Brazil's Soy Moratorium: Current Expansion Capacities, Extension to the Cerrado, and Increasing Compliant Production

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Dedication

This thesis is dedicated to my loved ones for their unconditional encouragement, love, and support.

Abstract

Brazil's Soy Moratorium has been credited with reducing deforestation rates in Amazonia, yet compliant land is finite and diminishing in response to rapidly increasing international demand for exports. Furthermore, whereas the Soy Moratorium has lessened the role of soy as a direct driver of Amazonian forest loss, it does not apply to the Cerrado, where recent soy expansion has come at the cost of ecologically valuable vegetation. Here we quantify the remaining potential for Soy Moratorium-compliant expansion at the microregion level in both the Amazon, where the current Soy Moratorium applies, and in the Cerrado, under a scenario where the Soy Moratorium is extended to the biome. We evaluate 189 microregions including all soy producing area in the Amazon and all area in the Cerrado. We determine potential compliant production increases for both regions using three approaches: expanding soy onto all Soy Moratorium-eligible land, closing yield gaps on current lands, and introducing integrated-crop-livestock systems with soy (ICLS) onto established pasture. We find 18.0 Mha of additional remaining eligible area in the Amazon and a hypothetical 67.9 Mha in the Cerrado, of which 81.0% and 62.3%, respectively, are estimated to be suitable for soy production. Utilizing all available land could over quintuple production from 2014 levels (466% increase), while restricting expansion to suitable land would result in a quadrupling of soy production (324% increase). However, any new soy expansion on eligible land would displace existing land uses, which may lead to leakage. Closing yield gaps on current lands could increase production only marginally (21.8% increase), while ICLS could generate meaningful production increases through areal expansion (37.5%

increase) without facing leakage obstacles and while increasing financial benefits for farmers. Our findings suggest that adoption of a Cerrado Soy Moratorium would lead to a spatial shift in production away from rapidly transforming soy centers such as Matopiba and Central Mato Grosso, and into central and southwestern Cerrado where there is more concentrated eligible expansion area.

Abbreviations: SoyM, Soy Moratorium; ICLS, integrated crop-livestock systems with soybeans; BA, Bahia; DF, Distrito Federal; GO, Goiás; MA, Maranhão; MG, Minas Gerais; MS, Mato Grosso do Sul; MT, Mato Grosso; PA, Pará; PI, Piauí; PR, Paraná; RO, Rondônia; SP, São Paulo; Matopiba, geographical boundary composed of the states Maranhão, Tocantins, Piauí, and Bahia; IBGE, Brazilian Institute of Geography and Statistics; PPCerrado, Plan for the Prevention/Control of Deforestation and Forest Fires; CAR, 'Cadastro Ambiental Rural' or the environmental registry of rural lands

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Introduction

In recent decades, Brazil has emerged as a major player in the global market for commodity soybean (FAO 2013, IBGE 2014). Growing world demand for food, feed, and fuel has led to a heavier reliance on commodities from the tropics, where most of the globe's remaining arable land resides (Lambin and Meyfroidt 2011). As the world's largest soy exporter and second largest producer behind the United States, Brazil has dramatically expanded its soy industry to keep pace with foreign markets (FAO 2013; DeFries et al. 2010; Rudel et al. 2009). Exports began to compose increasingly greater shares of Brazil's soybean sector in the early 2000s, leading to forest conversion for cropland and infrastructure to transport product to market (Fearnside 2001). In recent years, the majority of these exports have been destined for China, where there is growing demand for animal feed to support increasing meat consumption (AliceWeb 2014; Nepstad et al. 2006).

The vast potential for cropland expansion onto forested land prompts debate about how to best manage tradeoffs between increasing food production and conserving tropical forest for its biodiversity and ecosystem services (Foley et al. 2007; Fearnside 2005; Morton et al. 2006; West et al. 2010). Historically, the world's highest deforestation rates have occurred in Brazil, where agricultural land uses have replaced large tracts of forest (Rudel et al. 2005). Most forest loss has been concentrated in Amazonia's 'arc of deforestation,' though has shifted in recent years to 'Matopiba' (Maranhão, Tocantins, Piauí, and Bahia), a rapidly expanding soy frontier where most of the Cerrado's native vegetation resides (Rudel et al. 2005, Dickie et al. 2016).

Soy's close relationship with forest loss has been targeted by high-profile policy efforts in Brazil (Nepstad et al; 2006, Barona et al. 2010; Macedo et al. 2012; Gibbs et al. 2015). In 2006, Greenpeace led an awareness campaign highlighting the link between soy and deforestation (Greenpeace International 206), compelling the country's largest soy buyers to commit to the Soy Moratorium (SoyM), a zero-deforestation agreement that precludes any purchasing of soy grown on land cleared after 2006. The date has since changed to 2008 for congruity with the latest version of Brazil's Forest Code legislation (Código

Florestal 2012). The SoyM has been credited with minimizing soy's impact as a direct driver of deforestation in the Amazon by reducing forest loss from new soy expansion to less than 1% (Gibbs et al. 2015; Rudorff et al. 2011), though this does not consider soy's indirect contributions to forest loss (Barona et al. 2010).

The SoyM limits expansion to designated areas by withholding market access from producers who have recently deforested. High compliance rates have been well-documented by the Brazilian Association of Vegetable Oil Industries (ABIOVE) since the policy's inception (ABIOVE 2016). However, there is limited work exploring future capacities for compliant soy expansion, and no work examining this at the microregion scale as we do here (Gibbs et al. 2015; Rudorff et al. 2011). Further, no previous assessments spatially explore the potential impact associated with extending the SoyM into the Cerrado, where between 40-55% of vegetation has already been cleared (Machado et al. 20014; Sano et al. 2010), and deforestation rates are 2.5 times greater than in the Amazon (Strassburg et al. 2017). In the years following the SoyM's establishment, between 2007-2013, 40% of new soy expansion in the Cerrado replaced native vegetation (Gibbs et al. 2015), and soy area roughly doubled in Matopiba alone (Rudorff et al. 2015). Of the remaining Cerrado vegetation, 89% is on land that is suitable for soy production, and 40% of this suitable area is eligible to be legally cleared under the Forest Code (Strassburg et al. 2017, Strassburg et al. 2014, Soares-filho et al. 2014). Some argue a Cerrado SoyM could fill the niche presented by this policy gap (Gibbs et al. 2015, Strassburg et al. 2017).

One limitation of the SoyM is that it does not provide a clear template for compliant producers to avoid financial loss or production decreases. In addition to increasing yield and compliant expansion, soy production could be increased through integrated crop-livestock management methods, where pastures and crops are rotated in the same area. Integrated crop-livestock systems with soy (ICLS) may serve as a feasible way to increase production, while decreasing land competition between soy and pasture, improving soil quality, and maximizing farmer profit (Luis et al. 2014). Integrated systems that use crop-pasture rotation have higher profitability than continuous grain and cattle production by themselves due to increased concentrations of organic matter in the soil, allowing higher stocking rates (De Oliveira et al. 2014). Despite this promise, adoption rates remain low. In 2011, integrated crop-livestock systems were only being used on 1% (1.5Mha) of pastures in Brazil (Gil et al. 2015; LAPIG 2015). However, the diverse benefits associated with the methods suggest great potential for more widespread adoption (Gil et al. 2015).

Here we document the remaining municipal SoyM eligible land in the Amazon, and provide an estimate of microregion compliance outcomes given an extension of the policy to the Cerrado biome with a cutoff date of 2008. We then explore three pathways for increasing compliant production under the Amazon and Cerrado SoyMs: 1) expanding onto land cleared before 2008 that is currently occupied by other land uses 2) increasing yields on current production lands and 3) implementing ICLS methods on existing pasturelands. Finally, we spatially present these findings, highlighting where capacities to increase compliant soy production in the future are greatest and where they are limited.

Methods

Study Area. We limited the scope of our study to the 13 Brazilian states that contain the Amazon or Cerrado biomes and that grew soybeans in 2014: Bahia, Distrito Federal, Goiás, Maranhão, Mato Grosso, Pará, Rondônia, Minas Gerais, Mato Grosso do Sul, Piauí, Paraná, São Paulo, and Tocantins. These states accounted for 82% of Brazilian soy production and 84% of deforestation in 2014 (Table 1) (IBGE 2014; LAPIG 2015). Approximately 38% of the area is in the Amazon, 37% in the Cerrado, and 25% in other biomes. The study's primary datasets use agricultural information from the Brazilian Institute of Geography and Statistics (IBGE) and results from Dias et al. (2016). While IBGE data is often reported at the municipal level, yearly changes to municipal borders can pose continuity issues for estimating historical land uses. For consistency, we use the microregion, which is composed of multiple municipalities and has a set legal boundary over time, as our unit of analysis. Of the 325 microregions in the study states, we focus on 52 soy producing regions in the Amazon, and 173 (154 soy-producing) in the Cerrado

(Figure 1). We consider 189 microregions when evaluating ICLS production increases, embodying all microregions with Cerrado acreage or that produce soy in the Amazon.

Estimating Cleared Land and Soy Area by Biome. We use the 1-km agricultural land use maps developed by Dias et al. (2016) to provide the amount of cleared land before 2008 in hectares for each microregion and for the biome portions within it. This approach uses a combination of remote sensing and agricultural census data to create historical land use reconstructions. Since agriculture is the main deforestation activity in the study area, we consider the cleared land before 2008 to be equal to the total agricultural land use in 2008, which is the sum of all cropland, and pastureland (natural and planted).

