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Pathways for recent Cerrado soybean expansion: extending the soy moratorium and implementing integrated crop livestock systems with soybeans

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Abstract

The Brazilian Soy Moratorium has effectively reduced forest conversion for soybeans in Amazonia. This has come at the expense of the region's pasturelands, which have increasingly ceded space for compliant soy expansion. The question of extending the policy to the Cerrado, where recent soy expansion has come at the cost of ecologically valuable vegetation, plugs into a wider discussion on how to reconcile competing commodities on finite amounts of cleared area. Innovative management strategies that allow different land uses to coexist are urgently needed. Integrated crop-livestock systems with soybeans (ICLS) rotates beef and soy on the same area, and shows promise as a means to improve production, farmer benefit, and environmental impacts. Here we reconstruct historical land use maps to estimate Cerrado Soy Moratorium outcomes with benchmark years in 2008 and 2014, we then estimate additional production afforded by ICLS implementation between 2008 and 2014. We find that if a 2008 Cerrado Soy Moratorium were in place, 0.7 Mha of 2014 Cerrado soy area would currently be in violation of the policy. Roughly 96% of this acreage is found in Matopiba (82%) and Mato Grosso (14%) states, suggesting that adoption may have slowed recent production in these rapidly transforming soy centers, in contrast to central and southwestern Cerrado where there is more concentrated eligible expansion area. Changing the benchmark to 2014 could have added 0.7 Mha of eligible expansion area, though over 80% of these additions would be in states with the most 2008 eligible area (Distrito Federal, Mato Grosso, Maranhão, Minas Gerais, Mato Grosso do Sul). Meanwhile, ICLS adoption could have added between 4.0 and 32 Mha of new soy land to the study area without additional clearing between 2008 and 2014, though this would depend on rigorous accompanying land zoning policy to guide implementation. The roughly 5 Mha of Cerrado soybean expansion that actually occurred between 2008 and 2014 could have been accommodated on 2008 suitable pasture area given an ICLS rotation frequency of every 6 years or less. Conservation estimates presented here represent the upper limit of what is possible, as our scenario modeling does not account for variables such as leakage, laundering, or rebound effects.

Introduction

In recent decades, Brazil has emerged as a major player in the global market for commodity soybean [1, 2]. Growing world demand for food, feed, and fuel has led to a heavier reliance on commodities from the tropics, where most of the world's remaining arable land exists [3]. 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 [1, 4, 5]. Exports began to comprise 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 [6]. Numerous demand-side initiatives in the EU and US have sought to leverage the power of these markets for conservation with varying degrees of success [7, 8]. While the EU has stringent demand side requirements in place, its companies operate within the most vulnerable forest frontiers in Brazil, making their sourcing particularly associated with forest risk [9]. Over the past decade, an increasing share of Brazil's soy exports have gone to China, as the Chinese government relies more heavily on imports to achieve domestic food security amidst shrinking available agricultural land in the country [10–12]. While Chinese interest in sustainable sourcing is beginning to materialize for high forest risk commodities such as beef and palm oil, sustainable soybean commitments are still scarce and face obstacles of traceability and cost [13].

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 [14–17]. Historically, the world's highest deforestation rates have occurred in the Brazilian Amazon's 'arc of deforestation', where agricultural land uses have replaced large tracts of forest [18]. While aggressive environmental policy has significantly curbed Amazonian deforestation rates over the past decade, in the neighboring Cerrado biome vegetation suppression rates are still 2.5 times greater than in the Amazon [19–21]. Previous work has identified the Cerrado's savanna as an important leverage point for climate stabilization, biodiversity preservation, and the provision of invaluable ecosystem services such as water regulation [22–26]. Of particular concern is 'Matopiba' (composed of states Maranhão, Tocantins, Piauí, and Bahia), a rapidly expanding soy frontier where most of the Cerrado's native vegetation resides [19, 20].

The close relationship between soybean production and deforestation has been targeted by several high-profile policy efforts [11, 19, 27, 28]. In 2006, after a provocative awareness campaign led by Greenpeace [29], the country's largest soy buyers committed to the Soy Moratorium, a zero-deforestation agreement that precludes any purchasing of soy grown on Amazonian land cleared after 2006. This benchmark has since changed to 2008 for congruity with the latest version of Brazil's Forest Code legislation [30]. The agreement 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% [19, 31], though this statistic does not consider soy's indirect contributions to forest loss [27, 28]. It also does not account for possible laundering occurrences, where soy grown on recently deforested area is funneled into the supply chain using loopholes that exist under complex property arrangements [32].

The Soy Moratorium limits expansion to designated areas by withholding market access from producers who have recently deforested. This has served as persuasive motivation for producers and high compliance rates have been well-documented by the Brazilian Association of Vegetable Oil Industries (ABIOVE) since the policy's inception [33]. However, in the years following the Soy Moratorium's establishment (2007–2013), 40% of new soy expansion in the Cerrado replaced native vegetation [19], and soy area roughly doubled in Matopiba alone [34]. 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 [24, 26, 35]. A Cerrado Soy Moratorium has been discussed as a means to fill the niche presented by this policy gap [19, 24, 36], yet no previous assessments formally explore the impacts associated with extending the initiative into the region, where between 40% and 55% of vegetation has already been cleared [20, 23].

Critics of the Soy Moratorium point out the policy fails to provide a clear template for compliant producers to receive incentives, and has not incorporated local farmer representation in decision making processes [37, 38]. The Brazilian government has begun to emphasize integrated crop-livestock management methods, where pasture and crops are rotated in the same area, as a means to decrease greenhouse gas emissions, restore degraded pasture, and increase soy production and farmer benefit within compliant area [39]. In 2010 at the Conference of the Parties to the UN Framework Convention on Climate Change Brazil committed to doubling its integrated-systems acreage as part of their commitment to reduce greenhouse gases [40]. In particular, integrated crop-livestock systems with soy (ICLS) have the potential to decrease documented land competition between soy and pasture, while improving soil quality, and maximizing farmer profit [41].

