ENVIRONMENTAL STUDIES

Expanding the Soy Moratorium to Brazil's Cerrado

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The Cerrado biome in Brazil is a tropical savanna and an important global biodiversity hot spot. Today, only a fraction of its original area remains undisturbed, and this habitat is at risk of conversion to agriculture, especially to soybeans. Here, we present the first quantitative analysis of expanding the Soy Moratorium (SoyM) from the Brazilian Amazon to the Cerrado biome. The SoyM expansion to the Cerrado would prevent the direct conversion of 3.6 million ha of native vegetation to soybeans by 2050. Nationally, this would require a reduction in soybean area of approximately 2%. Relative risk of future native vegetation conversion for soybeans would be driven by the Brazilian domestic market, China, and the European Union. We conclude that, to preserve the Cerrado's biodiversity and ecosystem services, urgent action is required, including a zero native vegetation conversion agreement such as the SoyM.

INTRODUCTION

Brazil is a major global producer and exporter of commodities such as soybeans, maize, beef, and sugar. During the past decade, commercial agriculture has become an important driver of tropical deforestation. Soybeans are Brazil's most important cash crop, with approximately 70% of Brazilian soybean production being exported worldwide (*1*). Within Brazil, the Cerrado has been at the center of the country's recent agricultural boom. In 2015, only 13% of Brazil's soybean production was harvested in the Amazon, while 48% came from the Cerrado biome (*2*). Inside the Cerrado, the Matopiba—a region that includes portions of Maranhão, Tocantins, Piauí, and Bahia states—is at the forefront of agricultural expansion, with the soybean area increasing by 253% between 2000 and 2014 (*3*). Currently, almost a quarter of the Cerrado's soybean area is located in Matopiba. Brazil's soybean production is expected to continue to grow in the coming decades. Given the high availability of suitable land, the country has the potential to become the world's largest soybean producer by 2025, with a production of 135 million metric tons (Mt), surpassing the United States (*4*). The Cerrado is likely to be the main location of this expansion.

Because only 19.8% of undisturbed native tropical savanna remains in Brazil's Cerrado (*5*), conversion of the remaining habitat is a major threat to biodiversity. More than 4800 endemic plant and vertebrate species in the Cerrado could become extinct in the coming decades unless additional conservation measures are taken (*5*). The Cerrado also spans some of the largest watersheds in Brazil (*5*) and stores 13.7 billion metric tons of carbon (*6*). Compared to the Amazon Forest to the north, the Cerrado attracts much less attention, although it is much less protected and is more converted and its remaining habitat is being converted at a faster rate (*7*). Unlike the Amazon, where almost half of the area is under some sort of conservation protection, only 13% of the Cerrado is protected. Under Brazil's Forest Code (FC), there is a requirement to conserve 80% of the native vegetation on private lands in the Amazon biome but only 20% in the Cerrado (35% for the portion of the Cerrado located in the Legal Amazon). Moreover, the government's regulatory measures that, together with supply chain initiatives, were responsible for reducing deforestation in the Brazilian Amazon (*8*) are historically ineffective in the Cerrado because of lack of political will. However, there are at least 25.4 million ha (Mha) of land already cleared in the Cerrado that are suitable to accommodate agricultural expansion (*3*), suggesting that agricultural expansion and conservation of the remaining habitat may both be possible.

Between 2000 and 2014, approximately 30% of the soy expansion in the Cerrado occurred at the expense of native vegetation (*3*). A similar proportion of soy expansion in the Amazon occurred through deforestation between 2004 and 2005 (*9*), precipitating the implementation of the Soy Moratorium (SoyM) in the Amazon in 2006. The Amazon SoyM is a zero-deforestation agreement between civil society, industry, and government that prohibits the buying of soy grown on recently deforested land in the Brazilian Amazon. In May 2016, the Amazon SoyM was renewed indefinitely. Recently, more than 70 companies and social and environmental organizations signed a manifesto calling for a halt to native vegetation conversion in the Cerrado (*6*). However, the Cerrado is currently not covered by the SoyM.

Following the example of the Amazon, the private sector could play an important role in protecting the last undisturbed remnants of the Cerrado through the expansion of the SoyM without hindering the expansion of soybean production. However, the effects of such a moratorium on habitat loss and soybean production have not yet been quantified. Here, we analyze the impact of extending the SoyM to the Cerrado by projecting the future soy expansion in Brazil under scenarios with and without the SoyM. Our model approach, called Global Biosphere Management Model (GLOBIOM)–Brazil (*10*), is a regional version of the global land use partial equilibrium model GLOBIOM (*11*, *12*) and runs in 5-year time steps from 2000 to 2050. The use of an economic model is required because certain land use policy effects, such as indirect land use change and leakage

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across commodities or biomes, cannot be directly observed or disentangled from historical data (*13*). We estimate the spatially explicit location of (i) the avoided direct native vegetation conversion to soy, (ii) the avoided emissions of carbon dioxide by 2050, and (iii) the losses in soybean expansion that would occur by extending the SoyM to the Cerrado biome. We also considered a scenario with the rigorous enforcement of the FC and without the SoyM expansion to the Cerrado to evaluate the effectiveness of this supply chain agreement vis-à-vis Brazil's most important environmental law in reducing illegal native vegetation conversion (see Table 1 and Materials and Methods). We also calculated the area of native vegetation at risk of loss per 1000 metric tons of soybeans produced in each region of the Cerrado from 2021 to 2050. This allowed us to estimate which traders are expected to contribute most to future native vegetation conversion in the Cerrado based on our model projections and the TRASE (Transparent Supply Chains For Sustainable Economies) dataset of market share by region (*1*). We report the aggregate results for the six largest soy traders [ADM (Archer Daniels Midland), Amaggi, Bunge, Cargill, COFCO, and Louis Dreyfus Company—hereafter referred to as the Big 6], the ABIOVE (the Brazilian Association of Vegetable Oils Industry) and ANEC (Brazil's National Association of Grain Exporters) traders associations (which includes the Big 6), and the Chinese and the 28 European Union (EU) export markets, as well as Brazil's domestic consumption, assuming stable market shares of each group by 2050.