	Total Area	Native Vegetation	% of Total	Protected Area	% of Native Vegetation	% of Total	Planted Cropland	% of Total	Soy Area	% of Cropland	% of Total
Brazil	838.5	548.4	65.4%	264.5	48.2%	31.5%	76.2	9.1%	30.3	39.8%	3.6%
BA	56.5	26.6	47.1%	1.2	4.5%	2.1%	4.9	8.7%	1.3	26.5%	2.3%
DF	0.58	0.24	41.4%	0.1	41.7%	17.2%	0.2	31.0%	0.1	38.9%	12.1%
GO	34	13.8	40.6%	0.4	2.9%	1.2%	6.1	17.9%	3.2	52.5%	9.4%
MA	33.2	21.6	65.1%	3.5	16.2%	10.5%	2.0	6.0%	0.7	34.0%	2.0%
MT	90.3	64	70.9%	17.0	26.6%	18.8%	13.6	15.1%	8.6	63.2%	9.5%
MS	35.7	18.6	52.1%	1.0	5.4%	2.8%	4.6	12.9%	2.2	47.8%	6.2%
MG	58.7	19.4	33.0%	1.2	6.2%	2.0%	5.5	9.4%	1.2	21.8%	2.0%
PA	124.8	94.6	75.8%	62.2	65.8%	49.8%	1.3	1.0%	0.2	15.4%	0.2%
PR	19.9	2.4	12.1%	0.5	20.8%	2.5%	10.7	53.8%	5.0	46.7%	25.1%
PI	25.2	19.7	78.2%	1.1	5.6%	4.4%	1.5	6.0%	0.6	42.0%	2.5%
RO	23.8	14.3	60.1%	10.9	76.2%	45.8%	0.6	2.4%	0.2	34.5%	0.8%
SP	24.8	3.8	15.3%	0.9	23.7%	3.6%	8.3	33.5%	0.7	8.3%	2.8%
TO	27.8	19.9	71.6%	3.6	18.1%	12.9%	1.0	3.6%	0.7	72.0%	2.6%
Study Area	**555.3**	**318.9**	**57.4%**	**103.6**	**32.5%**	**18.7%**	**60.3**	**10.9%**	**24.7**	**41.0%**	**4.4%**

Table 1: Study area land uses in millions of hectares. Data compiled from IBGE and LAPIG.

The soybean planted area by biome in each microregion for the year 2014 was estimated using soybean planted area maps at the microregion level. These soybean planted area maps are created using a similar approach to that used by Dias et al. (2016). We calculate the fraction of soybean planted area in a microregion k in a year t [for t= (2008, 2014)] by dividing the IBGE soybean planted area by the cropland area (from Dias et al., 2016) in this microregion k in year t. Then, we multiply the grid cells of each microregion in the cropland map by the corresponding fraction of soybean planted area in the year t. The microregion boundaries used to extract the cropland area and perform the calculation were obtained from the 2014 microregion grid. The Cerrado soy area estimates are combined with survey data from 2014 on soybean acreage provided by the Brazilian Institute of Geography and Statistics (IBGE) to obtain estimates for the Amazon and other biomes. Census data counts double-cropped areas only once, but soy cultivated area from 2008 and 2014 surveys could be greater than the actual land use area if the farmers use double cropping. We anticipate these discrepancies are minor based on the strategy's deleterious effects on soil quality (Godoy 2011).

Estimating Remaining Compliant Land for Soy Expansion. We constructed the compliant expansion capacity calculation to understand each microregion's maximum potential to increase compliant soy acreage under the current SoyM and a Cerrado SoyM. Positive numbers indicate more land cleared before 2008 than 2014 soy land (i.e., compliance), and negative numbers indicate more 2014 soy area than land cleared before 2008 (i.e., non-compliance). For the Cerrado, this calculation provides a lower-bound estimate for areas in violation of a hypothetical 2008 SoyM, and an estimate for areas with additional expansion eligibility. We make the conservative assumption that all current soy area is occurring on land cleared before 2008. Non-compliant acreage would be higher and eligible expansion area lower if this were not the case.

SoyM expansion capacities are determined by:

$$\text{remaining SoyM eligible expansion area}_{MR,b} = (\text{land cleared before } 2008_{MR,b} - 2014 \text{ soy area}_{MR,b})$$

where the land cleared before 2008 and 2014 soy area refer to the calculated estimates described above for each biome (subscript b) within a microregion (subscript MR).

Land suitability is an important limiting factor. Gibbs et al. (2015) provide estimates for the amount of area suitable for soybeans on land cleared before 2007 by biome and state. We integrate these estimates at the state level and provide a minimum estimate for the portion of remaining SoyM eligible land that can be readily converted for soybeans (Figure 2). Due to data limitations, our values at the microregion level do not consider this adjustment, and should be considered absolute maximum values given land or technology improvements.

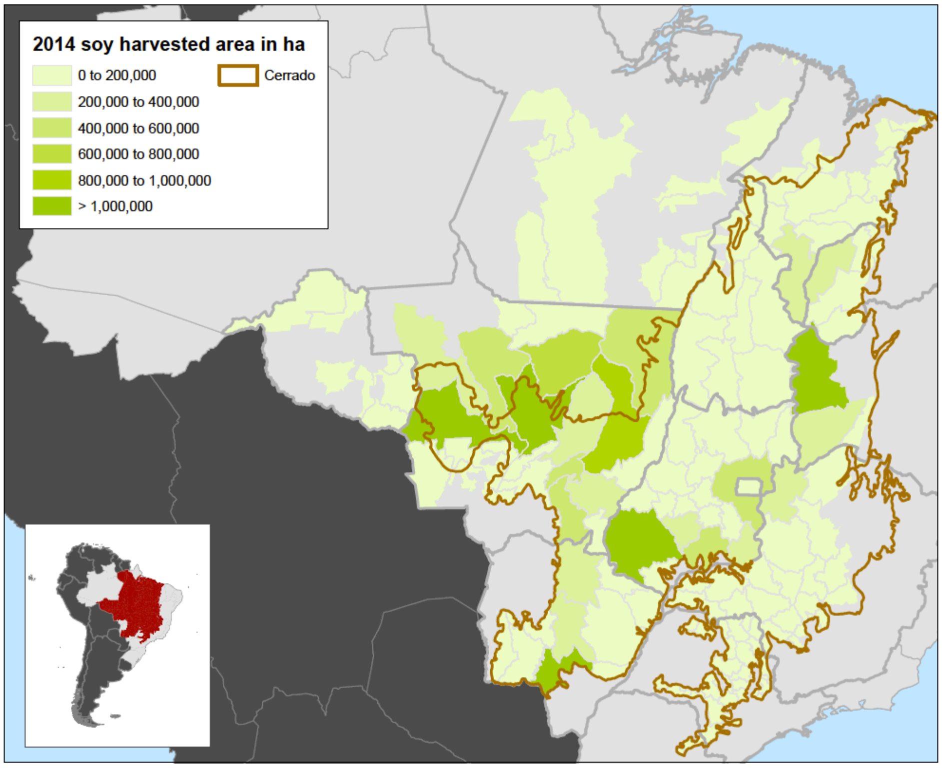


Figure 1. IBGE 2014 harvested soy area of microregions in the study area. All microregions at least partially outside the brown Cerrado boundary are included in the Amazon calcualtions, and all microregions within this boundary are included in the Cerrado calculations. Analyses for increasing compliant production consider all microregions pictured

Maximum Soy Expansion. We determined the maximum extent to which soy production could increase through expansion onto land cleared before 2008 by using estimates for land cleared before 2008 with five-year average microregion IBGE yields.

Production potential was determined by:

$$\text{total compliant expansion production potential}_{MR}$$
$$= (\text{land cleared before } 2008_{MR} \times \text{average yield}_{MR})$$

expansion production increase$_{MR}$

= (total compliant expansion production potential$_{MR}$ – 2014 actual quantity produced$_{MR}$)

where average yield refers to the mean microregion (subscript MR) yield between the years 2010 and 2014 and 2014 actual quantity produced uses IBGE data. In the Supplementary Material we repeat this calculation at the state level and incorporate suitability into the estimates (Figure S1).

Closing Yield Gaps. To determine maximum potential soybean yields in 2014, we adjust the 2010 estimates reported in Dias et al. (2016) by 0.044 tons/year, which is the average rate of increase between 1978-2016 (Hubbs et al. 2017) (see Table S4).

Production potential was determined by:

total compliant maximum yield production potential$_{MR}$

= $_{MR}$ b (2014 soy area$_{MR,b}$ × maximum yield$_{b}$)

maximum yield production increase$_{MR}$

= (new production potential$_{MR}$ – actual quantity$_{MR}$)

where 2014 soy area uses the calculated microregion (subscript MR) estimates by biome (subscript b), and maximum yield uses the adjusted regional value from Dias et al. (2016).

Integrated Crop-Livestock Systems with Soybeans. We estimate the additional soybean production from ICLS systems that could have been achieved from 2008 to 2014. ICLS producers typically rotate crops with pasture every two to 12 years (Gil et al. 2015; Bonaudo et al. 2014). We assume a conservative rotation frequency where soybeans are planted on all existing pasturelands once every eight years. We quantify microregion production increases and land sparing associated with these increases with an assumption that intensification can result in land sparing under the right circumstances (Nepstad et al. 2014; Cohn et al. 2014).

Of the 189 microregions assessed in the Cerrado and Amazon biomes, 161 had established pasture where ICLS could be implemented. The total pastureland (natural and planted) area for each municipality within a microregion was obtained from Dias et al. (2016). For each year between 2008 and 2014, we multiply annual municipal yield by one-eighth of the year's total pastureland. We then accumulate the yearly production between 2008 and 2014 and aggregate up to the microregion level.

To determine the potential quantity produced and land spared by ICLS methods:

ICLS quantity_{m}

$=_{m} y$ (soy $\text{yield}_{m,t} \times \frac{1}{8}$ pasture $\text{area}_{m,t}$)

ICLS quantity_{MR}

$= {}_{MR}\, m$ (ICLS $\text{quantity}_{m)}$

ICLS land spared_{m}

= (ICLS $\text{quantity}_{m} \div$ average yield_{m})

ICLS land spared_{MR}

$= {}_{MR}\, m$ (ICLS land spared_{m})

Where ICLS quantity in each microregion (subscript MR) is the sum of additional soy produced by each municipality (subscript m) within it over all years (subscript t). Soy yield refers to annual IBGE survey information from 2008 to 2014, and pasture area uses values from the Dias et al. (2016) database. ICLS land spared uses five-year average IBGE yields for the years 2010 to 2014.

