

Lack of Ambition, Not Leakage, is What Can Make Brazil's Soybean Supply-Chain Zero Deforestation Commitments Ineffective

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Introduction

Corporate voluntary commitments to reduce deforestation offer an important opportunity to conserve tropical forests (Lambin et al. 2018). Yet, the effectiveness of these commitments is difficult to evaluate (Garrett et al. 2019). Mechanisms that align the interests of agricultural producers and transnational commodity traders as well as the enforcing and monitoring of these mechanisms need to be developed (Newton, Agrawal, and Wollenberg 2013; Lambin et al. 2018; Carvalho et al. 2019; Ermgassen et al. 2020). In addition, supply-chain commitments interact with government policies that can help or hinder private initiatives (Le Polain de Waroux et al. 2017). Moreover, deforestation is a global phenomenon mediated by market forces (Gan and McCarl 2007; Villoria, Byerlee, and Stevenson 2014; Taheripour, Hertel, and Ramankutty 2019); efforts to reduce deforestation in one region may be offset by the displacement (leakage) of agricultural production to other regions (Villoria and Hertel 2011; Villoria 2019). The leakage of production from regions with zero-deforestation (ZD) commitments to other places with less stringent environmental regulations is a major threat to supply-chain ZD commitments (Alix-Garcia and Gibbs 2017; Lambin et al. 2018). Some critical aspects determining offsetting supply responses include the number of commodities covered as well as the geographic scope of the commitments (Garrett et al. 2019). Market structure also matters. Companies compete with each other for procuring commodities from farmers, so the extent to which non-committed buyers compete with committed buyers ultimately can decide the success of ZD commitments (Reis et al. 2020; Cf. Sexton 1990).

This paper explores the role of leakage in offsetting the potential benefits of ZD commitments implemented in Brazil's soybean supply changes. Brazil has the largest forest reserves in the world and is a mighty agricultural producer, recently displacing the U.S. as the major agricultural producer of soybeans. Soybeans are an important commodity responsible for an important part of land clearing in Brazil and other parts of South America (cite). The soybean supply-chain in Brazil's Amazon also offers what appears to be a successful initiative of private-led forest conservation (Heilmayr et al. 2020). Agricultural-driven deforestation has become an increasingly polarizing issue between the European Union and Brazil and has the potential of becoming a central issue in a potential trade agreement between the EU and the MERCOSUR countries (Rajão et al. 2020). Such

escalation of environmental issues in the context of economic agreements illustrates how forest conservation in South America can affect the broader set of options for economic development available to the region.

Leakage is determined by the degree to which producers in different locations compete in a common market (Villoria and Hertel 2011). Within Brazil, adoption of ZD commitments in the soybean supply chain split Brazil into mutually exclusive areas: those subject to commitments, or treated areas on the one hand, and those areas without commitments, or non-treated areas, on the other hand. In the case of the ASM this segmentation is along biome lines (treated Amazon vs. non-treated parts of the Amazon, Cerrado and other biomes) with leakage driven by the displacement of production from the treated Amazon to the other biomes as relative prices change due to the restrictions on land conversion stemming from the Moratorium. Existing assessments of zero-deforestation commitments include some measure of localized within- or cross-biome leakage in their analysis (Gollnow et al. 2018; Heilmayr et al. 2020; Soterroni et al. 2019), but to best of our knowledge, the cross-border leakage associated with Brazil soybean supply-chain ZD commitments remains unexplored.

In this paper we fill this gap by considering the extent to which the potential deforestation benefits of soybean ZD commitments in Brazil can be offset by displacing production elsewhere in the world, either within or outside Brazil. We pay special attention to Bolivia, Argentina, and Paraguay (henceforth the BAP region). Together with Brazil these countries are relatively land-abundant with ample scope for further expansion of their agricultural frontier (cite). These countries have also experienced expansion of soybean cultivation in the recent past (cite), increasing amounts of deforestation (cite), and form part of the supply-chain of a relatively reduced number of transnational traders (cite). All: suggested citations are welcome, particularly if they nuance the assertions in the text.

Outside Brazil, the scope for leakage will depend on the strength with which the BAP and other competing regions perceive price changes that are caused by the land conversion restrictions in Brazil's treated regions as well as on the ability of producers outside the treated regions to change their production behavior in response to price changes. In turn, the strength of price transmission from Brazil into other regions depends crucially on the geographic patterns of bilateral trade flows. Tracking changes in prices and how they are transformed into production and land use requires an economic, multi-region trade model with explicit treatment of sub-national land markets. For this, we modify the widely-used GTAP-AEZ model (Hertel et al. 2009) and database (Baldos 2017) to divide Brazil into three biomes: Amazon, Cerrado, and Others (see 4.1). In turn, each biome is split into treated areas and non treated areas using the TRASE database and other databases of land use in Brazil to infer the spatial footprint of the five potential spatial footprint scenarios (SFS) described below and depicted in in figure 1 (see subsection 4.2 for specific companies). (Florian: we probably need more details here, some of which can go to the Materials and Methods below. I also think your maps are very useful. We may try to craft a figure with them next to the barplots in figure 1, or send them to the supporting online materials SOM.):

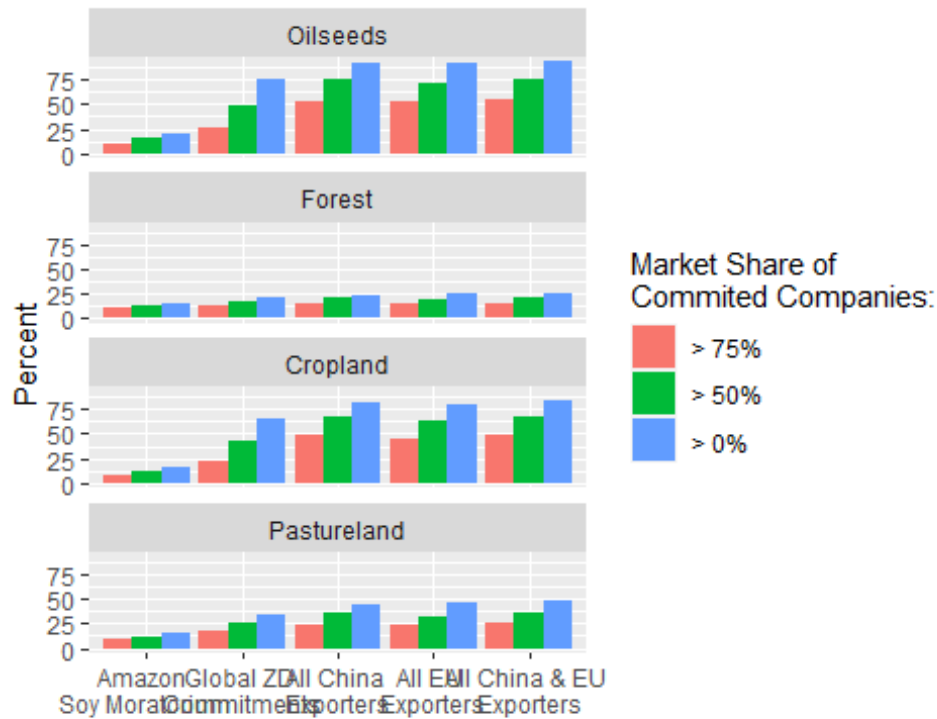


Figure 1: Percentage of Brazil's soybean, forest, cropland, and pastureland areas subject to voluntary Zero Deforestation Commitments under different assumptions of the market share needed to make the commitments effective

