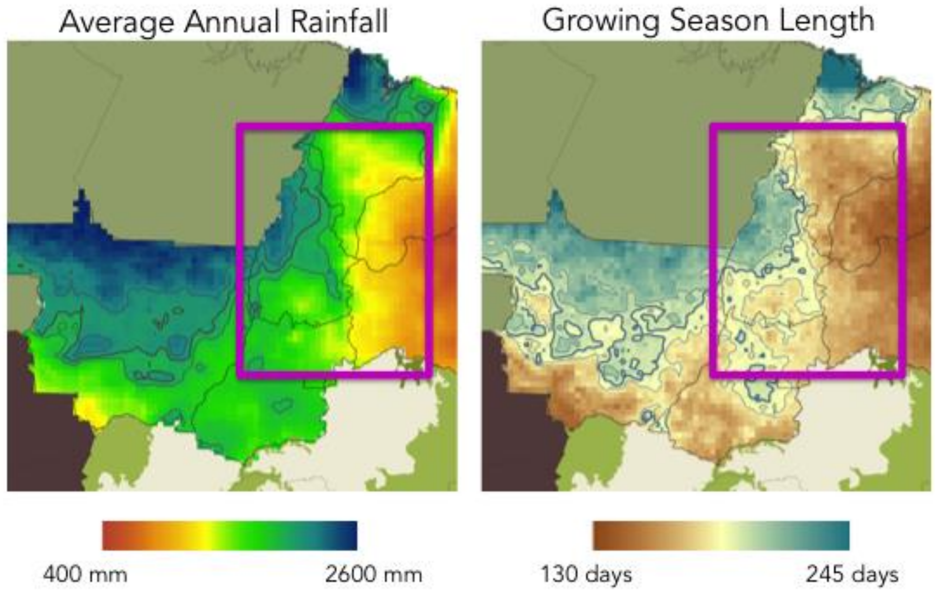
SFigure 4. Comparison of government reported cropland area (soy – green, corn – orange, cotton – purple, total – black) across Goias (dotted lines, referred in legend to as 'GOV') to mapped agricultural area using the modified Spera et al. (2014) algorithm (solid lines, referred in legend to as ARC'). Double-cropping is counted twice.



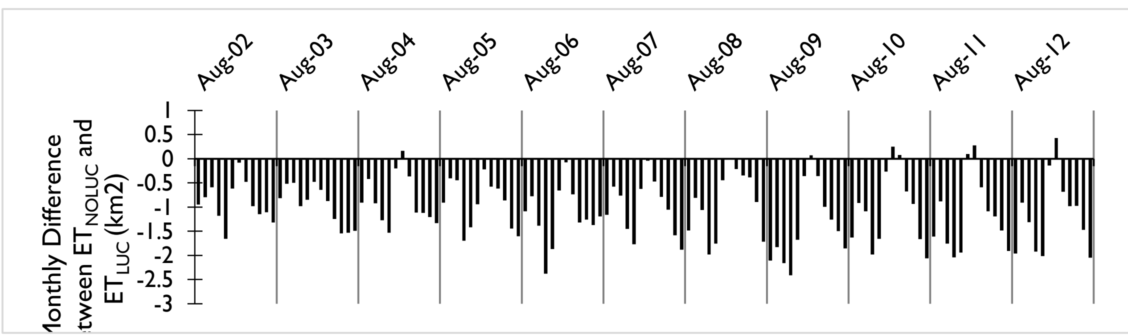
SFigure 5. Comparison of government reported cropland area (soy – green, corn – orange, cotton – purple, total – black) across Mato Grosso (dotted lines, referred in legend to as 'GOV') to mapped agricultural area using the modified Spera et al. (2014) algorithm (solid lines, referred in legend to as 'ARC').



SFigure 6. Cropland area in the Matopiba region in 2013 and baseline (6) land cover classes. Land areas brought into agriculture after 2002 were derived from this analysis. Sources of new cropland include pasture (purple) and natural Cerrado vegetation (orange).



SFigure 7. Average annual rainfall and average annual growing season duration as calculated from TRMM data over 1999 – 2014. Annual growing season duration was computed using the method outlines in Marengo et al. (2001) to determine the onset and end of the rainy season.



SFigure 8. Monthly difference between ET_{NOLUC}, a derived, interpolated surface in which no land use change has occurred after August 2002, and ET_{LUC}, the observed monthly composite ET data. Grey lines demarcate August in each calendar year.

Tables:

STable 3. Regression result for each month. Single [double] cropping represents the fraction of a 0.25 x 0.25 degree grid cell with single [double] cropping. Climatic Research Unit (CRU) temperature data and TRMM precipitation data were aggregated at the 0.0625 degree grid cell. “Temp*Precip” represents the temperature and precipitation interaction term. Standard errors presented below regression coefficients. * p < 0.05, ** p < 0.01, *** p < 0.001

	AugET 2002	AugET 2003	AugET 2004	AugET 2005	AugET 2006	AugET 2007	AugET 2008	AugET 2009	AugET 2010	AugET 2011	AugET 2012
Single Cropping	-260.7***	-216.3***	-173.4***	-186.6***	-180.0***	-149.2***	-194.8***	-261.8***	-228.1***	-246.4***	-228.8***
	(11.67	(6.941	(6.478	(4.709	(6.408	(4.972	(6.726	(6.693	(5.47	(7.975	(7.353
Double Cropping	445.7***	101.5	-100.8	-152.1***	-353.3***	-205.6***	-320.0***	-90.38	-264.3***	-187.7***	-313.7***
	(129.5	(86.62	(78.04	(41.89	(50.19	(49.64	(41.64	(73.49	(25.33	(33.19	(24.63
CRU Temperature	-47.33***	-63.47***	-56.52***	-46.26***	-40.33***	-28.14***	12.19***	56.73***	-8.837**	16.20***	5.762***
	(1.669	(1.88	(1.589	(1.102	(1.727	(1.336	(1.546	(1.985	(2.792	(1.708	(1.379
TRMM Precipitation	-415.8***	-10.96***	-80.99***	-60.70***	-111.1***	-173.3***	-39.15	-102.4***	-440.8***	-113.9***	-30.64
	(23.05	(1.914	(5.027	(7.598	(9.664	(8.765	(20.29	(8.769	(68.01	(10.95	(39.35
Temp * Precip	16.26***	0.542***	2.978***	2.185***	4.107***	6.620***	1.826*	3.920***	16.38***	4.271***	1.475
	(0.856	(0.0719	(0.185	(0.283	(0.348	(0.336	(0.712	(0.327	(2.514	(0.394	(1.458
SpatcorET	-0.0118***	-0.0214***	-0.0244***	-0.0130***	-0.0244***	-0.0264***	-0.0243***	-0.0205***	-0.0143***	-0.0265***	-0.0283***
	(0.000828	(0.000944	(0.000914	(0.000664	(0.000948	(0.00107	(0.000963	(0.000873	(0.00176	(0.00105	(0.00108
SpatcorTemp	-12.50***	-8.137***	-5.829***	-3.706***	-3.832***	-3.309***	-5.188***	-3.707***	-4.581***	-4.904***	-3.267***
	(0.205	(0.212	(0.166	(0.0998	(0.189	(0.235	(0.223	(0.226	(0.236	(0.208	(0.216
SpatcorAg		-102.4***	-82.22***	-40.82***	-89.80***	-63.64***	-65.32***	-33.35***	-10.03	-33.40***	-14.47*
		(10	(7.912	(5.192	(8.233	(7.61	(6.872	(7.738	(7.788	(7.706	(6.889
SpatcoPrec		-0.0150**	0.00132	-0.0347***	-0.0232***	0.011	-0.138***	-0.123***	-0.114***	-0.195***	
		(0.0056	(0.0061	(0.0031	(0.0062	(0.0095	(0.0065	(0.0057	(0.0076	(0.0071	
Observations	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749
R^2	0.455	0.586	0.56	0.524	0.497	0.415	0.662	0.644	0.597	0.63	0.485

STable 4. Regression result for each month. Single [double] cropping represents the fraction of a 0.25 x 0.25 degree grid cell with single [double] cropping. Climatic Research Unit (CRU) temperature data and TRMM precipitation data were aggregated at the 0.0625 degree grid cell. “Temp*Precip” represents the temperature and precipitation interaction term. Standard errors presented below regression coefficients. * p < 0.05, ** p < 0.01, *** p < 0.001

	SepET 2002	SepET 2003	SepET 2004	SepET 2005	SepET 2006	SepET 2007	SepET 2008	SepET 2009	SepET 2010	SepET 2011	SepET 2012
Single Cropping	-238.8***	-156.6***	-113.4***	-101.9***	-142.3***	-108.0***	-181.2***	-265.9***	-183.5***	-160.9***	-157.2***
	(12.19	(6.323	(4.077	(3.906	(4.431	(3.379	(6.176	(8.015	(4.001	(4.663	(6.96
Double Cropping	419.3***	44.45	-54.33	-46.39	-252.4***	-77.12**	-379.6***	150.3	-150.4***	-181.9***	-182.2***
	(125.5	(84.36	(50.4	(29.27	(39.83	(29.87	(42.92	(78.74	(19.18	(15.58	(20.27
CRU Temperature	-87.95***	-75.85***	-37.73***	-43.55***	-20.99***	-37.01***	-13.82***	78.97***	-30.22***	-53.05***	-20.71***
	(3.79	(2.762	(1.591	(1.505	(2.013	(1.268	(2.94	(3.429	(1.474	(1.549	(1.583
TRMM Precipitation	-28.02***	-37.36***	35.64***	-2.097	-0.296	-25.44***	32.39***	21.89***	33.44***	45.47***	10.77**
	(2.012	(2.924	(5.95	(1.177	(0.843	(1.45	(3.739	(3.1	(3.543	(7.576	(3.558
Temp * Precip	1.031***	1.292***	-1.190***	0.0735	-0.00847	0.880***	-1.047***	-0.709***	-1.088***	-1.511***	-0.309*
	(0.0714	(0.103	(0.208	(0.0408	(0.0295	(0.0502	(0.128	(0.105	(0.119	(0.267	(0.125
SpatcorET	-0.0228***	-0.0253***	-0.0128***	-0.0140***	-0.0206***	-0.0192***	-0.0357***	-0.0303***	-0.0184***	-0.0198***	-0.0364***
	(0.000849	(0.000993	(0.000683	(0.000552	(0.000695	(0.000748	(0.000939	(0.000895	(0.000639	(0.000828	(0.00102
SpatcorTemp	-10.61***	-4.853***	-1.999***	-1.074***	-2.174***	-1.748***	-3.626***	-4.302***	-3.414***	-4.055***	-3.776***
	(0.256	(0.218	(0.14	(0.0864	(0.153	(0.188	(0.233	(0.246	(0.125	(0.154	(0.193
SpatcorAg		-113.4***	-93.92***	-58.85***	-105.4***	-62.58***	-115.8***	-47.56***	-41.10***	-51.74***	-66.17***
		(9.88	(6.017	(4.322	(6.859	(5.042	(6.998	(8.954	(5.384	(5.372	(6.163
SpatcoPrec		0.0272***	-0.0247***	-0.00784***	-0.00101	0.0350***	0.0292***	-0.181***	-0.0493***	-0.0333***	
		(0.0061	(0.0045	(0.0022	(0.0055	(0.0073	(0.0066	(0.0073	(0.0052	(0.0046	
Observations	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749
R^2	0.35	0.461	0.462	0.386	0.429	0.375	0.539	0.537	0.539	0.587	0.524

STable 5. Regression result for each month. Single [double] cropping represents the fraction of a 0.25 x 0.25 degree grid cell with single [double] cropping. Climatic Research Unit (CRU) temperature data and TRMM precipitation data were aggregated at the 0.0625 degree grid cell. "Temp*Precip" represents the temperature and precipitation interaction term. Standard errors presented below regression coefficients. * p < 0.05, ** p < 0.01, *** p < 0.001

	OctET 2002	OctET 2003	OctET 2004	OctET 2005	OctET 2006	OctET 2007	OctET 2008	OctET 2009	OctET 2010	OctET 2011	OctET 2012
Single Cropping	-295.4***	-106.7***	-183.9***	-82.64***	-213.7***	-129.5***	-110.7***	-276.2***	-112.1***	-140.1***	-81.53***
	(15.86	(10.36	(7.916	(7.325	(6.816	(5.864	(6.455	(6.836	(4.987	(6.647	(9.403
Double Cropping	557.5***	268.0*	-204.6*	-96.46	-183.1***	-46.21	-336.0***	120.3	-302.0***	-234.2***	-293.8***
	(143.3	(123.7	(83.4	(62.54	(42.96	(74.07	(37.94	(65.03	(23.94	(24.07	(28.65
CRU Temperature	22.07**	7.6	18.72**	6.314*	40.43***	11.33**	-26.02***	55.24***	-54.80***	25.72***	90.74***
	(6.907	(6.233	(6.296	(3.134	(6.584	(3.831	(3.478	(10.47	(7.855	(7.461	(4.616
TRMM Precipitation	53.58***	22.30***	14.65***	31.36***	7.271***	36.46***	62.84***	-1.761	-9.756***	0.199	51.30***
	(3.165	(3.164	(1.718	(3.02	(0.934	(2.867	(2.727	(1.363	(1.75	(1.225	(3.32
Temp * Precip	-1.949***	-0.778***	-0.492***	-1.049***	-0.261***	-1.185***	-2.017***	0.0471	0.335***	0.00371	-1.689***
	(0.115	(0.115	(0.0619	(0.103	(0.0335	(0.0991	(0.091	(0.0505	(0.0612	(0.0458	(0.115
SpatcorET	-0.0283***	-0.0379***	-0.0397***	-0.0366***	-0.0147***	-0.0274***	-0.0300***	-0.00935***	-0.0290***	-0.0200***	-0.0343***
	(0.000816	(0.00133	(0.00114	(0.00118	(0.000695	(0.00127	(0.00109	(0.000657	(0.000763	(0.000687	(0.00137
SpatcorTemp	-5.028***	-4.251***	-3.298***	-2.609***	-1.142***	-1.171***	-1.537***	-3.711***	-1.859***	1.357***	-3.146***
	(0.27	(0.292	(0.186	(0.165	(0.155	(0.25	(0.267	(0.198	(0.162	(0.162	(0.209
SpatcorAg		-168.0***	-149.2***	-114.0***	-45.92***	-85.05***	-64.14***	4.675	-89.30***	-19.53***	-83.34***
		(14.36	(10.33	(8.314	(7.15	(8.315	(9.027	(6.985	(7.152	(5.652	(8.225
SpatcoPrec		-0.0672***	-0.0579***	-0.0105*	-0.00422	0.0620***	0.0616***	-0.0619***	0.0342***	-0.0751***	
		(0.0070	(0.0073	(0.0041	(0.00582	(0.0113	(0.0091	(0.00567	(0.0068	(0.00514	
Observations	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749
R^2	0.349	0.419	0.423	0.467	0.203	0.563	0.629	0.402	0.404	0.283	0.624

STable 6. Regression result for each month. Single [double] cropping represents the fraction of a 0.25 x 0.25 degree grid cell with single [double] cropping. Climatic Research Unit (CRU) temperature data and TRMM precipitation data were aggregated at the 0.0625 degree grid cell. "Temp*Precip" represents the temperature and precipitation interaction term. Standard errors presented below regression coefficients. * p < 0.05, ** p < 0.01, *** p < 0.001

	NovET 2002	NovET 2003	NovET 2004	NovET 2005	NovET 2006	NovET 2007	NovET 2008	NovET 2009	NovET 2010	NovET 2011	NovET 2012
Single Cropping	-367.5***	-216.7***	-391.6***	-381.9***	-349.3***	-407.7***	-77.95***	-406.2***	-244.7***	-236.4***	-254.9***
	(19.55	(11.39	(8.946	(10.83	(10.56	(10.45	(7.087	(9.905	(7.715	(8.689	(6.75
Double Cropping	815.6**	750.3***	227	-154.1	-176.1*	497.3*	-311.8***	91.99	-42.25	-109.6***	-195.7***
	(255.6	(152.6	(116.1	(99.24	(71.89	(228.4	(51.62	(71.02	(38.75	(27.47	(22.43
CRU Temperature	215.2***	59.14***	-89.41***	115.8***	86.66***	-157.6***	170.0***	172.0***	134.0***	-4.037	112.3***
	(11.73	(8.228	(6.01	(7.121	(9.299	(9.792	(5.111	(7.521	(9.226	(6.586	(6.63
TRMM Precipitation	82.89***	8.206***	-1.929	22.32***	12.73***	-9.911***	3.763***	15.49***	20.43***	-2.679***	8.161***
	(3.21	(1.029	(1.17	(0.964	(1.403	(1.75	(0.634	(1.26	(1.394	(0.639	(0.545
Temp * Precip	-2.978***	-0.323***	0.0572	-0.799***	-0.471***	0.369***	-0.155***	-0.596***	-0.765***	0.0986***	-0.321***
	(0.117	(0.0387	(0.0421	(0.0343	(0.0524	(0.063	(0.0245	(0.0464	(0.0514	(0.0243	(0.0205
SpatcorET	-0.0322***	-0.0514***	-0.0356***	-0.0349***	-0.0101***	-0.0431***	-0.0217***	0.00369***	-0.0117***	0.00014	-0.0138***
	(0.00094	(0.00139	(0.00117	(0.0012	(0.00087	(0.00128	(0.000756	(0.000747	(0.000798	(0.000589	(0.00083
SpatcorTemp	-9.531***	-0.702*	-4.384***	1.062***	-0.327	-5.498***	2.180***	2.987***	3.625***	1.123***	0.960***
	(0.273	(0.305	(0.21	(0.21	(0.233	(0.279	(0.215	(0.226	(0.206	(0.175	(0.173
SpatcorAg		-110.5***	-155.0***	-90.39***	-48.15***	-182.1***	17.42*	54.57***	9.989	31.16***	13.05*
		(16.43	(10.44	(10.65	(11.62	(12.62	(7.752	(9.764	(8.967	(7.6	(6.602
SpatcoPrec		-0.105***	0.0117	0.143***	-0.0570***	0.275***	0.0220**	0.0355***	-0.00485	-0.0555***	
		(0.0085	(0.0066	(0.0060	(0.0087	(0.0135	(0.0068	(0.00766	(0.00804	(0.00666	
Observations	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749
R^2	0.366	0.398	0.476	0.275	0.116	0.34	0.54	0.267	0.141	0.094	0.273

STable 7. Regression result for each month. Single [double] cropping represents the fraction of a 0.25 x 0.25 degree grid cell with single [double] cropping. Climatic Research Unit (CRU) temperature data and TRMM precipitation data were aggregated at the 0.0625 degree grid cell. "Temp*Precip" represents the temperature and precipitation interaction term. Standard errors presented below regression coefficients. * p < 0.05, ** p < 0.01, *** p < 0.001