RESULTS

Impacts on native vegetation loss

We estimate the impacts of the SoyM on native vegetation loss by comparing the scenario with the SoyM expansion to the Cerrado (SoyM) and the baseline (see Table 1 and Materials and Methods). Soybeans are projected to expand by 12.4 Mha between 2021 and 2050 in Brazil according to the baseline, and the Cerrado is the likely location of most of this expansion: 10.8 Mha of new soybean fields will occur in the Cerrado compared to only 1.1 Mha in the Amazon (see fig. S1). Within the Cerrado, the Matopiba region will accommodate 86% (9.3 Mha) of this soy expansion (see fig. S2). Figure 1 (A and B) shows the spatial distribution of the avoided direct native vegetation conversion to soy according to the SoyM and FC scenarios (see also table S1). Regardless of the scenario, we observe that the lion's share of this conversion is likely to take place in Matopiba, a region on the border of the Cerrado and the Caatinga biomes where the largest undisturbed remnants of the Cerrado vegetation are located.

Figure 2 shows the amount of native vegetation conversion to soybeans in the Cerrado biome between 2021 and 2050 under three different scenarios: baseline, FC, and SoyM (see Materials and Methods). Compared to the baseline, the SoyM scenario would avoid 3.6 Mha of direct native vegetation conversion to soybeans, with 2.7 and 0.9 Mha coming from preventing legal and illegal native vegetation losses, respectively. Taking into account indirect effects (also referred to as leakage), which increase the native vegetation conversion to pasture and other crops by 10 and 65%, respectively, the SoyM still prevents the loss of 2.3 Mha of Cerrado by 2050 compared to the baseline. In comparison, the FC scenario would avoid 0.9 Mha of direct native vegetation conversion to soybeans. The FC scenario, which requires no illegal native vegetation removal to any land use class, would avoid only 25% of the total direct native vegetation conversion to soy prevented by full compliance with the SoyM.

Impacts on delaying SoyM implementation

We also evaluated the impacts of different starting dates (i.e., the cutoff dates determining when the soybeans grown on deforested areas can no longer be purchased) for the extension of the SoyM to the Cerrado: 2015 and 2025 (see Table 1 and Materials and Methods). These alternative scenarios allowed us to explore the consequences of delaying the implementation of the SoyM extension. If the SoyM had been implemented in 2015, then the avoided loss of the Cerrado due to full compliance with the SoyM would have increased to 4.3 Mha between 2016 and 2050 (see table S1). When the implementation is delayed until 2025, the avoided loss decreased from 3.6 to 2.9 Mha. Thus, delaying the implementation of the SoyM in the Cerrado caused an average loss of 140,000 ha/year from 2016 to 2025.

Impacts on soy production

Figure 3 (A and B) shows Brazil's soy area and production under different scenarios. Compared to the baseline, the impact of the SoyM in the soybean expansion is small—1.0 Mha or approximately 2% of Brazil's projected soy area in 2050. In terms of production, this corresponds to a loss of 0.9 Mt by 2050 in Brazil. Comparing the SoyM and FC scenarios, we observe that their impact in terms of soy area and production is similar. In the Cerrado alone, the decrease in soy expansion by 2050 will be 2.0 Mha under the SoyM scenario. However, 1.0 Mha of soybean fields migrate to other biomes (some to the Amazon but mostly to the Atlantic Forest), making Brazil-wide soybean area net loss only 1.0 Mha. This increase in soybean production in other biomes occurs at the expense of pastures (80%)

Table 1. Scenario assumptions. Main assumptions for the various scenarios, including governance [illegal deforestation control (IDC) in the Amazon (Amz) and the Atlantic Forest (AtlF) biomes; FC, rigorous enforcement of the FC in the whole country, which includes IDC in all Brazil's biomes, obligatory forest restoration, and compensation by the CRA], compliance with the SoyM, and different starting dates for the extension of the SoyM to the Cerrado.

Scenarios	Governance IDC	SoyM compliance		Starting date of the SoyM in the Cerrado
		Amazon	Cerrado	
Baseline	Amz and AtlF	Full	No	–
SoyM	Amz and AtlF	Full	Full	2020
FC	Brazil	Full	No	–
SoyM-15	Amz and AtlF	Full	Full	2015
SoyM-25	Amz and AtlF	Full	Full	2025