1. Amazon Soy Moratorium (SFS-ASM): limited to the spatial footprint in the Brazilian Amazon of the companies that implemented the moratorium in 2006.
2. Brazil-wide implementation of ZD commitments by the global signatories of the ... (All: I seem to recall the included firms signed some landmark pledge? can you fill in what is accurate here). This scenario is dubbed SFS-GZD and extends the ASM into Cerrado and other biomes with soybean production (see Soterroni et al. 2019 for a related study).
3. EU adoption of a rule to only import ZD soybeans from Brazil (SFS-EU): We simulate the effects that would have a total compliance of the companies that export to the EU an operate in Brazil with a potential requirement from the EU to allow in their markets deforestation-free soybeans only. This scenario, SFS-EU, extends the spatial footprint of the ZD commitments beyond what is covered by the SFS-ASM and SFS-GZD to include all the companies that export to the EU.
4. Total compliance with a supply-chain commitment by Brazil's soybeans supply chains to only export deforestation-free soybeans to China (SFS-CHN): This experiment obeys to the fact that it is China, and not Europe, the main market for Brazil's soybeans. This feature of global markets presents an interesting dilemma to the EU insofar they may lack market power to influence soybean traders and producers in Brazil to adopt zero deforestation supply changes. The difference between the effects of the SFS-EU and

SFS-CHN clarifies EU's leverage (when compared to China's) to shape deforestation outcomes via supply-side restrictions.

5. Supply-side restrictions imposed by both the EU and China (SFS-EC): This scenario explores any potential additional effect of joint restrictions.

An important feature of the SFS is that we assume that if either Europe or China impose restrictions on one company, and that company decides to comply with such mandates in order to preserve market share, the companies will apply those restrictions to their entire supply chain. In other words, we do not allow for different supply chains from the same trader when exporting to different destinations. This is a realistic assumption as companies consider supply-chain differentiation extremely costly due to the unwieldy procedures that would be needed to monitor, trace, and certify production (A cite will be nice here).

For each of the five SFS above we explore three effectiveness assumptions (EA), which reflect the uncertainty of how market structure influences the effectiveness of ZD commitments. The EA consist of assumptions about the minimum market share needed by committed traders to ensure that farmers face enough incentive to halt forest conversion to soybean production. We provide three possibilities. EA1 is the more restrictive assumption and requires that at least 75% of the soybeans in a given municipality are bought by committed companies. EA2 is less restrictive and requires a market share of 50%. EA3 is an upper bound of potential effectiveness and considers that a municipality will comply with the imposed land conversion restrictions if at least one committed company is present in the municipality. In addition we have two alternative forest definitions (see section @ref(#experiments) for details). Each SFS-EA and forest combination is a model experiment, for fifteen experiments total. In a robustness section yet to be drafted we document that the results of both forest definitions are very similar. In the main text of the article we only report forest definition A.

In each experiment we halt land conversion between forestry and agriculture in the areas assumed under ZD commitments by way of a subsidy that compensates producers for the economic losses of not transforming forests on to agriculture. This subsidy captures the economic incentives that the soybean buyers would need to provide to producers so they comply with ZD commitments.

A main finding below is that due to the overlapping spatial footprint of the traders serving both the EU and China's market, EU supply-side restrictions are as effective as if these were enforced by China. In order to give some additional context to the potential effects of ZD commitments influenced by EU mandates, we also explore an scenario in which the EU applies a unilateral import tariff on all the soybeans sourced from Brazil. Demand-based boycotts and import bans into the EU are increasingly discussed as potential instruments to exert pressure on Brazil's soybean supply chain (Rajão et al. (2020)). We contrast the land use outcomes of ZD supply-side commitment with the effects of the EU imposing demand-side import tariffs (of 25%, 50% and 75%) on soybeans originated in Brazil.

Results

Impacts on Soy Production

Figure ?? summarizes changes in oilseed area in each scenario. For each region the height of the bars correspond to the value obtained under EA2 (Market share >50%). The values of EA1 (Market share >75%) and EA3 (Market share >0%) are indicated by the range lines crossing each bar. In the text we report the values of E2 as central estimates and indicate the range implied by the effectiveness assumptions within parentheses. The value of E2 may fall out of the range bounded by E1 and E3 because of the non-linearity of the model.

NULL

Three patterns are common across all scenarios. First, some of the reduction in oilseed area due to land restrictions in Brazil are compensated by increases in oilseed area in the non-treated Brazilian biomes. For example, under E2, the ASM leads to a reduction of 24.1 (17.8-27 kha) kha of soybeans in the Amazon Biome—to keep these results in perspective, consider that Brazil harvested 24,300 kha of soybeans in 2011 (cite FAOSTAT), therefore the area reduced by the ASM is just 0.1% of Brazil's soybean area. This reduction is partially offset within Brazil by an expansion of oilseed area of 1.8 kha (0.9-1.92 kha) in the Amazon, 3.2 kha (2.4-3.7 kha) in the Cerrado, and 2.3 kha (1.6-2.7 kha) in other biomes.

In the ZD scenario, in addition to the reduction in oilseed area of the ASM commitments, the Cerrado and the other biomes of Brazil experience a reduction of their oilseed areas of 8.7 kha (4.1-12.4) and 2.4 kha (1.8-4.0 kha), respectively. These are partially offset by increases in the non-treated parts of Cerrado which experience an increase 2.88 kha (2.16-2.54 kha) as well as an increase in the rest of Brazil of 2.3 kha (1.7-2.0 kha). In the other three scenarios, the commitments encompass larger areas (figure 1), which are associated with larger reductions of soybean area of ≈ 12 kha (≈ 7 -16 kha), which are also somehow offset by minor cross-biome leakage within Brazil.

The second pattern of importance across scenarios is that cross border leakage of production into Argentina, Bolivia and Paraguay is almost nonexistent, in the order of 1-2 kha; instead, most of the supply response outside of Brazil—10.1 kha (7.2-12.3 kha) in the ASM; 15.3 kha (9.7-20.4 kha) under GZD commitments; and ≈ 18 kha (13-23 kha) in the other three scenarios—occurs in the the rest of the world, particularly North America (figure 2).