	DecET 2002	DecET 2003	DecET 2004	DecET 2005	DecET 2006	DecET 2007	DecET 2008	DecET 2009	DecET 2010	DecET 2011	DecET 2012
Single Cropping	-323.2***	-82.77***	-384.1***	-292.6***	-352.6***	-350.2***	-220.7***	-270.9***	-306.1***	-275.6***	-308.8***
	(15.38	(13.73	(13.11	(10.21	(14.95	(8.379	(8.026	(8.93	(8.222	(11.07	(9.945
Double Cropping	905.8**	1294.6***	1147.3***	67.46	-270.2***	607.6***	67.89	325.4***	83.61*	159.8***	175.8***
	(283	(209.8	(174.1	(111.8	(78.59	(166.6	(61.56	(83.37	(35.68	(45.14	(29.73
CRU Temperature	103.1***	21.51*	29.72**	32.50***	51.26***	12.32	83.86***	-16.9	-71.72***	40.81***	101.1***
	(11.07	(9.36	(10.93	(7.399	(10.57	(7.755	(6.701	(13.11	(11.01	(8.39	(5.13
TRMM Precipitation	0.504	-19.56***	-6.515***	1.464*	6.015***	-6.047***	4.953***	-6.574***	-11.07***	-3.434***	6.396***
	(0.991	(1.619	(1.963	(0.587	(1.491	(1.322	(0.681	(1.519	(1.328	(0.96	(1.15
Temp * Precip	-0.0636	0.766***	0.204**	-0.0484*	-0.236***	0.246***	-0.194***	0.256***	0.402***	0.113**	-0.225***
	(0.0373	(0.059	(0.074	(0.0223	(0.0549	(0.049	(0.0258	(0.0585	(0.05	(0.0364	(0.043
SpatcorET	-0.0154***	- 0.0450***	- 0.0232***	-0.0122***	-0.0167***	-0.0143***	- 0.00504***	-0.00108	0.00091	8.7E-06	- 0.00673***
	(0.000682	(0.00149	(0.0012	(0.000782	(0.000825	(0.000841	(0.000597	(0.000633	(0.000572	(0.000661	(0.000796
SpatcorTemp	-1.210***	-8.890***	-6.221***	2.510***	0.328	-0.497*	3.343***	-0.317	-0.397*	2.332***	2.009***
	(0.249	(0.249	(0.215	(0.178	(0.207	(0.208	(0.193	(0.205	(0.166	(0.206	(0.16
SpatcorAg		-14.43	-78.15***	7.771	-86.11***	-50.69***	25.48***	-1.064	-13.45	36.65***	34.50***
		(17.67	(13.86	(9.195	(11.77	(9.534	(7.421	(7.844	(8.211	(8.568	(7.784
SpatcoPrec		-0.311***	-0.149***	0.0210***	0.131***	0.168***	0.0432***	-0.0559***	0.0276***	-0.0481***	
		(0.009	(0.011	(0.0057	(0.0094	(0.0114	(0.0078	(0.0062	(0.0076	(0.0070	
Observations	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749
R^2	0.384	0.647	0.401	0.17	0.195	0.313	0.215	0.129	0.118	0.233	0.297

STable 8. Regression result for each month. Single [double] cropping represents the fraction of a 0.25 x 0.25 degree grid cell with single [double] cropping. Climatic Research Unit (CRU) temperature data and TRMM precipitation data were aggregated at the 0.0625 degree grid cell. "Temp*Precip" represents the temperature and precipitation interaction term. Standard errors presented below regression coefficients. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

	JanET 2003	JanET 2004	JanET 2005	JanET 2006	JanET 2007	JanET 2008	JanET 2009	JanET 2010	JanET 2011	JanET 2012	JanET 2013
Single Cropping	163.1***	89.28***	26.37*	-22.99	241.5***	47.14***	-16.68	146.9***	32.50***	221.5***	158.7***
	(20.86	(10.11	(13.06	(19.82	(16.36	(9.495	(12.87	(12.95	(9.422	(11.03	(10.92
Double Cropping	2194.3***	887.5***	1839.8***	1524.4***	604.5***	707.1***	841.9***	594.2***	479.0***	284.9***	450.4***
	(380.6	(150	(234.9	(159	(85.59	(201.1	(104.1	(118.3	(53.23	(46.11	(36.28
CRU Temperature	139.4***	7.002	-21.89*	67.54***	235.4***	127.0***	-9.975	-0.26	-25.18***	-69.73***	11.28
	(15.04	(13.79	(8.872	(5.326	(8.574	(8.405	(10.97	(8.156	(6.335	(5.58	(10.24
TRMM Precipitation	5.071**	-5.397***	-2.340**	11.38***	18.77***	-0.333	-10.92***	-5.465***	-6.260***	-10.40***	-2.512**
	(1.597	(0.883	(0.825	(1.36	(2.177	(0.895	(1.539	(0.985	(0.613	(0.569	(0.812
Temp * Precip	-0.201***	0.201***	0.0862**	-0.365***	-0.694***	0.0334	0.400***	0.208***	0.233***	0.420***	0.100**
	(0.06	(0.034	(0.0306	(0.05	(0.0806	(0.0348	(0.0584	(0.0371	(0.0237	(0.0227	(0.0309
SpatcorAg	16.98	19.58*	-76.74***	67.14***	22.14	24.08**	36.10***	-9.501	31.12***	12.25	20.25**
	(18.15	(8.947	(12.46	(15.44	(11.41	(7.663	(8.682	(8.078	(7.132	(6.351	(7.125
SpatcorET	-0.0148***	-0.00200**	-0.0190***	-0.00558***	-0.00316***	-0.00968***	0.00197***	0.00103	-0.00071	-0.00441***	-0.00744***
	(0.00124	(0.000747	(0.000992	(0.000757	(0.000892	(0.000631	(0.000447	(0.000597	(0.000481	(0.000538	(0.000572
SpatcorTemp	-7.164***	-5.375***	-4.967***	-1.140***	0.894***	-0.968***	2.658***	0.125	0.614***	1.517***	0.997***
	(0.254	(0.133	(0.202	(0.202	(0.227	(0.196	(0.198	(0.152	(0.145	(0.154	(0.13
SpatcoPrec	-0.119***	-0.0590***	-0.0871***	0.121***	-0.0870***	0.0038	-0.0179**	-0.112***	-0.0389***		
	(0.0104	(0.00708	(0.00695	(0.0104	(0.0134	(0.00657	(0.00629	(0.00852	(0.00676		
Observations	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749
R^2	0.351	0.352	0.279	0.277	0.285	0.47	0.126	0.056	0.059	0.174	0.138

STable 9. Regression result for each month. Single [double] cropping represents the fraction of a 0.25 x 0.25 degree grid cell with single [double] cropping. Climatic Research Unit (CRU) temperature data and TRMM precipitation data were aggregated at the 0.0625 degree grid cell. "Temp*Precip" represents the temperature and precipitation interaction term. Standard errors presented below regression coefficients. * p < 0.05, ** p < 0.01, *** p < 0.001

	FebET 2003	FebET 2004	FebET 2005	FebET 2006	FebET 2007	FebET 2008	FebET 2009	FebET 2010	FebET 2011	FebET 2012	FebET 2013
Single Cropping	252.7***	28.14**	186.1***	182.4***	209.3***	169.0***	53.98***	312.8***	89.24***	318.7***	327.0***
	(16.97	(9.43	(13.02	(11.73	(8.581	(8.739	(9.259	(9.598	(7.827	(10.21	(12.6
Double Cropping	1400.9***	817.9***	1542.4***	769.2***	251.5***	458.0**	763.7***	68.25	378.7***	99.04**	139.5***
	(337.4	(175.5	(241.9	(113.6	(60.03	(161.7	(85.84	(57.79	(49.19	(31.09	(32.56
CRU Temperature	86.18***	30.37***	67.07***	115.9***	52.59***	63.84***	32.26***	33.24***	35.08***	47.10***	40.73***
	(2.707	(2.646	(2.541	(2.601	(2.006	(2.085	(2.247	(2.225	(1.976	(2.026	(2.481
TRMM Precipitation	0.588***	-0.154***	0.596***	0.158***	-0.0937***	-0.0801**	-0.00856	0.0520*	-0.292***	-0.0757***	-0.115***
	(0.0298	(0.0221	(0.0312	(0.0232	(0.0205	(0.0243	(0.0186	(0.0219	(0.0118	(0.0199	(0.0239
Temp * Precip	16	24.31**	-20.09	38.68***	36.26***	22.52***	37.15***	7.401	34.10***	26.92***	38.81***
	(14.21	(9.122	(11.16	(10.25	(6.937	(6.752	(6.869	(6.54	(6.256	(5.899	(7.914
SpatcorAg	- 0.0287***	-0.00166*	-0.0160***	- 0.00411***	- 0.00793***	- 0.00569***	- 0.00395***	-0.00061	- 0.00603***	-0.00063	- 0.00810***
	(0.00095	(0.000756	(0.000963	(0.000581	(0.000647	(0.000565	(0.000457	(0.000538	(0.00045	(0.000463	(0.000473
SpatcorET	-0.19	-1.595***	-0.912***	0.907***	2.831***	1.716***	1.903***	0.421***	1.540***	2.274***	1.360***
	(0.193	(0.139	(0.148	(0.14	(0.155	(0.162	(0.156	(0.112	(0.115	(0.0978	(0.133
SpatcorTemp	-0.221***	-0.0489***	-0.0451***	-0.119***	-0.0443***	-0.0419***	-0.0673***	-0.0798***	-0.0507***		
	(0.00766	(0.00716	(0.00686	(0.00706	(0.00706	(0.00584	(0.00535	(0.00578	(0.00484		
SpatcoPrec	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749
	0.393	0.054	0.197	0.231	0.135	0.139	0.07	0.141	0.121	0.203	0.134
Observations	252.7***	28.14**	186.1***	182.4***	209.3***	169.0***	53.98***	312.8***	89.24***	318.7***	327.0***
R^2	(16.97	(9.43	(13.02	(11.73	(8.581	(8.739	(9.259	(9.598	(7.827	(10.21	(12.6

STable 10. Regression result for each month. Single [double] cropping represents the fraction of a 0.25 x 0.25 degree grid cell with single [double] cropping. Climatic Research Unit (CRU) temperature data and TRMM precipitation data were aggregated at the 0.0625 degree grid cell. "Temp*Precip" represents the temperature and precipitation interaction term. Standard errors presented below regression coefficients. * p < 0.05, ** p < 0.01, *** p < 0.001

	MarET 2003	MarET 2004	MarET 2005	MarET 2006	MarET 2007	MarET 2008	MarET 2009	MarET 2010	MarET 2011	MarET 2012	MarET 2013
Single Cropping	-26.35	-84.70***	71.96***	19.27	-38.12*	-32.40***	34.84**	110.8***	58.24***	95.61***	67.04***
	(14.24	(15.52	(14.93	(13.13	(15.6	(9.252	(10.64	(11.58	(8.083	(11.05	(14.27
Double Cropping	491.2	1499.6***	1244.6***	450.4***	426.8***	510.7**	314.4***	-11.03	394.3***	15.94	63.69*
	(288.7	(333.4	(263.6	(108.3	(92.31	(194.9	(58.1	(77.49	(53.41	(39.74	(30.36
CRU Temperature	164.5***	-72.05***	78.72***	36.86***	120.7***	-34.13***	95.92***	26.68***	80.34***	91.10***	54.32***
	(6.649	(11.06	(7.867	(8.29	(4.619	(7.825	(4.933	(6.992	(6.561	(5.555	(5.347
TRMM Precipitation	3.564***	-14.58***	-3.429***	-4.559***	29.32***	-8.170***	3.775***	0.0828	6.525***	3.925***	-1.879*
	(0.806	(1.098	(0.658	(0.693	(1.219	(0.773	(0.979	(0.777	(0.648	(1.117	(0.73
Temp * Precip	-0.146***	0.536***	0.130***	0.166***	-1.008***	0.321***	-0.149***	-0.0052	-0.241***	-0.138**	0.0722**
	(0.0305	(0.0415	(0.0249	(0.0262	(0.0439	(0.0294	(0.0373	(0.028	(0.0243	(0.0424	(0.0266
SpatcorAg	-22.76*	-11.2	-3.101	15.74	10.63	15.73	33.51***	-11.83	45.51***	34.30***	27.40***
	(10.32	(10.92	(10.45	(10.01	(11.23	(8.219	(7.745	(8.028	(6.497	(7.412	(8.019
SpatcorET	-0.0218***	-0.00734***	-0.0112***	-0.00796***	-0.00724***	-0.00392***	-0.00244***	-0.00297***	-0.00294***	-0.00347***	-0.001
	(0.000855	(0.00101	(0.000953	(0.000659	(0.00102	(0.000638	(0.000503	(0.000518	(0.000432	(0.00057	(0.000568
SpatcorTemp	-0.156	0.00342	0.293	1.671***	2.499***	0.918***	1.626***	1.317***	1.857***	-0.476***	0.955***
	(0.168	(0.169	(0.156	(0.158	(0.235	(0.178	(0.181	(0.166	(0.123	(0.129	(0.142
SpatcoPrec	-0.0908***	-0.0620***	-0.131***	-0.0858***	-0.0474***	-0.0816***	-0.0809***	-0.141***	-0.0756***		
	(0.0080	(0.0090	(0.0078	(0.0091	(0.013	(0.0075	(0.0057	(0.0072	(0.0054		
Observations	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749
R^2	0.45	0.168	0.238	0.153	0.289	0.098	0.153	0.063	0.08	0.213	0.16

STable 11. Regression result for each month. Single [double] cropping represents the fraction of a 0.25 x 0.25 degree grid cell with single [double] cropping. Climatic Research Unit (CRU) temperature data and TRMM precipitation data were aggregated at the 0.25 degree grid cell. "Temp*Precip" represents the temperature and precipitation interaction term. Standard errors presented below regression coefficients. * p < 0.05, ** p < 0.01, *** p < 0.001

	AprET 2003	AprET 2004	AprET 2005	AprET 2006	AprET 2007	AprET 2008	AprET 2009	AprET 2010	AprET 2011	AprET 2012	AprET 2013
Single Cropping	-325.2***	-387.0***	-291.0***	-195.0***	-162.1***	-122.2***	-100.2***	-243.2***	-143.5***	-100.4***	-127.9***
	(15.81	(19.15	(18.91	(11.84	(16.82	(10.78	(9.278	(11.53	(11.71	(11.85	(12.49
Double Cropping	1378.3***	1784.7***	1598.1***	654.3***	650.6***	432.9***	402.3***	759.9***	532.2***	508.2***	209.6***
	(362.2	(321.7	(326.7	(100.6	(93.97	(122.3	(52.39	(75.36	(48.56	(45.98	(31.52
CRU Temperature	144.1***	76.65***	118.4***	38.32***	159.5***	97.49***	-11.82	92.25***	15.39***	150.0***	62.76***
	(5.431	(4.968	(5.538	(5.151	(4.174	(6.962	(6.47	(4.131	(3.671	(3.451	(5.364
TRMM Precipitation	-4.640***	-5.998***	-0.292	0.656	-0.27	2.100*	-6.032***	5.375***	-12.14***	7.428***	-0.683
	(1.378	(0.809	(1.813	(0.554	(1.096	(0.968	(0.558	(0.948	(0.743	(1.354	(1.209
Temp * Precip	0.178***	0.239***	0.0818	-0.0161	0.0694	-0.0722*	0.237***	-0.160***	0.454***	-0.246***	0.0215
	(0.0511	(0.03	(0.0655	(0.0208	(0.0409	(0.0367	(0.0217	(0.0337	(0.0276	(0.0494	(0.0446
SpatcorAg	32.45**	-23.86	39.44**	17.24*	105.0***	-9.524	31.63***	5.987	15.35*	38.63***	27.03***
	(11.94	(14.25	(12.37	(7.859	(12.74	(7.959	(6.462	(7.863	(7.203	(7.203	(7.474
SpatcorET	-0.0183***	-0.0104***	-0.0169***	-0.00521***	-0.00833***	-0.00182***	-0.00425***	-0.00146*	-0.00065	-0.00139*	0.00395***
	(0.00101	(0.00112	(0.00131	(0.00055	(0.000856	(0.00053	(0.000481	(0.000719	(0.000564	(0.000642	(0.000621
SpatcorTemp	-2.727***	-2.895***	-3.861***	1.432***	-0.994***	0.422*	1.464***	-0.479**	-0.605***	-2.084***	-1.909***
	(0.197	(0.209	(0.194	(0.124	(0.237	(0.174	(0.151	(0.161	(0.172	(0.142	(0.137
SpatcoPrec	-0.0895***	-0.196***	0.0117	-0.0669***	-0.0101	-0.144***	-0.0519***	-0.183***	-0.0738***		
	(0.008	(0.012	(0.0093	(0.0071	(0.0128	(0.0076	(0.0047	(0.0086	(0.0071		
Observations	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749
R^2	0.576	0.312	0.555	0.149	0.704	0.209	0.246	0.483	0.277	0.561	0.268

STable 12. Regression result for each month. Single [double] cropping represents the fraction of a 0.25 x 0.25 degree grid cell with single [double] cropping. Climatic Research Unit (CRU) temperature data and TRMM precipitation data were aggregated at the 0.25 degree grid cell. "Temp*Precip" represents the temperature and precipitation interaction term. Standard errors presented below regression coefficients. * p < 0.05, ** p < 0.01, *** p < 0.001

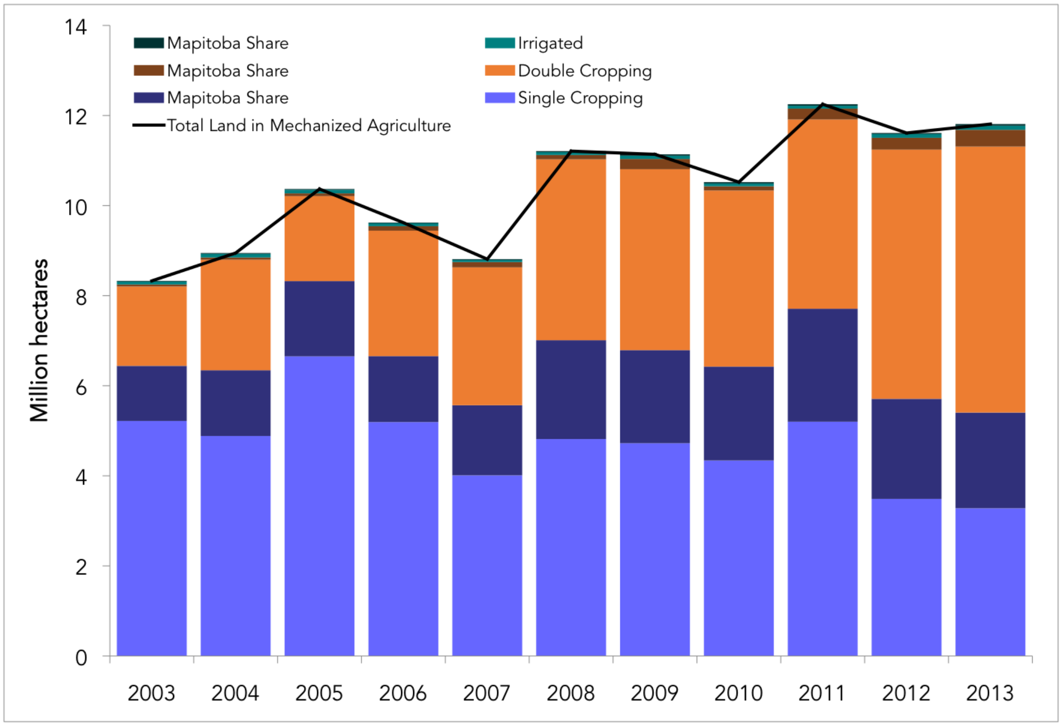
	MayET 2003	MayET 2004	MayET 2005	MayET 2006	MayET 2007	MayET 2008	MayrET 2009	MayET 2010	MayET 2011	MayET 2012	MayET 2013
Single Cropping	-217.4***	-293.4***	-186.5***	-232.0***	-118.1***	-197.7***	-132.2***	-146.8***	-91.48***	-18.86	-112.5***
	(13.71	(15.3	(16.74	(15.8	(13.51	(12.85	(8.563	(10.84	(11.31	(11.24	(12.32
Double Cropping	1433.6***	1917.8***	1879.1***	472.3***	730.0***	1248.8***	690.0***	757.8***	881.0***	763.8***	615.7***
	(291.3	(260.1	(266.9	(114	(109	(175.9	(52.29	(102.8	(47.59	(51.01	(32.23
CRU Temperature	65.94***	86.18***	20.15***	46.34***	111.0***	127.3***	19.78***	126.1***	76.34***	104.6***	51.42***
	(3.273	(2.401	(5.262	(3.767	(3.429	(2.977	(2.739	(2.551	(2.084	(2.174	(2.474
TRMM Precipitation	-50.29***	-48.58***	-39.21***	-15.33***	-68.72***	2.964*	-1.994***	0.81	-30.84***	-22.77***	-14.36***
	(1.476	(6.051	(1.453	(1.535	(1.852	(1.432	(0.574	(1.972	(1.419	(1.422	(2.594
Temp * Precip	1.914***	1.886***	1.546***	0.636***	2.676***	-0.0691	0.0989***	0.0107	1.165***	0.877***	0.613***
	(0.0544	(0.214	(0.0569	(0.057	(0.0708	(0.0536	(0.0216	(0.0687	(0.052	(0.0524	(0.094
SpatcorAg	20.43	-27.42	19.97	-50.20***	18.32	3.024	-27.90***	-3.769	18.45*	21.25*	29.13***
	(14.13	(16.26	(15.72	(11.51	(14.02	(9.517	(6.026	(8.087	(8.168	(8.916	(7.793
SpatcorET	-0.0305***	-0.00835***	-0.0337***	-0.0183***	-0.0372***	-0.0155***	-0.0106***	-0.0187***	-0.0164***	-0.0170***	-0.00640***
	(0.00144	(0.00153	(0.00189	(0.000824	(0.00148	(0.000863	(0.00071	(0.000961	(0.000767	(0.000971	(0.000891
SpatcorTemp	-3.740***	-1.893***	-5.262***	2.709***	1.529***	-3.383***	1.028***	-4.321***	-0.926***	-3.728***	-5.405***
	(0.241	(0.257	(0.252	(0.182	(0.341	(0.23	(0.191	(0.177	(0.22	(0.231	(0.187
SpatcoPrec	-0.174***	-0.143***	-0.187***	-0.156***	-0.113***	-0.160***	-0.150***	-0.236***	-0.150***		
	(0.0089	(0.011	(0.0111	(0.0080	(0.0168	(0.0084	(0.0052	(0.0077	(0.0073		
Observations	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749
R^2	0.758	0.591	0.606	0.572	0.719	0.667	0.481	0.659	0.658	0.71	0.63