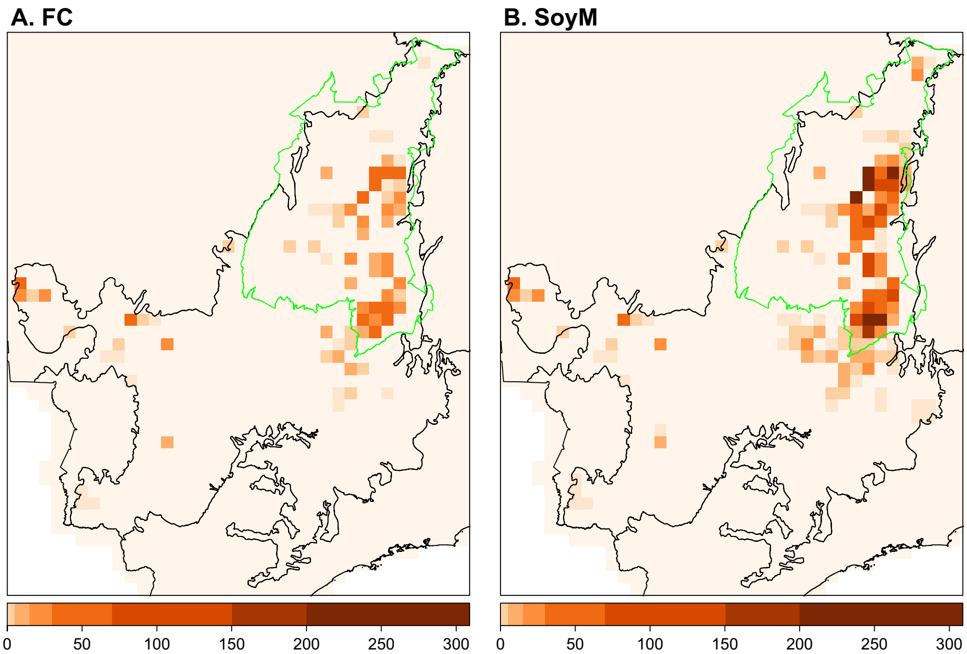

Fig. 1. Avoided direct conversion from native vegetation to soy. Spatial distribution of the avoided native vegetation conversion to soy in the Cerrado relative to the baseline between 2021 and 2050 under (**A**) the FC scenario (0.9 Mha) and (**B**) the SoyM scenario (3.6 Mha). The Matopiba region is highlighted in green. Color bar values are expressed in thousands of hectares per cell.

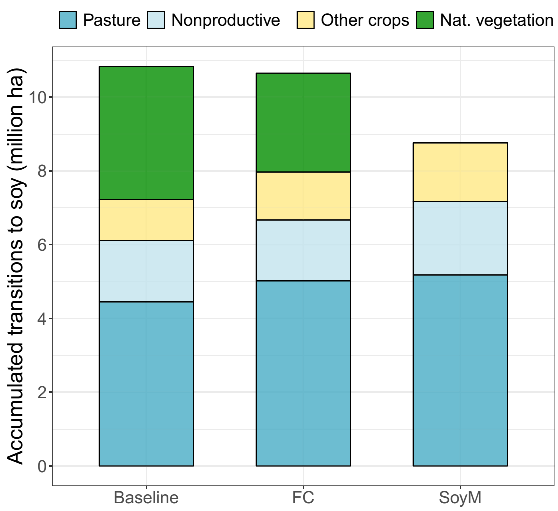

Fig. 2. Soybean expansion per land use class. Accumulated conversion from different land use classes to soy in the Cerrado biome as projected by the baseline, FC, and SoyM scenarios for the period 2021–2050.

and other nonproductive lands (mosaics of natural vegetation and areas previously converted from agriculture but not currently under production) and other crops (20%). In other words, no additional native vegetation is suppressed elsewhere.

Impacts on carbon emissions

The SoyM expansion also reduces carbon dioxide emissions. From 2021 to 2050, the SoyM avoids the emission of 0.59 gigatons of carbon dioxide equivalent ($GtCO_2e$) from the direct conversion of native vegetation to soybeans in the Cerrado or 12% of the projected emissions from deforestation and native vegetation loss in Brazil (see table S2 and Materials and Methods). Taking leakage into account, the net effect of expanding the SoyM to the Cerrado is the reduction of 0.38 $GtCO_2e$ of emissions from native vegetation loss or 8% of the country's emissions. Between 2021 and 2030, the avoided native vegetation loss due to the SoyM expansion to the Cerrado, considering leakage effects, would contribute to 0.10 $GtCO_2e$ or 11% of Brazil's Nationally Determined Contribution emission reduction target by 2030. Considering a total loss of 0.9 Mt in the production of soybeans by 2050 in Brazil and a soy price of 390 US$ per metric ton according to 2018 average Chicago soybean futures contract (*14*), the cost of extending the SoyM to the Cerrado biome amounts to 1.14 US$ per metric ton of carbon dioxide emissions avoided. In comparison, under the FC scenario in the same period, 0.15 $GtCO_2e$ of the emissions from the direct native vegetation conversion to soy are avoided. This figure rises to 0.48 $GtCO_2e$ if we include all emissions from native vegetation loss to any land use class in the same region and period.

Future native vegetation conversion risk

Figure 4 and Table 2 show maps and the aggregated results of soy-related native vegetation conversion risks, for the period 2021–2050, that different traders and associations could be exposed to from sourcing in different parts of the Cerrado. Traders that source a large proportion of their soy from regions with the most remaining native vegetation could be exposed to a high risk of native vegetation loss. In the absence of an agreement of zero conversion of native vegetation such as a SoyM in the Cerrado, ABIOVE and ANEC, which together represent more than 77% of Brazilian soy exports (*1*), would present a native vegetation conversion risk of 1.78 Mha. This figure represents 49% of the expected native vegetation conversion to soy between 2021 and 2050. Approximately 90% of this native vegetation loss