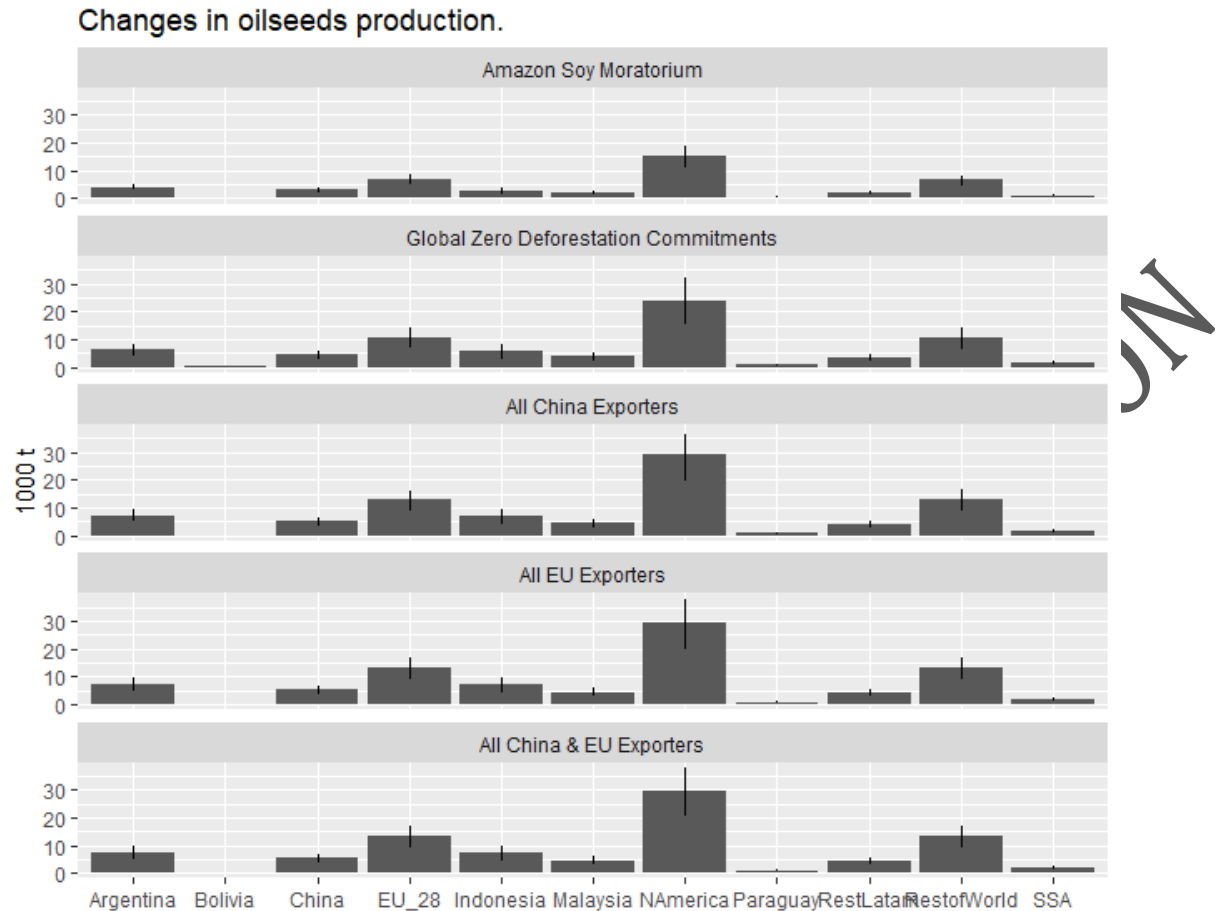


Figure 2: Changes in Oilseed Production Under Different Zero Deforestation Commitments. (By Country)

Finally, not all the reduction in soybean areas in Brazil's treated zones is replaced by cross-biome and cross-border leakage. Under the ASM there is a net reduction of oilseed area of 5.7 kha (3.9-6.2 kha). In the case of the GZD commitments, the reduction is of 10.3 kha (6.06-14.1 kha). The other three scenarios lead to a reduction in oilseed area of ≈ 13 kha (9-17 kha). The reduction in Brazil's area is associated with a reduction in global oilseed production of 8.9 kt (7.8-9.51 kt) under the ASM, 11 kt (9-12.4 kt) under the GZD commitments, and ≈ 12 kt (9.8-13.5 kt) in the other three scenarios (figure 3). Consistent with the results above, these are small volumes relative to global soybean production (the combined oilseed output of North America and Brazil in 2011 was 186 Mt) so global prices are virtually unchanged across scenarios (table 1)—that is, the ZD commitments have little price effect beyond the price increase of around 9.8% obtained in the baseline.

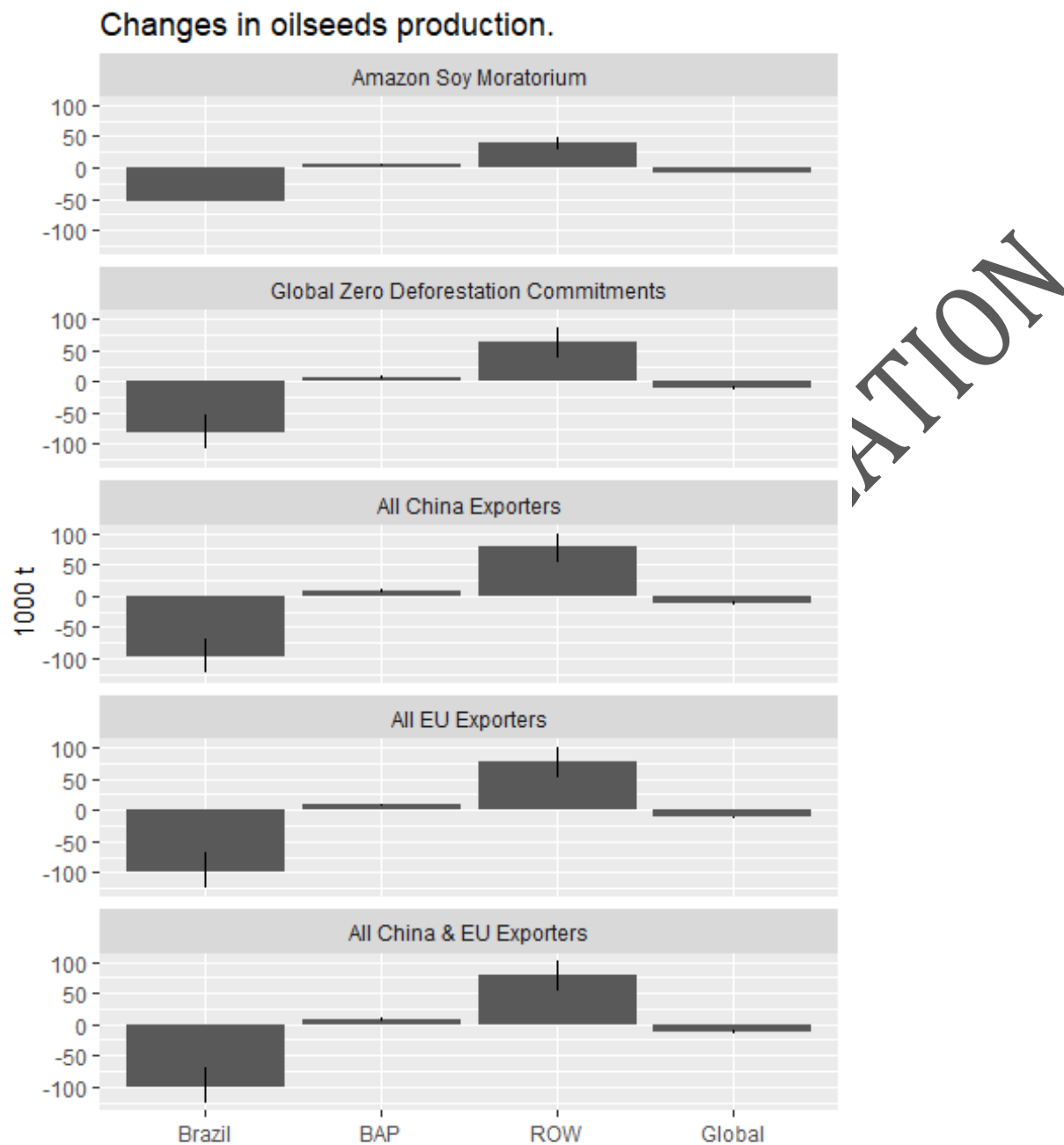


Figure 3: Changes in Oilseed Production Under Different Zero Deforestation Commitments. (By Country)