Results

Amazonian Soy Moratorium Expansion Capacities. The Amazon's 52 soy producing microregions contain 21.5 Mha of land cleared before 2008. 3.5 Mha grew soybeans in 2014, leaving roughly 18.0 Mha of SoyM-compliant expansion area. 49% (8.9 Mha) of this area is in Mato Grosso, 25% (4.6 Mha) in Pará, and 15% (2.7 Mha) in Rondônia (Table S2). Microregions Norte Araguaia, MT and Chapadinha, MA have the greatest and least amounts of remaining land with 1.5 Mha and about 630 ha respectively (Figure 2, Table S3).

Approximately 26% of SoyM-eligible land is being used to grow soy in Mato Grosso, Rondônia is using 7%, Pará 5%, Maranhão 2%, and Tocantins 1% (Figure 3a). The microregion with the highest fraction is Canarana, MT (73%), and the smallest fraction is in Chapadas do Alto Itapecuru, MT (< 1%). Approximately 81% of remaining eligible area is considered suitable according to state-level analysis, and the highest soy producing states (Mato Grosso, Pará, and Rondônia) are among the most suitable in the study area (Figure 3a).

Cerrado SoyM Violations and Expansion Capacities. The 173 microregions in the Cerrado have 82.7 Mha that were cleared before 2008. If all 2014 soy area (14.8 Mha) were growing on land cleared before 2008 then 67.9 Mha of SoyM-eligible area would remain for compliant conversion.

In the 154 soy-producing microregions, minimum violation area under a Cerrado SoyM would total roughly 34,000 ha, and maximum remaining compliant expansion area would equal 67.9 Mha. Alto Parnaiba Piauiense, PI was the only microregion with Cerrado SoyM violation, while potential compliant expansion area was found across all states. The most expansion opportunity was in Goiás with 23% (15.6 Mha) of the total, Mato Grosso do Sul with 19% (13.1 Mha), and Minas Gerais with 17% (11.2 Mha), and the states with the least opportunity were Distrito Federal (< 1%), Paraná (< 1%), and Piauí (1%) (Table S2).

Lavras, MG was the microregion with the least amount of expansion area with only about 40 ha, and Tres Lagoas, MS had the greatest with 3.4 Mha (Figure 2, Table S3).

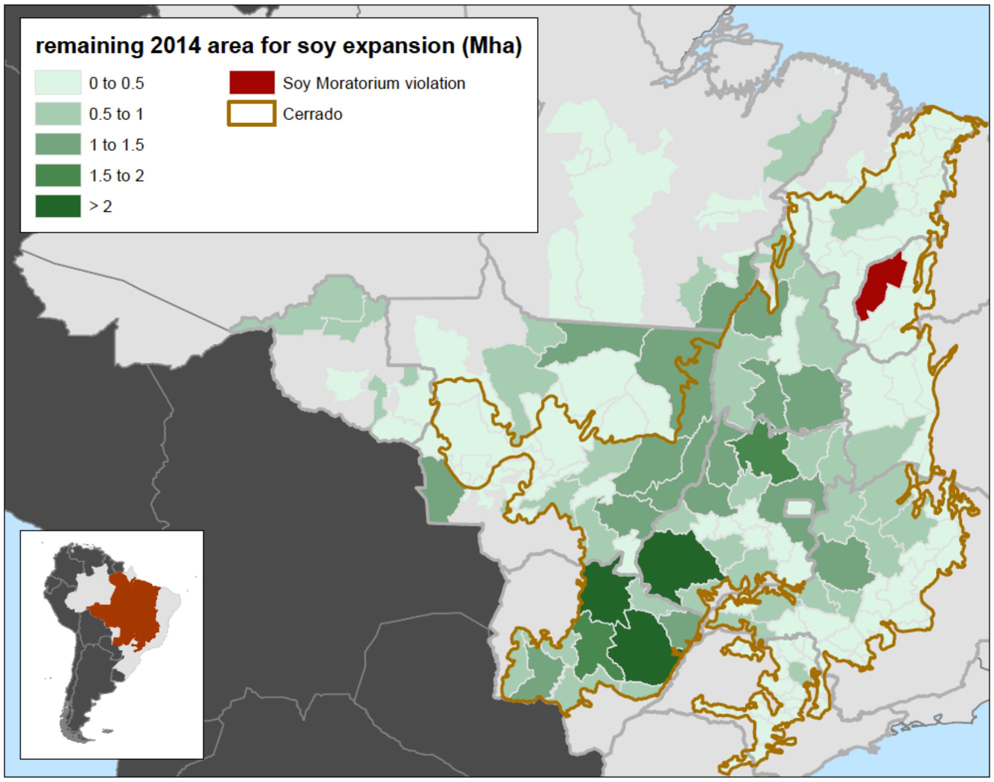
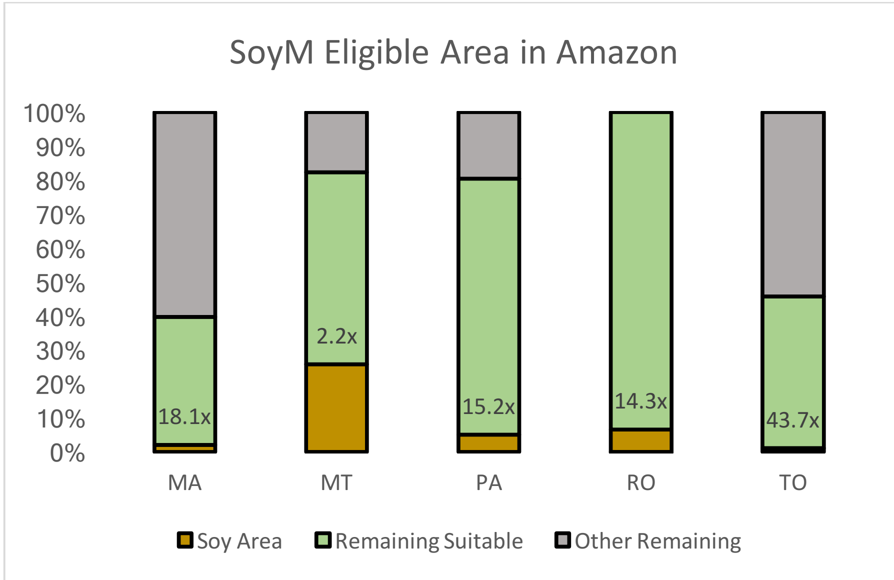
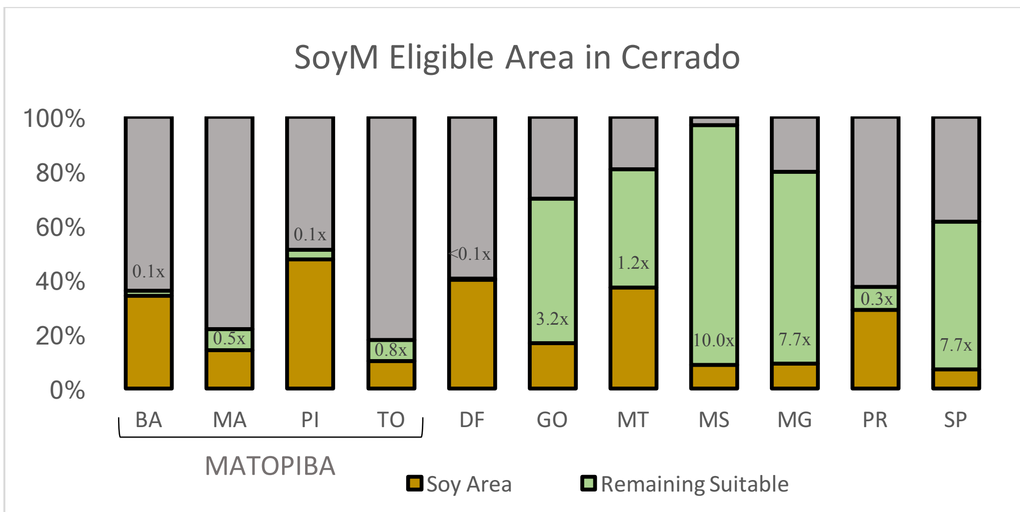


Figure 2: Maps of soy land debt and surplus expressed as the percentage of municipal soy acreage associated with debt or surplus.

Approximately 48% of Piauí's eligible area is being used for soy, followed by Distrito Federal with 40%, Mato Grosso with 37%, Bahia with 34%, and Paraná with 30% (Figure 3b). The lowest percent in a microregion was in Montes Claros, MG (< 1%) and the highest not in violation was in Parecis, MT (92%). Approximately 62.3% of remaining eligible area is suitable for soybean production when state-level analyses are carried out. The Matopiba region, Distrito Federal, and Paraná have the most limited capacities for expansion, while the states with the highest concentrations of eligible area also show the highest rates of suitability (Figure 3b).



a)



b)

Figure 3: 2014 distribution of pre-2008 cleared area by state. Numbers indicate the ratio between the remaining suitable SoyM eligible land and 2014 soy area in (a) the Amazon region where the current Moratorium applies (b) the Cerrado region where the Moratorium does not apply. Suitability estimates are from Gibbs et al. (2015).