STable 13. Regression result for each month. Single [double] cropping represents the fraction of a 0.25 x 0.25 degree grid cell with single [double] cropping. Climatic Research Unit (CRU) temperature data and TRMM precipitation data were aggregated at the 0.25 degree grid cell. "Temp*Precip" represents the temperature and precipitation interaction term. Standard errors presented below regression coefficients. * p < 0.05, ** p < 0.01, *** p < 0.001

	JunET 2003	JunET 2004	JunET 2005	JunET 2006	JunET 2007	JunET 2008	JunET 2009	JunET 2010	JunET 2011	JunET 2012	JunET 2013
Single Cropping	-360.4***	-413.1***	-270.7***	-266.3***	-354.4***	-184.4***	-118.0***	-140.7***	-158.7***	-107.5***	-112.2***
	(14.66	(12.57	(10.3	(12.16	(13.31	(9.197	(8.626	(8.542	(7.99	(8.881	(9.414
Double Cropping	1116.4***	1240.4***	913.4***	340.5***	530.9***	605.9***	458.5***	373.6***	281.0***	242.0***	-23.95
	(199.9	(192.2	(161.7	(90.17	(98.66	(120.5	(56.54	(102.5	(42.08	(52.46	(40.05
CRU Temperature	-10.11***	-20.33***	-20.28***	45.68***	41.00***	114.6***	111.1***	108.8***	79.53***	132.0***	62.91***
	(2.189	(1.708	(1.742	(1.927	(1.767	(1.999	(2.06	(1.818	(1.224	(1.602	(1.883
TRMM Precipitation	232.5***	-3.95	-272.0***	-184.5***	180.7***	-38.88***	-0.469	-112.9***	-496.1***	75.15***	-56.05***
	(20.73	(10.86	(14.33	(18.58	(11.29	(10.07	(2.166	(7.068	(20.77	(7.44	(2.441
Temp * Precip	-8.158***	0.416	10.84***	7.615***	-6.227***	1.670***	0.0784	4.559***	18.69***	-2.565***	2.114***
	(0.743	(0.398	(0.545	(0.719	(0.396	(0.386	(0.0864	(0.279	(0.76	(0.275	(0.0936
SpatcorAg	-131.2***	-182.4***	-80.28***	-97.63***	-73.67***	-77.65***	-0.696	-2.306	-13.15	86.86***	-21.94**
	(15.93	(13.73	(10.13	(11.76	(13.14	(9.514	(7.878	(10.74	(8.476	(7.999	(7.08
SpatcorET	-0.0489***	-0.0449***	-0.0325***	-0.0341***	-0.0508***	-0.0347***	-0.0157***	-0.0278***	-0.0138***	-0.00923***	-0.0246***
	(0.00154	(0.00145	(0.00148	(0.00121	(0.00183	(0.00112	(0.000655	(0.00113	(0.00111	(0.000982	(0.00104
SpatcorTemp	-7.478***	-4.807***	-6.138***	1.563***	3.093***	-0.419	-1.059***	-0.748***	-0.544**	-0.561***	-5.680***
	(0.247	(0.245	(0.182	(0.261	(0.384	(0.235	(0.186	(0.21	(0.201	(0.166	(0.233
SpatcoPrec	-0.0483***	-0.0388***	-0.0835***	-0.0627***	-0.0950***	-0.221***	-0.111***	-0.154***	-0.161***		
	(0.0088	(0.0093	(0.0066	(0.0090	(0.0178	(0.0082	(0.00535	(0.0076	(0.0068		
Observations	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749
R^2	0.601	0.434	0.603	0.491	0.422	0.641	0.733	0.723	0.7	0.75	0.69

STable 14. Regression result for each month. Single [double] cropping represents the fraction of a 0.25 x 0.25 degree grid cell with single [double] cropping. Climatic Research Unit (CRU) temperature data and TRMM precipitation data were aggregated at the 0.25 degree grid cell. "Temp*Precip" represents the temperature and precipitation interaction term. Standard errors presented below regression coefficients. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

	JulET 2003	JulET 2004	JulET 2005	JulET 2006	JulET 2007	JulET 2008	JulET 2009	JulET 2010	JulET 2011	JulET 2012	JulET 2013
Single Cropping	-350.4***	-354.2***	-266.8***	-278.1***	-137.8***	-188.2***	-203.6***	-241.4***	-221.1***	-205.0***	-226.6***
	(11.41	(9.368	(7.688	(9.371	(9.467	(8.991	(7.837	(8.076	(6.662	(8.2	(8.771
Double Cropping	167.7	464.9***	174.7	-262.8***	-180.2**	-91.57	-92.09*	-208.4***	-122.5***	-232.0***	-285.7***
	(124.5	(111.4	(91.29	(75.23	(62.02	(81.36	(46.94	(59.5	(37.07	(32.72	(36.66
CRU Temperature	-41.33***	-28.08***	-22.51***	20.79***	26.14***	48.32***	86.64***	35.65***	55.83***	49.03***	52.35***
	(1.491	(1.005	(1.261	(1.366	(1.273	(1.298	(1.256	(1.86	(1.254	(1.151	(1.206
TRMM Precipitation	-102.9*	-48.94*	-429.9***	-827.6***	-207.3***	-825.6***	82.33***	-189.6***	-31.31***	182.3***	262.9***
	(40.92	(21.78	(50.75	(76.78	(31.04	(43.71	(22.1	(22.15	(9.418	(41.23	(45.12
Temp * Precip	3.910**	2.156**	17.39***	31.18***	7.920***	31.85***	-2.747***	6.672***	1.322***	-6.218***	-8.685***
	(1.513	(0.794	(1.947	(2.887	(1.112	(1.668	(0.799	(0.809	(0.345	(1.462	(1.614
SpatcorAg	-121.2***	-61.61***	-60.60***	-114.3***	-78.58***	-59.05***	-26.85***	-46.11***	-27.39***	-9.898	6.714
	(11.87	(9.345	(8.524	(10.36	(10.92	(8.722	(7.955	(9.347	(7.421	(7.901	(7.584
SpatcorET	-0.0381***	-0.0185***	-0.0288***	-0.0348***	-0.0372***	-0.0333***	-0.0183***	-0.0377***	-0.0256***	-0.0313***	-0.0229***
	(0.00121	(0.00102	(0.00109	(0.00114	(0.0015	(0.00111	(0.000965	(0.00106	(0.00108	(0.00135	(0.00122
SpatcorTemp	-6.613***	-3.382***	-5.310***	-0.700**	1.050**	-0.266	-2.972***	-2.983***	-0.134	-0.690**	-2.019***
	(0.202	(0.145	(0.146	(0.225	(0.334	(0.252	(0.221	(0.204	(0.203	(0.221	(0.187
SpatcoPrec	0.0121	-0.0776***	-0.0855***	-0.0942***	-0.0988***	-0.127***	-0.145***	-0.128***	-0.166***		
	(0.0068	(0.0055	(0.0047	(0.0085	(0.0132	(0.0066	(0.00581	(0.0082	(0.0064		
Observations	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749	8749
R^2	0.515	0.629	0.502	0.442	0.503	0.616	0.706	0.569	0.628	0.568	0.695



SFigure 9. Area of large-scale mechanized agriculture across the Cerrado. The portion of the total large scale agriculture in Matopiba ('Mapitoba share') of each cropping category (single cropping, double cropping and irrigated) is shaded with darker colors.

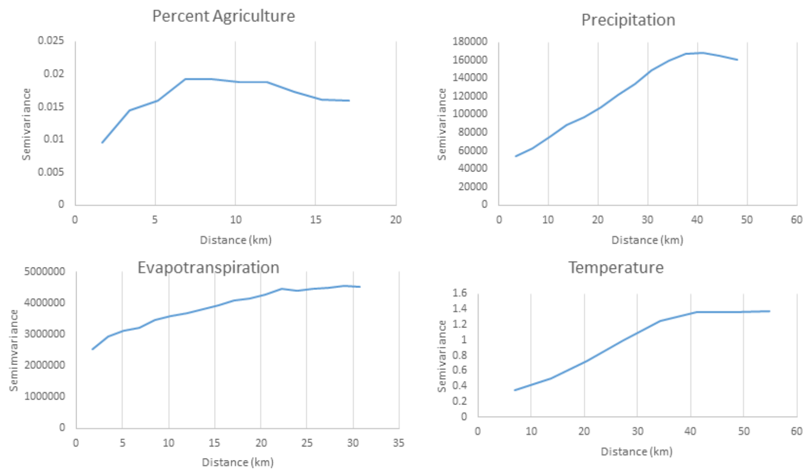
Land use classification methodology

We modified the algorithm by Spera et al. (2014) to account for crop rotations and crop calendars across Goais and Mapitoba. We downloaded all 16-day, 250 m MODIS13Q1 composites between August 2002 and July 2013 from the United States Geological Survey's Land Processes Distributed Active Archive Center. We define a year's growing season as the period from August of the previous year through July of the growing year itself. The difference between the Spera et al. algorithm (2014) and the modified version is the inclusion of single-cropped corn as a row crop. A single-crop corn rotation, although not frequently cultivated in Mato Grosso, is common in Goias and Mapitoba. Single-cropped corn is classified as such if the pixel is classified as row crop agriculture during earlier steps in the decision tree and if the maximum growing season EVI parameter is less than 0.6. If the maximum EVI parameter is greater than 0.6, then the pixel is classified as soy.

Google Earth Engine was used to collect both training (915 points) and validation (883 points) data. Our soy estimates are always conservative when compared to government statistics (SFig. 3 – SFig. 5).

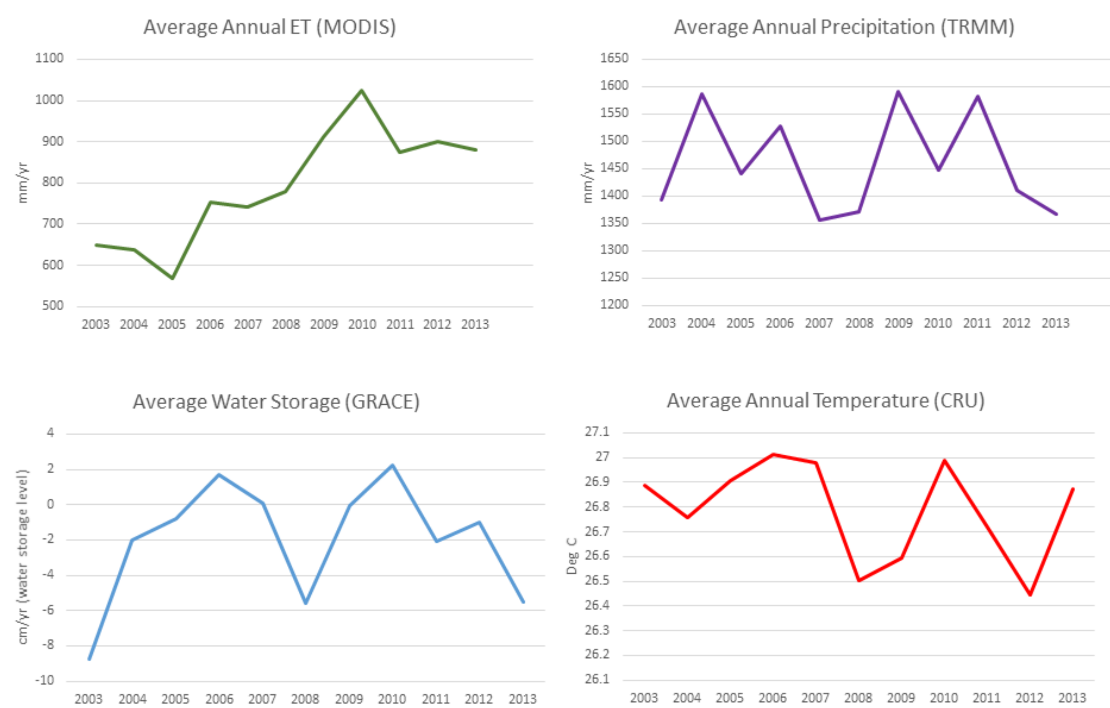
Semivariograms

We tested and accounted for spatial autocorrelation following the methods of (Cohn et al., in revision). Each of our variables (temperature, precipitation, evapotranspiration, and percent agriculture in each grid cell) exhibited spatial autocorrelation. We determined the radius of correlation using the semivariograms for each variable (below) and created a neighborhood variable for each, which was then included in our multivariate linear regressions (STables 3-14). The radius of correlation for our temperature variable was 45 km; the radius for precipitation was 40 km; the radius for evapotranspiration was 30 km; and the radius for agricultural area was 10 km. For each of these variables, we created a neighborhood variable which represented the average temperature, precipitation amount, evapotranspiration amount, and agricultural area within a buffer of the respective size for each corresponding radius. We determined these radii using the semivariograms shown in SFig10.



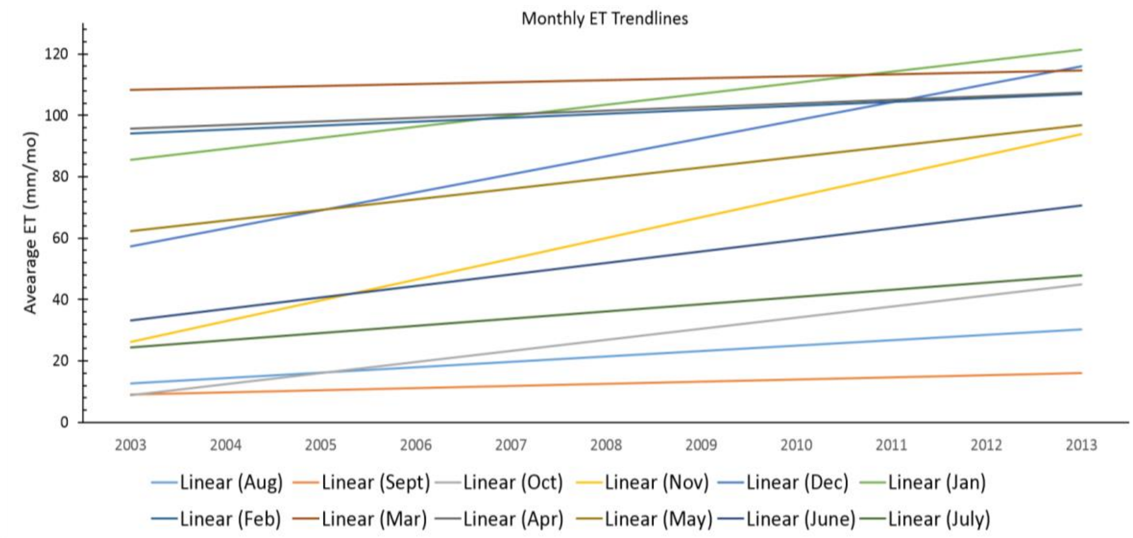
SFigure 10. Semivariograms for each variable exhibiting spatial autocorrelation. These data were used to determine the radii of correlation (percent agriculture – 10 km; precipitation - 40 km, evapotranspiration – 30 km; and temperature – 45 km) to create neighborhood variables.

Evapotranspiration Analysis

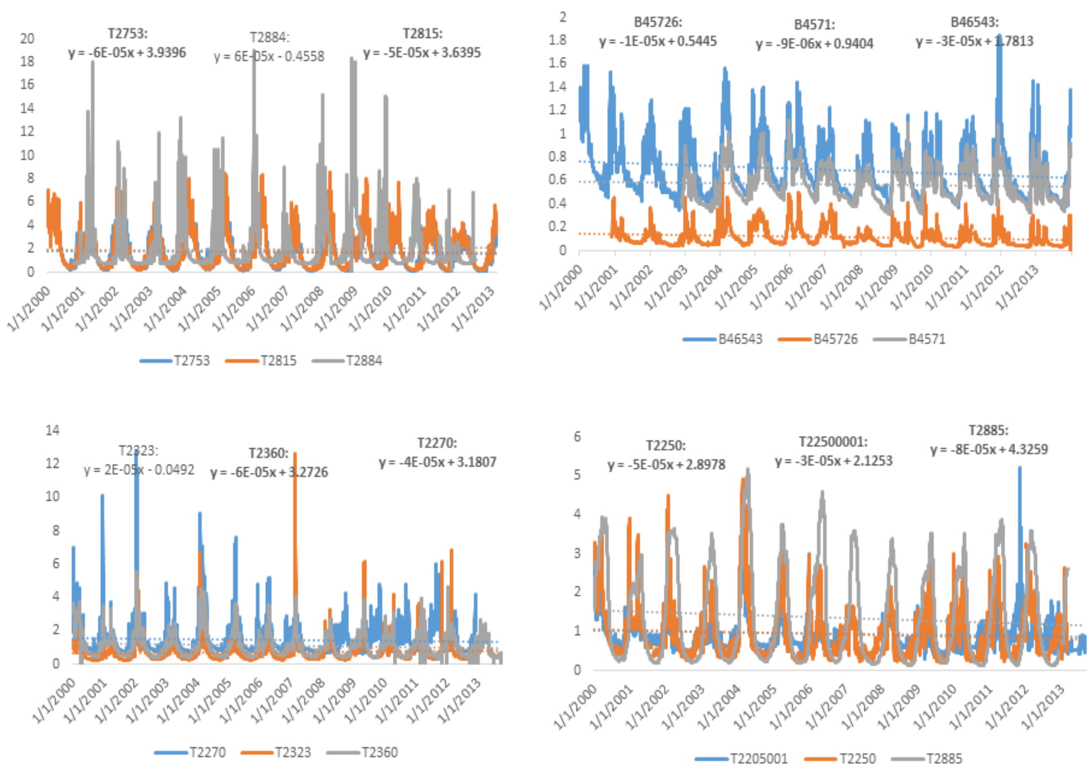


SFig 11. Climate data aggregated to annual averages across Maptioba.