In ICLS systems, initially degraded low-yield pastures undergo pH correction, fertilization, and compaction alleviation. A soy crop is then planted on the pasture, which fixes nitrogen and further improves soil fertility. After harvest, increased soil organic matter allows the land to be converted back to an improved yield pasture. Previous work suggests that crop-pasture rotation systems may have higher profitability than continuous grain and cattle production by themselves as the improved pasture enables higher stocking rates [40]. Currently adoption rates remain low due to initial investment, knowledge, and cultural barriers; in 2011, integrated crop-livestock systems were only being used on 1% (1.5 Mha) of pastures in Brazil [42–44]. Still, if the documented obstacles to ICLS adoption can be bridged by government

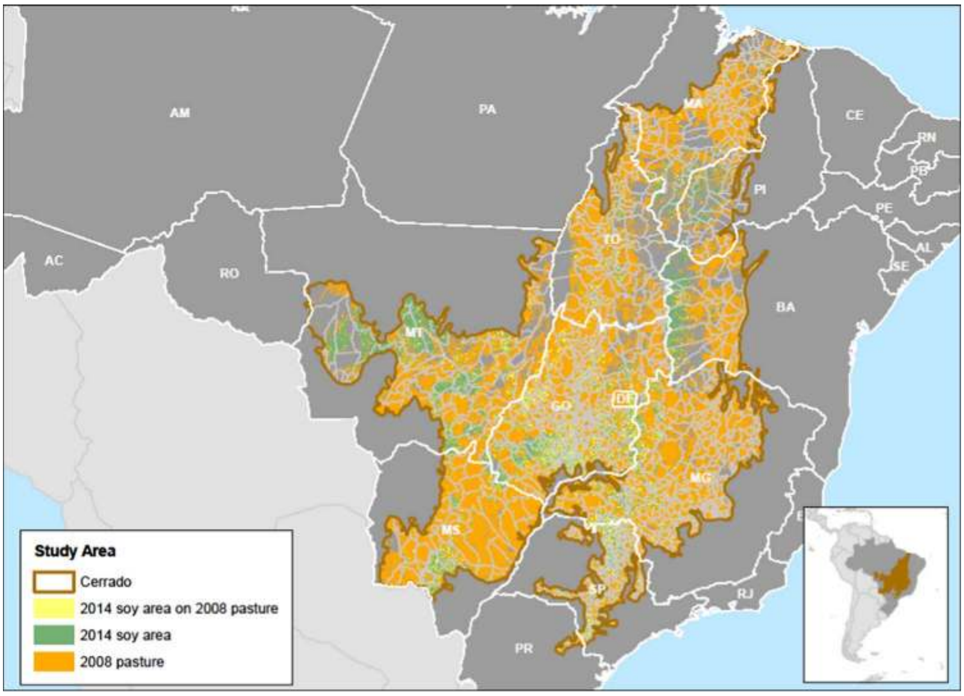

Figure 1. 2014 soy area by Agrosatélite is depicted in green. All municipalities at least partially inside the brown Cerrado boundary are included in Soy Moratorium calculations. Integrated crop-livestock with soy analyses consider all municipalities with orange or yellow established pasture in 2008, calculated using data from TerraClass Cerrado and LAPIG.

programs (e.g. the ABC plan), research incentives, or the agricultural credit created by the National Integrated Crop-Livestock-Forest Systems Policy (Law 12805, 29 April 2013), a diverse range of agricultural, environmental, and economic benefits could be leveraged [42, 43].

Here we estimate compliant expansion outcomes that may have occurred with an extension of the Soy Moratorium to the Cerrado biome with a cutoff date of 2008. We then examine how these estimates would change if the cutoff date were moved up to 2014. Finally, we examine the production outcomes that could have been generated by implementing ICLS regimes on all suitable 2008 pasture between years 2008 and 2014. We present these findings spatially, highlighting where capacities for increasing compliant soy production would be greatest, where they would be limited, and where ICLS approaches can be practiced for the greatest benefit.

Methods

Study area

We limit the scope of our study to the 870 municipalities that overlap with the Cerrado biome and that produced soybeans in 2014. This area spans 12 Brazilian states, including: Bahia (BA), Distrito Federal (DF), Goiás (GO), Maranhão (MA), Mato Grosso (MT), Rondônia (RO), Minas Gerais (MG), Mato Grosso do Sul (MS), Piauí (PI), Paraná (PR), São Paulo (SP), and Tocantins (TO) (figure 1, table 1). Together, these states accounted for 82% of Brazilian soy production and 84% of national deforestation across biomes in 2014 [2, 80].

Estimating soy moratorium eligible cleared area

We investigate Soy Moratorium scenarios with benchmark years in 2008 and 2014. We chose 2008 rather than 2006 as a benchmark year as this is congruous with the current Soy Moratorium in the Amazon, and because this year had greater data availability. 2008 also represents a more compelling hypothetical because it was the year the Soy Moratorium was overhauled to become more consistent with the Forest Code, which was a missed opportunity to implement the strategy nation-wide. We chose the year 2014 as a proxy for a policy implemented today because this was the most recent year of data available in all relevant datasets.

We use three datasets to estimate the amount of cleared area before years 2008 and 2014 that do not currently grow soybeans, referred to hereafter as 2008 eligible area and 2014 eligible area respectively. This area should be viewed as land where Soy Moratorium compliant expansion could feasibly occur. Conversely, ineligible areas refer to land where compliant expansion may not occur, such as land under natural vegetation, or land already growing soybeans. We combine land use maps developed by TerraClass Cerrado with Agrosatélite soy maps for the 2013/2014 harvest year, and LAPIG's annual Cerrado deforestation data produced from MODIS images (MOD13Q1) and