Maximum Compliant Expansion Production Increases. In total, 104 Mha was cleared before 2008 and 18.4 Mha grew soy in 2014. If all soy area is on land cleared before 2008, 85.7 Mha would remain for compliant expansion. Converting the remaining area for soy production could increase 2014 production levels by 466% (266 Mt. Roughly

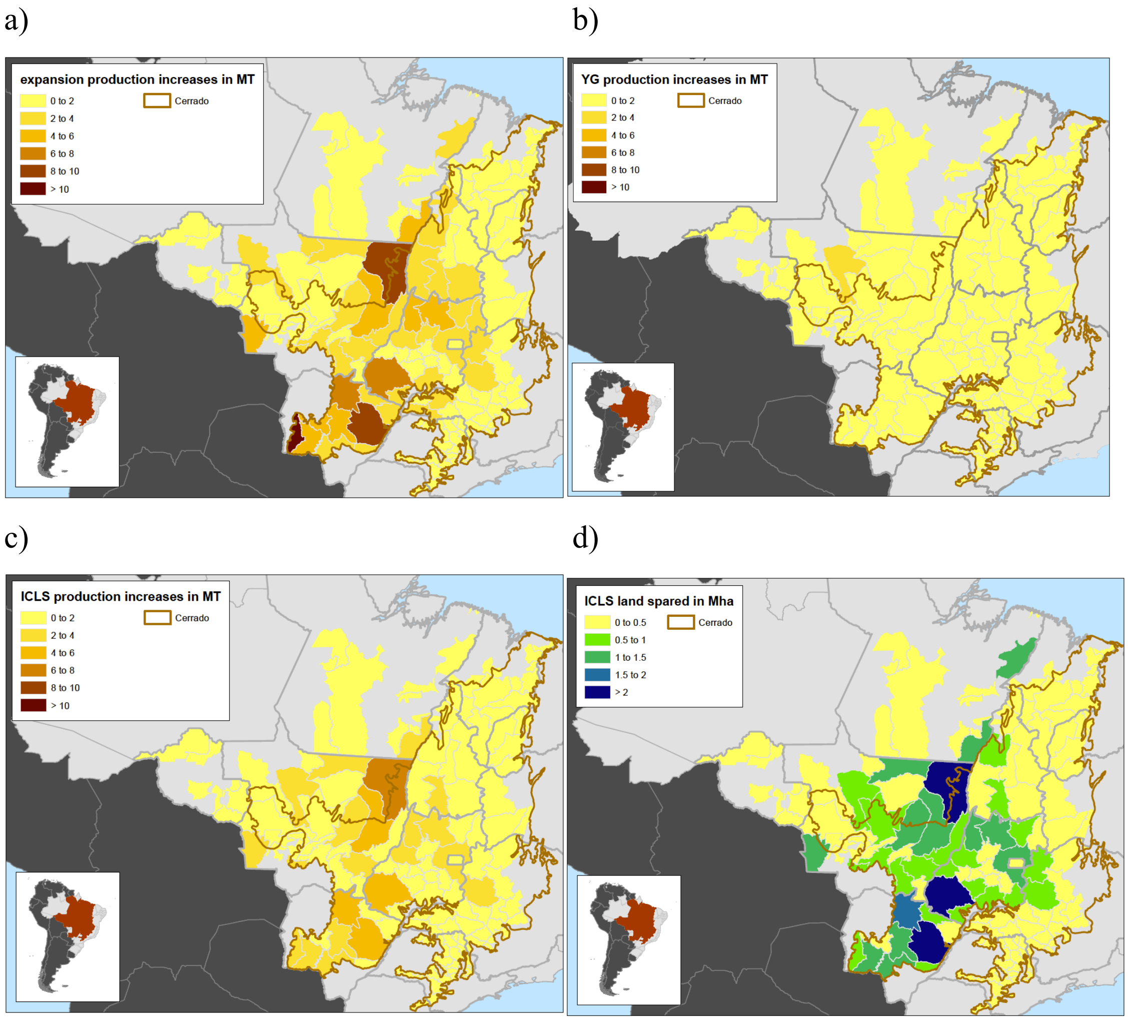


Figure 4: Scenarios that increase compliant production where (a) soy is planted onto all land cleared before 2008 (b) all 2014 soy area achieves regional maximum yields (c) soybeans are planted on established pasture once every eight years. The resulting land spared from ICLS increases is indicated in subplot (d).

20% of this potential exists in the Amazon, 70% in the Cerrado, and 10% in other biomes. State suitability estimates would limit production potential to a 324% increase from 2014 levels (see Supplementary Material).

Mato Grosso could increase production the most (57.2 Mt), while Distrito Federal and Paraná could increase the least with 0.3 Mt and 0.7 Mt respectively. Baixo Pantanal, MS has the greatest potential at the microregion level with 12.0 Mt, and the least potential is in Ponta Grossa, PR with roughly 2,100 t. There were 24 microregions that do not currently grow soy but that house 5.1 Mha of eligible land that could be brought to production (Figure 4a).

Closing the Yield Gap on Current Production Lands. Producing soy with maximum yields on current land would result in a 22% (12.4 Mt) increase from 2014 production levels. Approximately 20% of this potential resides in the Amazon, 70% in the Cerrado, and 10% in other biomes. Mato Grosso accounts for 42% of the total (5.2 Mt). The lowest potentials for increase hold less than 1% of the total in Rondônia (91,000 t), and Distrito Federal (27,000 t). Relative to current production, Piauí could increase its production by 37% (0.6 Mt), while Distrito Federal and Tocantins could only increase by 13% and 12% respectively. The microregion with the greatest quantity increase would be Arinos, MT (2.1 Mt) and the smallest would be Bocaiúva, MG (approximately 2 t) (Figure 4b).

Implementing Integrated Crop Livestock Systems with Soybeans. Roughly 12.2 Mha of new soy land was added to the 189 microregions in the ICLS study area between 2008 and 2014, or a 95% increase. If ICLS management strategies were adopted during this period, 150 Mt of additional soy could have been produced. Distributing this increase evenly across years would translate to a 38% increase in 2014 production. 17% (25.4 Mt) of this potential exists in Minas Gerais, 17% (24.6 Mt) in São Paulo, and 15% (22.5 Mt) in Mato Grosso, while Distrito Federal and Paraná had less than 1% with 0.2 Mt and 0.7 Mt respectively (Figure 4c, Table S5).

Given average yield, ICLS production increases could result in 45.8 Mha of land spared. Most potential exists in Minas Gerais (19%), Mato Grosso (16%), and São Paulo (14%). Matopiba only embodies a combined 19% of this potential due to lack of established pasture in the region (Figure 4d, Table S5). These calculations do not take into account additional land sparing that would presumably occur due to increased pasture productivity and intensification potential, which should be explored in future work.

Discussion

The most rigorous environmental standards in Brazil apply to Amazonia, where agriculture has been identified as an important leverage point for conservation efforts pivotal to stabilizing the world's climate (Soares-filho et al. 2014; Nepstad et al. 2014; Foley et al. 2011). Measuring the SoyM's individual impact on decreasing deforestation is complex in the context of a diverse policy mix in Brazil, including embargoes, credit mechanisms, command and control regulations, and voluntary agreements (Nepstad et al. 2014). Previous work suggests the SoyM has resulted in dramatic decreases to the amount of land cleared specifically for soybeans, and that compliance rates for the policy are high (Gibbs et al 2015, Rudorff et al. 2015). However, estimates of capacities for compliant future expansion have not been carried out at the microregion level. Our findings show the spatial variation in compliant expansion and production potential across local and regional scales. In general, Amazonian SoyM values highlight those areas where eligible land is plentiful and those where future compliance may be precarious without the adoption of new technology due to limited eligible land. The places in the Amazon with diminishing eligible area, or less than 25% of their 2014 soy area remaining, are located in central Mato Grosso (Figure S2). However, the peripheral parts of Mato Grosso, southern Rondônia, and eastern Pará do not grow soy on over 75% of their eligible area, and the vast majority of Amazonian microregions have greater than 400% of their 2014 soy area remaining for expansion, though this calculation does not consider suitability (Table S1, Figure S2).

Cerrado calculations present a conservative estimate of the area that would be in violation of a SoyM with a cutoff date of 2008, and approximate compliant expansion potential. Areas with less than 25% of 2014 soy area remaining without considering suitability are highlighted in central Mato Grosso, the southeastern Cerrado, and the Matopiba region (Figure S2). We find roughly 34,000 ha in Piauí with violation area, illustrating where a 2008 footprint-based SoyM may have prevented forest loss. In the event of implementation, expansion behaviors would be forced to shift away from these soy-centers and into places with the highest concentrations of SoyM eligible expansion area such as Goiás, Mato Grosso do Sul, and eastern Mato Grosso.

Challenges and Opportunities for Modifying the Soy Moratorium. Moratoria by their nature are designed to be 'quick-fixes,' or temporary measures that control a single issue in the supply chain with a few influential actors on the demand side (Lambin et al. 2014). Their simplicity is both beneficial and limiting. While the SoyM is exceptional because of its longevity, effectiveness, and popularity, some suggest that the SoyM's success in the Amazon is at least partially due to production and forest loss moving into the Cerrado (Macedo et al. 2012, Gibbs et al. 2015). Minimal environmental regulations present in the Cerrado may make it particularly susceptible to leakage, though further research is necessary to quantify this (Gibbs et al. 2015, Strassburg et al. 2017). Extending a SoyM to include the Cerrado is one way to address leakage from the Amazon, but stakeholder consensus is a major obstacle.

While the soy industry seems well poised to lead sustainability efforts in the Cerrado, political palatability for a new SoyM extension is limited (Dickie et al. 2016). In May of 2015, the Ministry of Agriculture announced plans for a high-profile development project called 'PDA-MATOPIBA'. These plans focus on agriculture and livestock development and may work to discourage agribusiness from adopting zero-deforestation commitments in the near future. While the SoyM was controversial at the time of its inception, Amazonian soy production makes up a much smaller portion of national production than the Cerrado's portion (IBGE 2014). This allowed its proponents to frame the policy as less likely to affect markets on a national scale (Dickie et al. 2016). Other Cerrado conservation efforts are underway, including a government created project called the Action Plan for the Prevention/Control of Deforestation and Forest Fires (PPCerrado) which supports the 2010 National Climate Change Policy by creating a deforestation monitoring system, increasing the number of conservation units, and titling and recognizing indigenous lands (MMA 2010). PPCerrado seeks to decrease deforestation in the Cerrado by 40%, though implementing these actions has not proved to be transparent or successful as of yet (Dickie et al. 2016). Another key regional effort entails registering all properties with the Forest Code's CAR system ('Cadastro Ambiental Rural' or the environmental registry of rural lands), which is a pivotal step for monitoring and enforcing the law. While the Forest Code legal reserve requirements in most of the Cerrado only require preserving 20% of properties as forest, southern and western areas of the biome show extensive land debt (Soares-filho et al. 2014). Substantial amounts of forest preserved under the SoyM are eligible to be cleared legally under the Forest Code (and vice versa), which has led to calls for more overlap and goal alignment between the two policies (Azevedo et al. 2015). Reforming the SoyM would present an opportunity to achieve this outcome if SoyM participants agreed to make CAR registration an additional criterion for compliance, as was the case for the successful 2009 beef moratorium (Azevedo et al. 2015, Gibbs et al. 2015).