Table 1: Percentage Changes in Oilseed World Prices from 2011 to 2016 under Baseline and ZD Scenarios

Experiment	Scenario	1	2	3
BA	SM	9.84	9.84	9.84
ZD	CN	9.84	9.84	9.84

ZD	EC	9.84	9.84	9.85
ZD	EU	9.84	9.84	9.85
ZD	SM	9.83	9.83	9.84
ZD	ZD	9.83	9.84	9.84

Land Cover Change

Figure 4 shows that in the case of the Amazon Soy Moratorium, the zones with land use restrictions amount to avoided deforestation of 528 kha, with a range of 385-605 kha depending on the assumption effectiveness about market shares. Around half of the avoided deforestation in the GZD zones is offset by increases in deforestation in non-restricted areas in the Amazon [119 kha (98.9-124 kha)], Cerrado [88.1 kha (63.9-99.9 kha)], and other parts of Brazil [58.1 kha (42.1-65.9 kha)]. Cross-border spillovers are negligible, with deforestation in the rest of the world increasing by 12.4 kha (9.9-13.6 kha). After accounting by leakage in land cover, the ASM leads to net gain avoided deforestation of 247 kha (168-289 kha). (TODO this is a quarter million ha. Can we put in perspective?)



Figure 4: Changes in Forests Under Different Zero Deforestation Commitments.

In the case of the GZD scenario, the addition of GZD commitments in the Cerrado and other parts of Brazil to the ASM result increases avoided deforestation in Brazil to 818 kha (274-419 kha) out of which 525 kha (384-591 kha) are in the Amazon, 227 kha (113-331 kha) are in the Cerrado, and 66.2 kha (51.9-122 kha) are in other biomes. Consistent with the results above, deforestation leakage in the BAP region is almost negligible in the order of 4.48 kha (2.9-5.8 kha). The rest of the world also sees a limited increase in deforestation in the order of 16.9 kha (12.2-21.1 kha).

The other three scenarios have similar outcomes. By increasing the spatial footprint of the commitments, total avoided deforestation in Brazil reaches 999 kha (728-1208 kha). Breaking them down by biome indicates that the contribution of the ASM remains in the order of ≈ 520 kha (380-587 kha). Therefore the increase in avoided deforestation relative to the GZD scenario comes mainly from further commitments in Cerrado [324 kha (205-452 kha)] and other Brazilian biomes [155 kha (142-169 kha)]. Even with this enlarged commitments, spillovers in the BAP region are in the order of 5.5 kha (3.9-6.7 kha) while the rest of the world experiences an increase in deforestation of 20.2 kha (15.1-23.9 kha).

EU Border Restrictions to Brazilian Soybeans

The limited spillovers into the BAP region and the ROW can be explained by two facts. First, as indicated above, the restrictions on land conversion implied by the ZD commitments have no discernible effect in soybean world prices because North America's producers quickly fills in the limited reduction of Brazil's soybean supplies maintaining global supply almost constant.

Second, in addition to a limited world price effect, the BAP countries, and specially Bolivia and Paraguay are relatively minor players in world markets with tenuous links to Brazil's producers. This can be seen in figure 5 (A table is available that can go to SOM). In particular, for Bolivia and Argentina, the EU market is far more important than China's market. Argentina, on the other hand, does compete in the Chinese market by it is a minor player when compared to Brazil and North America. In addition to the weak competition links in third markets, Brazil + BAP intraregional trade flows are almost nonexistent (See Validation section for some exceptional intraregional trade flows in the recent past). Together, the limited change in world prices and the low direct trade connections among the focus countries, result in the limited supply responses in Brazil's neighbors that we discussed above.

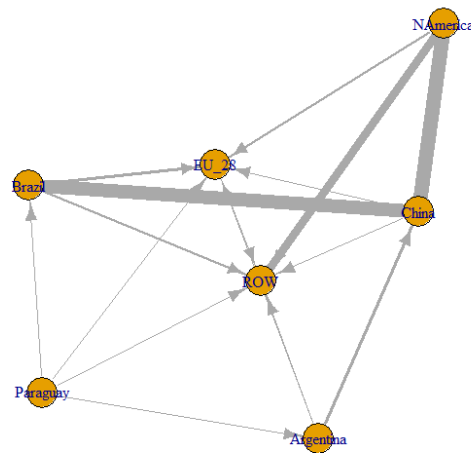


Figure 5: Soybeans Trade Network: Edge width represent 1000 USD. Only flows above 100 M USD are included. Data are averages 2009-2018.

The fact that forcing land use restrictions on Brazil-based traders that sell in the European market is as effective as those that supply the Chinese market—even though Europe has a much smaller market share than China of Brazilian soybean exports—is a strong indication that supply-side restrictions can be more effective than demand side restrictions. To test the degree of this assertion, we conduct an additional experiment in which the EU applies an import tariff to Brazilian soybeans only. We use three levels of tariff: 25%, 50%, 75%. Given the limited market share of global soybeans absorbed by the EU (relative to China) the EU tariff has a negligible effect on prices relative to baseline. As shown in figure 6, in Brazil, the tariff do discourage oilseed production (for 2.9 to 4.4 Mt, depending on the size of the tariff); however, a targeted import tariff is ineffective in slowing down deforestation: indeed, import tariffs of 25% and 50% encourage some additional deforestation (30 kha), and is only with a tariff of 75% that some forests are save (18.7 kha). This is order of magnitude lower than what is achieved with supply side commitments. This result is in line with the findings of (Taheripour, Hertel, and Ramankutty 2019), who find that supply-side measures are much more cost effective to reduce deforestation in Malaysia and Indonesia.

It is interesting to note that, in contrast to the ZD commitment scenarios above, where North America has the most pronounced supply response to the land use restrictions in Brazil, a tariff encourages production within the European Union. Brazil also increases its exports to other locations, including China (Need a plot for this).



Figure 6: Net Changes in Forest Area and Oilseed Production in Response to a EU tariff on Brazil's Soybeans

GHG Emissions

Emissions from the changes in land cover associated with the different experiments are calculated using the Agro-ecological Zone Emission Factor (AEZ-EF) Model (Plevin et al. (2014)). The AEZ-EF model closely follows IPCC GHG inventory methods and relies on its default values. The model includes cover-specific (cropland, pastures and forests) subnational carbon estimates for biomass (above and below-ground), dead organic matter, and soil carbon from (Gibbs, Yui, and Plevin (2014)). It also includes data on carbon remaining on harvested wood products, non-CO₂ emissions, and foregone sequestration. The carbon stock data is combined with assumptions about carbon sequestration from forest growth (foregone if converted), mode of conversion and CO₂ emissions from land clearing using fire, and the fraction of carbon that remains sequestered in wood products during a 30 year time horizon. The AEZ-EF model is designed to estimate land use emissions from land use transitions predicted by comparative static economic models, whereby one starts with a baseline and estimates the resulting final equilibrium. The AEZ-EF model underlies the emission estimates in several analysis of the indirect land use effects of biofuels emissions and land conservation measures (Taheripour, Zhao, and Tyner (2017), Taheripour, Hertel, and Ramankutty (2019)). (rewrite!)