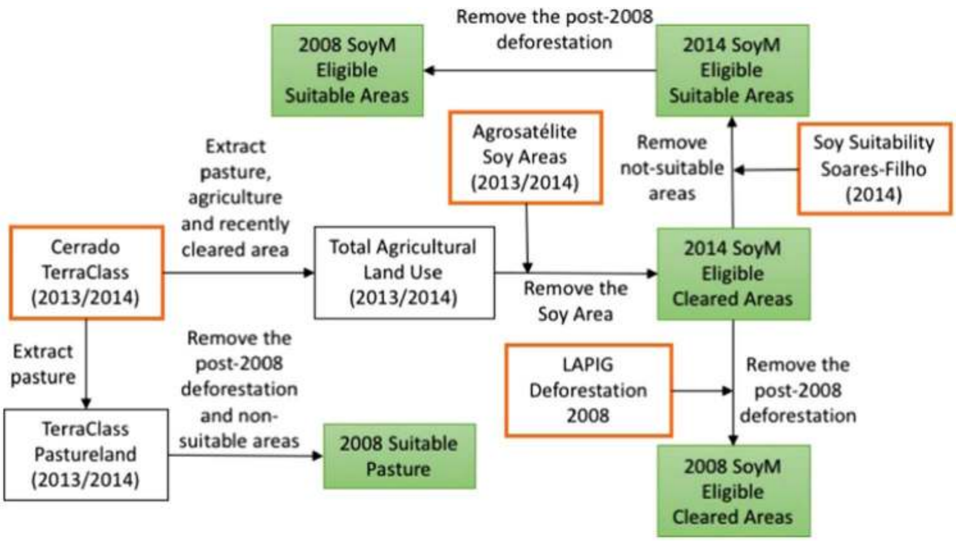

Figure 2. ArcGIS processes and datasets (TerraClass, Soares-Filho, LAPIG, Agrosatélite) used for estimating cleared area and suitable cleared area for 2008 and 2014, and 2008 suitable pasture area. Boxes with orange borders and white fill refer to input datasets, boxes with black border and white fill refer to intermediate outputs, and green boxes refer to final products.

Table 1. Cerrado study area land uses in hectares x 1000 in 2014 by state. Data compiled from TerraClass Cerrado, Agrosatélite, and LAPIG.

		Pasture		Native vegetation		Other agricultural land	
State	Total area	2008	2014	2008	2014	2008	2014
BA	15 125 000	2334 074	2450 000	1688 185	1018 000	1551 815	2222 000
DF	578 000	141 822	142 000	36 064	35 362	95 299	96 000
GO	32 962 000	13 821 204	13 977 000	1700 610	1377 000	4108 390	4432 000
MA	21 209 000	3274 934	3374 000	1903 250	1524 000	430 750	810 000
MT	35 883 000	6751 896	7911 000	2707 734	2154 000	5285 266	5839 000
MS	21 602 000	12 078 984	12 181 000	844 825	679 000	1646 175	1812 000
MG	33 372 000	11 711 907	11 876 000	1970 197	1599 000	2844 803	3216 000
PR	374 000	71 536	72 000	36 423	33 324	85 901	89 000
PI	9344 000	541 110	603 000	1367 323	779 000	241 677	830 000
RO	45 000	696	1000	190 077	190 077	0	0
SP	8114 000	2012 403	2022 000	187 780	152 893	3802 114	3837 000
TO	25 318 000	5260 049	5477 000	2540 866	1828 000	41 134	754 000
Study area	203 926 000	58 000 614	60 086 000	15 173 332	11 369 657	20 133 325	23 937 000

validated by LANDSAT and CBERS images for years 2008 through 2014 [25, 80].

We incorporate Soares-Filho's soy-suitability layer (2014) to determine area that was 2014 eligible and suitable, 2014 eligible and unsuitable, and suitable but under natural vegetation (figure 2) [35]. Finally, we remove annual deforestation polygons between 2008 and 2014 to obtain final estimates for 2008 (figure 2).

Estimating remaining suitable compliant land for soy expansion

Because agriculture is the main deforestation activity in the study area [45, 46] we consider the cleared land before 2014 to be equal to the total agricultural land use in 2014, which is the sum of all cropland, pastureland (natural and planted), and recently cleared area without designation in TerraClass. The latter category refers to land that has no vegetation, no agriculture, and no forestry uses present (0.18% of the total observed area) [80]. Second, we extract these land uses from Terraclass and mask the output with the Agrosatélite map of Cerrado soy area for the 2013/2014 crop year. We then exclude all area already growing soybeans to create 2014 eligible expansion estimates (figure 2).

Integrated crop-livestock systems with soybeans

We estimate the additional soybean production that ICLS systems could have contributed if implemented onto 2008 suitable pastures during the years between 2008 and 2014. Land was considered to be eligible for ICLS if they were pasture in 2008 and suitable for soybeans. ICLS producers typically rotate crops with pasture every 2–12 years [42, 47]. We assume a conservative rotation frequency where soybeans are planted onto suitable pasture once every 8 years

($n = 8$) and quantify municipal production increases using annual municipal average yield data from the Brazilian Institute of Geography and Statistics (IBGE) [2]. $n = 8$ is a conservative estimate intended only as a reference value. This assumption can be modified to other values of n, by multiplying our results by $8/n$ (equation (1)).

Of the 870 Cerrado municipalities that produced soy in 2014, 846 had suitable established 2008 pasture where ICLS could be implemented. Total pastureland area for each municipality was obtained from TerraClass Cerrado and bounded by Soares-Filho's suitability (2014) and LAPIG's deforestation (2008–2014) layers (figure 2). To determine ICLS quantity increases for each year between 2008 and 2014, we use the following calculation:

$$\text{ICLS quantity}_m = \sum_m y\left(\text{soy yield}_{m,t} \times \frac{1}{8}\text{2008 suitable pasture area}_m\right), \quad (1)$$

where ICLS quantity is the sum of the product of soybean yield in a year t for each municipality m and one eighth of 2008 suitable pasture area. Soy yield refers to annual IBGE yields, and pasture area uses values from the TerraClass database (2014).

Results

2008 Cerrado soy moratorium eligible area

The Cerrado contains 67.9 Mha of 2008 eligible cleared area. Of this area, 31.1 Mha (46%) are considered unsuitable for soybeans, leaving 36.8 Mha of suitable eligible area where soybeans could expand and remain in compliance with a 2008 Cerrado Soy Moratorium. Of this suitable area, 29% (10.8 Mha) was found in Mato Grosso do Sul, 22% (8.2 Mha) in Goiás, 21% (7.7 Mha) in Minas Gerais, 15% (5.6 Mha) in Mato Grosso, and 8% (2.8 Mha) in São Paulo. The remaining states contained less than 4% each (table 1, figure 3).

The same states that possess the most suitable eligible area also have the most suitable area under natural vegetation; Mato Grosso has 12.7 Mha (35%); Minas Gerais has 6.7 Mha (19%); Goiás has 5.2 Mha (15%); and Mato Grosso do Sul has 5.2 Mha (14%) (table 1, figure 3).