Questions arose as to whether the MODIS 16A2 evapotranspiration data were robust enough to analyze trends, since average annual ET increased during our study period (SFig. 11), and no trend appeared in precipitation (TRMM) data, water storage level (GRACE) data, or temperature (CRU) data. This increasing trend in ET is not as apparent when looking at monthly time series (SFig. 12). Using a non-parametric Pettitt test (Pettitt 1980), we found a change-point in November 2007. However, using a cumulative sum bootstrapping approach (Taylor 2000), we found different change points, depending on how the data were grouped, and sometimes no change point at all. We then analyzed each monthly trend individually, and found that ET increases dramatically for the months of November and December, but at lower rates during dry season months (SFig. 12). Historical stream flow data were downloaded from the National Water Agency (ANA – hidroweb.ana.gov.br) for rivers in our study region. Eighteen rivers within Tocantins and Bahia had ANA-collected daily stream flow data during our study period (SFig. 13). Of these 18 rivers, 14 showed decreasing trends in discharge over the time period. Decreasing streamflow is consistent with increasing ET with no trends in precipitation or water storage (SFig. 11 and SFig. 12). Thus, we present and use the entire MODIS ET time series during our time period and leave determination of the mechanisms behind these trends for future work.



SFigure 12. Trendlines from monthly MODIS ET data. Each line represents the trendline of change in ET across our study area for each month (delineated with different colors) during our study period. Although we noticed an overall increasing annual trend in ET, we note that this increase was not uniform across all months, instead, ET rates increased more in some months (November – yellow, December – blue, January – green) than others (September-orange, May – brown).



SFigure 13 Streamflow trends over time.

SUPPLEMENTARY REFERENCES

Cohn A, Gil JDB, Toledo C, Berger T (minor revisions requested) Patterns and processes of pasture to crop conversion in Brazil: Evidence from Mato Grosso State. Land Use Policy.

Marengo JA, et al. (2001) Onset and End of the Rainy Season in the Brazilian Amazon Basin. Journal of Climate,14 5, 883-852.

Rally da Safra (2015) Resultados Rally da Safra 2015 www.rallydasafra.com.br/downloads

Pettitt, A N (1980) A simple cumulative sum type statistic for the change-point problem with zero-one observations. Biometrika, 67 1, 79-84.

Spera S, et al. (2014) Recent cropping frequency, expansion, and abandonment in Mato Grosso, Brazil had selective land characteristics. Environmental Research Letters, 9, 064010.

Taylor, W (2000) Change-Point Analyzer 2.0 shareware program, Taylor Enterprises, Libertyville, Illinois. http://www.variation.com/cpa

CHAPTER 3

Drivers of Sugarcane Expansion in Goiás, Brazil

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ABSTRACT

Between 2003 and 2013, sugarcane area expanded six-fold, from 142,000 ha to 847,000 ha in Goiás State and the Federal District, Brazil. The recent expansion of sugarcane, coupled with the state's extensive history of cattle-ranching and soy-cultivation, makes Goiás an ideal location for studying food-energy-environment dynamics. Here, we ask what is driving this expansion of sugarcane, and use scenarios to determine whether natural vegetation or food production are threatened. Our results demonstrate that pasture is seven times more likely to be converted to sugarcane than soy, and most new sugarcane area was not sourced in native *Cerrado* vegetation. Although there exist few biophysical limitations to sugarcane expansion, capital, infrastructure, and institutions constrain production. Lastly, we show that although food production has not yet been affected by the expansion of sugarcane, areas where soy is currently cultivated are more likely than pasture to be converted to sugarcane in the future given the planned locations of new infrastructure. Thus, we suggest incentivizing the cultivation of sugarcane on degraded pastures and supporting increased pasture stocking rates to ensure continued protection of both natural vegetation and food production.

1. INTRODUCTION

As global demand for renewable energy resources increases, the world is looking to Brazil's extensive sugarcane production and processing experience as a model of sustainable biofuel development. In Brazil, sugarcane production has been markedly expanding since the early 2000s. Although São Paulo currently produces over half of the country's sugarcane, rising land prices are spurring investors and farmers to look elsewhere for ample, cheap land with less environmental regulation. Consequently, the Center-West region of Brazil has become an epicenter for sugarcane expansion. As sugarcane production expands, debates on the benefits of the crop, potential indirect land-use change, and the food-energy-environment 'trilemma' continue (Tilman et al. 2009). Here we focus on the dynamics and regional-scale drivers of sugarcane expansion in the Center-West state of Goiás (Figure 1), where planted sugarcane area increased almost six-fold from 142,000 ha to 847,000 ha between 2003 and 2013 (Rudorff et al. 2010).

Brazil leads the world in sugar production and falls behind only the United States in ethanol production (UNICA 2012). Sugarcane has been cultivated in Brazil since the arrival of Europeans in the 16th century and has been blended with gasoline since the 1930s (Hira and Oliveira 2009). Sugarcane production expanded in the 1970s after the first global oil crisis. No longer wanting to be reliant on oil imports, the Brazilian government began the ProAlcool program, which subsidized infrastructure and technology for the production of sugarcane-based ethanol on the large scale. More recently, access to global markets, high global sugar prices, renewable energy policies in both Brazil and other countries, and the advent of the flex-fuel vehicle (a car that can run on both pure ethanol and blended gasoline) in 2003 have increased demand for sugarcane production. Between 2003 and 2011, Brazil's National Bank for Social and Economic Development (BNDES) distributed over $28.3 billion in loans to ethanol plant owners (Mendonça et al. 2013). More recently, the global recession, problematic weather during harvesting, and the Brazilian government's decision to regulate gas prices to keep them intentionally lower, have made sugarcane production for ethanol slightly less attractive; the amount of sugarcane converted to ethanol versus raw sugar decreased steadily from 60% to 50% between 2008 and 2013. However, sugarcane area in the country continues to rise. (We recommend Hira & Oliveira 2009 for a comprehensive history of sugarcane production in Brazil.)

Here, we focus on the expansion of sugarcane in the state of Goiás between 2003 and 2013. We include the Federal District, home to Brazil's capital, Brasília, in our analysis (Figure 1). Goiás is historically a cattle ranching state: pastures cover over a third of the state's land area and there exist three cows for every one of the state's 6.5 million residents (MMA 2007, IBGE 2016). During our study period, the number of cows in the state increased from 20.2 to 21.6 million (Figure 2). Although total area in soy remained steady, hovering around 2 million planted ha, total area in intensive soy-corn double cropping doubled from 500,000 ha to over one million ha (Figure 2). Neither cattle nor double-cropping gains were as dramatic as the almost 490% increase in sugarcane area. Between 2003 and 2013, Goiás rose from Brazil's seventh-largest sugarcane producer to its third. (Today it is second only to São Paulo.) During that time, Goiás received R$ 3 billion in loans[1] from BNDES for sugarcane production and processing purposes and 32 new sugarcane mills opened (Hochstetler and Montero 2013, SIFAEG 2013). In 2013, Goiás produced over 40 million tons of sugar and 2 billion liters of ethanol (SIFAEG

[1] Approximately $USD 1.5 billion

2013). And there remains ample room for expansion: over 11 million ha of land have been deemed suitable for sugarcane production in the state (MAPA 2009).

Changes in land rent drive changes in land use, and competition over land for food and biofuels, environmental conservation efforts, land scarcity, the creation of new infrastructure, and adoption of agricultural innovations all interact to affect the processes and patterns of sugarcane expansion. Proximity to sugarcane mills is crucial, as sugarcane begins to degrade immediately after harvesting and needs be located within 50-100 km of a processing mill (Sparovek et al. 2007, Zuurbier and van de Vooren 2008, Nagavarapu 2010). Capital can be a major constraint on expanding large-scale, mechanized agriculture, pervasive throughout Goiás (Kaimowitz and Smith 2001). And the sugarcane industry is especially reliant on government support (Hira and Oliveira 2009). The existence of other agricultural economies of scale and access to technology may decrease whether land is converted from pasture or soy to sugarcane (Garrett et al. 2013). Factors such as silo capacity, slaughterhouses, the amount of soy in an area, and the existence of rural syndicates may also decrease likelihood of conversion. Land-use histories and agglomeration effects are often strongly linked to land-cover change (Lambin et al. 2001, Chomitz and Thomas 2003, Vera-Diaz et al. 2008, Garrett et al. 2013): pasture and soy land near other sugarcane may be more likely to be converted to that land use. Lastly, biophysical characteristics associated with land most preferential for sugarcane expansion include reliability of precipitation, cool minimum temperatures, slope, and soil type (Jasinski et al 2005, Vera-Diaz et al. 2008, Spera et al. 2014).

Here we use novel, 250 meter resolution pixel-level annual agriculture data to determine: (1) what type of land is being converted to sugarcane production; (2) which factors contribute to the conversion of pasture and soybean to sugarcane; (3) whether the expansion of sugarcane has affected the amount of land available for food production in the state; and (4) whether future food production is threated by potential sugarcane expansion.

2. METHODS AND DATA

2.1 Methods

Land owners will convert their land from pasture or soy to sugarcane (or sell their land to someone who will do so) if future returns to sugarcane (minus the land-cover conversion costs) will make them more money (Chomitz and Gray 1996, Chomitz and Thomas 2003). Thus, we use a pixel's conversion from pasture or soy to sugarcane as an indicator of changing land rents (Walker et al. 2009, Walker and Richards 2014).

We employ a discrete-time event history analysis (Allison 1982) to determine the factors contributing to changing land rents in Goiás and the Federal District: the "event" is a pixel's conversion to sugarcane during our analysis period.[2] As we demonstrate below, we can model this conversion using a logit model. Our pool of data includes any

[2] This conversion can only occur once: our dataset did not contain any clear instances of sugarcane converting back to soy or pasture. This observation is supported by previous studies that demonstrate that sugarcane is a "stickier" crop than soy (Nagavarapu 2010, Hausmann 2012). We begin our analysis period in 2003 because this is the first year spatially explicit sugarcane data are available for Goiás. Thus, our dataset exhibits both left censoring (142,0000 ha of Goiás were already cultivated with sugarcane in 2003) and right censoring (there still exists abundant soy and pasture with the potential to be converted).

pixel in Goiás between 2003 and 2013 with a land-cover classification of pasture or soy: this amounts to a panel dataset with over 26 million observations.

We model the probability, P, of converting to sugarcane, S, of pixel, i, at time, t, given this transition has not already occurred (Allison 1982):

$$P_{it} = \Pr[S_i = t | S_i \geq t, x_{it}] \qquad \text{Eq. 1}$$

P_{it}, then, equals:

$$P_{it} = \frac{1}{1+e^{-\alpha_t - \beta' \hat{x}_{it+\varepsilon}}} \qquad \text{Eq. 2}$$

where x_{it} is a matrix of independent variables likely to affect conversion to sugarcane.

This model is commonly estimated as a binary logistic regression model with variable-years (in our case, pixel-years) as the unit of analysis (Allison 1982):

$$\log\left[\frac{P_{it}}{1-P_{it}}\right] = \Pr[ConvertToSugarcane] = \beta' x_i + \alpha + \varepsilon \quad \text{Eq. 3}$$

We include year effects, ν_t, to control for year-to-year variation in demand, exchange rates, price, and policy. We also use geographical coordinates, σ, to control for unobserved and spatially organized soil and distance-to-market factors. Because only 1% of the total land area in pasture and soy was converted to sugarcane during our study period, we run multiple models to test the sensitivity of our results to exact specifications of our independent variables. Our final model is:

$$\begin{aligned} \Pr[ConvertToSugarcane] \\ &= \beta_1 PreviousLandCover_{t-1} + \beta_2 Institutional_{t-1} + \beta_3 Biophysical \\ &+ \beta_4 Infrastructure_{t+1} + \beta_5 Economies\ of\ Scale_t + \beta_6 Technology_t \\ &+ \beta_7 Capital_{t-1} + \sigma + v_t + \alpha + \varepsilon \end{aligned}$$

Finally, we use the results of our models to test three different scenarios to analyze trade-offs between land for food (soy and pasture) and fuel (sugar) in Goiás. We model where land might be converted to sugarcane based on: (1) purely biophysical parameters; (2) all variables except previous land use; and (3) where new sugarcane mills and transportation infrastructure are planned.

2.2 Data

We describe our datasets in the following sections. Descriptive statistics for all variables can be found in Table 1.

2.2.1 Annual Land-Cover Data

To determine the location of new land in sugarcane, and from what landuse it originated, we used 250 m resolution agricultural land-cover data of the state of Goiás and the Federal District (Spera et al. 2016). These annual row-crop data include soy, corn, cotton, and sugarcane single-cropping rotations, as well as soy-corn and soy-cotton double-cropping rotations. All but the sugarcane land-covers were derived using a decision-tree algorithm that relies on remote sensing vegetation index data as collected by the Moderate Resolution Spectroradiometer on the Terra satellite. The algorithm results were then integrated with a separate, annual sugarcane dataset (Canasat, Rudorff et al. 2010) to create the final annual agriculture dataset, which spans 2003-2013.

Because pasture is difficult to separate from natural *Cerrado* vegetation using moderate resolution remote sensing data, we integrated various pasture datasets to create annual pasture maps. Baseline pasture vegetation was defined using the 2002 Project for the Conservation and Sustainable Use of Brazilian Biological Diversity

(PROBIO), which was derived using 30 m resolution Landsat data (MMA 2007). To update the 2002 data, we used the Federal University of Goiás 2010 pasture map (LAPIG 2015), which was produced by integrating multiple remote sensing datasets. We updated the 2002 data to the 2010 map, and the 2010 map onwards to create annual pasture maps by using spatial data of *Cerrado* clearing from the Integrated Deforestation Warning System (SIAD) (LAPIG 2015). Both the 2010 pasture map and SIAD data have been validated to a high degree of accuracy. We then classified cleared land as pasture if it was marked as deforested by SIAD, and not converted to row-crop agriculture as highlighted by the Spera et al. (2016) algorithm within three years of being cleared. These spatially explicit pasture data were scaled up to the 250 m resolution and integrated with the Spera et al. (2016) dataset to create our annual land-cover data. These data provided us with the dependent conversion-to-sugarcane variables, the independent sugarcane-origin-land cover variables, and neighborhood soy and sugarcane independent variables.

2.2.2 Biophysical Data

Elevation data were derived from NASA Shuttle Radar Topography Mission (SRTM) 90m resolution digital elevation map (DEM). A 90 m resolution slope map was derived from the DEM using ENVI software. A seven-kernel smoothing window was applied to the slope map to account for incongruous slopes that resulted from divergent canopy heights at forest edges (Van Zyl 2001). Both the elevation and slope data were scaled up to a 250 m resolution.

The University of East Anglia's 0.5 degree Climate Research Unit V 3.23 annual precipitation and minimum and maximum temperature data (Harris et al. 2014) were downloaded for 1980-2000 and averaged over this time period. The data were then downscaled to 250 m resolution.

2.2.3 Institutions

A shapefile of registered and planned mills was downloaded from Brazil's Ministry of Agriculture (MAPA). We included both mills in the state of Goiás, and those within municipalities of other Brazilian states along Goiás' borders (Figure 3). We then researched company websites to determine when these mills became operational.

To determine annual travel times to these mills from each pixel in our dataset, we used a roads and railroads shapefile of Goiás and the surrounding municipalities. This shapefile also included data of planned infrastructure. We assigned unique speeds to each pavement type, and used the Network Analyst toolset in ArcGIS 10.2 to determine the travel time from every pixel in our dataset to the nearest sugarcane mill for every year of our analysis.

Rural syndicates are dues-collecting organizations that represent the needs and interests of the farm owners in the region (Chase 2003). The Brazilian Confederation of Agriculture and Livestock (CNA) provided a list of rural syndicates for the state of Goiás. A municipality-level dummy variable was created to indicate the presence of a rural syndicate.

To account for agglomeration effects we include the total area of sugarcane cultivated in each municipality for the previous year.

Silo location and capacity data were provided by the Brazilian National Food Supply Company (CONAB).

2.2.4 Capital

Annual BNDES bank loan data were provided by Hochstetler & Montero (2013). This dataset includes both the amount of money (R$) loaned, and the purpose for which it was loaned, and the municipality of the business/borrower. We then geolocated each loan designated for sugar or ethanol production, infrastructure expansion, or technology innovation to a 50 km buffer around the mill or farm's address. This variable is lagged in our models.

2.2.5 Economies of Scale

We use municipality-level variables of slaughterhouses and refrigerated warehouses (LAPIG 2015) and areal percentage cultivated with soybean (Spera et al. 2016) as proxies for economies of scale for pasture and soy industries.

3. RESULTS

3.1. Land cover dynamics

Seventy-eight percent of the new sugarcane in Goiás between 2003 and 2013 was sourced in pasture, while the remaining 22% was sourced from soy. These numbers are similar to pasture-to-sugarcane and soy-to-sugarcane land-cover dynamics reported in São Paulo and Mato Grosso do Sul during the study period (Nassar et al. 2008, Adami et al. 2012, Assunçao et al. 2015)

3.2. Year effects

The probability that either pasture or soy is converted to sugarcane during each year in our time period neatly aligns with the average sugar price received by the producer in Brazil (CONAB). This relationship mimics that between soy prices and land dynamics in Mato Grosso, Brazil (Richards et al. 2015), emphasizing the market's role in land dynamics in the country. The increasing trend may have to do with increasing global ethanol demand, the advent of the flex-fuel car in 2003 and motorcycle in 2009, and global sugar prices. We use year effects in all of our models to account for annual fluctuations in price, demand, policy, and other unobservable characteristics.

3.3 Final Model

The results of our final model are presented in Table 2. Pasture is more likely to be converted to sugarcane than soy: holding all other variables at their means, pasture is seven times more likely to be converted to sugarcane than soy fields. Pasture cultivation is often an extensive, low-income-generating activity (Sparovek et al. 2007). Thus, if improved technology, infrastructure, or capital, specifically for sugarcane, increases land rent for sugarcane in an area (Sparovek et al. 2007), then the future returns of converting pasture land to sugarcane are probably larger than future returns of converting soy land. However, as evidenced by our results, this dynamic may not be the case in regions with established cattle economies of scale. Using presence of slaughterhouses and refrigerated warehouses as proxies for these cattle economies, the significant negative relationship between conversion to sugarcane and this proxy demonstrates that land rents for pasture may be just as competitive as those for sugarcane in these regions.

Our results also show that probability of conversion to sugarcane increases through the creation of sugarcane mills and decreasing transportation costs and travel time to these mills. An institutional push through government loans increased the likelihood of conversion. Moreover, evidenced by the positive significant values associated with both the amount of soy in a region and the silo capacity in a region, conversion to sugarcane is more likely and less risky in established cropping regions than in those with no existing agricultural infrastructure or technology (Fischer et al. 2008).

Our results suggest that the existence of these syndicates in a municipality may block the implementation of sugarcane-infrastructure and dissuade farmers from converting their land to sugarcane. In 2006, rural syndicates and grain processing companies came together in the municipality of Rio Verde to pass a law prohibiting sugarcane expansion in the region. This law (which was later deemed unconstitutional) stated that sugarcane could only be cultivated on 10% of the town's arable area. Rio Verde is a soy-, corn-, poultry-, and pig-growing region, and its residents feared that sugarcane expansion would threaten investment in their existing supply chains. In 2010, the municipality of Jatai passed a similar bill limiting the production of sugarcane in the municipality to 50,000 ha and requiring those who want to expand sugarcane production to gain approval from various municipality agencies. Our results corroborate evidence that municipalities with existing grain or cattle supply chains and adequate representation can hinder the expansion of sugarcane into a region.