An important variable in persuading stakeholders to undertake another SoyM effort resides in the uncertainty of foreign markets. China's growing monopoly on the Brazilian soy market has not coincided with sending demand signals that promote sustainable production. As of 2015, 16 of the largest soy companies in China had no commitments in place to ensure their products were not associated with forest loss (Bregman et al. 2015). China's demand for deforestation-free soy could contribute to an impactful and synergistic regulatory landscape in the international supply chain. Global pressure on Chinese companies to adapt sustainability standards into their market is beginning to take hold. The recent establishment of the Sustainable Soy Trade Platform aims to increase the proportion of China's trade that involves soy producers who are legally registered with the FC (Sustainable Soy Trade Platform 2016). Formal commitment from China to eliminate forest risk from its commodity chains will prove paramount to efforts for expanding the SoyM to the Cerrado, and to reaching Brazil's ultimate goal of zero-net deforestation (Nepstad et al. 2006; Nepstad et al. 2013). The connection between compliance and limited environmental standards in China's soy supply chain should be explored in future research.

Increasing Compliant Production. In general, production increases can be achieved through intensification or extensification. We examined three intensification scenarios where production increases on currently cleared lands. Whether intensification results in land sparing or stimulates more deforestation is controversial. Previous work has argued that intensification can lead to both direct conversion and indirect displacement of other land uses (3, 46), but can also lead to land sparing if conditions are appropriate (Nepstad et al. 2014, Cohn et al. 2014). We find modest potential to grow compliant soy production through increasing yields in the study area. Previous work has shown that soy yields are already at 86% and 92.5% of their potential in the Amazon and Cerrado regions respectively, suggesting that it will be very difficult to close the gap further (Dias et al. 2016). While afforded production increases from closing the yield gap would be relatively marginal (22%), some areas could achieve significant gains thanks to relatively low yielding soybean in central Mato Grosso, southern Goiás, and western Bahia. Conversely, efforts to close the yield gap would likely not prove fruitful in states where yields are already close to the calculated maximum.

We find vast increases in compliant production (324%) are possible through suitable expansion methods, though pathways are limited to areas currently occupied by other land uses. A portion of eligible land is not suitable for soybeans, so land-use changes would be counterproductive in these areas (Figure S1). Leakage risk outlined by previous work should be a key consideration (Nepstad et al. 2006; Barona et al. 2010; Arima et al. 2011). Cattle remains the single greatest driver of deforestation in the tropics, and established pasture in the Cerrado should not be allowed to deforest new area to cede land for soybeans (Nepstad et al. 2006; Morton et al. 2006; Strassburg et al. 2017). Addressing these leakage issues may require policy intervention or management strategies that help to reconcile soy and beef as competing land uses.

ICLS management practices present an alternative where new production area can occur without additional clearing, and without other land uses being displaced by soy. Rotating soy with pasture increases productivity in each commodity, improves crop resilience to drought and frost, enhances soil health, promotes water conservation, and increases carbon storage (Luis et al. 2014; Gil et al. 2015; Salton et al. 2014). We show that a conservative ICLS implementation between 2008 to 2014 would grow national soy production by 30%, though Matopiba showed limited potential as it has not engaged in large scale ranching in the past (Spera et al. 2016). Although low ICLS adoption rates persist due to labor and implementation costs (Dickie et al. 2016, Balbino et al. 2011), surveys show that integrated systems are becoming more widely recognized as financially beneficial in the long term and as an opportunity to diversify within intensified systems (Gil et al. 2015). The Brazilian Agricultural Research Corporation (EMBRAPA) has started emphasizing integrated systems as a means to qualify for Brazil's ABC Plan, which rewards sustainable production practices with low-interest loans (Salton et al. 2014). Limited data exist on the exact financial implications for ICLS adoption. One previous study showed average ICLS stocking densities of 3.4 animals per hectare versus 0.98 animals per hectare in conventional systems, and the ICLS cattle reached slaughter weight a year earlier than normal (Gil et al. 2015). This result indicates producers could expect to eventually over triple their bottom-line from increased efficiency of cattle production alone. Land sparing from cattle intensification and potential ICLS adoption for soy producers should also be carefully examined in future work as options for soy producer adoption are both lower risk and lower cost than for cattle producers. In general, to maximize adoption, strategies should be tailored to each audience. For ranchers, the rehabilitation of degraded pastures and eventual high stocking densities should be emphasized, and for soy producers, the low initial cost and quick returns.

Limitations. We use the microregion as our unit for analysis due to accuracy issues when converting to municipal level estimates. 2014 IBGE surveys may count soy-soy double-cropping harvested hectares twice, though this practice is generally unfeasible due to the incurred risks of Asian rust (Godoy 2011). For this reason, we assume soy-soy area is negligible. Our calculations of compliant expansion capacities at the microregion level assume that all SoyM eligible land is suitable for soybean growth and that the maximum possible amount of soybean area in the Cerrado is occurring on land cleared before 2008. We do consider suitability at the state level, which shows higher rates in the Amazon than the Cerrado, despite the Amazon having lower concentrations of eligible land. Microregions face additional expansion limitations from other policy, such as the Legal Reserve requirement in the Forest Code. Completely compliant expansion under both the

Forest Code and the SoyM would dually require land cleared before 2008 and Forest Code surplus (Soares-filho et al. 2014). All assumptions result in generous estimates for expansion capacities in the Amazon and Cerrado, and conservative estimates for violations in the Cerrado. The yield gap and ICLS scenarios are not affected by these assumptions.

Conclusions. The SoyM has helped reduce deforestation in the Amazon and, if extended to the Cerrado, could hold promise for similar impact; however, implementation of this extension faces major political obstacles. Here we quantified and mapped potentials for expansion and production that is SoyM-compliant. Increasing production while adhering to environmental standards may prove feasible in some areas, and too daunting a task in areas with diminishing eligible area. One reason the SoyM worked well in the Amazon is because there was plenty of grazing land near traditional soy producing regions, and soy could easily expand onto these lands. This is not the case in other traditional soy producing regions in Cerrado, such as western Bahia, where there is little grazing land available to accommodate soy expansion. Central Mato Grosso has limited Amazonian expansion area where future soy production must increase yield on current compliant lands, shift onto eligible area in other parts of the state, or implement ICLS strategies. Similar approaches would be needed in the Matopiba region if the SoyM were extended into the Cerrado. Reforming the SoyM to apply in the Cerrado may help mitigate future legal clearing allowed by the Forest Code in the region, and could seize on opportunity to more closely align the two policies by adding a requirement for producers to be registered with CAR. As a major importer, China could disrupt some of the inertia in the Cerrado by implementing zero-deforestation standards in its supply chains that stimulate sustainable production. Meanwhile, traditional strategies to increase compliant production face problems of scale and leakage. Integrated systems, such as ICLS, provide economic and environmental benefit while increasing production and minimizing leakage risk, and should be heavily emphasized in high potential areas as a way to meet growing demand while maintaining compliance. Financial implications for adoption and high resolution analysis should be explored in depth in future work.

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Appendices

Appendix A: Maximum Suitable Expansion Analysis

We repeat the maximum soy expansion analysis at the state level to incorporate the suitability estimates from Gibbs et al. (2015).

Production potential was determined by:

$$\text{total compliant expansion production potential}_S = (\text{suitable cleared land}_S \times \text{average yield}_S)$$

where total compliant production potential refers to the maximum state (subscript S) production if all suitable cleared land not already growing soy were to return average yields. Average yield refers to the mean state yield between the years 2010 and 2014.

Confining soybean expansion to all eligible suitable area would result in a 324% (168 MT) production increase from 2014 levels given average state yields, as opposed to the estimated 466% (266 MT) increase determined when omitting suitability and analyzing at the micro region level. Roughly 26% of this potential exists in the Amazon, and 74% exists in the Cerrado. Mato Grosso still houses most of this potential with 24% of the total (40.9 MT), then Mato Grosso do Sul with 22% (36.3 MT), Goiás with 18% (29.7 MT), Minas Gerais with 15% (25.1 MT), Pará and Rondônia follow with 6% each (10.6 MT), and the remaining states house less than 5%.

It is notable that Matopiba only contains a combined 4% of the suitable production potential (6.8 MT). The region's capacity to expand within the confines of a 2008 benchmark diminish by 82% when considering land suitability. Piauí, where we find violation area for a Cerrado SoyM, demonstrates virtually no capacity to expand soybean production without using land cleared after 2008. Meanwhile states like Mato Grosso, Mato Grosso do Sul, Goias, Minas Gerais, Pará, and Rondônia have mostly suitable remaining eligible area.