Need to describe figure 7, but the point is that there is some GHG savings due to the commitment. I need to check the size of this commitments to Brazil's and Global LUC emissions. Also need to discuss how an import tariff actually increases emissions. The main point is that the costs are not very high and, in the case of the commitments, much falls on China. An import tariff of the EU on Brazil's soybeans, in contrast, benefits BAP and North America and China!

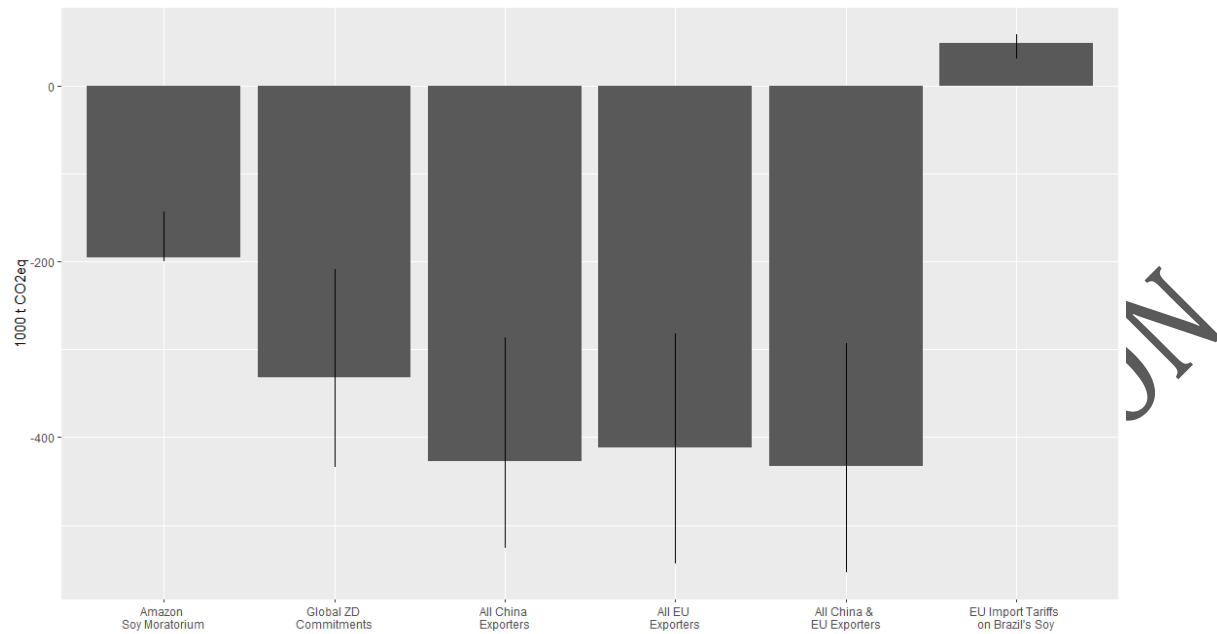


Figure 7: Change in Land Use Change Emissions (Scenario minus Baseline)

Effects on Global and Regional Welfare

Figure 8

These are the global and regional costs of the commitments.

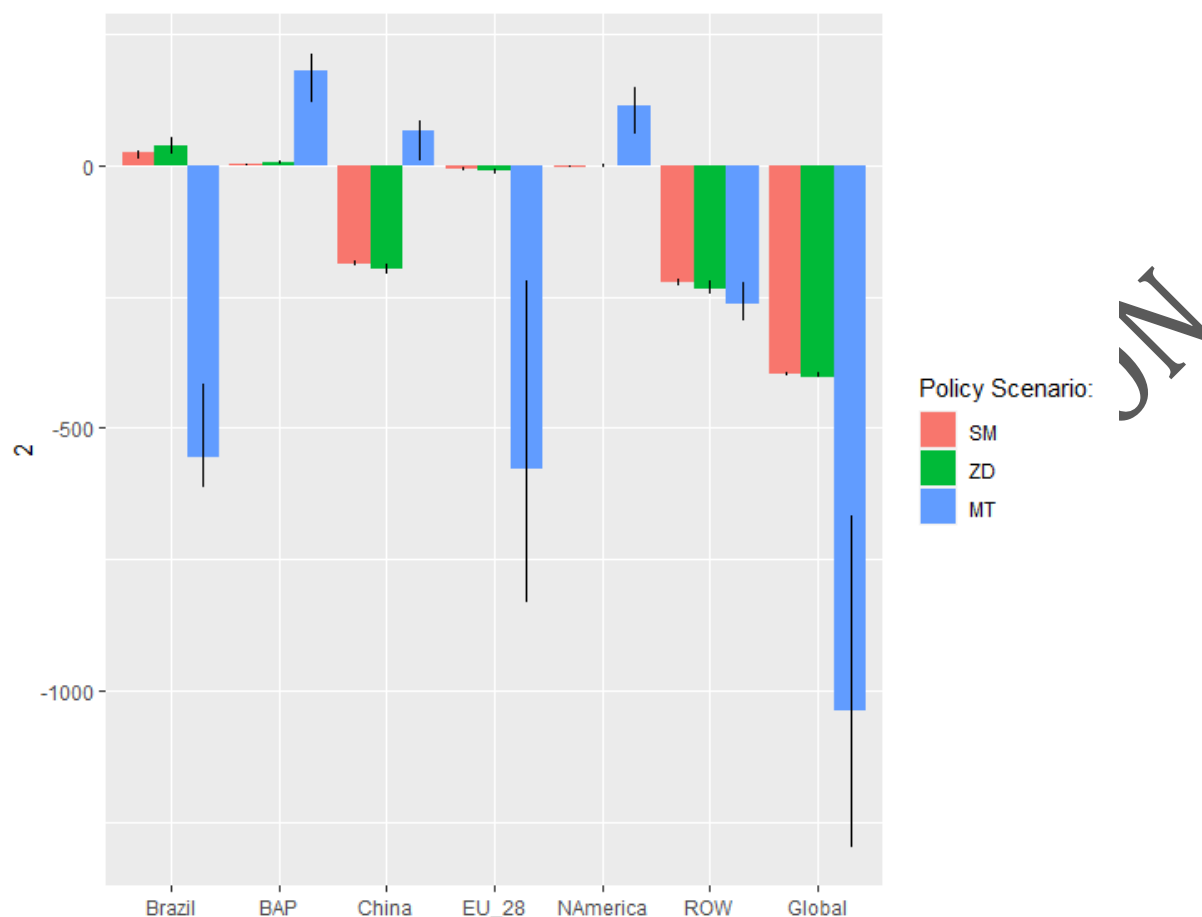


Figure 8: Changes in Economic Welfare. (By Region and Global)

Discussion

The potential for production leakage is often seen as a potential factor hindering the effectiveness of supply-side commitments. What our results suggest is that, given the structure of the soybean market, cross-border leakage is a minor concern. The main reason of this is that reduction in exports coming out of Brazil (in our case because of supply-side restrictions to farming) are quickly replaced with North American (US) exports, so global volumes and world prices remain relatively constant.