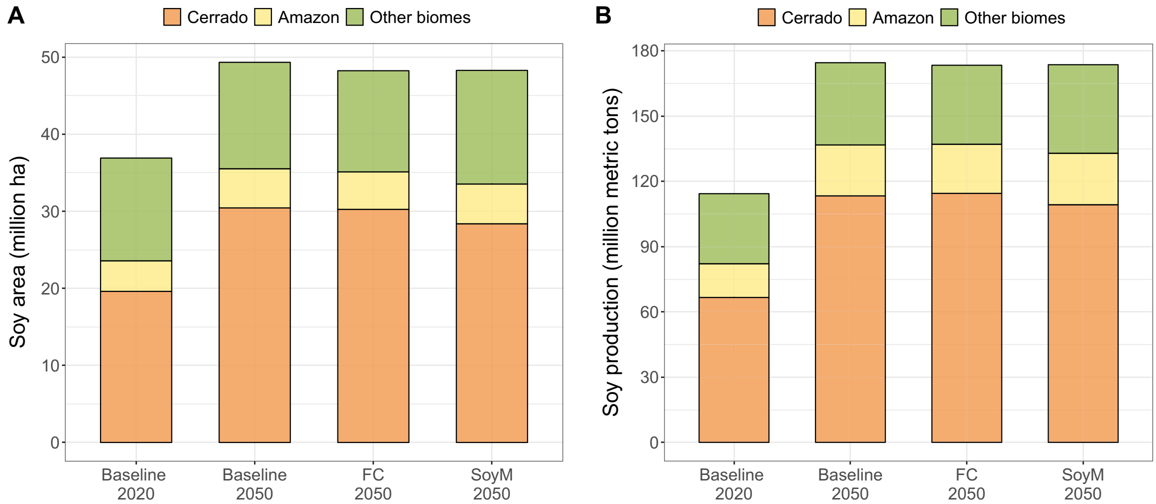

Fig. 3. Soybean area and production in 2020 and 2050. Total (**A**) soybean area and (**B**) soybean production within Brazil's major biomes in 2020 for the baseline scenario and in 2050 for the baseline, FC, and SoyM scenarios. Compared to the baseline, between 2021 and 2050, Brazil's soybean area and production are projected to expand by 11.4 Mha and 59.3 Mt, respectively, under the SoyM scenario, and by 11.3 Mha and 59.1 Mt, respectively, under the FC scenario.

would occur in the Matopiba region. The estimated future risk exposure of the Big 6 traders—the largest traders of Brazilian soy—and all members of the ABIOVE/ANEC associations is 1.32 Mha or 37% of all future soy-related native vegetation loss in the Cerrado. At the company level, the estimated relative future native vegetation conversion risk is unevenly distributed among the Big 6 traders. From 2021 to 2050, Amaggi could contribute to the direct conversion of 63.69 ha of native vegetation to soy for every thousand metric tons of soybeans sourced annually from the Cerrado. On the opposite side of the spectrum, Louis Dreyfus' relative risk is much lower (1.74 ha/1000 metric tons per year) because it operates in areas with very little Cerrado remnants (see Fig. 4).

At the market level, although China is the destination of almost 41% of the soy produced in Brazil, the Brazilian domestic market displays the greatest risk, with 1.65 Mha or 46% of the future native vegetation conversion to soy in the Cerrado. In comparison, the risks of China and the EU are 1.15 Mha (32%) and 0.45 Mha (12%), respectively. In relative terms, Brazil's internal market risk is 44.88 ha/1000 metric tons per year—the highest among all consumer markets. Although the volume of soy sourced from Cerrado and exported to China is 2.5 times greater than the volume exported to the 28 EU member countries, their relative risks are almost the same, 37.52 and 37.06 ha/1000 metric tons per year, respectively.

DISCUSSION

The Cerrado is a global biodiversity hot spot and provides essential ecosystem services for Brazil, including the provision of water, agricultural products, and carbon sequestration (*15*). The Amazon and the Cerrado also provide direct regulation of the regional climate via transpiration, which is the source of most of the regional rainfall—the water source that soybeans and other crops depend upon in this rain-fed agricultural system (*16*). If the SoyM expansion to the Cerrado biome is applied from 2021 onward, then it would prevent 3.6 Mha of the direct loss of native vegetation due to soy expansion, with only a 2% decrease in the soybean area in Brazil by 2050. Even with an estimated leakage of 36%, which reduces the total avoided native vegetation loss in the Cerrado by 1.3 Mha (from 3.6 to 2.3 Mha), we find an ecologically meaningful benefit of expanding the SoyM to the Cerrado. In terms of carbon emissions, 2.3 Mha of avoided native vegetation losses in the Cerrado represent a reduction of 0.38 $GtCO_2e$ or 8% of the country's total deforestation-related emissions from 2021 to 2050. A delay in implementing the SoyM results in the conversion of 140,000 ha of the remaining Cerrado vegetation every year. This is equivalent to a loss of approximately one Emas National Park per year from 2016 to 2025. The Emas National Park is one of the Cerrado's most important conservation units and a UNESCO World Heritage Site. In one decade, the accumulated loss due to soy expansion will cover an area almost as large as half of Belgium.

More than 80% of the future native vegetation conversion to soy is likely to take place in Matopiba, regardless of the scenario. Matopiba is Brazil's latest agricultural frontier, where soybeans have already expanded by 253% from 2001 to 2014 (*3*) and are expected to expand by 318% by 2050 compared to 2015 in our baseline scenario. This region is also well known for its unstable climate conditions, with successive droughts and crop shortfalls (*2*). However, the conversion of the Cerrado's vegetation is now occurring at a faster rate within Matopiba. Thus, even a SoyM restricted to Matopiba would have important benefits.