Approximately 19% of all 2008 eligible cleared area was already being used to grow soy in 2014. Of this, 47% of Piauí's pre-2008 cleared area is already used for soy, 41% of Paraná's, 40% of Mato Gross's, 34% of Distrito Federal's, and 31% of Bahia's, while the remaining states use less than 20% combined (figure 3(a)). If they were able to maximize the amount of suitable eligible area present, states Mato Grosso do Sul and São Paulo could both increase their 2014 soy acreage by over 8 times, while Distrito Federal, Minas Gerais, Goiás, and Mato Grosso could more than double their 2014 soy acreage. Matopiba states could increase less; soy area in Bahia could increase by 67%, in Tocantins by 43%, in Maranhão by 28%, and in Piauí by 15%. Piauí contains more soy acreage on land cleared after 2008 (0.2 Mha) than it has eligible cleared area (0.1 Mha), suggesting the state may have had a land debt if the policy had been adopted in 2008. While the Matopiba states together possess roughly 12.7 Mha of 2008 eligible area, 88% of this area is not considered suitable for soybeans. If land improvements were to occur in these areas, their potentials for Soy Moratorium compliance may increase as land becomes more suitable.

We find that between 2008 and 2014, 1.4 Mha of soy-suitable area was cleared. Roughly half (0.7 Mha) of this did not grow soybeans in 2014, making it eligible for compliant expansion given a 2008 Moratorium. The other half (0.7 Mha) did grow soy in 2014 and would be in violation of a 2008 Soy Moratorium. Of this, 82% of this acreage is located in Matopiba, and 96% in Matopiba and Mato Grosso states combined. These areas highlight where recent soy expansion has come at the cost of forest between 2008 and 2014. This violation area contributed 8.9 Mt of soybeans to the market between 2008 and 2014.

2014 Cerrado soy moratorium eligible area

The Cerrado contains an additional 4.2 Mha of 2014 eligible cleared area compared to 2008 levels (72.1 Mha total). 3.5 Mha (83%) of this are unsuitable for soybeans, leaving 0.7 Mha of suitable 2014 eligible area for future compliant conversion (37.5 Mha total). States possessing the largest additions of the latter include Distrito Federal (20%), Mato Grosso (20%), Bahia (18%), Minas Gerais (13%), and Mato Grosso do Sul (10%) (figures 3 and 4).

In addition to possessing the highest amounts of 2014 eligible area Mato Grosso, Minas Gerais, and Mato Grosso do Sul also possessed the highest concentrations of 2008 eligible area. Bahia's additional 2014 eligible expansion area could enable the expansion of its 2014 soy area by up to 9% compared to 2008 eligible area levels. Other Matopiba states would show little additional expansion capacities as most of their pre-2014 cleared area already grew soy in 2014; Tocantins and Piauí could expand their 2014 soy area up to an additional 3%, and Maranhão up to 2% compared to 2008 levels (figure 4).

Of the 3.8 Mha of land cleared between 2008 and 2014, 77% of deforestation occurred in Matopiba (62%) and Mato Grosso (15%). The vast majority of post-2008 deforestation occurred on unsuitable land for soybeans. States with the highest proportion of their suitable land under natural vegetation are found to be Tocantins (83%), Maranhão (75%), Mato Grosso (69%), Bahia, (68%), and Distrito Federal (64%). Mato Grosso do Sul (32%), and São Paulo

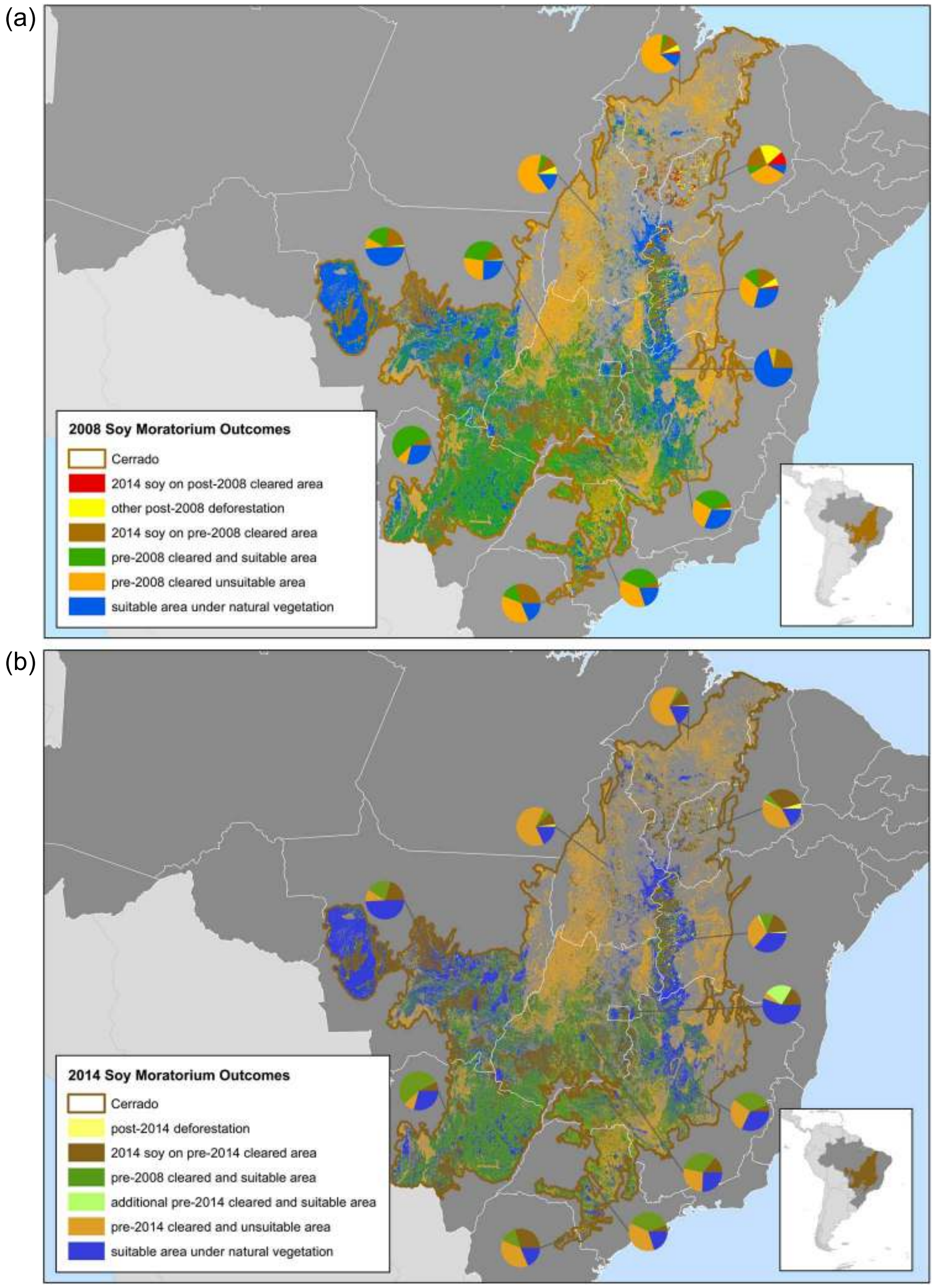

Figure 3. Relevant land use distributions and possible compliance outcomes for a (a) 2008 and (b) 2014 Cerrado Soy Moratorium.