The US-Brazil dominance of the market would not preclude a priori Argentina, Bolivia, and Paraguay, filling the void of potential supply restrictions in Brazil. So, a natural question is why these countries do not take some of the market shares lost to Brazil. The answer lies in an additional feature of the soybean market. That is, intraregional trade is relatively low, and therefore, direct price transmission from Brazil to most of the BAP countries is tenuous. An additional and more subtle aspect is that most of the baseline growth in Brazil's soybean exports and world prices is driven almost exclusively by China (see also ???). For both, the US and Brazil, China is the main market where the producers of the two

countries are highly sensitive to developments in either country. In contrast, Bolivia and Paraguay depend more on EU markets than on China's market, and therefore their supply response (relative to the US) is much more tenuous.

With limited cross-border leakage, the effectiveness of ZD commitments will depend on how widely they cover the areas suitable for soy production within Brazil. ZD commitments in a single swath of a biome will cause production displacement to other places without commitments. As our results demonstrate, the more pervasive the commitments, the least scope for cross-biome leakage within Brazil.

From an implementation perspective, this suggests that a Brazil-wide ZD commitment would be effective and would have rather limited consequences elsewhere, as long as market structures remain constant. This suggestion of the models needs to be tempered by the possibility of changes in international trade patterns as a response to the restrictions. This is an important limitation of our work, and of most trade and economic models that rely on bilateral trade flows to track changes in land use. As in many other contexts, this underlies the fact that voluntary commitments cannot fill in the role of environmental regulation for environmental protection. After all, even without commitments, countries wishing to gain market share from Brazil could simply lower their standards.

Another limitation of our work is that it assumes perfect compliance with ZD commitments for the areas that we classify as likely to comply. Different game theoretic and industrial organizations approaches outside our modeling framework could be mobilized for a more detailed study of the incentives to comply. In this sense, our results could be more broadly interpreted in the sense that any supply-side initiative that restricts deforestation in Brazil be more effective the more widespread the coverage and will have limited spillover effects in Brazil's neighborhood.

The use of supply side measures to control deforestation offers a cost effective alternative to demand-side measures such as import-tariff or other boycott measures that try to stop soybeans at the border. A key driver of the better performance of supply-side measures (using either avoided deforestation, GHG emissions, or global welfare as a metric) is that traders will probably be reluctant to differentiate their supply changes given the enormous costs and practical difficulties of monitoring and implementation. As our results indicate, the fact that the same group of traders serving China's market also serve the EU market leverages the EU's ability to influence environmental outcomes in Brazil. As forest conservation move up to the forefront of the trade and economic joint agendas of Brazil and the EU, a fair appreciation of the role of suppliers, and the scope of voluntary commitments to reduce deforestation may lead to the most beneficial global outcomes. This lends supports to the recent findings of (???) in Brazil and (Taheripour, Hertel, and Ramankutty 2019) in Malaysia and Indonesia.

Materials and Methods

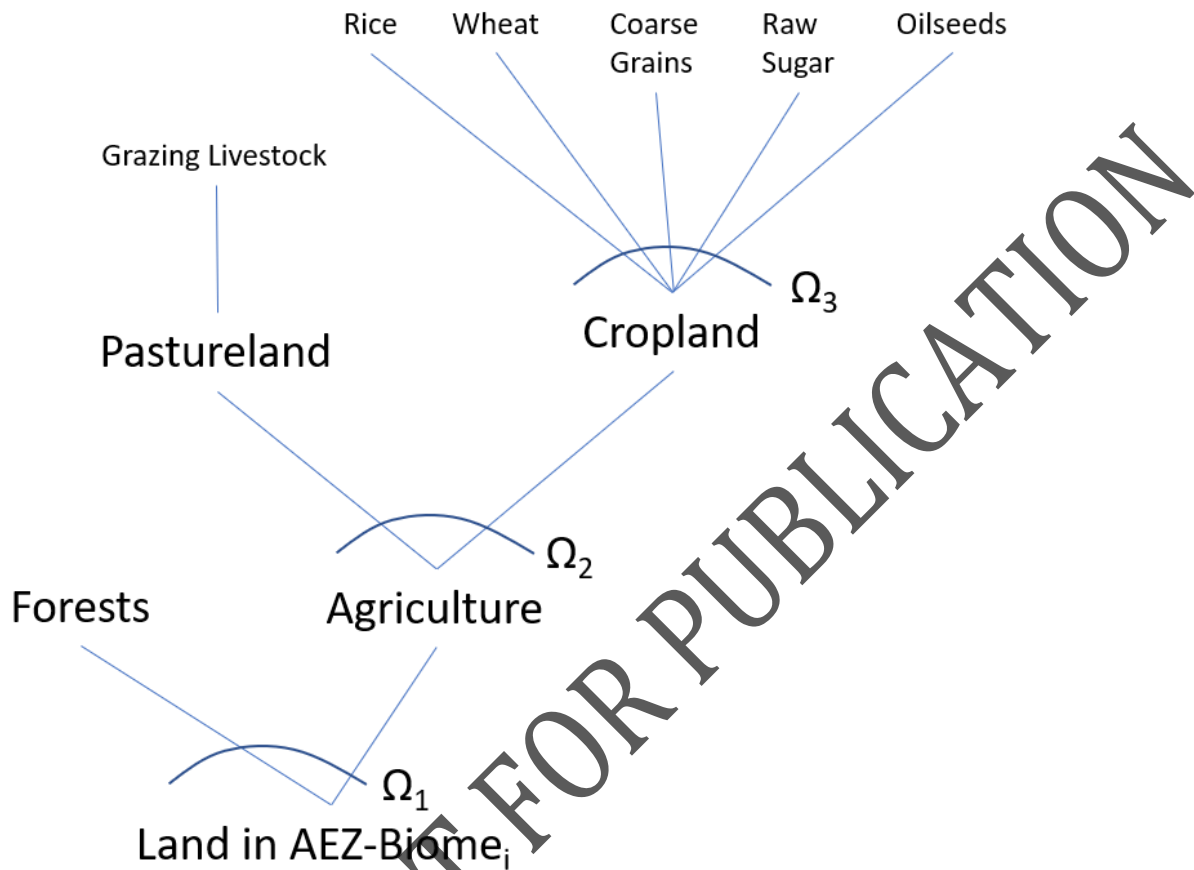
Modeling Framework

This paper uses a medium run applied general equilibrium (AGE) model (Hertel 1997) with explicit treatment of subnational land markets, nicknamed GTAP-AEZ (Hertel et al. 2009). Underlying the model there is a database that consistently represents production, consumption and trade patterns of 140 regions and 57 sectors in year 2011 (Aguiar, Narayanan, and McDougall 2016). In order to make model solution times and output manageable, we aggregated the model to 11 regions: Brazil, Bolivia, Argentina, Paraguay, Rest of Latin America, US-Canada (North America), European Union (28 countries), China, Malaysia and Indonesia, sub-Saharan Africa, and the Rest of the world. We also collapse the 57 commodity sectors into 18 sectors. The database is complemented with data on agricultural land rents by land use and natural land covers at the level of Agroecological Zones (AEZ), also centered in 2011 (Baldos 2017).