A growing number of private sector actors are voluntarily pledging to eliminate deforestation from their commodity supply chains. Furthermore, consumer awareness of deforestation is increasing, providing companies with incentives to adhere to the responsible sourcing of commodities. As of September 2017, more than 470 businesses have made commitments to curb deforestation and degradation linked to the production of palm oil, soy, timber, pulp, and cattle (*17*). Initiatives such as the Consumer Goods Forum, the Tropical Forest Alliance 2020, and the 2014 New York Declaration on Forests are laudable and cover multiple commodities and regions by various stakeholders, including public, private, and civil society actors, but may fail to provide a clear pathway for the implementation of their targets (*18*). Zero-deforestation agreements such as the SoyM are considered easy to monitor and effective in reducing deforestation for

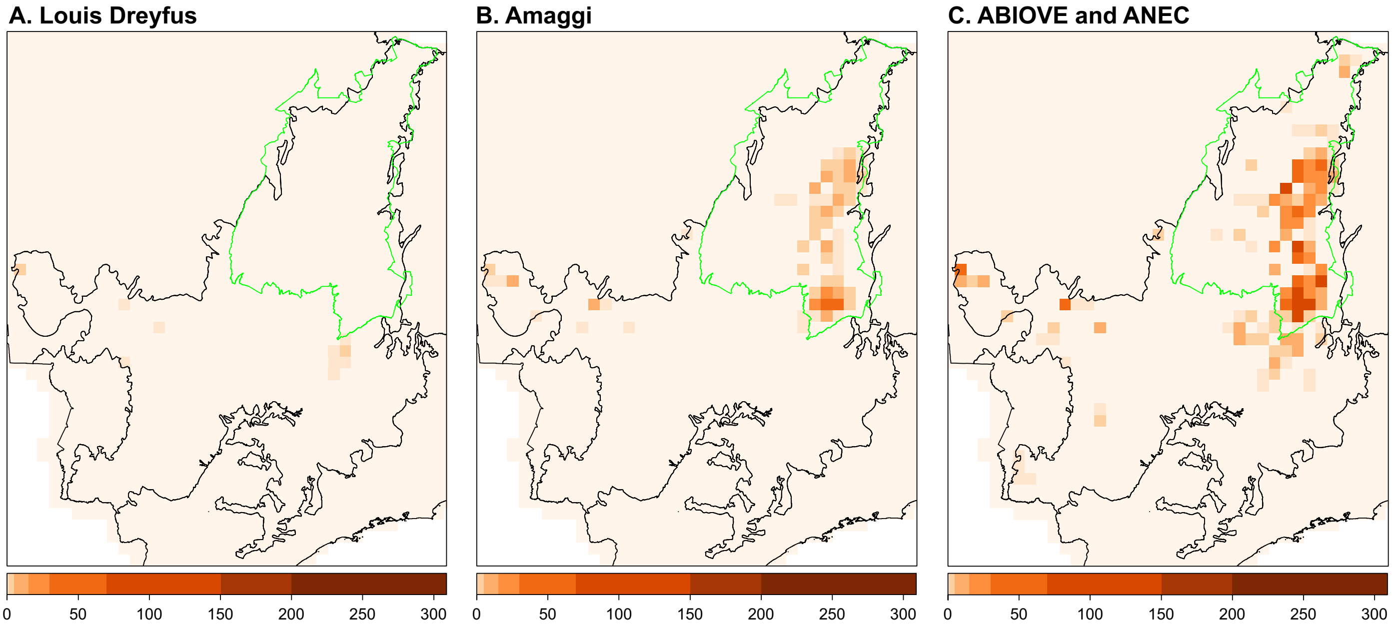

Fig. 4. Native vegetation area at risk. Area of native vegetation at risk estimated for the following traders or associations: (**A**) Louis Dreyfus, (**B**) Amaggi, and (**C**) ABIOVE and ANEC traders associations, which includes the Big 6. Color bar values are expressed in thousands of hectares per cell.

a specific commodity, although leakage must be addressed to meet deforestation goals (*18*).

The Cerrado Manifesto indicates an increasing recognition of the vanishing Cerrado vegetation and asks the actors in commodity supply chains to protect this biome. Our risk analysis, based on our baseline projections and on the TRASE dataset, reveals which traders and markets have the highest future exposure to soy-related native vegetation loss. Traders and consumer markets, such as China, the EU, and Brazil, could use these results to adjust their supply chains or their consumer habits to source deforestation-free soybeans. These results could also be used by policy makers and other relevant stakeholders to target their policies and campaigns toward achieving optimal preservation results.

One may argue that the FC is one of the most restrictive environmental laws in the world, and additional measures, such as a moratorium, are unnecessary and could harm the soy sector. Under the FC scenario, the avoided native vegetation conversion to soy would only be 0.9 Mha in the Cerrado. Even if it was rigorously enforced, the FC would still allow 2.7 Mha of native vegetation loss for soybean production in the Cerrado to proceed. This is allowed because Brazil's FC only concerns illegal deforestation. In the Cerrado, 20% of the native vegetation within private properties (35% in the Legal Amazon) must not be converted according to the FC, and the farmers have at their disposal a large area of native vegetation to be legally converted. In terms of production, the FC would reduce the soybean area in Brazil as much as the SoyM, i.e., 2% reduction by 2050. The FC is not enough to protect the Cerrado, given its low level of legal reserve (LR) requirements and its lack of enforcement. Furthermore, supply chain agreements can play a particularly important role in the absence of strong governance. For example, an estimated 65% of the soy farms surveyed in the Amazon's Mato Grosso region do not comply with the FC but do comply with the SoyM (*19*).

