Supplemental Materials

Materials and Methods

References only for the Supplement

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1. Study Area

The study area included the entire Cerrado biome outside federally protected conservation areas (ICMBio, 2016) and Indigenous Territories (Funai, 2016).

2. Assessment of annual clearing

The heterogeneity of the vegetation and land use dynamics in the Cerrado make some land cover transitions difficult to map with satellite data (Brannstrom et al, 2008), though in recent years there has been a boom in availability of maps of conversion and of land use/land cover there. We rely on the MODIS-based SIAD-Cerrado due to its full coverage, its use of an official land use map (PROBIO) as its baseline, and its availability as an annual time series. Other datasets, including PRODES-Cerrado, provide higher-resolution maps but lack some of these other benefits. SIAD-Cerrado relies on automatic classification to track clear cutting, or total removal of native vegetation, and masks out previously cleared areas in subsequent years of analysis. Thus, the estimates are for gross conversion only and exclude both degradation and conversion of regenerating vegetation, in addition to regrowth of any secondary vegetation on areas already classified as cleared. We found SIAD-Cerrado's moderate spatial resolution to be adequate for quantifying the portion of clearing due to soy expansion because soy properties are generally well above the 6.25 ha size of a single MODIS pixel (median property size = 251ha). Clearing for soy is also typically unambiguous because planting requires full removal of native vegetation. SIAD-Cerrado data have an accuracy of 76-79% (Rocha et al, 2011).

We compared SIAD-Cerrado with the PRODES-Cerrado (MMA, 2018). PRODES-Cerrado classified 14Mha more area as cleared (SIAD-Cerrado: 86 Mha versus PRODES: 100 Mha). Some of this difference was due to incorporation of the "non-forest" areas from the PRODES-Amazon product into the 2008 PRODES-Cerrado clearing data, which appears to have inflated the numbers for that year. Cumulative agreement between the two datasets through 2016 was 86% of SIAD-Cerrado cleared area and 116% of PRODES cleared area, though disagreements for individual years were much greater, suggesting that the datasets differed largely according to the timing of clearing.

3. Assessment of soy location and expansion

3.1 Soy extent

Our analysis used two spatial datasets of crop extent to create a time series of annual soy maps that covers the period from 2001-14. We used annual MODIS-based maps of cropland produced by NASA for the years 2001-12 and a Landsat-based map for the year 2014 produced by the firm Agrosatélite ("AgSat"), which includes the range of soy, corn, and cotton, to extend the time period (Rudorff et al 2015). The NASA maps had an accuracy of 76-94% when assessed with areal and ground photos for the years 2010-11 (Gibbs et al 2015a). The AgSat data agreement with official, municipal level agricultural statistics data exceeds 90% (IBGE 2015; Dias et al 2016).

The NASA dataset included two subsets of maps — a one-year version ("1yr") covering 2001-13 and a two-year version ("2yr") covering 2001-12. These maps were produced using automatic classification of the MODIS Normalized Difference Vegetation Index (NDVI) to produce seven phenology metrics and one tree cover metric, as described in greater detail in Noojipady et al 2017 and Gibbs et al 2015a, and were then used to identify areas where a crop had been planted according to the soy crop calendar. Each 1yr map was produced independent of previous years and the 2yr version adds additional robustness since it combines two years and retains only the areas where soy was identified in both years. See Gibbs et al. 2015a for full details.

To maximize both the reliability of the data and the length of our time series, we combined the NASA 2yr maps with the final year of the NASA 1yr series (2013) and the AgSat map (2014). We updated the naming of the 2yr maps by shifting them one year earlier so that they would refer to the first year that soy was detected instead of the second, as was the case in previous studies. For example, under the previous naming convention based on the second year of soy identification, NASA_2yr_2007 was where NASA_1yr_2006 + NASA_1yr_2007 overlapped; with our year-label adjustments, NASA_2yr_2007 became where NASA_1yr_2007 + NASA_1yr_2008 overlap. This shift shortened the length of the time series of the 2yr data by one year, because the map previously labeled NASA_2yr_2013 was relabeled as NASA_2yr_2012. To make up for the "loss" of NASA_2yr_2013 and to avoid a gap in our time series, we used AgSat 2014 as the second year check on the 1yr NASA map for 2013 (NASA_1yr_2013) to create a 2yr 2013 map that retained all areas identified as soy in both the 1-year 2013 NASA data and in the 2014 AgSat map. The final year of our time series is the 2014 AgSat map, which is based on manual classification of higher resolution Landsat images with consultation of contemporaneous MODIS images rather than a second year of crop identification to confirm the presence of soy.