Appendix B: Supplementary Figures

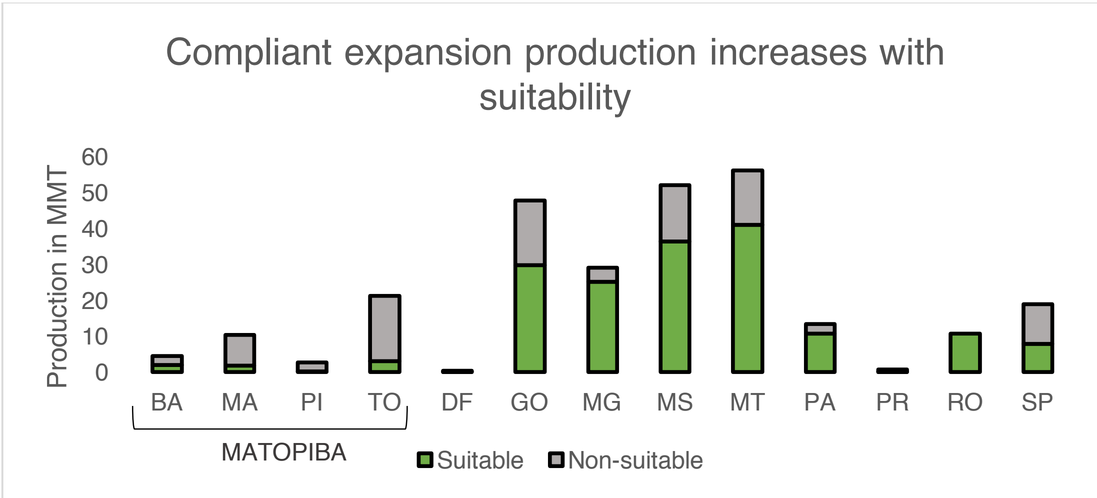
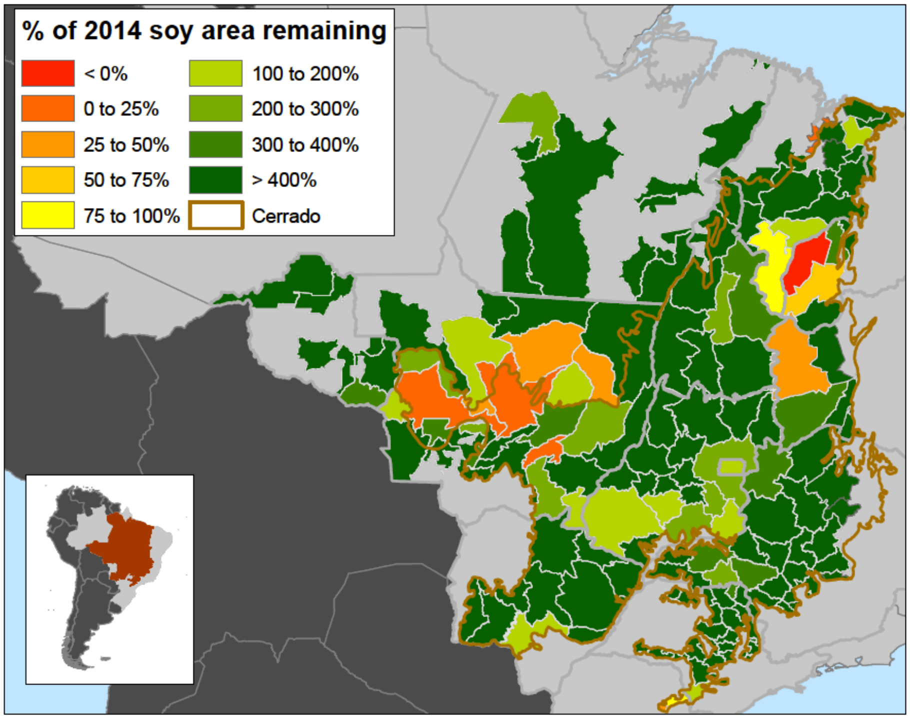


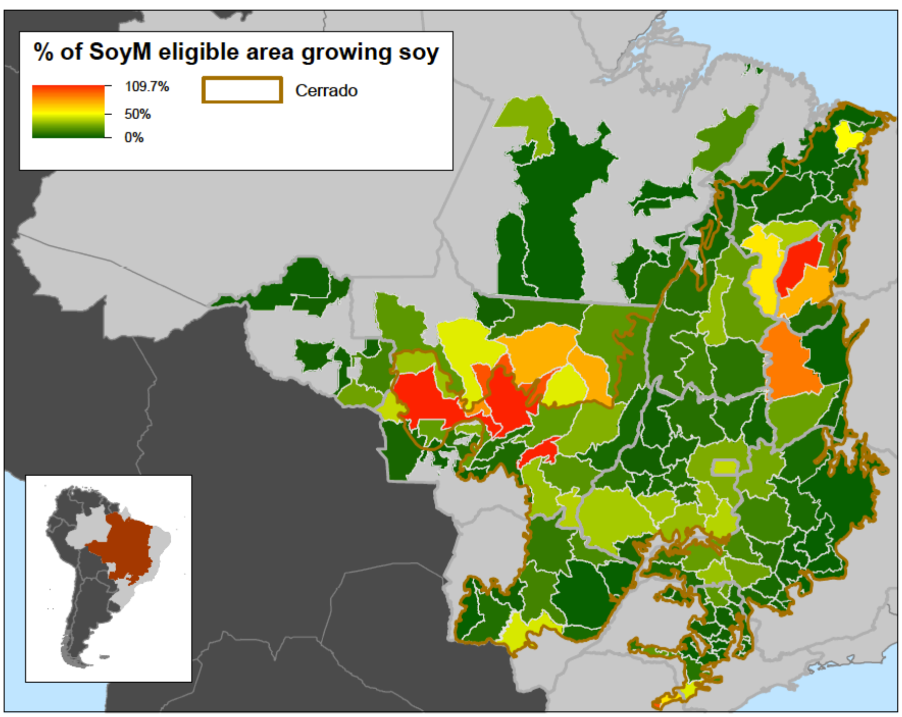
Figure S1: State distribution of eligible expansion production increases that could occur on suitable soybean land. Suitability estimates are obtained from Gibbs et al. (2015).

Table S1: Distribution of micro region entries within Amazonia and Cerrado expressed as the percentage of 2014 IBGE soy area that remains for Soy Moratorium compliant expansion.

Bin	*Amazonia*	*Cerrado*
<25%	1	4
25-50%	2	4
50-75%	0	2
75-100%	1	2
100-200%	4	11
200-300%	2	8
300-400%	1	9
>400%	32	113



a)



b)

Figure S2: Distributions of Soy Moratorium eligible area. (a) The percentage of 2014 soy area that remains for compliant expansion. (b) The percentage of land cleared before 2008 being used to grow soybeans in 2014.

Appendix C: Data Tables

Table S2: State total and remaining eligible area in hectares				
State	**Amazon Cleared before 2008**	**Cerrado Cleared before 2008**	**Amazon Remaining Eligible Area**	**Cerrado Remaining Eligible Area**
BA	-	3,735,526	-	2,462,513
DF	-	179,528	-	107,728
GO	-	18,670,252	-	15,559,464
MA	674,438	4,665,260	937,408	4,001,422
MT	12,042,384	14,862,481	8,949,838	9,340,228
MS	-	14,326,702	-	13,065,041
MG	-	12,363,140	-	11,231,803
PA	4,826,996	-	4,587,825	-
PR	-	282,880	-	200,879
PI	-	1,296,073	-	678,762
RO	2,936,516	-	2,745,095	-
SP	-	5,190,007	-	4,822,788
TO	972,388	7,079,558	962,443	6,367,281
Total	**21,452,722**	**82,651,408**	**18,182,609**	**67,837,910**

Table S3: Soy Moratorium eligible area and 2014 soy area estimates in hectares					
State	**Micro Region**	**Cleared before 2008**	**Cerrado cleared before 2008**	**2014 IBGE soy area**	**2014 Cerrado soy area**
BA	Barra	336,240	205,502	0	0
BA	Barreiras	1,497,876	1,497,876	1,060,455	1,057,101
BA	Bom Jesus da Lapa	366,489	295,704	2,000	1,993
BA	Cotegipe	489,014	489,014	0	1,560
BA	Guanambi	518,966	278,548	0	1
BA	Juazeiro	46,125	8,327	0	0
BA	Santa Maria da Vitória	960,553	960,553	213,914	212,358
DF	Brasília	179,528	179,528	72,000	71,800
GO	Anápolis	509,109	509,109	23,815	24,208
GO	Anicuns	377,133	377,133	12,880	12,938
GO	Aragarças	718,585	718,585	62,300	62,362
GO	Catalão	752,561	682,253	260,100	254,816
GO	Ceres	764,226	764,226	17,660	17,778
GO	Chapada dos Veadeiros	789,288	789,288	37,004	36,890
GO	Entorno de Brasília	1,766,556	1,766,556	458,757	458,826
GO	Goiânia	353,241	353,241	27,050	26,716
GO	Iporá	472,970	472,970	10,205	10,025
GO	Meia Ponte	1,405,235	1,187,528	406,310	364,336
GO	Pires do Rio	596,307	596,307	185,700	185,715
GO	Porangatu	1,781,786	1,781,786	91,904	91,760
GO	Quirinópolis	973,011	645,542	34,000	14,985
GO	Rio Vermelho	1,292,922	1,292,922	19,805	19,764
GO	São Miguel do Araguaia	1,511,344	1,511,344	14,566	14,576

GO	Sudoeste de GO	3,485,830	3,485,083	1,192,060	1,192,246
GO	Vale do Rio dos Bois	921,751	921,751	307,950	307,699
GO	Vão do Paranã	814,627	814,627	14,929	15,149
MA	Alto Mearim e Grajaú	698,764	588,730	7,500	7,034
MA	Baixada Maranhense	101,637	1,600	0	0
MA	Baixo Parnaíba Maranhense	211,179	177,806	5,185	3,840
MA	Caxias	231,988	215,261	3,080	2,966
MA	Chapadas das Mangabeiras	406,134	406,134	141,651	141,625
MA	Chapadas do Alto Itapecuru	435,854	403,331	10,895	10,880
MA	Chapadinha	117,913	116,618	58,557	57,894
MA	Codó	224,684	224,684	0	2
MA	Coelho Neto	62,883	62,883	1,470	1,473
MA	Gerais de Balsas	750,089	750,089	399,894	400,226
MA	Imperatriz	666,940	371,514	10,495	79
MA	Itapecuru Mirim	193,008	171,716	0	1
MA	Lençóis Maranhenses	134,911	131,793	0	14
MA	Médio Mearim	322,216	258,611	0	0
MA	Pindaré	265,150	80,088	900	4
MA	Porto Franco	380,173	380,173	37,600	37,490
MA	Presidente Dutra	184,279	184,279	313	312
MA	Rosário	228,920	139,949	0	0
MT	Alta Floresta	757,372	0	9,828	0
MT	Alto Araguaia	488,763	488,763	180,181	181,387
MT	Alto Guaporé	1,431,499	112,466	35,130	2,944