(34%) have the lowest proportions of suitable area under natural vegetation.

Implementing integrated crop livestock systems with soybeans

We estimate that Cerrado pastureland for the year 2008 covered roughly 58.9 Mha, of which 54% (31.9 Mha) was suitable for soybeans and thus eligible for ICLS implementation. Of the 1375 Cerrado municipalities with established pasture in 2008, 846 municipalities had area suitable for soybeans. If ICLS management strategies were to have been adopted on all 2008 suitable pasture between 2008 and 2014, average annual municipal yields would allow an extra 63.4 Mt of soy to have been produced throughout the period. 31% (19.7 Mt) of this potential exists in Mato Grosso do Sul, 26% (16.8 Mt) in São Paulo, 19% (12.2 Mt) in Mato Grosso, and 17% (11.0 Mt) in Goiás (table 1, figure 5). The remaining states had less than 4% of the potential each, with Matopiba containing less than a combined 2% of the increased production potential in the Cerrado due to persisting low yields (figure 5) [2]. This increase would have grown annual national production by an average of 13%.

An 8 year ICLS rotation would have led to a 4.0 Mha increase in soy area throughout the study period; 1.3 Mha of this land is found in Mato Grosso do Sul (33%), 0.9 Mha in Goiás (24%), 0.8 Mha in Minas

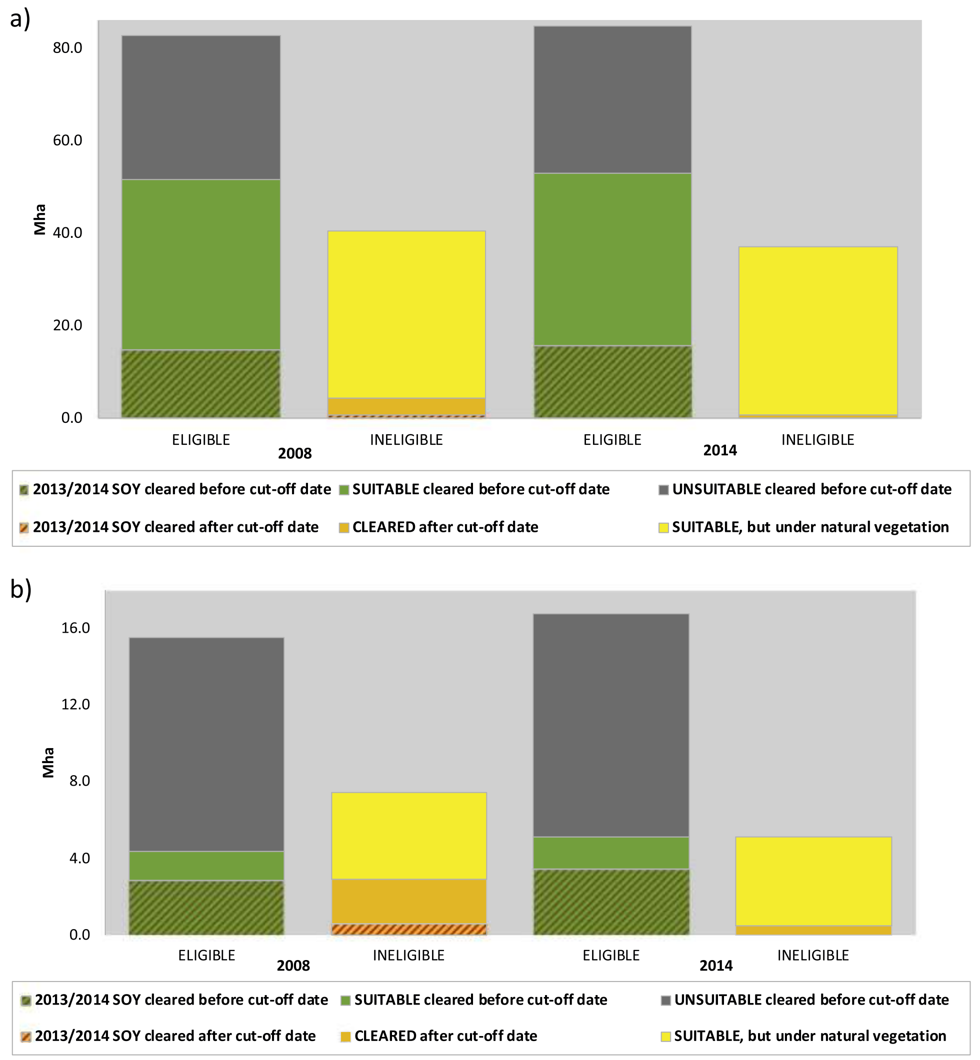

Figure 4. Distributions of 2014 levels of eligible and ineligible area for Soy Moratoriums for 2008 and 2014 in (a) all Cerrado states and in (b) Matopiba. The term 'cut-off date' refers to years 2008 and 2014, accordingly.

Gerais (20%), 0.7 Mha in Mato Grosso (16%), and less than 5% in the remaining states. Matopiba only embodied a combined 16% of the new soy area potential due to lack of established pasture in the region (table 1, figure 5). This compares to roughly 5 Mha of soy expansion in the study area that actually occurred during the period. In order to completely accommodate this acreage on suitable pasture, it would have required a minimum rotation frequency of one planting every 6 years.

Implementing integrated crop livestock systems with soybeans

In the unlikely scenario that all suitable area were to adopt soybean production and rotate every year ($n = 1$ for equation (1)), we estimate the maximum upper boundary for additional soy area during the period to be 31.9 Mha, and the maximum quantity produced given municipal average yield to be 507 Mt. Likewise, if $n = 100$, and soybeans were rotated only once every hundred years, the additional soy land added to the Cerrado would be 0.3 Mha and the additional quantity produced would equal 5.1 Mt in the study period.