The 2014 indicated an increase of 16% (1,882,103 ha) compared to MODIS-based 2013 maps from NASA. This increase was larger than those indicated in earlier years where we have only NASA data for comparison. This large increase had little impact on the analysis of how much Cerrado clearing was for soy because it was included only at the end of our time series, though it could suggest that we have underestimated soy's role in conversion during previous years.

Nonsoy years in common cropping regimes of soy-corn and soy-cotton rotations are reflected in our data, though we consider these to be soy areas due to their periodic use to grow soy. For example, we compared a map of soy, corn, and cotton areas in the Cerrado produced by AgSat for 2007 with our 2014 map. Of the 2014 cotton area, 49% was planted with soy in 2007 (257,389 ha). A smaller portion of this area (37%; 175,682 ha) was cotton in 2007. The residual area (14%, 95, 835 ha) included areas identified as other crops, pasture, or native vegetation in 2007. Trends were similar with corn: 40% (495,717 ha) of the 2014 corn was soy in 2007, 19% (235,178 ha) was corn in 2007, and the residual 41% (506, 776 ha) was identified as other crops, to pasture, or native vegetation. Given the seven-year window in these data, it is also possible that some portion of the areas that appeared to persist in corn or cotton and of the residual areas also had one or more years of soy planting. Inclusion of corn and cotton accounted for an additional 1,237,574 ha, and 528,831 ha, respectively, in our soy area totals for 2014 (a total of 10% of the crop area). The NASA maps do not distinguish among crops; though they were designed to identify soy planting, they likely also capture some corn and cotton areas (Gibbs et al 2015a).

3.2 Annual soy expansion

We used our time series of soy extent to create a single soy expansion dataset that identifies the year in which soy was planted for the first time in a specific location in each of the years from 2002-14. We used the 2001 soy extent as the base year and erased all areas in the 2002 extent that overlapped with 2001, leaving only areas of newly expanded soy from 2002. Next, we erased all areas in the 2003 extent that overlapped with the 2001 extent plus 2002 expansion leaving only areas of newly expanded soy from 2003. We continued this process for each subsequent year through 2014 and combined all the years into a single map of soy extent with each area labeled with the first year it was planted.

4. Annual clearing due to soy expansion

To identify areas that were cleared for soy, we assessed land use in CLEARING YEAR t = 0 through CLEARING YEAR t + 3. We considered an area to be cleared for soy if it had been planted at any point within this period. We removed soy polygons outside of cleared areas and those where the soy expansion date was earlier than the SIAD-Cerrado clearing data and attributed these cases to disagreements between datasets. In sum, we excluded 5.68% of the total soy area across all years. Our estimates are conservative because we allowed only three years to pass after clearing before attributing the clearing to soy, though conversion may take longer than three years. Note that the amount of clearing for soy near the end of our analysis window (2012-14) was even more underestimated because we had fewer than three years of post-conversion data.

To enable comparisons with existing policies and previous work, we also produced estimates for the clearing caused directly by soy expansion, based on areas of total Amazon deforestation reported by PRODES (INPE, 2015) and on estimates of clearing for soy described in Gibbs et al (2015a). We found that Amazon deforestation for soy accounted for one to six percent of annual deforestation in the period just prior to the Soy Moratorium, or approximately 86,000 ha per year in 2002-05. The data on clearing for soy in Gibbs et al (2015a) cover only the states of Mato Grosso, Pará, and Rondônia, but at least 97% of the soy produced in the Amazon was produced in those three states at that time.

5. Property level assessments

Our property level assessments were based on a map we created by combining two official datasets of rural property boundaries. Property boundaries from MMA are from the national System of Rural Environmental Registry (SICAR), which is based on self-declaration of the property location for later verification and enforcement of environmental policies (MMA, downloaded on 29 November 2016). Property boundaries from INCRA are based on officially registered land survey data and are made available through an online cadaster (INCRA, downloaded on 26 October 2016).

We removed overlap within and between the datasets to avoid double counting. Specifically, we removed duplicate properties within each dataset that had identical geometry (i.e. 100% of area was overlapped). We also removed obvious errors such as extremely large properties that were millions of hectares in size in the SiCAR data, and we used an INCRA public settlement map to identify and remove any SiCAR properties that had geometry identical to settlements (INCRA, 2016). Finally, we applied additional procedures to reduce redundancy in our final combined dataset. We deleted SiCAR properties when >10% of their area overlapped with INCRA private properties, thereby giving priority to INCRA private properties because these boundaries are certified while SiCAR data are largely self-declared. Where INCRA properties were overlapped by multiple SiCAR properties that covered >10% of the INCRA property area, we removed the SiCAR properties with the greatest percentage overlap until the total overlap with each INCRA property became less than 10%. We also removed properties that fell within federal and state protected areas, including indigenous areas. The final dataset includes minor overlaps between properties. As a result, 3,302,455ha (2.87%) of the total area covered by property boundaries may have been counted twice.