Naturally, the best scenario in terms of conservation of the Cerrado would be the combination of SoyM and FC, with the latter being fully enforced in the biome. If rigorously enforced, then the FC scenario would generate 12.1 Mha of restored forests and 6.2 Mha of debts compensated via the environmental reserve quotas (CRA) mechanism (see Materials and Methods) by 2050 at the national level (in the Cerrado, 2.9 and 3.2 Mha, respectively). The combination of FC and SoyM scenarios would avoid not only the same amount of direct native vegetation to soybeans as the SoyM scenario but also the illegal conversion of 2.2 Mha of native vegetation to other land uses, such as pasture or other crops. In this study, both the SoyM and the baseline scenarios assume full compliance with the SoyM and the illegal deforestation control in the Amazon biome. Thus, by construction, there cannot be leakages to the Amazon biome in our simulations due to the extension of the SoyM to the Cerrado. However, previous results (*10*) indicate that the removal of any deforestation control in the Amazon would greatly expand deforestation in this biome while decreasing the conversion of native vegetation in the Cerrado. From these results, we may infer that the expansion of the SoyM to the Cerrado would generate leakages in the Amazon to the extent that the level of compliance with the ban on illegal deforestation or the SoyM agreement falls in the Amazon biome.

A study such as this has several caveats. One source of uncertainty is the level of adherence to a voluntary agreement such as the SoyM. To obtain the maximum and minimum estimates of native vegetation loss, we assumed either full or no compliance of all the companies sourcing soy from the Cerrado. In reality, although only six large soy traders (the Big 6) accounted for more than half of the soy exports from Brazil in 2015, the soy business involves thousands of companies who have different deforestation footprints and must independently comply with any voluntary moratorium. The volume of unknown trade flows in the TRASE dataset (*1*) is approximately 10% and is not associated with any trader. Furthermore, the use

Table 2. Future native vegetation conversion risk. The columns show per trader, trader associations, or consumer market; the future soy sourced in million metric tons (Mt); the future native vegetation conversion risk or the area at risk of being converted to soy in million hectares (Mha); and the relative future native vegetation conversion risk in hectares per 1000 metric tons of soy sourced by a given trader, trader association, or consumer region over 30 years. The projections on soy area and production are from the baseline scenario projections of GLOBIOM-Brazil between 2021 and 2050, and the market share of companies or consumer regions are from the TRASE dataset for the year 2015 (*1*).

Trader, trader association, or market	Future soy sourced (Mt)	Future native vegetation conversion risk (Mha)	Future relative native vegetation conversion risk (ha/1000 metric tons per year)
ADM	177.05	0.20	33.89
Amaggi	127.18	0.27	63.69
Bunge	305.91	0.38	37.27
Cargill	247.18	0.43	52.19
COFCO	42.22	0.03	21.32
Louis Dreyfus	172.73	0.01	1.74
Big 6	1072.26	1.32	36.93
ABIOVE/ANEC	1353.13	1.78	39.46
China	919.49	1.15	37.52
28 EU countries	364.29	0.45	37.06
Brazil	1103.00	1.65	44.88

of the 2015 TRASE dataset implies that the market shares of individual companies remain constant over time, which oversimplifies the dynamics of the soy market. To evaluate the sensitivity of our results to the main drivers of land use change in Brazil, we also run our main scenario for two contrasting shared socioeconomic pathways (SSPs), SSP1 "sustainability" and SSP3 "fragmentation," which projects different demands for soy. In comparison to their respective baselines, the SoyM scenario would avoid 5.2 Mha (SSP1) and 3.4 Mha (SSP3) of direct native vegetation conversion to soybeans in the Cerrado biome. Taking into account the leakages to other land uses, the SoyM still prevents the loss of 2.5 Mha (SSP1) and 1.5 Mha (SSP3) of the Cerrado by 2050. Under SSP1 and SSP3, Brazil-wide soybean losses under the SoyM expansion are 1.1 and 1.0 Mha, respectively. However, the soybean area reduction in the Cerrado was lower in these scenarios [1.8 and 1.4 Mha for SSP1 and SSP3, respectively]. Thus, the migration to other biomes is smaller under SSP1 (0.6 Mha) and SSP3 (0.4 Mha).

The soybean industry has the potential to remove deforestation and native vegetation loss from its supply chain, demonstrating to consumers and other sectors that socially responsible corporate actions can conserve natural habitats, including the Cerrado. The expansion of the SoyM to the Cerrado would build off its successful previous application in the Amazon. Extending the SoyM to the Cerrado would involve little technical or administrative challenges because the methods for monitoring deforestation and tracking production have already been developed and applied in the Amazon or are under development for the Cerrado. Furthermore, because the amount of Cerrado converted to pasture is as large as the amount converted to soy, a comprehensive moratorium on the expansion of pasture into native vegetation would also be required to successfully conserve the Cerrado. The successful expansion of the SoyM would help provide a roadmap for the beef sector to clear its supply chain of native vegetation conversion. However, cattle are mobile, and this type of specificity poses challenges for monitoring and certification, suggesting that the technical ability to implement a cattle moratorium will require longer development (*20*). This makes it even more urgent to address the ongoing conversion of the remaining native Cerrado vegetation via the immediate extension of the SoyM to the Cerrado.

With less than 20% of undisturbed native vegetation remaining, multiple actions are required to conserve this unique region. The expansion of the SoyM to the Cerrado is necessary, but it is not, by itself, sufficient to protect the biodiversity and ecosystem services of this biome. A public-private policy mix, such as the combination of both the rigorous enforcement of the FC and the full compliance with the SoyM expansion to the Cerrado, is essential to preserve the last remnants of the Cerrado. However, the enforcement of the FC has been a major issue in the Cerrado and elsewhere. In recent years, Brazil's government has abandoned command-and-control policies to halt illegal deforestation and has been otherwise removing environmental protections (*21*). There is no sign of recovering strong environmental governance in the near future, given the country's deep political crisis. Consequently, the need for private sector leadership is even greater, and the expansion of the SoyM to the Cerrado is increasingly important. To preserve the biodiversity and ecosystem services provided by the remaining 19.8% of the undisturbed Cerrado, urgent action is required, including a moratorium on the expansion of soybean production into native vegetation in the Cerrado.