Discussion

The most rigorous environmental standards in Brazil do not yet apply in the Cerrado, where agriculture has been identified as an important leverage point for conservation efforts pivotal to stabilizing the world's climate [21, 35, 69]. Measuring the Soy Moratorium'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 [21]. Previous work suggests the Soy Moratorium has resulted in less land cleared specifically for soybeans in Amazonia, and that compliance rates for the policy are high [33, 34]. Although no evidence exists showing voluntary commodity-based efforts, such as the Soy Moratorium, have been effective at slowing the overall rate of land clearing, questions about extending the

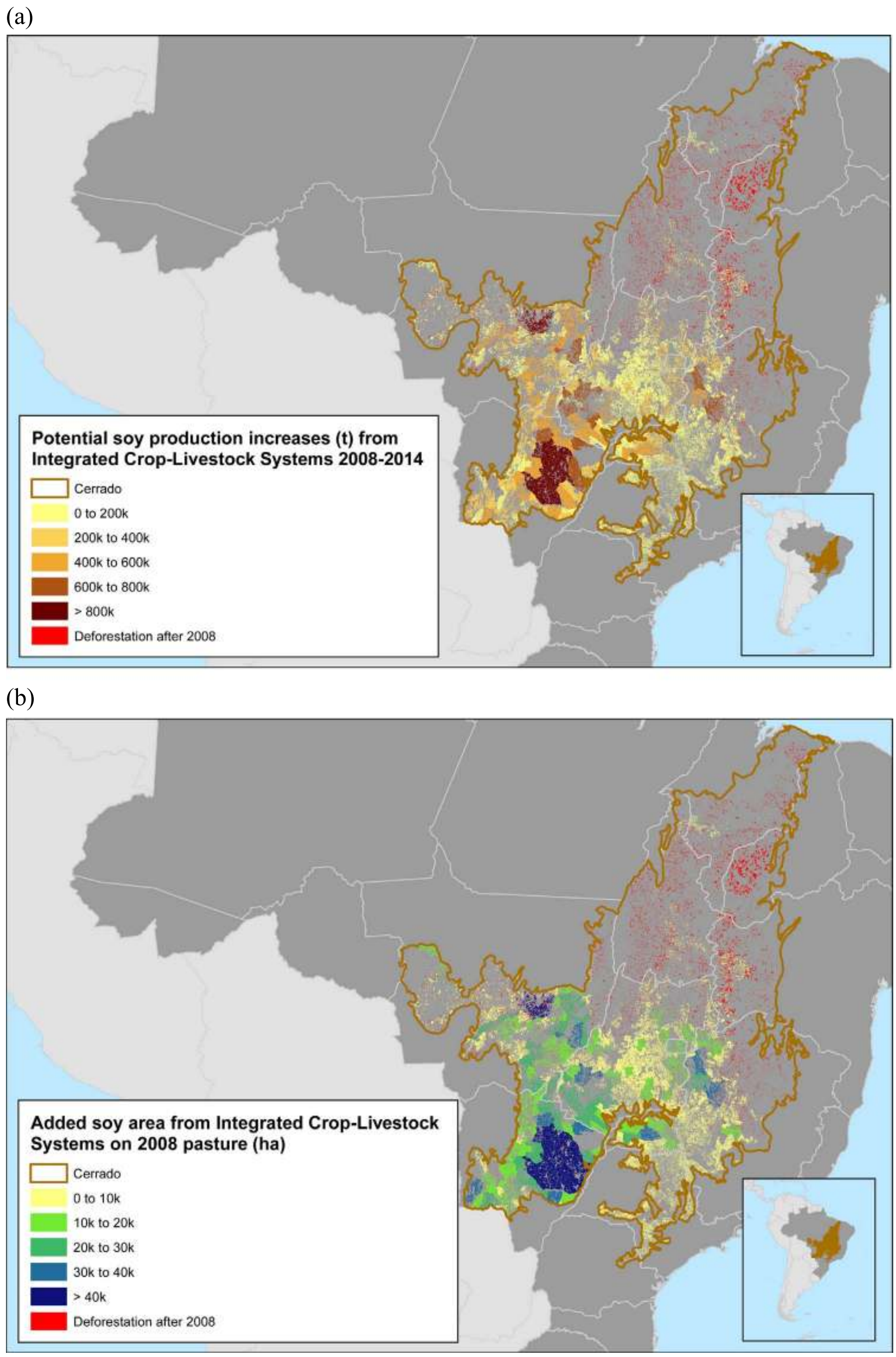

Figure 5. Integrated crop-livestock systems with Soy scenario where soybeans are planted onto 2008 pasture once every eight years ($n = 8$) between 2008 and 2014 depicting (a) additional quantity produced and (b) new soy area added. For $n = 16$, divide the legend numbers by 2, and for $n = 4$, multiply by 2.

agreement to the Cerrado are ongoing and have not been formally explored [19, 22, 48].

We present the first estimates for compliant expansion and production potentials across local and regional scales for a Cerrado Soy Moratorium. We find that if a Cerrado Soy Moratorium had been implemented in 2008 alongside the overhauled Amazonian policy, then 0.7 Mha of Cerrado deforested area between 2008 and 2014 would be in violation of the policy as of 2014. This 0.7 Mha should be considered the maximum amount of area that a Cerrado Soy Moratorium may have spared from conversion, if appropriate policy were in place that prevented clearing for other land uses, and if new compliant soy area minimized its role in deforestation via displacement. The spatial distribution of the 2008 eligible area suggests that a 2008 Cerrado Soy Moratorium would eventually lead soy expansion behaviors to shift away from soy-centers such as Matopiba and Central Mato Grosso and into places with the highest concentrations of 2008 eligible area, such as Goiás, Mato Grosso do Sul, Minas Gerais, and eastern Mato Grosso. It should be noted that developing local infrastructure to produce, store, and transport soybeans to markets may make these highly eligible areas more vulnerable to land use change [49–51]. While a Cerrado Soy Moratorium may halt new clearing for soybeans, soy could still displace other land uses occupying eligible area that go on to deforest elsewhere. This phenomenon, which shifts soy's role in forest loss from direct to indirect rather than eliminating it, has been well-observed in Amazonia [27, 32].