3.4 Scenarios

Figure 5 shows the results of our scenario outcomes (A-C) compared with the extent of soy, sugarcane, and pasture areas in Goiás in 2013 (D). Figure 5A shows the probability of conversion if planned mills were opened and planned railroads were constructed (Figure 3). Figure 5B shows the probability of conversion to sugarcane if previous land cover were not considered. Scenarios A and B show higher probabilities of conversion in soy areas in the southern half of the state. Figure 5C shows the probability of conversion based solely on biophysical variables.

As demonstrated by our model, biophysical parameters have little effect on whether or not land is converted to sugarcane (Fig 5C). These results agree with the Ministry of Agriculture's zoning analysis for sugarcane suitability in which they designate 58% of total previously cleared land in the state—a third of Goiás' total area—as suitable.

With few agronomic limitations, extant annual-crop economies and costs associated with transportation, capital, and infrastructure are the key factors in affecting likelihood of conversion to sugarcane. In scenarios where future location of mills and construction of the North-South railroad are considered (Fig 5A), and previous land use is not considered (Fig 5B), areas currently cultivated with soy have higher average probabilities of conversion than pasture areas (Fig 5D).

4. DISCUSSION AND CONCLUDING REMARKS

The recent expansion of sugarcane coupled with the state's extensive history of cattle-ranching and soy-cultivation make Goiás an ideal location for studying food-energy-environment dynamics. Between 2003 and 2013, sugarcane expansion did not affect food production in the state, as sugarcane area, double-cropping area, and the amount of cattle in Goiás all increased simultaneously. These dynamics are similar to those reported in the state of Mato Grosso do Sul (Assunçao et al. 2015).

Also similar to dynamics evidenced in other Brazilian states (Sparovek et al. 2009, Nassar et al. 2008, Assunçao et al. 2015), sugarcane expansion was not responsible for direct deforestation in Goiás. However, it should be noted that our work does not address indirect land-use change – a complex issue often brought up when discussing expansion of sugarcane. Sugarcane expansion has been deemed somewhat ineffectual at offsetting greenhouse gas emissions due to potential indirect land-use change (Searchinger et al. 2008, Leite et al. 2009, Andrade de Sa et al. 2013, Lapola et al. 2010). Yet, many of these studies demonstrate that increasing cattle stocking rates may mitigate these indirect land-use changes (Leite et al. 2009, Lapola et al 2010, Alkamim et al. 2015). Our scenario results support this recommendation. Our results demonstrate that soy areas are more likely to be converted to sugarcane as new planned infrastructure is built (Fig 5A). However, policies incentivizing increasing cattle stocking rates may free up previously cleared pasture land for sugarcane expansion, leaving current and future productive areas less vulnerable to conversion.

Our results also demonstrate that biophysical factors are not limiting sugarcane production. Instead, capital, transportation costs, and institutions are factors more likely affecting the attractiveness (or not) of conversion to sugarcane. As infrastructure improves and more mills open, hence lowering transportation costs, we can expect an increase in sugarcane production. The tendency for mills to open in the southwestern half of the state may be due to its proximity to São Paulo. Not only is São Paulo Brazil's leading producer of sugarcane, but also it contains the main shipping ports that allow for global distribution of both sugar and ethanol. However, the construction of the North-South Railroad in Goiás would link the upper portion of the state to both processing mills and markets that the region could not previously access easily. Most of the remaining intact *Cerrado* vegetation in Goiás exists in these northern regions, and our scenarios demonstrate that the completion of this railroad could increase the likelihood of conversion in this region. These results again emphasize the need for policies to dis-incentivize future *Cerrado* clearing, and instead move sugarcane onto previously cleared land – potentially through increasing cattle stocking rates on pastures.

The results of our scenarios have demonstrated that areas where soy is currently cultivated have, on average, higher probabilities of conversion to sugarcane. In 2010, a law went into effect prohibiting the public and private funding to producers that want to expand sugarcane onto land outside that deemed suitable by the ZAE Cana. However, this law does not apply to companies that had already planned expansion, or those with environmental licensing. The ZAE Cana highlights 11 million ha as suitable for sugarcane production in Goiás. Moreover, the current Brazilian Forest Code allows for landowners to clear 80% of their land if it falls in the *Cerrado* biome, which the entire state of Goiás does. Over 50% of this biome has already been cleared for agropastoral purposes (Klink and Machado 2005). Thus, looking forward, policies should work to prohibit future clearing of intact *Cerrado*, subsidize cultivation of sugarcane on only marginal pastoral and agricultural areas rather than all land previously cleared, and incentivize increasing cattle-stocking rates to ensure the state continues to model environmental sustainability.

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REFERENCES

Adami M, Mello MP, Aguiar DA, Rudorff BFT, de Souza AF (2012) A Web Platform Development to Perform Thematic Accuracy Assessment of Sugarcane Mapping in South-Central Brazil. Remote Sensing 4(10), 3201–3214.

Alkamim A, Sparvoek G, Clarke KC (2015) Converting Brazil's pasture to cropland: An alternative way to meet sugarcane demand and to spare forestlands. Applied Geography 62, 75-84.

Allison PD (1982) Discrete-time methods for the analysis of event histories. Sociological Methodology 1, 61-99.

Andrade de Sa S, Di Falco S, Palmer C (2013) Dynamics of indirect land-use change: empirical evidence from Brazil. Journal of Environmental Economics and Management 65(3), 377-393.

Angelsen A, Kaimowitz D (2001) Agricultural Technologies and Tropical Deforestation. Wallingford, UK: CABI Publications.

Assuncao J, Pietracci B, Souza P (2015) Fuelling Development: Sugarcane Expansion Impacts in Brazil.

Chase J (2003) Regional prestige: Cooperatives and agroindustrial identity in southwest Goias, Brazil Agriculture and Human Values 1, 37-51.

Chomitz KM, Gray DA (1996) Roads, land use, and deforestation: a spatial model applied to Belize. World Bank Economics Review 10(3), 487–512

Chomitz KM, Thomas TS (2003) Determinants of land use in Amazonia: A fine-scale spatial analysis. American Journal of Agricultural Economics 85(4), 1016-1028.

Fischer G, Teixeira E, Hizsnyik ET, Velthuizen H van (2008) Chapter 2 – Land use dynamics and sugarcane production. In: Sugarcane Ethanol: Contributions to climate change mitigation and the environment. Edited by Peter Zuurbier and Jos van de Vooren. Wageningen Academic Publishers, The Netherlands.

Garrett RD, Lambin, EF, Naylor RL (2013) The new economic geography of land use change: supply chain configurations and land use in the Brazilian Amazon. Land Use Policy 34, 265-275

Geist HJ, Lambin EF (2002) Proximate causes and underlying driving forces of tropical deforestation. BioScience 52(2), 143-150.

Harris I, Jones PD, Osborn TJ, Lister DH (2013) Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset. International Journal of Climatology 34(3), 623-642.

Haussman C (2012) Biofuels and Land Use Change: Sugarcane and Soybean Acreage Response in Brazil. Environmental and Resource Economics 51(2), 163-187.

Hira A, Oliveira LG (2009) No substitute for oil? How Brazil developed its ethanol industry. Energy Policy 37, 2450-2456.

Hochstetler K, Montero AP (2013) The Renewed Developmental State: The National Development Bank and the Brazil Model. Journal of Development Studies 49(11), 1484-1499.

IBGE Brazilian Institute of Geography and Statistics (2016) Efetivo dos Rebanhos – Cabeças, http://www.sidra.ibge.gov/br/bda/pecua

Jasinski E, Morton D, DeFries R, Shimabukuro Y, Anderson L and Hansen M (2005_ Physical landscape correlates of the expansion of mechanized agriculture in Mato Grosso, Brazil. Earth Interactions 9, 1–18

Klink CA, Machado RB (2005) Conservation of the Brazilian Cerrado. Conservation Biology 19, 707-713.

Lambin EF, Turner BL, Gest HJ, Agbola SB et al. (2001) The causes of land-use and land-cover change: moving beyond the myths. Global Environmental Change 11(4), 261-269.

LAPIG Laboratoorio de Processamento de Imagens e Geoprocessamento (2015) SIAD-Cerrado. www.lapig.iesa.ufg.br/lapig/index.php/produtos/lapig-maps

Lapola Dm, Schaldach R, Alcamo J, Bondea A, Koch J, Koelking C, Priess J (2010) Indirect land-use changes can overcome carbon saving from biofuels in Brazil. PNAS 107(8), 3388-3393.

Leite RCC, Lean MRLV, Cortez LAB, Griffin WM, Scandiffio MIG (2009) Can Brazil replace 5% of the 2025 gasoline world demand with ethanol? Energy 34, 655–661.

MAPA Ministry of Agriculture, Livestock and Food Supply (2009) Zoneamento Agroecológico da Cana-de-Açúcar Expandir a produção, preservar a vida, garantir o futuro. Brasilia, DF.

Mendonça ML, Pitta FT, Xavier CV (2013) The sugarcane industry and the global economic crisis. Transnational Institute and the Network for Social Justice and Human Rights, Report.

MMA Ministry of the Environment (2007) Áreas Prioritárias para Conservação, Uso Sustentável e Repartição de Benefícios da Biodiversidade Brasileira: Atualização—Portaria MMA n°9, de 23 de janeiro de 2007. Ministério do Meio Ambiente, Secretaria de Biodiversidade e Florestas, Brasília.

Nagavarapu S (2010) Implications of unleashing Brazilian ethanol: trading off renewable fueld for how much forest and savanna land. Working paper.

Nassar AM, Rudorff BFT, Antoniazzi LB, de Aguiar DA, Bacchi MRP, Adami M (2008) Chapter 3 – Prospects of the sugarcane expansion in Brazil: impacts on direct and indirect land use changes. Edited by Peter Zuurbier and Jos van de Vooren. Wageningen Academic Publishers, The Netherlands.

Richards P, Pelligrina H, VanWey LK, Spera SA (2015) Soybean development: the impact of a decade of agricultural change on urban and economic growth in Mato Grosso, Brazil. PLoS One 10(4), e0122510.

Rudorff BFT, Aguiar DA, Silva WF, Sugawara LM, Adami M, Moreira MA (2010) Studies on the rapid expansion of sugarcane for ethanol production in Sao Paulo State (Brazil) using Landsat Data. Remote Sensing 2(4), 1057-1076.

Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D, Yu T (2008) Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. Science 319, 1238-1240.

SIFAEG Sindicato da Industria de Fabricacao de Etanol do Estado de Goias (2016) Noticias: Goias: Investimentos em nemovas usinas caem no Estado. http://www.sifaeg.comEl.br/noticias/goias-2/

Sparovek G, Berndes, G, Egeskog A, de Freitas FLM, Gustafsson S, Hansson J (2007) Sugarcane ethanol productiin in Brazil: an expansion model sensitive to socioeconomic and environmental concerns. Bioefuels, Bioproducts and Biorefining 1(4), 235-316.

Sparovek G, Barretto A, Berndes G, Martins S, Maule R (2009) Environmental, land-use and economic implications of Brazilian sugarcane expansion 1996-2006. Mitigation and Adaptations Strategies for Global Change 14(3), 285-298.

Spera SA, Cohn AS, VanWey LK, Mustard JF, Rudorff BF, Risso J, Adami M (2014) Recent cropping frequency, expansion, and abandonment in Mato Grosso, Brazil had selective land characteristics. Environmental Research Letters 9, 064010.

Spera SA, Galford GL, Coe MT, Macedo MN, Mustard JF (2016) Land Use Change Affects Water Recycling in Brazil's Last Agricultural Frontier, Global Change Biology, in press.

Tilman D, Socolow R, Foley JA, Hill J, Larson E, Lynd L, Pacala S, Reilly J, Searchinger T, Somerville C, Williams R (2009) Beneficial Biofuels – The Food, Energy and Environment Trilemma. Science 325, 270-271.

UNICA (2012) Overview & Outlook: Brazilian Sugarcane Industry. Presentation to the U.S. Energy Information Administration, Washington DC.

Vera-Diaz MDC., Kaufmann RK, Nepstad DC, Schlesinger P (2008) An interdisciplinary model of soybean yield in the Amazonas: the climatic, edaphic, and economic determinants. Ecological Economics 65(2), 420-431.

Walker R, Browder J, Arima E, Simmons C, Pereira MC, Shirtoa R, de Zen S (2009) Rancing and the new global range: Amazonia in the 21st century. Geoforum 40(5), 732-745.

Walker R, Richards P. The ghost of Von Thunen lives; A political ecology of the disappearance of the Amazonia rainforest. In Land Chance Science, Political Ecology, and Sustainability: Synergies and Divergences, Eds: Brannstrom C, Vadjunec JM, New York, NY, 24–47.

Zuurbier P, van de Vooren J (2008) Chapter 1. Introduction to sugarcane ethanol contributions to climate change mitigation and then environment. In: Sugarcane Ethanol: Contributions to climate change mitigation and the environment. Edited by Peter Zuurbier and Jos van de Vooren. Wageningen Academic Publishers, The Netherlands.

Van Zyl J J (2001) The shuttle radar topography mission (SRTM): a breakthrough in remote sensing of topography. Acta Astronaut 48, 559–565.

TABLES

Table 1.

Descriptive Statistics of Variables Considered in Goiás Sugarcane Analysis between 2003 and 2013		
	Mean	SD
Biophysical		
Annual precipitation (mm)	1536.71	100.28
Slope (deg)	2.32	2.18
Elevation (m)	585.55	217.25
Annual min temp (°C)	15.55	0.84
Annual max temp (°C)	25.15	0.98
Capital		
Bank loans ($R)	5,497,528	40,909,330
Institutional		
Travel time to sugarcane mill (minutes)	83.38	55.44
Silo capacity/ha-municipality (tons/ha)	0.07	0.14
Silo capacity (tons)	1136.88	4161.29
% Sugarcane area in municipality	0.41%	1.21
Economies of scale		
% Pixels in municipality with slaughterhouses	19.6%	—
% Soy area in municipality	5.29%	9.75
Previous Land Cover		
Percent from soy	13.80%	—
Percent from pasture	86.20%	—
Dependent Variable		
Percent converted to sugarcane	1%	—
Percent remained soy or pasture	99%	—
N	26,729,530 pixel-years	

Table 2

Final Model

		β	Robust Standard Error
Original Land Cover			
	From Soy	0	—
	From Pasture	1.623***	0.009167
Capital			
	Lagged bank loans	0.00225***	0.000234
Institutional			
	Lead Travel Time to Mill	-0.0494***	0.000191
	Silo capacity	1.621***	0.0178
	Rural Syndicates	-0.801***	0.00514
	Lagged sugarcane area	0.288***	0.000942
Economies of scale			
	Slaughterhouses	0.135***	0.00576
	Lagged percent soy	0.0106***	0.000328
Biophysical			
	Max Temperature	1.877***	0.017
	Min Temperature	-2.039***	0.0205
	Elevation	-0.00177***	0.0000234
	Slope	-0.272***	0.00186
	Precipitation	-0.00363***	0.0000282
Latitude		-0.00000193***	2.47E-08
Longitude		-0.000000124***	3.44E-08
Year Effects		yes	
Intercept		1.448***	0.253
N		26729530	

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

FIGURE CAPTIONS

Figure 1. Study area. Land covers in Goiás State in 2013. The yellow areas are pasture and the light green areas are soy. The black areas represent land that was sugarcane in 2003 and has remained such through 2013. The orange and darker green areas indicate land converted to sugarcane from pasture and soy, respectively, during our study period. The Federal District (DF), home to Brasília, is also highlighted. Inset: Brazil and

its biomes. The Cerrado biome, in which Goiás and the Federal District fall, is highlighted in beige.

Figure 2. Area of soy (green), soy-corn double-cropping (blue), and sugarcane (black, all right y-axis) and number of cows (orange, left y-axis) in Goiás between 2003 and 2013.

Figure 3. Map of some data used in analysis. Note that mills in municipalities neighboring Goiás state (light grey) were used to determine annual travel time to sugarcane mills.

Figure 4. The price received by Brazilian sugar producers is plotted as a dotted-black line (right y-axis) and the predicted probability of conversion to sugarcane for each year during our study period (with 95% confidence intervals), is plotted as a solid,black line (left y-axis). We choose the summer before each growing season to plot the predicted probability of conversion – for example, the probability of converting to sugarcane in 2003 growing season, which spans August 2002-July 2003, is plotted in June of 2002.

Figure 5. Scenario outcomes of the predicted probability of a conversion to new sugarcane (A,B,C). Box A is the probability of conversion to new sugarcane if the planned mills and railroads were opened. Box B is the probability of conversion to sugarcane if previous land cover were not considered. Box C shows the predicted probability of sugarcane if just biophysical variables are considered. Box D is a map of sugarcane area (pink), soy area (green) and pasture area (yellow) in Goiás in 2013.