MT	Alto Pantanal	1,142,577	186,391	6,570	984
MT	Alto Paraguai	237,039	69,281	59,120	11,897
MT	Alto Teles Pires	2,527,553	2,012,509	2,270,424	1,719,771
MT	Arinos	1,202,588	174,469	583,425	117,590
MT	Aripuanã	912,368	297,735	213,200	97,495
MT	Canarana	2,381,146	1,819,492	913,813	502,472
MT	Colíder	1,348,716	0	117,253	0
MT	Cuiabá	1,080,032	659,768	40,545	27,541
MT	Jauru	526,690	23,902	4,185	68
MT	Médio Araguaia	1,277,323	1,277,323	36,564	36,061
MT	Norte Araguaia	3,173,552	1,355,678	519,028	182,577
MT	Paranatinga	1,460,523	1,112,026	380,163	224,173
MT	Parecis	1,628,424	1,329,674	1,341,100	1,221,091
MT	Primavera do Leste	509,484	509,484	460,500	460,148
MT	Rondonópolis	1,331,754	1,273,161	426,357	400,420
MT	Rosário Oeste	400,246	400,246	19,700	19,410
MT	Sinop	912,749	60	654,718	165
MT	Tangará da Serra	741,192	326,779	90,337	65,773
MT	Tesouro	1,433,275	1,433,275	251,452	250,284
MS	Alto Taquari	2,600,102	2,252,593	229,210	216,327
MS	Aquidauana	1,677,521	768,714	10,150	9,478
MS	Baixo Pantanal	4,733,503	622,360	2,420	960
MS	Bodoquena	1,561,978	1,555,979	65,360	65,316
MS	Campo Grande	1,890,848	1,887,853	247,710	246,860
MS	Cassilândia	964,459	964,459	196,433	128,459
MS	Dourados	2,031,177	1,312,630	1,154,770	567,555

MS	Iguatemi	105,405	3,145	205,718	78
MS	Nova Andradina	834,959	528,122	34,650	15,778
MS	Paranaíba	1,123,290	1,031,730	1,238	1,088
MS	Três Lagoas	3,507,762	3,399,119	10,165	9,763
MG	Alfenas	41,280	16,213	6,680	979
MG	Araçuaí	46,552	18,624	0	0
MG	Araxá	562,818	562,818	130,200	130,129
MG	Belo Horizonte	66,017	55,612	0	3
MG	Bocaiúva	113,744	113,744	0	0
MG	Bom Despacho	385,053	382,629	3,380	3,379
MG	Campo Belo	103,379	48,603	0	8
MG	Capelinha	174,439	123,596	0	0
MG	Conceição do Mato Dentro	90,445	25,436	0	0
MG	Curvelo	338,436	338,436	50	51
MG	Diamantina	57,313	55,075	0	0
MG	Divinópolis	209,940	146,943	170	96
MG	Formiga	178,619	121,425	4,900	3,885
MG	Frutal	883,199	633,040	24,455	23,792
MG	Grão Mogol	94,552	94,552	0	0
MG	Itabira	45,652	26,871	0	0
MG	Itaguara	18,635	448	0	0
MG	Ituiutaba	606,997	418,415	55,233	32,513
MG	Janaúba	463,355	275,948	0	0
MG	Januária	619,077	546,742	15,000	16,932
MG	Lavras	31,847	40	3,008	0

MG	Montes Claros	836,810	784,081	0	1
MG	Oliveira	21,091	517	90	2
MG	Pará de Minas	68,189	30,942	0	1
MG	Paracatu	1,528,560	1,528,560	178,300	178,455
MG	Passos	351,463	281,865	15,950	11,079
MG	Patos de Minas	639,304	639,304	33,470	33,386
MG	Patrocínio	636,377	633,589	91,090	91,110
MG	Pirapora	684,885	684,885	21,854	21,451
MG	Piuí	366,510	366,510	8,950	10,000
MG	Salinas	256,729	82,109	0	0
MG	São Sebastião do Paraíso	150,397	120,733	3,150	774
MG	Sete Lagoas	348,746	342,983	1,080	1,073
MG	Três Marias	430,366	430,366	1,950	1,953
MG	Uberaba	449,732	449,732	142,950	143,003
MG	Uberlândia	916,171	757,245	198,850	157,571
MG	Unaí	1,125,055	1,125,055	268,650	268,827
MG	Varginha	171,276	99,454	10,140	880
PA	Altamira	486,384	0	1,470	0
PA	Bragantina	36,023	0	120	0
PA	Conceição do Araguaia	1,449,666	8,307	69,450	800
PA	Itaituba	339,072	0	1,350	0
PA	Marabá	438,887	0	500	0
PA	Paragominas	809,371	0	117,989	0
PA	Parauapebas	82,239	0	600	0
PA	Redenção	435,770	0	1,560	0

PA	Santarém	145,275	0	40,932	0
PA	São Félix do Xingu	612,617	0	6,000	0
PR	Jaguariaíva	160,445	79,775	87,950	43,036
PR	Ponta Grossa	96,007	2,142	203,000	1,525
PR	Telêmaco Borba	162,094	39,732	194,780	30,341
PR	União da Vitória	151,261	151,261	39,450	701
PR	Wenceslau Braz	22,531	9,971	61,600	6,398
PI	Alto Médio Gurguéia	315,587	311,420	196,385	193,285
PI	Alto Parnaíba Piauiense	349,187	349,187	382,803	382,896
PI	Baixo Parnaíba Piauiense	80,743	23,477	334	0
PI	Bertolínia	154,795	141,200	29,976	29,371
PI	Chapadas do Extremo Sul Piauiense	313,374	308,077	11,231	11,231
PI	Floriano	146,846	58,922	500	499
PI	Litoral Piauiense	40,115	16,283	1,050	15
PI	Médio Parnaíba Piauiense	44,817	2,898	4,020	11
PI	São Raimundo Nonato	63,834	9,451	0	0
PI	Teresina	175,934	75,157	500	3
RO	Alvorada D'Oeste	348,181	0	4,829	0
RO	Ariquemes	549,511	0	8,365	0
RO	Cacoal	545,986	0	5,920	0
RO	Colorado do Oeste	448,561	0	101,410	0
RO	Porto Velho	528,839	0	4,041	0
RO	Vilhena	516,957	1,521	67,405	549

SP	Araraquara	441,156	421,552	4,234	4,228
SP	Assis	482,871	208,948	146,476	41,415
SP	Auriflama	100,209	23,150	1,972	314
SP	Avaré	355,212	345,695	22,010	21,686
SP	Barretos	165,624	138,863	5,356	4,297
SP	Batatais	229,392	193,888	5,480	5,482
SP	Bauru	475,254	299,250	507	329
SP	Botucatu	213,345	153,007	1,450	816
SP	Campinas	64,457	26,117	1,273	905
SP	Capão Bonito	52,699	2,766	17,700	1,257
SP	Catanduva	57,635	14,964	200	0
SP	Fernandópolis	53,864	9,923	833	0
SP	Franca	209,736	209,736	5,619	5,638
SP	Itapetininga	182,433	72,509	20,200	8,935
SP	Itapeva	437,034	266,307	174,028	118,752
SP	Ituverava	88,218	88,218	18,720	18,714
SP	Jaboticabal	290,337	220,078	7,620	7,108
SP	Jaú	274,825	150,391	2,983	1,095
SP	Limeira	140,552	65,531	3,656	891
SP	Marília	177,582	47,288	4,361	2,242
SP	Moji Mirim	149,443	128,498	850	850
SP	Nhandeara	84,317	34,057	1,200	280
SP	Novo Horizonte	84,512	16,383	130	0
SP	Ourinhos	219,473	96,009	48,420	15,455
SP	Piracicaba	116,229	75,479	637	184
SP	Pirassununga	82,862	32,097	4,080	1,381

SP	Presidente Prudente	317,585	140,701	36,656	9,343
SP	Ribeirão Preto	600,725	561,673	5,700	5,626
SP	Rio Claro	122,116	101,388	60	30
SP	São Carlos	95,510	95,246	1,190	1,189
SP	São João da Boa Vista	252,357	170,741	4,100	3,397
SP	São Joaquim da Barra	431,185	431,185	81,766	81,746
SP	São José do Rio Preto	462,016	226,625	9,766	2,469
SP	Sorocaba	18,369	42	2,340	1
SP	Votuporanga	168,414	121,703	3,616	1,165
TO	Araguaína	1,244,878	638,750	14,460	11,905
TO	Bico do Papagaio	631,625	437,899	7,500	6,922
TO	Dianópolis	1,364,920	1,364,920	93,645	93,707
TO	Gurupi	1,251,613	1,251,613	147,419	147,396
TO	Jalapão	743,138	743,138	154,732	157,557
TO	Miracema do Tocantins	1,381,040	1,208,506	70,340	63,599
TO	Porto Nacional	469,899	469,899	138,316	139,278
TO	Rio Formoso	964,834	964,834	91,962	91,914
	TOTAL	**111,147,661**	**77,141,355**	**18,755,590**	**13,370,528**

Table S4: Maximum yield estimates from Dias et al. (2016) in T/ha		
Region	**2010 Max. Yield**	**Adjusted 2014 Yield**
Amazonia	3.5	3.676
Cerrado	3.2	3.376
MATOPIBA	3.1	3.246

Table S5: Integrated Crop Livestock Systems with Soybean Estimates				
State	**Micro Region**	**ICLS production increases (T)**	**Avg. IBGE Yield (T/ha)**	**ICLS land spared (ha)**
BA	Barra	-	-	-
BA	Barreiras	587,761	2.88	249,904
BA	Bom Jesus da Lapa	160,509	3.35	288,340
BA	Cotegipe	-	-	-
BA	Guanambi	-	-	-
BA	Juazeiro	-	-	-
BA	Santa Maria da Vitória	922,678	2.53	514,976
DF	Brasília	199,232	3.13	63,648
GO	Anápolis	817,906	2.86	402,250
GO	Anicuns	506,109	2.97	250,304
GO	Aragarças	1,568,331	3.00	607,517
GO	Catalão	1,273,088	3.10	459,982
GO	Ceres	738,829	3.02	462,309
GO	Chapada dos Veadeiros	551,582	2.76	582,914
GO	Entorno de Brasília	2,853,306	2.93	1,091,126
GO	Goiânia	472,237	2.96	253,673
GO	Iporá	461,306	2.92	321,524