5.1 Legality of annual clearing at the property and microwatershed levels

To assess the legality of annual clearing, we updated the map of LR requirements from Soares-Filho et al (2014) with special state level requirements for Piauí state (State of Piaui, 2007), which were not accounted for in the original map. We then overlaid this updated LR requirement map with our map of property boundaries to determine how much LR was required in each property.

Our estimates for LR requirements took into consideration the presence of Permanent Protected Areas (APP; areas around rivers and streams, and on steep slopes). Under the FC, all degraded APPs must be replanted or allowed to regenerate, and intact APPs may be used to meet LR requirements (i.e., an LR deficit from past clearing may be removed with an intact APP of the same or larger size). However, an APP cannot replace LR area for the purposes of clearing additional areas. The resolution of our vegetation map limited our ability to fully assess whether APPs were intact because many of them are small, so we elected to assume that the total amount of vegetation on the property included intact APPs. This means that we considered that a property had met its LR requirements when it had vegetation area equal to or exceeding the LR amount, plus the size of the APP area. There may have been cases, for example, where a property had an LR surplus of an amount equivalent to the size of the APP but whose APP was not actually intact. In these cases, we considered the property to be ineligible for additional legal clearing; in fact, it could undergo additional (legal) clearing equivalent to the size of the APP, while at the same time being required to replant or allow the APP area to regenerate. These cases would lead us to slightly overestimate the number of properties meeting the vegetation requirements under the FC and, conversely, slightly underestimate the number of properties with LR surpluses.

It is important to note that we could not evaluate all aspects of legality with the available data; our study considered only whether clearing exceeded the FC limits for LRs at the time it occurred. We did not consider whether producers had the required permits for clearing or if excess clearing prior to 2008 was later compensated off-property or otherwise forgiven. Some of the farms that cleared illegally in the past and that our data did not detect may have become compliant with the FC through off-property LR compensation or through replanting (Soares-Filho et al 2014; Sparovek et al 2012). In addition, the 596 soy properties and 515 nonsoy properties that are smaller than four fiscal modules and cleared between 2003-8 may be considered FC compliant if they have not cleared illegally since 2008.

A second analysis of annual clearing legality relied on 12th order watersheds (microwatersheds) provided by Brazil's national water agency (ANA, 2016), similar to the approach in Soares-Filho et al (2014), to ensure that the 38% of our study area for which we lacked property boundaries did not affect our results. Indeed, our microwatershed level results were very similar to those attained by using the property boundaries and we present both sets of results in table 2. The ANA uses the Otto Pfafstetter System for coding watersheds, in which a first order watershed is continental in scale. The order numbers of watersheds increase as they grow smaller. The 12th order watersheds we use are the smallest defined by the agency. For our analyses at the microwatershed level, we did not scale up the property data to the microwatershed, but instead treated each microwatershed as though it were a property itself.

An analysis based on PRODES-Cerrado at the microwatershed level yielded similar results as analyses with SIAD-Cerrado (89% of clearing within the legal limits since 2003) once we masked out areas along the border with the Amazon biome for which the clearing year in PRODES-Cerrado was uncertain (Brito et al 2018).

5.2 LRs on soy and nonsoy properties

We overlaid our property level dataset of LR requirements with a map of native vegetation in 2015 to assess whether properties contained an LR surplus. To provide the largest estimate of LR area possible so as to avoid exaggerating the number of properties out of compliance, we accounted for potential regrowth in previously deforested areas and for errors in the SIAD-Cerrado maps by including vegetation from the 2013 Terraclass land cover map in addition to remaining vegetation according to SIAD-Cerrado. In other words, our vegetation map for this analysis included areas not identified as cleared by either PROBIO, SIAD-Cerrado, or PROBIO, as well as areas of disagreement between SIAD-Cerrado and PROBIO, and TerraClass.

In cases where our TerraClass + SIAD-Cerrado/PROBIO map overlapped with soy, we considered the soy to be in error. This had a small impact on our analysis of the allocation of soy properties versus nonsoy properties; the number of soy properties declined by 378, from 42,256 to 41,878, when we removed from our group of soy properties those that had soy only on areas that were considered to be native vegetation by our TerraClass + SIAD-Cerrado/PROBIO map. These are the properties detailed in Table 4 of the main text.