Between 2008 and 2014 roughly 20% of the 3.8 Mha of deforestation in the Cerrado was for soybeans, suggesting that a 2008 moratorium may have had a significant impact on preserving natural vegetation. This is especially true in Matopiba, where 82% of the area resided, and where commitments to sustainable commodity production have been minimal [25]. Because of the government's active promotion of agricultural development in the region in recent years, a future moratorium, even with a later benchmark year, would only improve feasibility if a significant amount of non-soy cleared land accumulated between 2008 and the benchmark date. However, moving the benchmark up to 2014 would have only added 0.7 Mha of suitable eligible area throughout the entire study area. Only 28% of this would be in Matopiba, while the vast majority of additions would be concentrated in states that already have the most land cleared before 2008. This small amount may prove unconvincing in the context of the substantial investments being made by the Ministry of Agriculture (MAPA) for future agribusiness development in the region. In May of 2015, MAPA announced plans for a high-profile project called the Plano de Desenvolvimento Agropecuário do Matopiba (PDA-MATOPIBA), which focuses on agriculture and livestock development and may work to discourage agribusiness from adopting new zero-deforestation commitments in the near future [22].

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 [52]. Their simplicity is both beneficial and limiting. While the Soy Moratorium is exceptional because of its longevity, high compliance levels, and popularity, some suggest that the Soy Moratorium's perceived success in the Amazon is at least partially due to production and forest loss moving into the Cerrado [19, 28, 54]. Minimal environmental regulations may make the biome particularly susceptible to leakage, though recent work has found mixed evidence of this [19, 24, 49, 54, 55]. Extending a Soy Moratorium into the Cerrado may begin to address these leakage issues, but competing policy options and stakeholder consensus are major obstacles.

While the Soy Moratorium 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 [2], allowing its proponents to frame the policy as less likely to affect markets on a larger scale [22]. Another reason the Soy Moratorium worked well in the Amazon is due to the abundance of grazing lands near traditional soy producing regions, which allowed soy to easily expand in a compliant manner. This is not the case for traditional soy producing regions in the Cerrado, such as western Bahia, where there is little grazing land available to accommodate new soy expansion.

Other Cerrado conservation efforts are currently underway, including the government created Action Plan for the Prevention/Control of Deforestation and Forest Fires (PPCerrado), which seeks to create a deforestation monitoring system, increase the number of conservation units, and title and recognize indigenous lands [56]. However, there have been ongoing issues with execution and transparency [22]. Another key regional effort includes 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 Forest Code legal reserve obligations in most of the Cerrado only require preserving 20% of properties as forest, southern and western areas of the biome show extensive land debt [35]. The substantial amounts of forest preserved under the Soy Moratorium but eligible to be cleared legally under the Forest Code (and vice versa) has led to calls for more overlap and goal alignment between the two policies [36]. Reforming the Soy Moratorium presents an opportunity to achieve this outcome if Soy Moratorium participants agree to make CAR registration an additional criterion for compliance, as was the case for the 2009 beef moratorium [36, 57]. Finally, 70 signatories have recently endorsed the Cerrado Manifesto, a sustainable commodity sourcing agreement that relies on voluntary company pledges to reduce deforestation, though the effectiveness of this commitment will not be immediately measurable [58].

An important variable in persuading stakeholders to undertake another Soy Moratorium effort resides in the uncertainty of foreign markets. China's growing stake in the Brazilian soy export market has not coincided with sending demand signals that promote sustainable production [59]. As of 2017, only 1 of 14 of the largest soy companies in China had commitments in place to ensure their soy products were not associated with forest loss [60]. While global pressure on Chinese companies to adopt sustainability standards into their market is beginning to take hold, formal commitment from China to eliminate forest risk from its commodity chains will prove paramount to efforts for expanding the Soy Moratorium to the Cerrado, and to reaching Brazil's ultimate goal of zero-net deforestation [11, 61]. The connection between compliance and limited environmental standards in China's soy supply chain should be further explored in future research.

Increasing compliant production

Production increases can generally be achieved through intensification or extensification. Previous work has shown that soy yields are already at 92.5% of their potential in the Cerrado region, suggesting that it may be very difficult to close the gap further [62]. While vast increases in compliant production are possible through expansion onto suitable eligible area, pathways are limited to areas currently occupied by other land uses. Leakage risk outlined by previous work should be a key consideration [11, 27, 63]. 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 while ceding land for soybeans [11, 16, 24]. Policy interventions and management strategies that help to deescalate land use competition between soy and beef are urgently needed.

ICLS management practices present an alternative where new production area can occur without additional clearing, and without other land use displacement. Previous studies have shown that rotating soy with pasture may increase productivity in each commodity, improve crop resilience to drought and frost, enhance soil health, promote water conservation, and increase carbon storage [39, 42, 64]. We show that a conservative ICLS implementation between 2008 and 2014 could grow total national soy production by 13% in the same period, though Matopiba showed limited potential as the region has not engaged in large scale ranching in the past [65].

The examined scenario assumes that already established pasture would completely accommodate new soy expansion between 2008 and 2014. A 100% soy-onto-pasture expansion rate is not far from what occurred in reality for the period. From 2000 to 2014, 80% of Brazil's total cropland expansion has been onto pasture [66]. in the Cerrado specifically, previous work has shown that between 2007 and 2014, 74% of new soy area expanded onto pasture or non-soy cropland—non-soy crops comprise approximately 3% of all agricultural land in the Cerrado, so the vast majority of this expansion can be assumed to have been onto pasture [25]. Trends differed in Matopiba and Mato Grosso, where for the same time period 62% and 68% of soy expansion occurred over native vegetation, respectively [62]. For Matopiba, the low soy-onto-pasture expansion rates and limited quantities of established pasture may serve as insurmountable obstacles for producers implementing ICLS management at a meaningful scale. However, we show Mato Grosso as having one of the highest potentials for increased soy production through ICLS (figure 5), suggesting that pivoting the state towards ICLS management could serve a role in slowing high rates of expansion onto native vegetation. Further, if excluding these regions, the remaining states (DF, GO, MG, MS, PR, SP) had 89% of their soy expansion occur over pasture between 2007 and 2014 [62]. These high rates coupled with high potentials for production increases (figure 5) make these places exceptionally well-poised to emphasize ICLS implementation.