GO	Meia Ponte	1,914,382	2.72	654,877
GO	Pires do Rio	888,078	3.11	288,678
GO	Porangatu	3,215,765	3.10	1,216,118
GO	Quirinópolis	1,663,226	2.54	837,792
GO	Rio Vermelho	2,015,549	3.02	847,392
GO	São Miguel do Araguaia	3,001,558	3.19	1,276,964
GO	Sudoeste de GO	5,219,735	3.09	1,741,073
GO	Vale do Rio dos Bois	1,452,631	2.95	501,999
GO	Vão do Paranã	992,573	2.60	560,164
MA	Alto Mearim e Grajaú	398,594	2.60	1,699,432
MA	Baixada Maranhense	-	-	-
MA	Baixo Parnaíba Maranhense	10,060	2.74	10,988
MA	Caxias	77,009	2.48	92,043
MA	Chapadas das Mangabeiras	739,449	2.87	257,204
MA	Chapadas do Alto Itapecuru	331,344	2.98	245,331
MA	Chapadinha	21,580	2.40	10,103
MA	Codó	-	-	-
MA	Coelho Neto	6,321	2.29	11,032
MA	Gerais de Balsas	641,853	2.89	276,689
MA	Imperatriz	67,138	2.72	97,845
MA	Itapecuru Mirim	-	-	-
MA	Lençóis Maranhenses	-	-	-
MA	Médio Mearim	-	-	-
MA	Pindaré	97,329	3.21	181,076
MA	Porto Franco	515,932	2.74	381,757
MA	Presidente Dutra	21,532	2.83	38,327

MA	Rosário	-	-	-
MG	Alfenas	1,033,569	2.47	317,533
MG	Araçuaí	741,735	-	252,068
MG	Araxá	3,832,614	2.94	1,547,256
MG	Belo Horizonte	2,070,138	-	712,772
MG	Bocaiúva	469,760	-	151,792
MG	Bom Despacho	1,749,264	2.42	565,268
MG	Campo Belo	2,245,828	-	746,420
MG	Capelinha	1,105,101	-	379,751
MG	Conceição do Mato Dentro	4,468,069	-	1,451,614
MG	Curvelo	3,430,673	2.50	1,087,971
MG	Diamantina	1,745,151	2.00	760,401
MG	Divinópolis	566,967	0.88	270,922
MG	Formiga	1,504,930	2.73	563,658
MG	Frutal	6,595,018	2.81	2,549,855
MG	Grão Mogol	3,625,152	-	1,198,397
MG	Itabira	1,118,700	-	378,205
MG	Itaguara	92,688	-	29,490
MG	Ituiutaba	1,874,306	2.75	701,675
MG	Janaúba	853,008	1.00	482,684
MG	Januária	1,371,860	1.93	440,097
MG	Lavras	1,120,127	2.73	537,738
MG	Montes Claros	2,708,814	-	1,183,435
MG	Oliveira	5,824,616	1.80	1,915,303
MG	Pará de Minas	1,310,483	-	558,167
MG	Paracatu	2,032,507	2.91	809,764

MG	Passos	2,885,865	2.64	1,117,698
MG	Patos de Minas	3,530,994	2.83	1,452,427
MG	Patrocínio	1,841,173	3.09	584,240
MG	Pirapora	2,473,650	2.90	898,496
MG	Piuí	199,930	2.52	70,867
MG	Salinas	1,469,337	-	593,043
MG	São Sebastião do Paraíso	763,168	2.70	567,876
MG	Sete Lagoas	5,423,963	2.65	2,325,785
MG	Três Marias	43,442	3.06	16,838
MG	Uberaba	-	3.00	-
MG	Uberlândia	739,007	2.81	255,200
MG	Unaí	-	2.87	-
MG	Varginha	-	2.67	-
MS	Alto Taquari	253,555	3.08	282,434
MS	Aquidauana	-	2.65	-
MS	Baixo Pantanal	-	2.53	-
MS	Bodoquena	-	2.77	-
MS	Campo Grande	62,448	2.67	272,591
MS	Cassilândia	5,397	3.17	-
MS	Dourados	1,542	2.86	19,228
MS	Iguatemi	144,460	2.75	107,941
MS	Nova Andradina	1,266,037	2.71	552,131
MS	Paranaíba	-	2.45	-
MS	Três Lagoas	-	2.75	-
MT	Alta Floresta	-	3.27	-
MT	Alto Araguaia	858,050	2.97	386,759

MT	Alto Guaporé	21,805	3.13	-
MT	Alto Pantanal	114,573	3.12	359,556
MT	Alto Paraguai	-	3.09	-
MT	Alto Teles Pires	-	3.12	-
MT	Arinos	3,257	2.34	1,810
MT	Aripuanã	-	2.93	-
MT	Canarana	2,598,901	3.11	878,957
MT	Colíder	271,363	3.20	200,182
MT	Cuiabá	1,083,774	3.04	484,663
MT	Jauru	906,231	3.34	304,998
MT	Médio Araguaia	676,565	2.73	602,444
MT	Norte Araguaia	357,195	3.08	171,273
MT	Paranatinga	-	3.07	-
MT	Parecis	83,971	2.99	36,578
MT	Primavera do Leste	122,096	3.14	232,563
MT	Rondonópolis	434,846	3.09	205,336
MT	Rosário Oeste	312,576	3.14	109,205
MT	Sinop	1,294,871	3.12	457,358
MT	Tangará da Serra	1,641,171	3.06	687,385
MT	Tesouro	104,137	3.10	90,292
PA	Altamira	1,173,894	2.88	410,912
PA	Bragantina	4,571	2.15	2,419
PA	Conceição do Araguaia	3,860,287	3.16	1,240,213
PA	Itaituba	744,191	2.85	261,120
PA	Marabá	320,586	2.70	118,735
PA	Paragominas	1,942,866	2.95	660,805

PA	Parauapebas	57,656	2.70	21,354
PA	Redenção	592,809	2.70	191,229
PA	Santarém	255,862	2.80	92,704
PA	São Félix do Xingu	748,649	2.75	272,236
PI	Alto Médio Gurguéia	121,852	2.22	37,124
PI	Alto Parnaíba Piauiense	31,434	2.59	8,971
PI	Baixo Parnaíba Piauiense	160,773	2.56	50,126
PI	Bertolínia	326,306	2.68	107,898
PI	Chapadas do Extremo Sul Piauiense	48,546	2.32	14,957
PI	Floriano	295,163	2.81	190,224
PI	Litoral Piauiense	374,575	3.06	143,818
PI	Médio Parnaíba Piauiense	-	2.99	-
PI	São Raimundo Nonato	169,553	-	147,452
PI	Teresina	243,718	2.49	330,321
PR	Jaguariaíva	4,569	3.34	9,774
PR	Ponta Grossa	-	3.43	-
PR	Telêmaco Borba	8,776	3.22	5,851
PR	União da Vitória	-	3.00	-
PR	Wenceslau Braz	-	3.13	-
RO	Alvorada D'Oeste	394,317	3.03	127,199
RO	Ariquemes	1,088,134	3.02	368,809
RO	Cacoal	537,698	3.01	196,551
RO	Colorado do Oeste	1,094,317	3.21	341,820
RO	Porto Velho	738,630	2.64	309,653
RO	Vilhena	1,022,439	3.18	436,157

SP	Araraquara	71,459	2.72	32,897
SP	Assis	254,475	2.75	95,129
SP	Auriflama	116,232	2.60	44,775
SP	Avaré	375,124	2.92	127,530
SP	Barretos	31,997	2.49	12,915
SP	Batatais	68,027	2.51	76,607
SP	Bauru	207,099	2.87	247,011
SP	Botucatu	98,877	2.76	90,975
SP	Campinas	20,791	2.74	14,930
SP	Capão Bonito	49,490	2.89	16,910
SP	Catanduva	-	1.99	-
SP	Fernandópolis	51,362	2.86	-
SP	Franca	173,748	2.79	71,461
SP	Itapetininga	216,111	3.00	90,221
SP	Itapeva	536,483	3.06	199,131
SP	Ituverava	26,473	2.81	9,615
SP	Jaboticabal	29,594	2.60	16,115
SP	Jaú	30,883	2.63	21,376
SP	Limeira	19,681	2.40	7,477
SP	Marília	127,586	2.34	142,836
SP	Moji Mirim	174	2.31	257
SP	Nhandeara	19,131	2.34	8,709
SP	Novo Horizonte	24,429	2.40	15,750
SP	Ourinhos	203,403	3.01	75,326
SP	Piracicaba	54,031	2.43	51,018
SP	Pirassununga	14,184	2.65	5,553

SP	Presidente Prudente	525,436	2.43	259,620
SP	Ribeirão Preto	184	2.66	115
SP	Rio Claro	22,370	2.70	33,766
SP	São Carlos	28,979	2.51	23,087
SP	São João da Boa Vista	91,687	2.91	64,758
SP	São Joaquim da Barra	40,359	2.64	14,354
SP	São José do Rio Preto	252,512	2.52	174,525
SP	Sorocaba	15,654	2.80	6,242
SP	Votuporanga	179,704	2.67	110,107
TO	Araguaína	835,791	2.57	656,102
TO	Bico do Papagaio	170,246	2.90	455,024
TO	Dianópolis	1,076,547	3.04	1,011,431
TO	Gurupi	2,435,362	3.01	942,947
TO	Jalapão	896,877	2.99	432,717
TO	Miracema do Tocantins	1,983,985	2.80	845,895
TO	Porto Nacional	751,393	2.92	286,132
TO	Rio Formoso	1,161,649	2.94	461,067
TOTAL		**149,536,689**	**-**	**64,044,584**