FIGURES

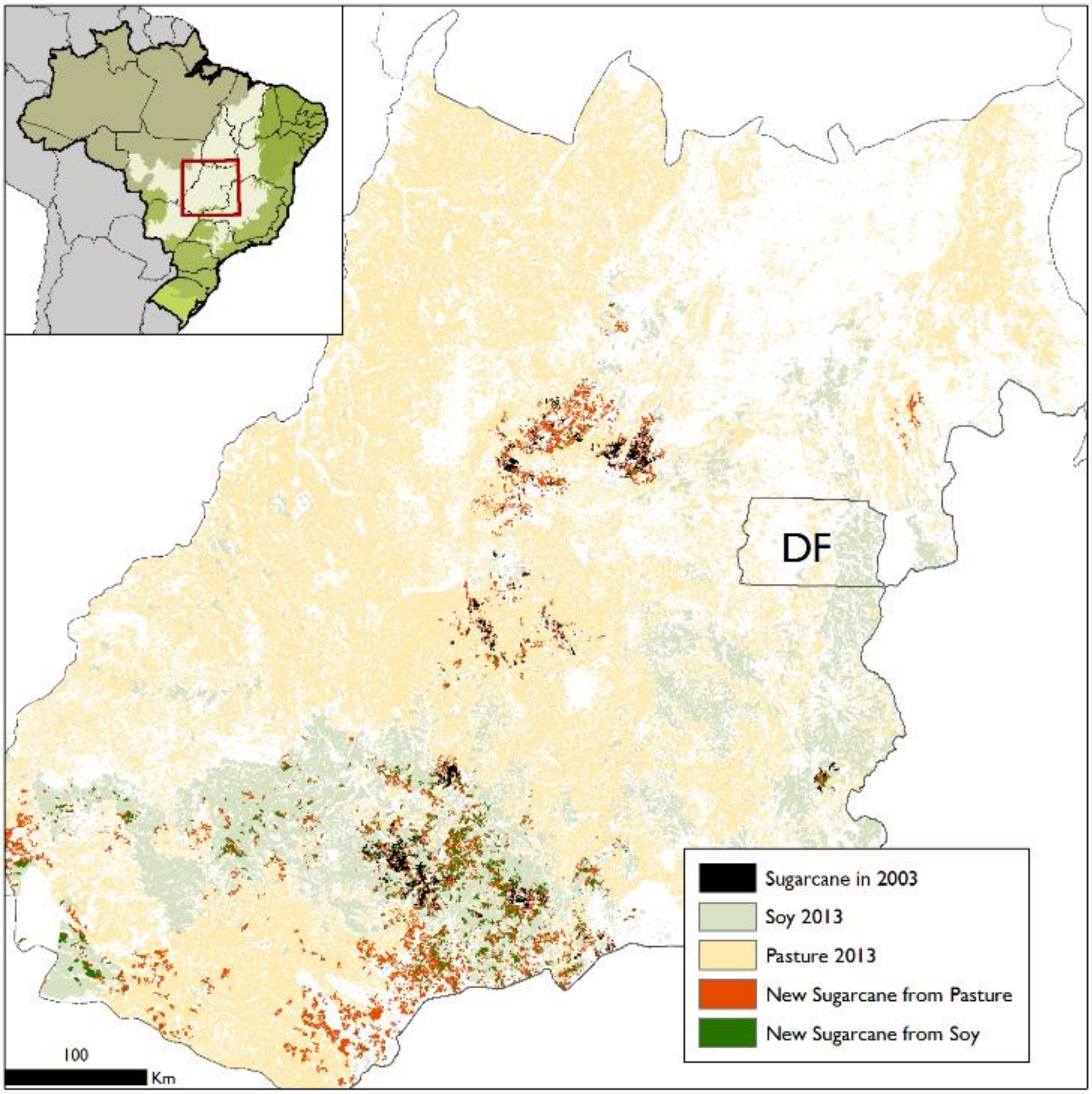


Figure 1

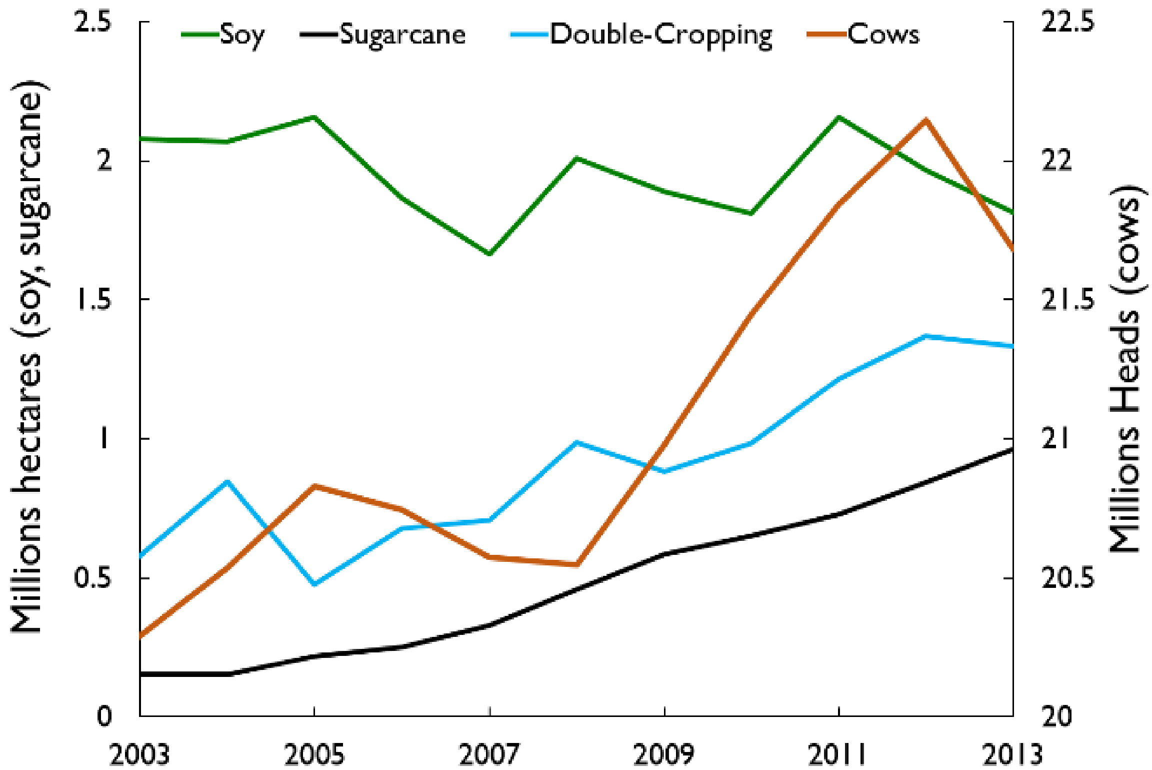

Soy
Sugarcane
Double-Cropping
Cows
Millions hectares (soy, sugarcane)
Millions Heads (cows)
2.5
2
1.5
1
0.5
0
22.5
22
21.5
21
20.5
20
2003
2005
2007
2009
2011
2013

Figure 2

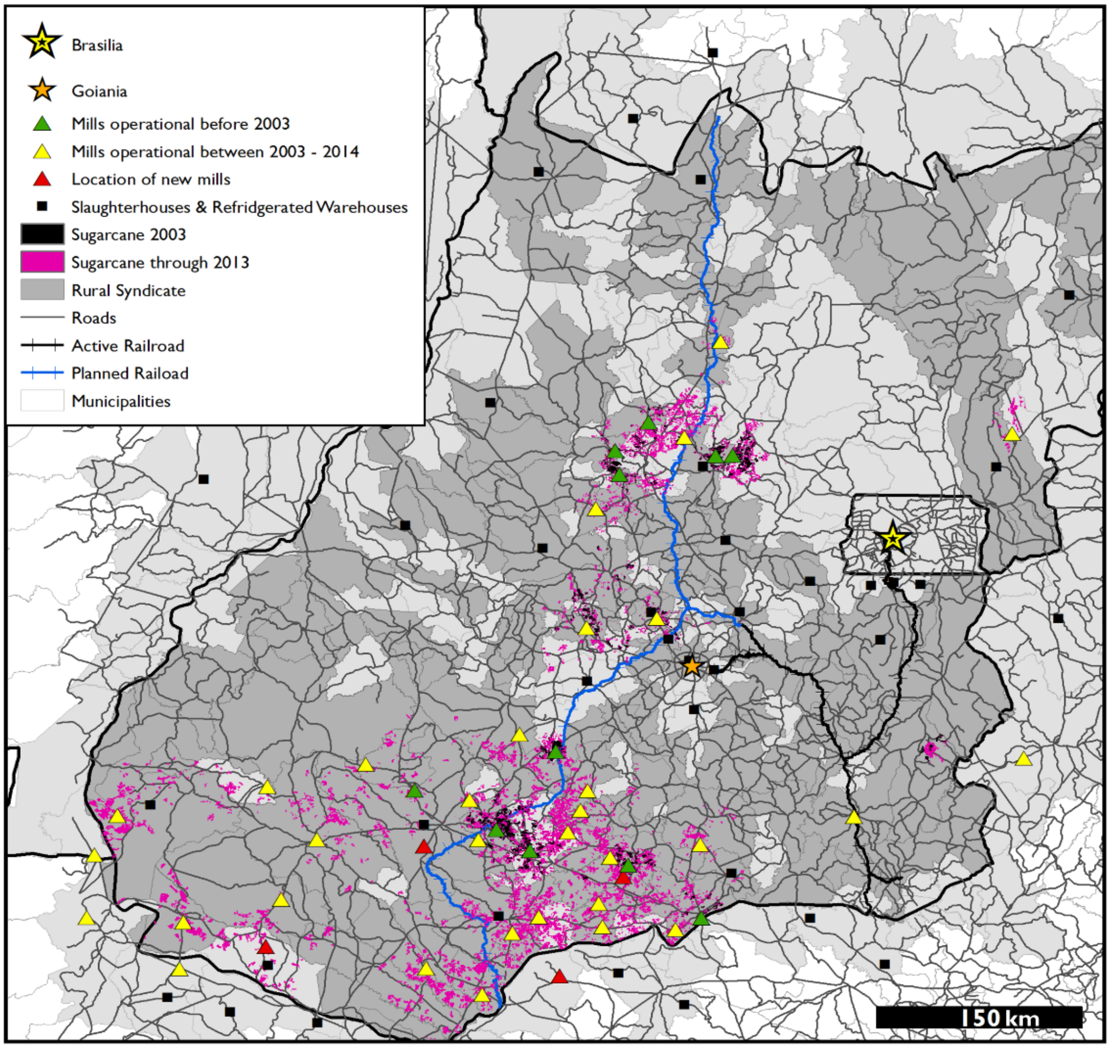
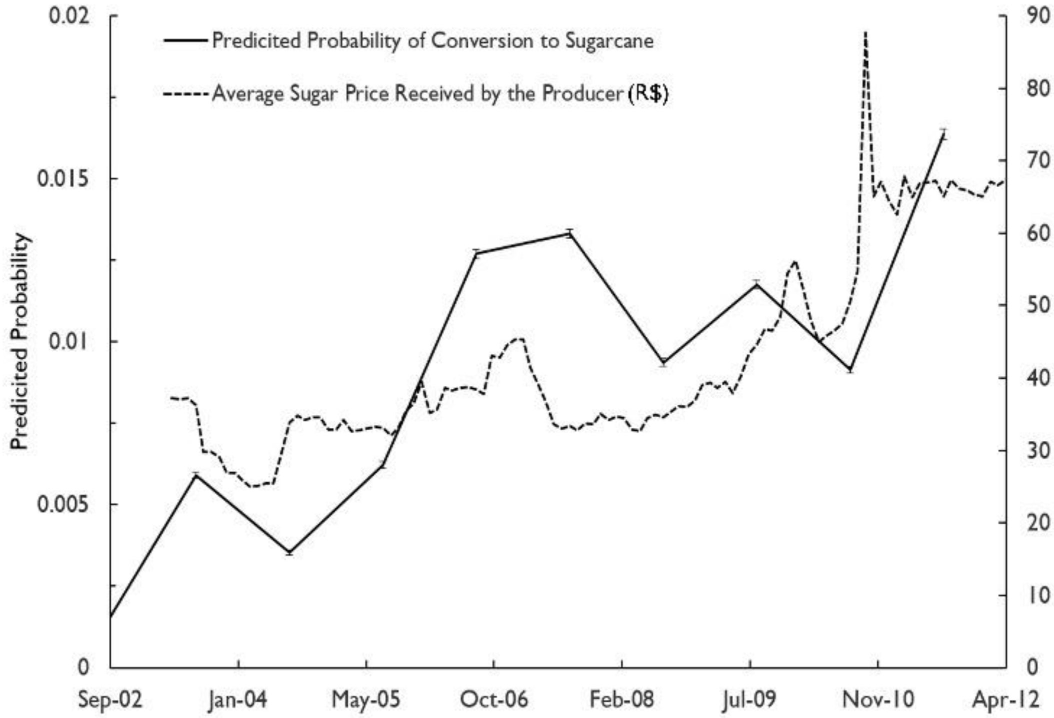

Brasilia
Goiania
Mills operational before 2003
Mills operational between 2003 - 2014
Location of new mills
Slaughterhouses & Refridgerated Warehouses
Sugarcane 2003
Sugarcane through 2013
Rural Syndicate
Roads
Active Railroad
Planned Railroad
Municipalities
150 km

Figure 3



Predicited Probability of Conversion to Sugarcane
Average Sugar Price Received by the Producer (R$)
Predicited Probability
Price of Sugar (R$)
0.02
0.015
0.01
0.005
0
90
80
70
60
50
40
30
20
10
0
Sep-02
Jan-04
May-05
Oct-06
Feb-08
Jul-09
Nov-10
Apr-12

Figure 4

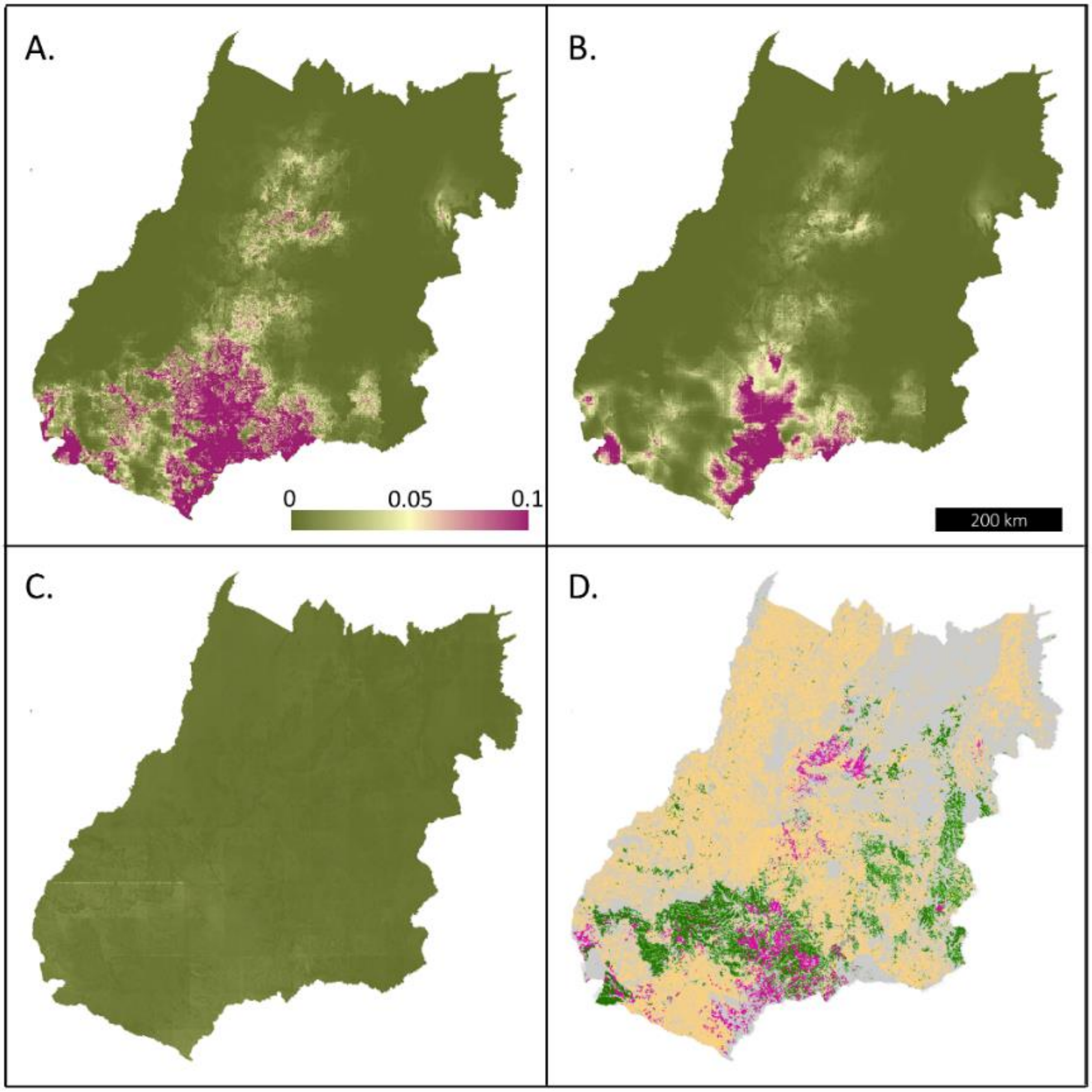


Figure 5

CHAPTER 4

Synthesis: Land-Use and Land-Cover Change across the Brazilian Cerrado

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1. INTRODUCTION

Agricultural production and development in the Brazilian Cerrado has increased Brazil's role in the global marketplace and has ramifications for the global food security, renewable energy resources, and climate change. The Cerrado has been referred to as a "sacrifice zone"—i.e., an environmental trade-off as a means to conserve land in the Amazon (Branstromm 2001, Oliveira and Hecht 2016); and today over 37 million ha of the Cerrado remain legally clearable (Soares-Filho et al. 2014). Here, we analyze land-use change dynamics across the Cerrado, and demonstrate how policies incentivizing intensive agricultural practices such as double-cropping—planting two crops in one growing season—may allow for continued agricultural production while conserving the remainder of the biome.

Brazil is the first and only tropical country to rival the five major temperate grain exporters—the United States, European Union, Argentina, Australia, and Canada—and currently hails as the top exporter of beef, soy, chicken, orange juice, and coffee (FAS 2016). Currently ranked as the seventh largest in the world, Brazil's economy is bolstered by its agricultural sector: agricultural and agribusiness account for almost 25% of Brazil's gross domestic product (GDP) (CEPEA 2016). Even though Brazil's overall GDP shrunk by 3.8% in 2015 due to both a recession and political unrest, the agricultural sector's GDP increased by 1.8% and was the only sector to report any job growth (Lewis 2016, MAPA 2016). The development of the agricultural sector, though, has come at the cost of expansive land clearing, primarily in the oft-overlooked Brazilian Cerrado.

The Cerrado spans 2 million km^2 across central Brazil (Figure 1). Although the Cerrado is broadly classified as savannah, it is comprised of a diverse array of flora with a wide range of physiognomies, spanning closed-canopy forests to grasslands (Eiten 1972). There is no mention of the region in the environmental section of Brazil's Constitution (1988) and, as a result, it has remained relatively unprotected (Hecht 2005). Estimates suggest that 40-55% of the Cerrado's native vegetation has already been cleared, primarily for agropastoral purposes (Klink and Machado 2005, Sano et al. 1010). Since 2000, more than 5.5 million ha of land have been converted from natural vegetation to large-scale, market-oriented agriculture (Figure 1) (Spera et al. 2016).

We argue that the Cerrado does not have to continue to be a sacrifice zone and that Brazil can increase agricultural production while protecting the remainder of the biome. We first demonstrate why the Cerrado is crucial in terms of ecosystem services and agricultural production. We then introduce the policy currently governing the land-use changes in the biome. We compare the drivers of agricultural dynamics—especially the trend toward intensive double cropping—in southern Mato Grosso and Goiás to northern Mato Grosso. We conclude by using these case-study regions to discuss the mechanisms by which effective conservation policy might be applied to Brazil's newest, and potentially last, agricultural frontier, the Matopiba region.

2. THE CERRADO

The Cerrado harbors half of Brazil's agricultural area, 5% of the world's biodiversity, and high rates of species richness (Cavalcanti and Joly 2002, Klink and Machado 2005): 44% of the plant species and 9.2% of vertebrates are endemic to the biome (Calvacanti and Joly 2002). The Cerrado is home to 837 species of birds, 180 species of reptiles, 113 species of amphibians, and a number of threatened mammals, including the jaguar, giant anteater, giant armadillo, and maned wolf (Carvalho et al. 2009, Persson et al 2014). Moreover, the biome contains between 97-179 Mg/ha of CO_2-e (for comparison, the Amazon contains 280-450 Mg/ha of CO_2-e) (PMBC 2013, Garrett and Rausch 2016).

Beginning in the 1940s, nationalistic government policies encouraging development and the securitization of borders, coupled with labor shortages in southern Brazil, initially motivated migration to the Amazon and Cerrado (Hecht and Cockburn 1989, Fearnside 2005, Nepstad et al. 2006, Jepson 2006). In 1960, Brasília became Brazil's new, Cerrado-based, centrally-located capital (Figure 1). Later in that decade, the Brazilian government reframed its agricultural policies to invest in large-scale, mechanized, export-oriented agriculture (Jepson 2006). Investment in infrastructure and agricultural research, government-supported subsidies, and state- and private-led colonization schemes, such as the Development Program for the Cerrado (POLOCENTRO) and the Japanese-Brazilian Cooperative Program for Cerrado Development (PRODECER), further incentivized migration of farmers from southern Brazil to the Cerrado in the 1970s and 1980s (Garrett and Rausch 2016). PRODECER is especially noteworthy because of its international ties and export-oriented goals. PRODECER was a Japanese-Brazilian cooperative that provided capital to commercial farms in the Cerrado, which Japan saw a means of securing its own soy supply (Jepson et al. 2010). During this time, the federal government designated millions of dollars to fund transportation infrastructure and agricultural infrastructure and research across the Cerrado (Jepson et al. 2010).