MATERIALS AND METHODS

GLOBIOM-Brazil model

The GLOBIOM-Brazil model (*10*) is based on the GLOBIOM model (*11*, *12*) and has been adapted to incorporate Brazil's specificities and local policies (*22*). As with GLOBIOM, GLOBIOM-Brazil is a global partial equilibrium model that simulates the competition for land among the main sectors of the land use economy (agriculture, forestry, and bioenergy) subjected to resource, technology, and policy restrictions. GLOBIOM is recursively run for 10-year time steps, starting at the baseline year of 2000. For this study, the GLOBIOM-Brazil model was adapted to run for a 5-year time step with a greater temporal resolution, which allows more flexibility in defining the starting dates of Brazil's local policies. The competition for land was simulated at the pixel level by maximizing the sum of consumer and producer surpluses. Exogenous drivers, such as gross domestic product (GDP), population growth, and dietary trends, were derived from the SSPs (*23*) developed for the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In this study, we used the "middle of the road" SSP2, which projects 71% of exogenous soybeans yield increase due to technological change, a 36% growth in Brazil's population, and a 266% increase in Brazil's GDP per capita by 2050 compared to 2000. According to the Brazilian Institute of Geography and Statistics (IBGE), the population in Brazil will increase from 173 million in 2000 to 223 million in 2030, a growth of 29%, which is close to the SSP2 projections for the same year (29.7%). We also used two contrasting pathways, SSP1 sustainability and SSP3 fragmentation, to analyze the uncertainties regarding the future demand for soy and soybean expansion related to changes in the socioeconomic drivers of land use change in Brazil. The SSP1 and

SSP3 project, respectively, 83 and 43% of soybeans yield increase, 25 and 54% growth in Brazil's population, and 355 and 120% increase in Brazil's GDP per capita by 2050 compared to 2000. The bioenergy demand (biodiesel, bioethanol, charcoal, and heat and electricity) was also established exogenously per region using the World Energy Outlook 2010 projections. Brazil's future bioethanol demand was taken from the Ministry of Mines and Energy and the Energy Research Enterprise projections (*24*). On the supply side, endogenous production adjustments were made by the model to meet the demand for all 30 economic regions. GLOBIOM optimizes land use over six land use classes, including croplands, pasture, unmanaged forests or native vegetation, and nonproductive land. As a result of the optimization procedure, the final demand, processing quantities, prices, and trade at the equilibrium state were obtained for each region and product. The geographically explicit representation of the model was a uniform grid with a spatial resolution of approximately 50 km by 50 km at the equator for Brazil and 250 km by 250 km for the other 29 regions of the world. The 18 crops modeled by GLOBIOM-Brazil included soybeans, maize, and sugarcane and made up 86% of the total cultivated area in Brazil in the baseline year of 2000. The potential yields for the different crops and management systems were defined at the pixel level and relied on the biophysical model EPIC (Environmental Policy Integrated Climate) (*25*). Productivity can increase endogenously in the model through shifts between management systems (from low to high input) or from the reallocation of production to more suitable areas, which allows endogenous changes of yields in response to market signals. A remote sensing data study (*26*) concluded that all maize harvested in Mato Grosso state in 2001 and 2010 was produced using a double cropping system with soybeans. In addition, according to official statistics, between 2003 and 2015, the area of single crop maize decreased approximately by 4 Mha, whereas the area of double crop maize (or safrinha maize) jumped by more than 6 Mha. Most safrinha was cultivated with soybeans. Thus, for this study, a double cropping system for soybeans and maize was included in GLOBIOM-Brazil on the basis of standard runs of the EPIC model for high-input systems. An exogenous yield increase due to future technological changes was also allowed for all crops and management systems on the basis of the economic growth projections given by the SSPs (*27*). Eight livestock production systems were specified for ruminants, from grazing humid to mixed arid systems. Bovine and small ruminant productivity and feed requirements were estimated by the RUMINANT model (*28*, *29*). Switches among production systems allow for feed substitution and for the intensification or extensification of livestock production. In addition, a semi-intensive cattle ranching production system was also implemented for Brazil (*30*). Wood products come from forestry land use classes such as short rotation plantations. Harvesting costs and annual mean increments were computed by the forestry model G4M (*31*). GLOBIOM-Brazil uses a consistent 2000 land cover and land use map for Brazil. This map combines information from official statistics on livestock and crop production from different satellite images and from maps of the protected areas (*10*). Internal transportation costs per pixel and product to different destinations (nearest state capital and nearest seaport) were estimated on the basis of the national transport infrastructure (*10*).