As explained in the next subsection, we further modified the database by splitting each AEZ into biomes (Amazon, Cerrado, and Other). In turn, each biome was divided into zones that are likely to be compliant with ZD commitments based on effectiveness assumptions about market shares (see below). In addition, we also used two alternative forest definitions. The result of this procedure is 36 distinct databases, each containing an scenario of interest.

The GTAP-AEZ framework is based on decision nests at which agricultural producers decide on land cover conversions (figure 9). For example, from pastures to cropland, and then on the allocation of individual crops within the cropland. As producers in different AEZ are connected through factor markets (land, labor and capital), competition among land uses, as well as by supply chains, the GTAP-AEZ model is ideally suited to study within-country changes land use across AEZs. Moreover, through an explicit treatment of international trade flows, the GTAP-AEZ framework allows for tracking the effects of regional policies on land use patterns in other countries. The GTAP modeling framework has played an important role in understanding market-mediated effects of important policies including biofuels (e.g., Hertel et al. 2010), the effects of productivity gains during the Green Revolution (Stevenson et al. 2013), and, more recently, policies to curb deforestation (Taheripour, Hertel and Ramankutty 2019). Based in this voluminous literature, we have updated the standard GTAP-AEZ model to include a nesting structure that separates the decision of converting from forests to agricultural land from the decision of converting from pastures to cropland; this modification follows Taheripour and Tyner (2013), and is justified on the observation that deforested lands transition first onto pastures, and then onto cropland. We also adopt the regional elasticities of transformation, from natural covers to agricultural land, and between pastures and cropland, calibrated based on recent historical changes in land use by Taheripour and Tyner (2013). A critical assumption underlying the GTAP-AEZ framework is the productivity of marginal, hitherto, uncultivated lands, as it determines the extensive margin of land expansion; Taheripour et al. (2012) have used a terrestrial ecosystem model that suggests that in most parts of the world, marginal lands would be as productive as those lands currently under production; we use their parameters to update our model. Another key assumption in the GTAP-AEZ

model is the response of yields to changes in commodity and input prices (Golub and Hertel 2012); we use the assumptions embedded in GTAP-AEZ. Given the uncertainty regarding these parameters, we conduct systematic sensitivity analysis.



(#fig:gtapmodel) Land Supply Structure in the GTAP AEZ Model with Biome Splits. Notes: At the top Constant Elasticity of Transformation (CET) nesting structure, a representative, a profit-maximizing producer operating under constant returns to scale choose the crop mix that maximizes profits subject to resource and technological constraints. The parameter Ω_3 is an elasticity of transformation that captures the ease of converting cropland into each use. The mix of crops generates a change to the rents accruing to cropland. The optimal allocation between cropland and pastureland is determined by comparing the changes in the rents accruing to the two uses; Ω_2 captures the ease with which pasturelands can be converted to croplands, and vice versa. At the bottom of the supply tree, the land rents for the overall agricultural activity are compared to the rents earned by forested lands. The relative size of these rents in conjunction with the elasticity of transformation Ω_1 determine the ease with which forests are converted into cropland, and vice versa. We implement Zero Deforestation Commitments by setting Ω_1 equal to zero for the intersections of Agroecological Zones (AEZ) and Biomes (Cerrado and Amazonia) where companies with GZD pledges have a dominant market share.

Table (#tab:gtapmodifications) Modifications to the GTAP-AEZ model.

Modification	Source	Rationale
Split Brazilian AEZs with soybean production (4,5,6,12) into Biomes and likelihood to comply with commitments.	Companies' pledges (ADM, Amaggi, Bunge, Cargill, Louis Dreyfus, Cofco, Glencore, Denofa do Brazil); land cover and land use from Prodes and Mapbiomas.	The AEZ #5 in Brazil encompasses both the Cerrado and Amazon Biomes, which have distinct commitments.
Nesting structure that separates the decision of converting from forests to agricultural land from the decision of converting from pastures to cropland	Taheripour and Tyner (2013)	It is better representation of land use transitions in South America.
Regional elasticities of transformation, from natural covers to agricultural land, and between pastures and cropland	Taheripour and Tyner (2013)	calibrated based on recent historical changes in land use. We use them for systematic sensitivity analysis of model results.
Modified productivity of marginal, hitherto, uncultivated lands	Endogenous determination and Taheripour et al. (2012)	Endogenous determination of this parameters helps to cope with the inability of the CET functions to track physical land; For sensitivity analysis we use Taheripour et al. (2012), which are based on a terrestrial ecosystem model that suggests that in most parts of the world, marginal lands would be as productive as those lands currently under production
Income elasticities of demand	Muhammad et al. (2011)	Provide an updated set of elasticities.

Experiments

Florian, this is such an important part of the paper that I think it would be worthwhile to develop a short narrative detailing the processing of each database beyond what we have here. This may sound strange, but all the CGE exercises that I am aware of, run a plethora of experiments over a single database. We did not. We ran exactly the same experiment over 36 databases! This is what made this project so time consuming, and I think, innovative and truly interdisciplinary. For reviewers familiar with economic modeling this will not escape

unnoticed so let's give them a good sense about the spatial work underlying our results. We also should think how to bring the maps that you have in your readme into the paper. Perhaps as SOM?

Each experiment consists of a combination of (1) a potential spatial footprint scenario (SFS) of zero-deforestation commitments; (2) one assumption about the minimum market share of the committed companies that is necessary to make the commitments effective, and (3) two different definitions of land cover in Brazil. In the main text we report results of the fifteen experiments with forest definition "A". In the sensitivity analysis below we demonstrate that the results with either database are quantitatively similar. Below we offer detail of the companies involved in each SFS, the market shares of each EA, and the forest definitions. Sources of all these data are also discussed.

Companies in each Spatial Footprint Scenarios (SFS):

1. SFS-ASM: Soy Moratorium Companies (implemented in 2006, present in 2011 and in 2017): Abc Industria, ADM, Amaggi, Bunge, Cargill, Louis Dreyfus, Seara, Fiagril, Nidera, Noble, Cofco, Baldo, Imcopa, Agrex, CHS, Coamo, Engelhart CTP, Gavilon, Glencore, Invivo, Marubeni, Multigrain, Nova Agri, Olam, Perdue, Sodrugestvo, Timbro, Selecta, Binatural(not present), JBS(not present), Oleos menu(not present), Agribrazil(not present), Culturale(not present)
2. SFS-GZD: Global ZD commitments + Soy Moratorium (scenario implementation in 2017): ADM, 2015 Company pledge Amaggi, 2017 Company pledge Bunge, 2015 Company pledge Cargill, 2014 NYDF Louis Dreyfus, 2018 Company Pledge Cofco, 2019 Soft Commodities Forum Glencore, 2019 Soft Commodities Forum DENOFA (DO BBRAZIL), 2014 NYDF
3. SFS-EU: EU exporting companies + Soy Moratorium (scenario implementation in 2017):
 - 155 traders exporting to EU + SWITZERLAND (2017)
 - EU countries appearing as importers: BELGIUM, BULGARIA, CROATIA, CYPRUS, DENMARK, FINLAND, FRANCE, GERMANY, GREECE, HUNGARY, IRELAND, ITALY, LATVIA, LITHUANIA, NETHERLANDS, POLAND, PORTUGAL, ROMANIA, SLOVAKIA, SLOVENIA, SPAIN, SWEDEN, UNITED KINGDOM.
4. SFS-CHN: China exporting companies + Soy Moratorium (scenario implementation in 2017):
 - 140 traders export to China Soy Moratorium (Mainland and Hong Kong) (2017)
5. SFS-EC:: EU China combined + Soy Moratorium
 - 223 traders (2017)

Effectiveness Assumption regarding Market Shares:

We define a treated region as a region where we think there will be high enough compliance to block soy from going into forest areas if:

- Effectiveness Assumption 1: all munis where the market share of Soy Moratorium GZD signatories is > 75% of the soy volume produced (i.e. exported) in that region.
- Effectiveness Assumption 2: all munis where the market share of Soy Moratorium GZD signatories is > 50% of the soy volume produced (i.e. exported) in that region.
- Effectiveness Assumption 3: all munis where the market share of Soy Moratorium GZD signatories is > 0% of the soy volume produced (i.e. exported) in that region.