Agricultural areas in the Cerrado expanded notably after innovations by the newly-created, government-funded Brazilian Agricultural Corporation (EMBRAPA) during the late 1970s. Initially deemed unsuitable for crop agriculture due to its highly acidic, aluminum-rich, nutrient-depleted soils, the southern Cerrado was cleared for pastoral purposes beginning in the 1940s. However, technological advances led by EMBRAPA engendered what *The Economist* would later call, "The miracle of the Cerrado" (2010). The addition of lime to increase soil pH and decrease aluminum toxicity, in tandem with the modification of soy's photoperiod requirement, facilitated the widespread cultivation of the crop in this biome, particularly in Mato Grosso and Goiás. Agricultural cooperatives, like those mentioned above, helped farmers to implement these new techniques and to secure land titles and credit through the early 1990s (Jespon et al. 2010).

Agricultural policies and dynamics shifted again during the 1990s and 2000s. The Brazilian government minimized government-based agricultural credit and instead both encouraged farmers to obtain private loans and promoted free trade and foreign investments in export-oriented agriculture (Jepson et al. 2010, Garrett and Rausch 2016). Agricultural cooperatives then began assisting farmers to gain credit and capital from international agricultural corporations (Jepson et al. 2010). Brazil's agricultural sector became an integral part of global markets (Jepson et al. 2010), both driving and being driven by global commodity prices, global environmental policy initiatives, and even the strength of its own economy. Exchange rates, for example, have played a large role in Brazilian agricultural dynamics: a stronger Brazilian *real*, fueled by a growing economy, made Brazilian exports less attractive during the mid-2000s, whereas a weak *real* (by which the early 2000s and current time period are characterized) made Brazilian exports cheaper and more attractive to international buyers (Richards et al. 2012, Richards and Hoelle 2016). Over the past 15 years, technological advances, coupled with global demand for soy, cotton, corn, and sugar products, have greatly affected the land-cover dynamics across the Cerrado and turned the region into a neo-liberal, market-oriented agricultural breadbasket (Hecht 2005, Jepson 2006, Branstromm 2009, Jepson et al. 2010, DeFries et al. 2013).

Replacing natural Cerrado with agropastoral lands has affected biodiversity (Françoso et al. 2015), carbon stocks (Bustamante et al. 2006), and the regional water balance via changes in evapotranspiration (Spera et al. 2016). This last point is critical because future agricultural production and ecosystem sustainability depend on a stable precipitation regime. Successful crop yields in the Cerrado are contingent on a long, stable wet season, as over 95% of the crops in this region are rain-fed (IBGE 2016). Moreover, climate modeling experiments have shown that preserving remnant Cerrado may be integral to the health of both the Cerrado and Amazon biomes (Costa and Pires 2010, Malhado et al. 2011, Coe et al. 2013, Spracklen et al. 2012, Oliveira et al. 2013). Thus, the region is important in terms of ecosystem services and agricultural and economic development.

3. ENVIROMENTAL POLICY WITHIN THE CERRADO

The Cerrado biome is subject to less environmental regulation than the Amazon. The Brazilian Forest Code, passed in 1965, is the backbone of environmental governance in Brazil. Under the Forest Code, landowners with property in the Amazon biome are required to conserve 80% of their land as forested "legal reserve" (Verissimo et al. 2011, Soares-Filho et al. 2014). Moreover, 44% of areas throughout the Amazon are legally designated as protected areas that cannot be deforested (Verissimo et al. 2011, Soares-Filho et al. 2014). Landowners in the Cerrado, however, are required to maintain just 20% of their properties as legal reserve, and only 3% of the land throughout the Cerrado is legally designated as a "protected area" (Françoso et al. 2015). As highlighted in the inset in Figure 1, the "Legal Amazon" boundary differs in extent from the ecological Amazon biome boundary. The Legal Amazon boundary is associated with the Amazon River watershed, and portions of the Cerrado, like those in Mato Grosso, Tocantins, and Maranhão, fall under this designation (Figure 1). Under the Brazilian Forest Code, if landowners own Cerrado property within the Legal Amazon, legal reserve requirements increase to 35%. Taken together, these Forest Code parameters leave 37 million hectares of intact Cerrado legally clearable (Soares-Filho et al. 2014).

In 2010, the Action Plan for Prevention and Control of Deforestation and Fires in the Cerrado was passed as part of Brazil's National Climate Change Policy (MMA 2016). This plan introduced many conservation goals, including expanding the number of permanently protected areas in the biome and reducing deforestation rates by 40% of the

1998-2008 average (MMA 2016). There has been little effort and support to put this plan into action (Garrett and Rausch 2016) and, consequently, Cerrado deforestation rates skyrocketed in 2011 and 2012, exceeding even Amazon deforestation rates (PRODES 2016, LAPIG 2015).

While the federal environmental policies described above provide a baseline and framework for environmental policy in the Cerrado, voluntary supply-chain-oriented conservation policies have been touted as models of deforestation governance in export- and market-oriented agricultural regions, such as the Cerrado and Amazon (Nepstad et al. 2014, Gibbs et al. 2015). The Soy Moratorium, which stemmed from internationally driven Amazon conservation efforts, is an agreement signed by Greenpeace and Brazil's soybean exporters and producers, in which the signing parties committed only to trade soy that was not cultivated on lands cleared after July 2006. This agreement was recently indefinitely extended.

The Roundtable for Responsible Soy (RTRS), established in 2006, is another globally-driven effort to curb the expansion of soy onto native vegetation and to encourage environmentally responsible cultivation and production of soy and soy products through certification schemes (RTRS 2016). Like the Soy Moratorium, the RTRS stemmed from a collaborative effort between NGOs, environmental conservation groups, and members of the soy industry (RTRS 2016). Unlike the Soy Moratorium, however, which applies only to Brazil, farmers in countries all over the world are encouraged to gain certification from the RTRS. To meet RTRS standards, farmers must comply with their respective country's labor and environmental regulations, and not expand soy onto "high-value conservation areas," some of which occur in the Cerrado (Garrett and Rausch 2016). The RTRS certification process is expensive, and often only large, wealthy farms have the opportunity to gain accreditation (Garrett and Rausch 2016). As of 2013, only 30 farms, amounting to less than 1% of Brazil's total soy production, had been certified (Garrett and Rausch 2016).

In the following section, we discuss the agricultural development of and dynamics in Mato Grosso and Goiás. We then compare the drivers of these land-use changes in Southern Mato Grosso and Goiás to Northern Mato Grosso, and highlight the implications for the development of the Matopiba region. We divide Mato Grosso into halves because although the entire state falls within the Legal Amazon, the northern half falls within the Amazon biome, and the southern half falls within the Cerrado biome (Figure 1). Thus, policies such as the Soy Moratorium only apply to the northern half of Mato Grosso.

4. RECENT AGRICULTURAL DYNAMICS ACROSS THE CERRADO

Due to its proximity to the economic hub and ports of São Paulo state, Goiás was one of the first areas within the Cerrado to be settled, and pastoral agriculture was promoted as a means of economic development (Katzman 1975, Klink and Moreira 2002). Beginning in the 1940s, after decades of mining boom-and-bust cycles, the Brazilian government invested heavily in transportation infrastructure and encouraged settlement in Goiás through colonization schemes and subsidies as part of the "March to the West" (Klink and Moreira 2002).

Although Goiás is historically a ranching state—pastures cover over 30% of the state's land area—it is also a major crop producer and exporter of soy, corn, and sugarcane. Most farms in this area are large, capital-intensive operations, with over 80% of the total agricultural area in the state belonging to farms larger than 100 ha (Figure 3) (IBGE 2006).

Mato Grosso is similar to Goiás in terms of both its settlement history and predominance of large-scale, capitalized, commercial farming operations. Between 1970 and 1990, 35 different private corporations began 104 projects that resulted in the colonization of 3.9 million ha of land in Mato Grosso. (Jepson 2006). Over 89% of the total farm area in the state belongs to farms larger than 100 ha in size, and over 74% of the total farm area belongs to farms larger than 1000 ha (IBGE 2006) (Figure 3). Mato Grosso currently produces over 10% of the world's soy on less than 8% of its own land (IBGE 2016).

Analysis of the drivers of sugarcane expansion in Goiás highlights the complex interactions between local and global influences on land-use and land-cover change within the Cerrado. Goiás has increased area planted in sugarcane over six-fold since 2000. Global sugar prices are significantly related to the likelihood of converting land to sugarcane (Spera et al., in review). Locally, however, capital, infrastructure, and institutions affect the attractiveness of conversion to sugarcane (Spera et al, in review). Local actors also play a large role in land-use dynamics: municipalities with rural syndicates and existing soy and cattle economies can hinder sugarcane expansion (Spera et al. in review). Rural syndicates within Goiás have blocked the expansion of sugarcane in their municipalities, demonstrating the clout that farmers and agricultural lobbyists have even on a county scale. Like sugarcane production in Goiás, agricultural production in Mato Grosso is affected by global, national, and local drivers (Vera-Diaz et al. 2008, Garrett et al. 2013, Spera et al. 2014, Richards et al. 2016).

Cultivated land in both Goiás and Mato Grosso has trended toward intensive double-cropping agriculture. In Goiás, between 2001 and 2013, planted sugarcane area increased from less than 142,000 ha to over 870,000 ha, soy-corn double-cropping areas increased from 373,000 ha to 1,400,000 ha, and the number of cows in the state increased from 20 million to 22 million (Spera et al. in review, IBGE 2016). In Mato Grosso, intensive soy-corn double-cropping rotations expanded from 460,000 ha to over 3,800,000 ha over the last 15 years (Spera et al. 2016).

Of late, much of this expansion of intensive agriculture has occurred on previously cleared land. Of the total Cerrado clearing that has occurred since the turn of the millennium, less than 10% has occurred within Goiás (LAPIG 2016) (Figure 2). The state has instead been converting degraded pasture to row-crop agriculture and intensifying existing row-crop agriculture as a means of increasing production (Spera et al. in review) with minimal consequential competition over land for food (soy, corn, and cattle) and fuel (sugarcane) (Spera et al. in review). Likewise, both Amazon and Cerrado clearing rates have declined in the state of Mato Grosso since the early 2000s (Figure 2) (PRODES 2016, LAPIG 2016). In both states, the increase in intensive agriculture and decrease in clearing of natural vegetation are due to land scarcity created by both environmental legislation and biophysical limitations. Whether driven by policy or physical land scarcity, Brazilian farmers in the states of Goiás and Mato Grosso have demonstrated that they are able to increase their agricultural production by intensifying their existing agricultural lands through double cropping.

Policy drives intensification in northern Mato Grosso

In the northern, Amazon portion of Mato Grosso, declining deforestation rates have been primarily attributed to effective governance. During the mid-2000s, the Brazilian government not only began monitoring deforestation using remotely sensed satellite data, but also expanded the number of permanently protected areas within the Amazon biome (Soares-Filho et al. 2010). The decoupling of soy production from deforestation rates in Mato Grosso after 2006 has also been partly attributed to the Soy Moratorium (Macedo et al. 2012, Gibbs et al. 2015). In conjunction with this decrease in deforestation has been an increase in intensive agriculture. This Amazon-based environmental regulation created a type of land scarcity; as a result, in order for farmers in northern Mato Grosso to increase production while still complying with the Soy Moratorium, they needed to intensify their existing agricultural lands, rather than to expand onto new lands.

Land scarcity drives intensification in Goiás and southern Mato Grosso

In Goiás and the southern, Cerrado portion of Mato Grosso, the trend toward intensification rather than expansion can be attributed to biophysical land scarcity. In both regions, local variables, such as biophysical suitability, local institutions, and access to infrastructure are related to where native vegetation and pasture are converted to extensive and intensive agricultural lands (Jasinski et al. 2005, Vera-Diaz et al. 2008, Spera et al. 2014, Spera et al. in review). In Goiás, only 30% of the Cerrado remains undisturbed (MMA 2007). In the Cerrado of Mato Grosso, the most suitable agricultural lands have specific biophysical qualities (good soils, low slopes, low minimum temperatures, high elevations, etc.) and are close to paved roads (Spera et al. 2014). Yet, due to high rates of land clearing in Mato Grosso's Cerrado during the early 2000s, the area of highly suitable agricultural land for both single- and double-cropping decreased by 40% and 50% respectively between 2001 and 2011 (Spera et al. 2014).

In these regions, it is not policy that is constraining agricultural expansion and driving agricultural intensification; rather, there simply exists little remaining suitable land not in production (Spera et al. 2014). In the southern Cerrado, then, scarcity of suitable agricultural land has contributed to decreasing deforestation rates and provided an impetus for increasing production of intensive double-cropping (Spera et al. 2014, Spera et al. in review).

5. BRAZIL'S LAST AGRICULTURAL FRONTIER

In May of 2015, 337 municipalities in the northeastern Cerrado states of Maranhão, Tocantins, Piauí, and Bahia were officially deemed "Matopiba" by the Brazilian government, and a bill was ratified committing the government to investing in infrastructure, agricultural technology, and the expansion of the rural middle class. Matopiba is the newest, and potentially last, agricultural frontier region within the Cerrado (Figure 1).

Unlike Goiás and Mato Grosso, Matopiba does not have a rich colonization history: this northeastern portion of the Cerrado still contains a large portion of intact natural vegetation and most clearing of natural Cerrado vegetation during the past decade has occurred within Matopiba (Figure 2). Due to lack of infrastructure, the region is relatively disconnected from global markets, and poor logistics currently limit agricultural investments and expansion in the region.

Also unlike Goiás and Mato Grosso, there still exist abundant smallholder farmers in the region (Figure 3). Embrapa reports that 94% of the farmers in Matopiba are classified as "very poor" or "poor," while just 5% belong to the middle class (Embrapa 2015). The 0.42% of farmers that comprise the upper class generate almost 60% of the farm income in the region (Embrapa 2015).

The spatial configuration of the landscape is inherently different in Matopiba. Whereas Goiás and Mato Grosso are characterized by large farms clustered along major transportation networks, Matopiba is characterized by a fragmented agricultural landscape with smallholders distributed throughout. The region developed without being highly influenced by the location of infrastructure and, as a result, it has the opportunity to develop differently than either Mato Grosso or Goiás. Currently, the Brazilian government expects cultivated agricultural areas in Matopiba to expand by another 2.7 million ha by 2025 (MAPA 2015). We argue, however, that increased agricultural production can be achieved without clearing more land through the promotion of double cropping.

Environmental policies effective in Mato Grosso and Goiás will not be effective in Matopiba. The Soy Moratorium and the Roundtable for Sustainable Soy are only accessible to wealthy, large-scale farms in regions with extant supply chains. Furthermore, farmers throughout Brazil have demonstrated their strength as lobbyists (Branstromm 2009, Spera et al. in review). Case studies have demonstrated that farmers are only willing to comply with environmental regulations if their productivities remain unaffected and there exists a fiscal incentive, such as access to credit (Branstromm 2009). For example, farmers who are members of the Association of Bahian Farms and Irrigators only comply with agricultural and environmental laws insomuch as it allows them to receive credit and increase their agricultural productivity (Branstromm 2009). On the national level, a strong agricultural lobby successfully fought for deforestation amnesty in the 2012 update to the Brazilian Forest Code.

Developers of the Matopiba region, then, can learn from the land-use change dynamics of Mato Grosso and Goiás. The agricultural dynamics in Goiás and Mato Grosso demonstrate that it is possible to increase agricultural production without clearing what is left of natural vegetation. Only 15% of the large-scale agriculture in Matopiba is double-cropped (Spera et al. 2016). Intensifying agriculture from single-cropping regimes to double-cropping regimes on the remaining 85% of already cultivated land will provide large gains in agricultural production. Moreover, this is technologically feasible because Embrapa has already developed a Matopiba-adapted soybean cultivar that matures in only 110 days, which enables the cultivation of two crops per growing season. Rather than continue to clear new land for agriculture, the government could partner with smallholder-based agricultural cooperatives and promote intensive agriculture for farmers who have already cleared land in the region.

It is important to recognize that the expansion of intensive agriculture in Matopiba may not be easily taken up by smallholders. Instances of violent conflict and vocal smallholders resisting agribusiness' entry to the region have already been reported (Guest 2015, Hill 2015, Arsenault 2016). Thus, smallholders face high transaction costs if they want to either keep their land or participate in Brazil's export market. Providing these smallholders who comply with existing environmental regulation access to credit, capital, and agricultural technology may help increase agricultural productivity on land that has already been cleared. A fifth of the variation in agricultural productivity in Brazil has been correlated with credit access (Assunção and Chiavari 2015). Moreover, nearly 40% of all smallholder farmers in Brazil do not have land titles (Lapola et al. 2014). Agricultural cooperatives, which proved so integral to the colonization of Mato Grosso and Goiás, may be crucial to helping smallholders navigate the legal system and acquire property rights. In regions like Matopiba, giving smallholders property rights, access to subsidized credit, and intensive agriculture technology may help them increase production gains and access the agricultural market.

Furthermore, across the Cerrado, between 50-60% of the pastures are degraded (Strassburg et al. 2014, Assunção and Chiavari 2015). The Brazilian government could also focus on improving these pasture lands. Increasing pasture productivity by just 20% would allow Brazil to meet food and energy demands until 2040 (Strassburg et al. 2014). Positive incentives for increasing cattle stocking rates on productive pasture, in addition to increasing agricultural production on previously cleared land and degraded pastures, may prove to be an effective policy that also disincentives new Cerrado land clearing.

Intensive agriculture has been linked to positive socioeconomic (better schools, jobs, and higher GDPs per capita) and environmental (evapotranspiration rates akin to native Cerrado vegetation) outcomes elsewhere in the Cerrado (VanWey et al. 2013, Richards et al. 2015, Spera et al. 2016). Incentivizing intensive agriculture would promote socioeconomic development and provide a means for increasing agricultural production without sacrificing what is left of the Cerrado.

6. CONCLUDING REMARKS

The land-use and land-cover dynamics in the Cerrado are driven and constrained by multiple economic and institutional factors acting at various temporal and spatial scales. Increased agricultural production has engendered local socioeconomic benefits and greatly contributed to Brazil's economic gains in the mid-2000s. The expansion, however, has also incurred negative environmental effects including biodiversity losses, carbon losses, and modification of the regional water cycle. The continued expansion of agriculture in the Cerrado highlights the consequences of prioritizing the conservation of one ecosystem over another.

Brazil's government and economy are currently troubled. A weak *real* makes Brazilian exports more attractive, potentially incentivizing deforestation (Richards and Hoelle 2016). Brazilian President Michel Temer (who succeeded Dilma Rousseff following her 2016 impeachment), recently named Blairo Maggi, "King of Soy," Brazil's new Minister of Agriculture. Maggi, who has been bestowed Greenpeace's "Golden

Chainsaw" award for his deforestation record while governor of Mato Grosso, led the charge by the agribusiness lobby to provide amnesty to farmers who illegally cleared land before 2009 in the 2012 update to the Brazilian Forest Code. And, some have suggested that farmers will again clear land en masse, expecting future amnesty-based amendments to the Forest Code with Maggi's new position (Anderson 2016).

We recommend that conservation of the remaining Cerrado ecosystem should be considered a high priority. As highlighted above, policies supporting intensive double-cropping and reclamation of degraded pastures could be integral to this preservation. Our Mato Grosso and Goiás case studies have demonstrated that farmers are capable of increasing agricultural production by intensifying their land when either policy or land scarcity have constrained expansion. It seems, then, that the Cerrado does not need to continue to be sacrificed for increases in agricultural production. The Brazilian government should focus their efforts on managing and intensifying previously cleared lands. However, a pro-business government not focused on *sustainable* development coupled with increased global demand for Brazilian goods due to a weaker *real* leave both the Amazon and Cerrado biomes in a precarious state.