Scenarios

Our baseline scenario reflects the business as usual framework of governance in Brazil in terms of deforestation. In this scenario, we assumed that the control of illegal deforestation as stipulated in the Brazil's FC was enforced only in the Amazon and the Atlantic Forest biomes and that the conversion of native vegetation (legal or illegal) was allowed at all times in the Cerrado (see the "Validation" section for a comparison of deforestation and native vegetation loss between the model projections and the official estimates). The baseline scenario also considers full compliance with the SoyM in the Amazon biome from 2006 onward but no compliance with the SoyM in the Cerrado. The baseline is the scenario that better reproduces the observed deforestation and loss of native vegetation rates in the Amazon (*10*) and the Cerrado between 2003 and 2017 (fig. S3). Building on the baseline, the SoyM scenario includes the SoyM with full compliance in the Cerrado biome after 2020. The SoyM was implemented as a full ban on the conversion from forests or native vegetation to soy. Two different starting dates for implementing the SoyM in the Cerrado were assumed in the SoyM scenario: 2015 (SoyM-15) and 2025 (SoyM-25). We also considered the FC or FC scenario (*10*), which includes illegal deforestation control in all Brazil's biomes, obligatory forest restoration, compensation by the CRA, and the SoyM in the Amazon biome after 2006 but without its expansion to the Cerrado (see Table 1 for a scenario overview). The FC identifies the LR or the minimum percentage of forests or native vegetation that must be preserved within private properties. The LR varies from 80% in the Amazon biome to 20% in the Atlantic Forest, and it also defines areas of permanent preservation (APP) such as riversides and hilltops. In this study, environmental debts of LRs and APPs were based on the Rural Environmental Cadastre (CAR, Portuguese acronym) from December 2016 (*32*) aggregated to 50 km by 50 km. LR surpluses is estimated per pixel (50 km by 50 km) as the amount of native vegetation that exceeds the LR requirements (*10*). Under the FC scenario, the CRA system compensates LR debts per pixel by trading the deficits with the surpluses within a biome and starting with the larger amounts (*10*).

Native vegetation conversion risk

We estimated the absolute future native vegetation conversion risk (measured in hectares) per trader or consumer market in each grid cell of the Cerrado biome as the product between the total area directly converted from native vegetation to soy between 2021 and 2050, as projected by the baseline scenario and the market share of traders, traders associations, or consumer regions tracked by the TRASE dataset (*1*) for the year 2015 (see Table 2). We also computed the relative future native vegetation conversion risk for a trader, trader association, or consumer market by dividing its future risk by its amount of soy traded during a given period. This indicator is a measure of the native vegetation loss intensity of each trader, trader association, or consumer market regarding its volume of soy sourced in 30 years (from 2021 to 2050), i.e., the intensity of loss in hectares per 1000 metric tons of soy sourced per year (ha/1000 metric tons per year).

Emissions estimates

Greenhouse gas estimates of land use changes take into account the carbon content in the equilibrium states of the land cover classes. The CO_2 coefficients for emissions and sinks were determined by the difference in the carbon content between the original class and the new class. Deforestation or native vegetation loss produces positive emissions. The release of carbon from the terrestrial biosphere to the atmosphere as CO_2 occurs in one simulation period (5-year time step) for deforestation. In this study, we specifically accounted for the positive emissions from native vegetation conversion to soybeans. The future land use changes were estimated by the model, and the biomass map was taken from the third Brazil's Emissions Inventory (*33*), used in the official communications to United Nations Framework Convention on Climate Change in 2016. The carbon stock information of this map takes into account the values of living above- and below-ground biomass per vegetation type for each Brazilian biome.

Validation

For validation purposes, the baseline projections of GLOBIOM-Brazil regarding soybean area and production were compared with the official statistics from the Municipal Agricultural Production (PAM), a survey undertaken yearly by the IBGE. In 2015, Brazil's soybean area amounted to 32.1 Mha, with a production of 97.3 Mt according to PAM/IBGE (*2*). The baseline scenario projects, for the same year, a soybean area of 32.8 Mha and a soybean production of 98.5 Mt. The differences between the official statistics and the model outputs for soybeans at the national level were smaller than 2% in 2015. For the Cerrado, GLOBIOM-Brazil estimates a soybean area of 17.5 Mha, an overestimation of 13.8% when compared to PAM/IBGE. For the Matopiba region, GLOBIOM-Brazil estimates a soybean area of 3.1 Mha in 2015, an underestimation of 14% when compared to PAM/IBGE. Between 2000 and 2015, the model estimates a soy expansion of 273% in Matopiba [for a comparison, Carneiro-Filho and Costa (*3*) estimated a 253% soy expansion in this region between 2000 and 2014]. In 2026, Brazil is projected to produce 133.4 Mt of soybeans according to the baseline scenario. This projection of our model compares favorably to other projections, being only 2% smaller than the soybean production estimated by the Organisation for Economic Cooperation and Development/Food and Agriculture Organization of the United Nations (*4*) and 9% smaller than the projections from the Ministry of Agriculture, Livestock, and Supply (Brazil) (*34*) for the same year. The accumulated deforestation from PRODES (Programa de Cálculo do Desflorestamento da Amazônia)/National Institute of Space Research (INPE) between 2001 and 2015 in the Amazon biome amounts to 19.3 Mha, while the baseline scenario projects 17.9 Mha for the same period and region, a difference of less than 8%. For the Cerrado biome, the native vegetation loss varies according to the source (see fig. S3). Between 2008 and 2014, the INPE estimates 7.8 Mha, and Carneiro-Filho and Costa (*3*) estimated 3.7 Mha of native vegetation loss. Taking the average between these two estimates, the accumulated native vegetation loss between 2008 and 2014 was 5.72 Mha, and our baseline scenario projects 5.96 Mha (0.85 Mha per year). The percentage of native vegetation due to soy expansion over native vegetation in the Cerrado biome between 2000 and 2015 was 32%. Carneiro-Filho and Costa (*3*) estimated this percentage to be 31% between 2000 and 2007 and 26% between 2007 and 2014.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/5/7/eaav7336/DC1
Fig. S1. Soybean area evolution.
Fig. S2. Map of soybean expansion.
Fig. S3. Native vegetation conversion in the Cerrado.
Table S1. Avoided native vegetation loss.
Table S2. Emissions estimates.

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