Our estimates of the legality of clearing each year do not account for potential off-property compensation or LR consolidation (“Reserva Legal em condominio”) (CIFlorestas) because data on these types of compensation mechanisms were unavailable. These potential off-property compensation areas could mean that more properties comply with the FC than our estimates indicate, while other properties with LR surplus cannot, in fact, clear this surplus due to their enrollment in one of these mechanisms. We also identified properties smaller than four fiscal modules — an administrative sizing schema that varies according to municipality but ranges from 5 to 110 ha in the Cerrado — and considered them to be compliant as long as they did not clear after 2008, regardless of the extent of their remaining vegetation, due to exceptions for older clearing on these small properties in the 2012 FC (Soares-Filho et al 2014). However, while these properties may be compliant with the FC, they may not have surplus LR to clear in the future.

An analysis based on PRODES-Cerrado yielded results similar to the analysis based on SIAD-Cerrado + TerraClass (51% of soy farms have cleared beyond the legal limits, compared with only 19% of nonsoy farms).

6. Land area suitable for soy expansion

6.1 Soy suitable areas

We estimated the soy-suitable areas under native vegetation that could be cleared legally as well as those that have already been cleared, excluding land defined by TerraClass as urban, water, mining, mixed, and other. Our approach followed a method similar to the one used in Gibbs et al (2015a) and Soares-Filho et al (2014) but relied on more refined suitability data.

We used two suitability maps. Our main suitability map was a new, higher resolution product created by AgSat based on a methodology similar to the Agricultural Zoning of Climate Risk approach (Portuguese acronym – ZARC) of Brazil's agricultural research agency (Rudorff et al 2015; Embrapa 2015). The ZARC classifies municipalities according to the risk of crop failure associated with planting specific crop and cultivar types within ideal time windows, as defined by climatic factors, like historical rainfall calendars, and sanitation policies. Specifically, the Agsat suitability map was created by cross-referencing municipalities considered by ZARC to have potential for soybean production with soil and topographic maps. The map classified the Cerrado into four classes of soy suitability: high potential; medium potential; low potential; and inadequate, according to whether the area was in a municipality with the climatic conditions and soil types required to support soybean production. To further define agricultural capacity, these edaphoclimatic potential maps were classified in terms of slope (>12% were considered restricted for soy production), and elevation (higher elevations, above 500 m, are more favorable for soy due to reduced diurnal temperature variation and their tendency to have deeper soils with better drainage, compared with lower elevations). For this analysis, we considered areas with high and medium potential and lacking slope or elevation restrictions to be suitable (referred to in the main text as "highly suitable").

Based on a second map of suitability, which used simpler, more generalized criteria, we identified additional areas that may also be suitable for soybean production (identified in the main text as "potentially suitable areas"). These additional suitable areas are based on slope, soil type, and climate zoning, as described in Gibbs et al, (2015a) and Soares-Filho et al (2014).

6.2 Use of cleared suitable areas

Cleared suitable areas are typically not idle. To determine the main current uses of cleared suitable areas, we used TerraClass to identify pastures (INPE 2015), and a specialized map to identify sugarcane fields (Rudorff et al 2011). Sugarcane areas were removed from pasture areas in cases where the two layers overlapped because we considered the sugarcane maps to be more precise.

7. Surveys of farmers and soy companies

We conducted phone interviews with soy silo operators and field interviews with farmers to enhance our understanding of dynamics between farmers and soy companies. For phone interviews, we used contact information and addresses from the CONAB silos database to identify 1,988 silos in municipalities where soy is produced (Conab). We placed calls to each silo that listed a phone number and asked the individual who answered the phone (usually a receptionist or a manager) to participate in a short survey about their practices with soy, the services provided by each unit, and dates of operation. We reached 907 silos; the remainder were not surveyed due to a combination of wrong numbers, refusal to participate, or closure of the facility. Of the facilities surveyed, 556 reported receiving soy (either purchased or stored in the name of a producer); 135 self-classified their unit as a commodity "trader" operation; 116 reported that their unit may export soy, at least occasionally; and 115 belonged to one of the 28 companies that are signatories to the Soy Moratorium via their membership in Abiove or Anec.

The presence or absence of silos does not provide a full picture of a company's activity. Our phone surveys and fieldwork in Matopiba and in Mato Grosso (three trips between 2014-16) confirmed that companies also buy soy in places where they have not installed silo infrastructure. Farmers in the Matopiba region reported that the arid conditions there made it possible to store soy on the farm in simple silos or in large sacks until the buyer came to collect it, without risk of spoilage, (which is common in more humid locations closer to the Amazon). Large companies may also buy directly from farmers who store their soy in smaller “service” silos or from smaller companies that buy soy from farmers. This situation describes approximately 20% of the soy facilities that responded to our phone survey. These complexities in the soy sector of the Cerrado confirm what we learned by talking to knowledgeable informants in the field — that soy farmers have many options for selling their soy other than major trading firms (Carneiro Filho & Costa, 2016).

References to Supplement only

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