REFERENCES

Anderson JL (2016) A Way Forward For Brazil. The New Yorker. http://www.newyorker.com/news/daily-comment/a-way-forward-for-brazil

Arima EY, Richards P, Walker R, Caldra MM (2011) Statistical Confirmation of indirect land use change in the Brazilian Amazon. *Environmental Research Letters* **6(2)**, 024010.

Arsenault C (2016) 'Losing our land like losing our lives' Brazil activist tells world bank. Reuters. http://www.reuters.com/article/us-landrights-brazil-agriculture-idUSKCN0WI2QY

Assunção J, Chiavari J (2015) Towards Efficient Land Use in Brazil. Climate Policy Initiative, 28 pp.

Barona, E., Ramankutty, N., Hyman, G., & Coomes, O. T. (2010). The role of pasture and soybean in deforestation of the Brazilian Amazon. *Environmental Research Letters 5(2)*, 024002.

Branstromm C (2001) Conservation-with-Development Models in Brazil's Agro-Pastoral Landscapes. *World Development* **29(8)**, 1345-1359.

Branstromm C (2009) South America's Neoliberal Agricultural Frontiers: Places of Environmental Sacrifice or Conservation Opportunity. *AMBIO: A Journal of the Human Environment* **38(3)**, 141-149.

Bustamante MMC, Corbeels M, Scopel E, Roscoe R (2006) Soil carbon storage and sequestration potential in the Cerrado Region of Brazil. In: Lal R, Cerri CC, Bernous M, Etchevers J, Cerri I (Ed.) Carbon sequestration in soils of Latin America. CRC Press, 285-304.

Calvalcanti RB, Joly CA (2002) Biodiversity and conservation priorities in the Cerrado reigon. In: Oliveira PS, Marquis RJ (Ed.) Ecology and natural history of a Neotropical Savanna. New York: Columbia University Press, 351-367.

Carvalho FMV, Junior PDM, Ferreira LG (2009) The Cerrado into-pieces: Habitat fragmentation as a function of landscape use in the savannas of central Brazil. *Biological Conservation* **142**, 1392-1403.

CEPEA (Center for Advanced Studies on Applied Economics) (2016) BR Agribusiness GDP. <http://cepea.esalq.usp.br/english/GDP>

Coe MT, *et al.* (2013) Deforestation and climate feedbacks threaten the ecological integrity of south–southeastern Amazonia. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* **368**, 20120155.

Costa MH, Pires GF (2010) Effects of Amazon and Central Brazil deforestation scenarios on the duration of the dry season in the arc of deforestation. *International Journal of Climatology* **30**, 1970–1979.

DeFries RS, Herold M, Verchot L, Macedo MN, Shimabukuro Y (2013) Export-oriented deforestation in Mato Grosso: Harbinger or exception for other tropical forests? *Philosophical Transactions of the Royal Society-Biology* **368**, 20120173.

The Economist (2010). The miracle of the Cerrado. The Economist Newspaper Limited, London.

Eiten G (1972) The Cerrado vegetation of Brazil. Botanical Review **38**, 201-341.

Embrapa (Brazilian Agricultural Research Corporation) (2015) MATOPIBA: Delimitacao, Caracterizacao, Desafios e Oportunidades para o Desenvolvimento – BAHIA www.embrapa.br/gite/projectos/matopiba/matopiba.html.

FAS Foreign Agricultural Service, United States Department of Agriculture (2016) Production, Supply and Distribution Online Reports. http://apps.fas.usda.gov/psdonline/psdHome.aspx

Fearnside PM (2005) Deforestation in Brazilian Amazonia: history, rates, and consequences. *Conservation Biology* **19(3)**, 680-688.

Françoso RD, et al. (2015) Habitat loss and the effectiveness of protected areas in the Cerrado Biodiversity Hotspot. *Natureza & Conservação* **13**, 35–40.

Garrett RD, Lambin EF, Naylor RL (2013) The new economic geography of land use change: supply chain configurations and land use in the Brazilian Amazon. *Land Use Policy* **34**, 265-275.

Garrett RD, Rausch LL (2016) Green for gold: social and ecological tradeoffs influencing the sustainability of the Brazilian soy industry *The Journal of Peasant Studies* **43(2)**, 461-493.

Gibbs HK, Rausch L, Munger J, Schelly I, Morton C, Noojipady P, Soares-Filho B, Barreto P, Micol L, Walker NF (2015) Brazil' Soy Moratorium Supply chain governance is needed to avoid deforestation. *Science* **347(6220)**, 377-378.

Guest P (2015) The Nutcrackers and 'the Chainsaw Queen': The Fight for Control Over Brazil's Amazon. VICE News. https://news.vice.com/article/the-nutcrackers-and-the-chainsaw-queen-the-fight-for-control-over-brazils-amazon

Hecht S, Cockburn A (1989) The Fate of the Forest: Developers. Destroyers and Defenders of the Amazon (New York: HarperPerennial, 1990)

Hecht SB (2005) Soybeans, development and conservation on the Amazon frontier. *Development and Change* **36(2)**, 375-404.

Hill D (2015) Future of Brazil's babassu fruit breakers threated by deforestation. The Guardian. https://www.theguardian.com/environment/2015/aug/18/future-brazils-babassu-fruit-breakers-threatened-deforestation

IBGE. Brazilian Institute of Geography and Statistics (2006) http://www.sidra.ibge.gob/br/

IBGE. Brazilian Institute of Geography and Statistics (2016) http://www.sidra.ibge.gob/br/

Jasinski E, Morton D, DeFreise R, Shumaburkuro Y, Anderso L (2005) Physical Landscape Correlatios of the Expansion of Mechanized Agriculture in Mato Grosso, Brazil. *Earth Interactions* **9(16)**.

Jepson W (2006). Private agricultural colonization on a Brazilian frontier, 1970–1980. *Journal of Historical Geography* **32(4)**, 839-863.

Jepson W, Brannstrom C, Filippi A. (2010). Access regimes and regional land change in the Brazilian Cerrado, 1972–2002. *Annals of the Association of American Geographers* **100(1)**, 87-111.

Katzman MT (1975) Regional Development Policy in Brazil: The Role of Growth Poles and Development Highways in Goias. *Economic Development and Cultural Change* **24(1)**, 75-107.

Klink CA Moreira AG (2002) Past and current human occupation and land-use. In: Oliveira PS, Marquis RJ (eds.). The Cerrado of Brazil. Ecology and natural history of a neotropical savanna. pp. 69-88. Columbia University Press, New York.

Klink CA, Machado RB (2005) Conservation of the Brazilian cerrado. *Conservation Biology* **19(3)**, 707-713.

Knox RG, Longo M, Swann ALS, Zhang K, Levine NM, Moorcrof PR, Bras RL (2015) Hydrometeorological effectsof historical land-conversion in an ecosystem-atmosphere model of Northern South America. *Hydrology and Earth Systems Science* **19**, 241-273.

LAPIG (Laboratóorio de Processamento de Imagens e Geoprocessamento) (2015) SIAD-Cerrado. www.lapig.iesa.ufg.br/lapig/index.php/produtos/lapig-maps

Lapola DM, Martinelli LA, Peres CAC, Ometto JPHB, Ferreira ME, Nobre CA, Aguar APD, Bustamante MMC, et al. (2014) Pervasive transition of the Brazilian land-use system. *Nature Climate Change* **4**, 27-35.

Lewis, JT (2016) “Agriculture in Brazil’s One Bright Spot” The Wall Street Journal, April 8, 2016 http://www.wsj.com/articles/agriculture-is-brazils-one-bright=spot-14015712

Malhado ACM, Pires GF, Costa MH (2010) Cerrado Conservation is Essential to Protect the Amazon Rainforest. *AMBIO* **39**, 580-584.

MAPA (Ministério da Agricultura, Pecuária e Abastecimento) (2015) Projeções do Agronegócio: Brasil 2014/15 a 2024/25 Projeçoes de Longo Prazo.

MAPA Ministry of Agriculture (2016) PIB da agropecuaria tem alta de 1,8% em 2015. Noticias. http://agricultura.gov.br/communicaco/noticias/2016/03/pib-da-agropecuraria-tem-alta-de-1porcento-em-2015

MMA Ministry of the Enironment (2016) Plano de Ação para Prevenção e Controle do Desmatamento e das Queimadas no Cerrado < http://www.mma.gov.br/florestas/controle-e-preven%C3%A7%C3%A3o-do-desmatamento/>

Nepstad DC, Stickler CM, Almeida OT (2006). Globalization of the Amazon soy and beef industries: opportunities for conservation. *Conservation Biology* **20(6)**, 1595-1603.

Nepstad D, McGrath D, Stickler C, Alencar A, Azevedo A, Swette B, Bezerra T, DiGiano M, Shimada J, da Motta RS, Armijo E, Castell L, brando P, Hansen MC, McGrath-Horn M, Carvalho O, Hess L (2014) Slowing Amazon deforestation through public policy interventions in beef and soy supply chains. *Science* **344(6188)**, 1118-1123.

Oliveira LJC, Costa MH, Soares-Filho BS, Coe MT (2013) Large-scale expansion of agriculture in Amazonia may be a no-win scenario. *Environmental Research Letters* **8**, 024021.

Oliveira G, Hecht S (2016) Sacred groves, sacrifice zones and soy production: globalization, intensification and neo-nature in South America. *The Journal of Peasant Studies* **43(2)**, 251-285.

Perrson M, Henders S, Kastner T (2014) Trading Forests: Quantifying the Contribution of Global Commodity Markets to Emissions from Tropical Deforestation. *CGD Working Paper 384*, Washington, DC. Center for Global Development.

Plano Brasileiro de Mudanças Climáticas (PBMC) (2013) Sumário Executivo Do Volume 1 – Base

Científica Das Mudanças Climáticas. Rio de Janeiro, Brasil.

PRODES (2016): Câmara G, Valeriano DM, Soares JV (2006) Metodologia para o Cálculo da Taxa Anual de Desmatamento na Amazônia Legal. INPE. (http://www.obt.inpe.br/prodes/ index.html)

Richards, P. D., Myers, R. J., Swinton, S. M., & Walker, R. T. (2012). Exchange rates, soybean supply response, and deforestation in South America. *Global Environmental Change* **22(2)**, 454-462.

Richards P, Pellegrina H, VanWey L, SPera S (2015) Soybean Development: The Impact of a Decade of Agricultural Change on Urban and Economic Growth in Mato Grosso, Brazil. *PLoS ONE* **10(4)**, e0122510

Richards P, Hoelle J (2016) Brazil's thriving soy industry threatens its forests and global climate targets. The Conversation. http://theconvseration.com

Sano EE, Rosa R, Brito JLS, Ferreira LG (2010) Land cover mapping of the tropical savanna region in Brazil. *Environmental Monitoring Assessment* **166**, 113–124.

Soares-Filho B, Moutinho P, Nepstad D, Anders A, Rodrigues H, Garcia R, Dietzch L, Merry F, Bowman M, HIssa L, Silvestrinin R, Maretti C (2010) Role of Brazilian Amazon protected areas in climate change mitigation. *PNAS* **107(24)**, 10821-10826.

Soares-Filho B, Rajao R, Macedo M, Carneiro A, Costa W, Coe M, Rodrigues H, Alencar A (2014) Cracking Brazil's Forest Code. *Science* **344**, 363-364.

Spera SA, Cohn AS, VanWey LK, Mustard JF, Rudorff BF, Risso J, Adami M (2014) Recent cropping frequency, expansion and abondement in Mato Grosso, Brazil had selective land characteristics. *Environmental Research Letters* **9**, 064010.

Spera SA, Galford GL, Coe MT, Macedo MN, Mustard JF (2016) Land Use Change Affects Water Recycling in Brazil's Last Agricultural Frontier, Global Change Biology, in press.

Spera SA, VanWey LK, Mustard JF (in review) The drivers of sugarcane expansion in Goiás.

Spracklen DV, Arnold SR, Taylor CM (2012) Observations of increased tropical rainfall preceded by air passage over forests. *Nature* **489**, 282–285.

Strassburg BBN, Latawiec AE, Barioni LG, Nobre CA, da Silva VP, Valentim JF, Vianna M, Assad ED (2014) When enough should be enough: Improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. *Global Environmental Change* **28**, 84-97.

VanWey, L. K., Spera, S., de Sa, R., Mahr, D., & Mustard, J. F. (2013). Socioeconomic development and agricultural intensification in Mato Grosso. *Philosophical Transactions of the Royal Society B: Biological Sciences* **368(1619)**.

Vera-Diaz, M. D. C., Kaufmann, R. K., Nepstad, D. C., & Schlesinger, P. (2008). An interdisciplinary model of soybean yield in the Amazon Basin: the climatic, edaphic, and economic determinants. *Ecological Economics* **65(2)**, 420-431.

Verissimo A, Rolla A, Vedoveto M, deFurtada SM (2011) Areas Protegidas na Amazonia Brasiliera: avancos e desafios. Imazon/ISA.

FIGURE CAPTIONS

Figure 3. Map of cropland agriculture between 2003 and 2013 across the Cerrado states of Mato Grosso (MT), Goiás (GO), Maranhão (MA), Tocantins (TO), Piauí (PI) and Bahia (BA), the latter four of which comprise the Matopiba region. Brasília, Brazil's capita, is highlighted with a red star. The map is derived from MODIS 250 m Enhanced Vegetation Index (EVI) data (Spera et al. 2016) and highlights the expansion and intensification of row-crop agriculture throughout the Cerrado. Between 2003 and 2013, Goias predominantly experienced an intensification of row-crop agriculture, Mato Gross experienced an expansion and intensification of row-crop agriculture, and Matopiba experienced an expansion of row-crop agriculture. Inset: The Cerrado biome is featured in ecru, and our region of interest is bounded by the blue box. The Amazon forest is the olive green region in the northwestern portion of the country, and the Atlantic Forest is the green region along the eastern portion of the country. The Legal Amazon boundary is cross-hatched.

Figure 4. The black line (left y-axis) represents the total area deforested each year within the Cerrado. The bar graphs represent the percentage of total deforestation in each region: green is Goiás and the Federal District, blue is Mato Grosso, purple is Matopiba, and orange is the remainder of the Cerrado.

Figure 3. The bar graphs represent the percentage of total farm area in each size category in each state: blue is percentage of total farm area belonging to farms smaller than 10 ha, purple is 10 – 100 ha, green is 100 – 1000 ha, red is greater than 1000 ha.

FIGURES

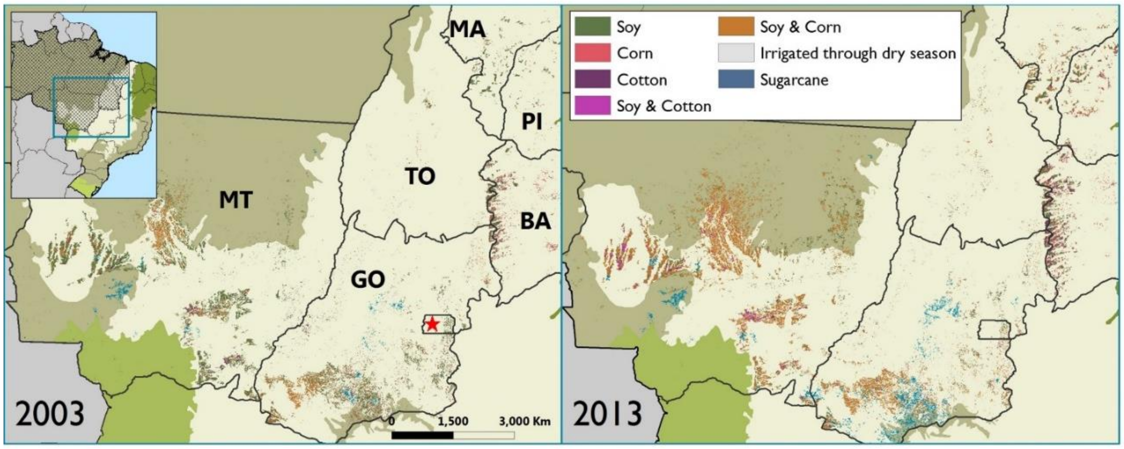

Figure 1

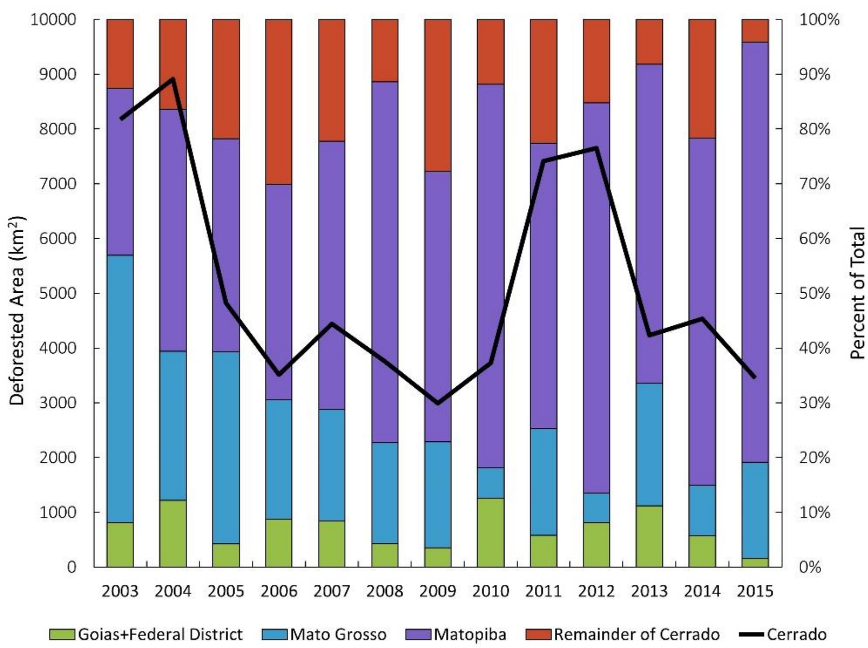

Figure 2

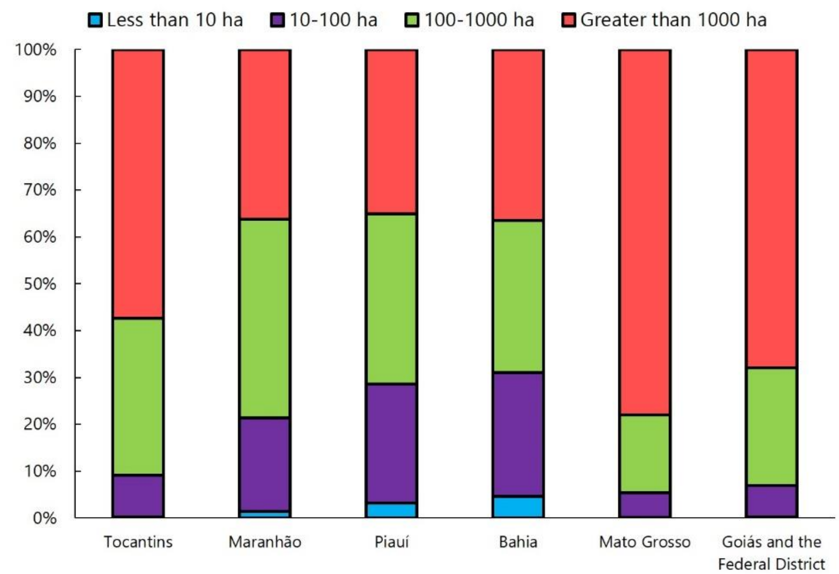
Less than 10 ha
10-100 ha
100-1000 ha
Greater than 1000 ha
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Tocantins
Maranhão
Piauí
Bahia
Mato Grosso
Goiás and the Federal District

Figure 3