We estimate that it would require a minimum rotation frequency of one planting every six years in order to accommodate all of the Cerrado's soy expansion for the study period onto 2008 suitable pasture using ICLS. However, any new soy area on already established pasture may or may not lead to land sparing. Under specific policy contexts, intensification has been associated with positive conservation outcomes [67–70]. The Amazon is a particularly successful example of this; being subject to intensive land use zoning regulation, credit restrictions for bad actors, and private market mechanisms has synergistically worked to create conditions where intensification contributes to land sparing [21, 61, 67–70]. However, in regions that are absent of these conditions, a 'rebound effect' has been found to occur, where increased productivity leads to more incentive to clear new lands and thus exacerbates land conversion pressures in the region [71]. If proper conditions were present in the Cerrado, it is possible that this 4.0 Mha of new soy area could result in land spared. However, successfully leveraging ICLS for conservation outcomes depends heavily on the presence of regulatory conditions highlighted in previous work [21, 72], likely in the form of land-use-zoning policy that guides implementation, introduction programs targeted to specific areas, and credit incentives to help bridge initial costs of adoption [67, 73]. While it is possible that another Soy Moratorium could play a role in this regulation, it is likely that a more comprehensive zoning policy that accounts for indirect land use change and combines economic and ecological standards (e.g. Map of Ecological Zoning for Sugarcane) would be more effective [72]. It is important to note that if these ideal policy conditions were present, the improved pasture yield that results from ICLS implementation may contribute an additional land sparing effect, which should be studied in-depth in future work.

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 [64]. The conditions under which ranchers may decide to adopt ICLS are complex. Cattle ranches are most often large properties (>300 ha) located far from towns, and are associated with having limited access to credit and machinery [74]. Access to machinery, in particular, correlates with whether cattle ranches use crop-pasture systems versus cattle alone [74]. Some frontier regions face other socio-economic barriers to implementing ICLS systems, such as lack of technical and economic expertise, lack of quality labor, lack of credit access, high financial costs, being far from supply chain infrastructure, and the absence of business models that are applicable to small-scale farmers [42, 43, 73, 75]. These obstacles have resulted in low adoption rates historically [22, 76], yet surveys show integrated systems are becoming more widely recognized as financially beneficial in the long term and as a welcome opportunity for specialized farmers to diversify within intensified systems [42]. In the current landscape, where ranchers face increasingly low prices offered by the meatpacking industry along with high pasture recuperation costs, ranchers may be more eager to experiment with income augmentation through integrating soy production onto pasture [57, 77–78]. 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 [42]. While this result presents an optimistic picture for producers, more research is needed to quantify the long-term financial implications for adoption.

The land sparing effects of ICLS-based cattle intensification and potential adoption for soy producers should also be carefully examined in future work. To date, adoption efforts have focused primarily on soy producing municipalities, as adoption is both lower risk and lower cost than for cattle producers [64]. This analysis makes the case for a more concerted effort to extend programs into pasture producing municipalities to achieve maximum benefit. In general, 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

Our estimates that use data from 2008 to 2014 assume that land uses in the Cerrado have remained relatively static over time and do not move around from year to year. Municipalities 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 a Cerrado Soy Moratorium dually requires land cleared before 2008 or 2014 and Forest Code surplus [35]. The model presented is not dynamic and is meant for simple bookkeeping. Leakage, laundering, and rebound effects have not been incorporated. Soy expansion is also subject to many variables outside of the scope of this study, including profitability, market networks, connectivity, and infrastructure [49–51]. While this work focuses specifically on land availability, future work that integrates these variables would be invaluable to ongoing discussion surrounding the viability of a Cerrado Soy Moratorium and ICLS adoption.

We consider an eight-year crop-pasture rotation to be conservative given common regimes highlighted in ICLS literature [40–42, 63, 75]. We chose this conservative rotation frequency because ICLS has never been explored at the scale we discuss here, and may have other barriers to adoption. The financial benefits of ICLS may be insufficient to drive widespread adoption. For example, the perception that cattle ranching requires less labor than other more complex crop systems may work to dissuade those considering adoption in areas where labor is scarce, meanwhile, uncertain markets increase the appeal of acquiring low-risk savings in the form of cattle while enjoying the elevated social status associated with the profession [44, 74, 79].

Finally, combining datasets from four different sources can result in compatibility uncertainties. Our methods integrate LANDSAT-based 30 × 30 resolution data from TerraClass Cerrado, Agrosatélite, and LAPIG, with 60 × 60 resolution data from Soares-Filho (2014). To reconcile the different resolutions of these datasets ArcGIS automatically resamples using the nearest neighbor assignment to the coarsest resolution of the input datasets, creating marginal losses of accuracy.

Conclusions

The Soy Moratorium is often credited with contributing to deforestation reductions in the Amazon, but implementing a Cerrado extension faces major political and geographical obstacles. Here we quantified and mapped potentials for Soy Moratorium-compliant expansion for the years 2008 and 2014. If the Soy Moratorium were to have been extended into the Cerrado simultaneously with the Amazon's policy in 2008, Matopiba and Mato Grosso regions would possess 0.7 Mha of 2014 soy area in violation of the policy. This area may have been spared clearing over the period if certain policy conditions were also present, and could be interpreted as the cost of failing to implement policy across all vulnerable areas in close proximity at the time. In general, reforming the Soy Moratorium to apply in the Cerrado could help mitigate future legal clearing allowed by the Forest Code in the region, and would present an opportunity to more closely align the two policies by adding a requirement for producers to be registered with CAR, though other more comprehensive land use zoning tools may prove more effective. 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. Regardless, a Cerrado Soy Mortorium would do little to deescalate competition between beef and soybeans for cleared production area.

While ICLS strategies show promise for preventing new clearing in many Cerrado states, Matopiba's general lack of established pasture and suitable cleared area are problematic for the strategy. The region's lack of viability as a sustainable commodity producer suggests that other conservation methods should be emphasized, such as setting aside natural area for Legal Reserve balance, for protected areas, or for compliance with international REDD+ mechanisms, which are beyond the scope of this work. Meanwhile, traditional strategies to increase compliant production face problems of scale, infrastructure, 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 areas with high potential as a means to meet growing demand on less land, while improving environmental outcomes. Optimal policy guidance and the financial implications for adoption should be explored in depth in future work.

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