Data Sources:

- GZD Market share: Trase v24 (www.trase.earth) - calculated as EXPORT MARKET SHARE (domestic production not included - implicitly assuming similar companies involved in the domestic market as in the export market)
- AEZ Shapefile from the GTAP AEZ model, (projection WGS-84)
- Municipalities: IBGE 2015 (intersect with AEZ based on largest intersecting area)
- Soy harvested area: IBGE (<https://sidra.ibge.gov.br/tabela/1612>)
- Soy production: IBGE (<https://sidra.ibge.gov.br/tabela/1612>)
- Soy harvest also cropped with corn: IBGE - Corn 2nd harvest, calculated as the area of 2nd harvest corn that is <= the area of soy harvested. (<https://sidra.ibge.gov.br/tabela/839>)
- Cattle head (<https://sidra.ibge.gov.br/Tabela/3939>)
- Total cropland area: derived from Mapbiomas v4, classes: 18,19,20 (derived via GoogleEarthEngine, <http://mapbiomas.org/en/google-earth-engine>)
- Total pasture area: derived from Mapbiomas v4, class: 15 (derived via GoogleEarthEngine, <http://mapbiomas.org/en/google-earth-engine>)
- A Total forest area:
- Amazon Biome: Prodes (derived via GoogleEarthEngine) (<http://www.dpi.inpe.br/prodesdigital/dadosn/mosaicos/> #2018)
- Other Biomes: Mapbiomas v4, classes: 1,2,3,4,5 (forest area was derived excluding forest regrowth, with forest base year of 2006 - derived via GoogleEarthEngine, <http://mapbiomas.org/en/google-earth-engine>)
- Total forest area (including grasslands - Mapbiomas):
- Amazon Biome: Prodes (derived via GoogleEarthEngine) (<http://www.dpi.inpe.br/prodesdigital/dadosn/mosaicos/> #2018)
- Other Biomes: Mapbiomas v4, classes: 1,2,3,4,5, 12 (forest area was derived excluding forest regrowth, with forest base year of 2006 - derived via GoogleEarthEngine, <http://mapbiomas.org/en/google-earth-engine>)

Baseline Simulations and Model Validation

The base model is calibrated to the global equilibrium of production, consumption and international trade in year 2011. The baseline simulation results from disturbing the base year equilibrium with a comprehensive set of economic shocks that capture the changes in the economy from 2011 to 2016. Therefore, the baseline simulation gives model estimates of how different is the global economy in 2016 relative to 2011. We closely follow the strategy of (Yao, Hertel, and Taheripour 2018) and (Taheripour, Hertel, and Ramankutty 2019). The baseline includes the macroeconomic shocks in table 3, the shocks to agricultural factor and input productivity in table 4 and the production shocks for oilseed in the BBAP region and China in table 5. Shocks to the consumption of sugar cane, coarse grains, and vegetable oils for ethanol and biodiesel production are also included (14% and 56% increase in the demand of vegetable oils and coarse grains by the chemical sector in the EU, 19% increase in the demand of coarse grains for ethanol in the U.S., 10% increase in China, and 1% increase in the demand for raw sugar for ethanol in Brazil)

Table 3: Percentage Change in Macroeconomic Drivers of Land Use Between 2011 and 2016

Region	Capital Stocks	Employment	Investments	Population	Real GDP
Argentina	22.72	4.58	-7.39	5.11	3.23
Bolivia	40.38	4.62	33.56	7.73	25.78
Brazil	23.14	5.10	-34.88	4.41	0.62
China	59.74	1.59	25.10	2.59	36.10
EU_28	22.44	2.17	6.96	0.68	6.84
Indonesia	43.16	8.01	22.60	6.07	25.84
Malaysia	35.86	15.05	21.07	8.49	25.41
NAmerica	14.92	6.65	8.34	3.67	10.74
Paraguay	15.95	9.61	22.85	6.62	21.37
RestLatam	28.75	10.13	0.74	6.39	-1.87
RestofWorld	NA	NA	7.49	6.56	15.41
SSA	35.92	16.63	16.22	13.06	18.87

Notes: For all the variables we take the averages during 2010-2012 and 2015-2017 as endpoints of the period.. Sources: Real GDP (Output side) comes from the World Development Indicators. The rest of the variables come from the Penn World Tables 9.1.

Table 4: Percentage Change in Agricultural Input and Factor Productivity between 2011 and 2016

Region	Capital Productivity	Fertilizer Productivity	Labor Productivity
Argentina	10.07	7.51	12.86
Bolivia	6.33	-22.06	7.96
Brazil	0.49	-6.97	34.36
China	-16.29	8.47	44.09
EU_28	7.07	4.92	23.56
Indonesia	-16.17	-8.91	18.13
Malaysia	-5.73	-5.76	20.80
NAmerica	9.23	-2.36	17.22
Paraguay	15.90	-10.44	20.42
RestLatam	9.16	-0.61	14.69
RestofWorld	1.37	-2.43	16.48
SSA	3.92	-9.11	6.74

Notes: Productivity is defined as 2004-2006 international US dollars per 40 CV tractor-equivalent machinery unit (proxy for capital); per metric ton of N, P2O5, and K2O nutrients of fertilizer consumed (fertilizer); per 1000 persons economically active in agriculture, +15 yrs, male+female. We estimate the growth rate of each ratio during 2009-2015 (last available year) and then calculate the net percentage change between 2016 and 2011. Source: International Productivity Dataset, USDA Economic Research Service which is based on FAOSTAT.

Table 5: Percentage Change in Harvested Area and Production of Oilseed Between 2011 and 2016

GTAPSector	Region	Area	Production
Oilseeds	Argentina	3.07	21.24
Oilseeds	Bolivia	9.79	40.60
Oilseeds	Brazil	31.24	38.37
Oilseeds	China	-11.15	-3.30
Oilseeds	EU_28	4.73	13.07
Oilseeds	Indonesia	33.58	38.16
Oilseeds	Malaysia	0.62	5.57
Oilseeds	NAmerica	11.97	30.28
Oilseeds	Paraguay	20.37	33.64
Oilseeds	RestLatam	33.78	28.04
Oilseeds	RestofWorld	10.88	10.76
Oilseeds	SSA	8.57	11.99

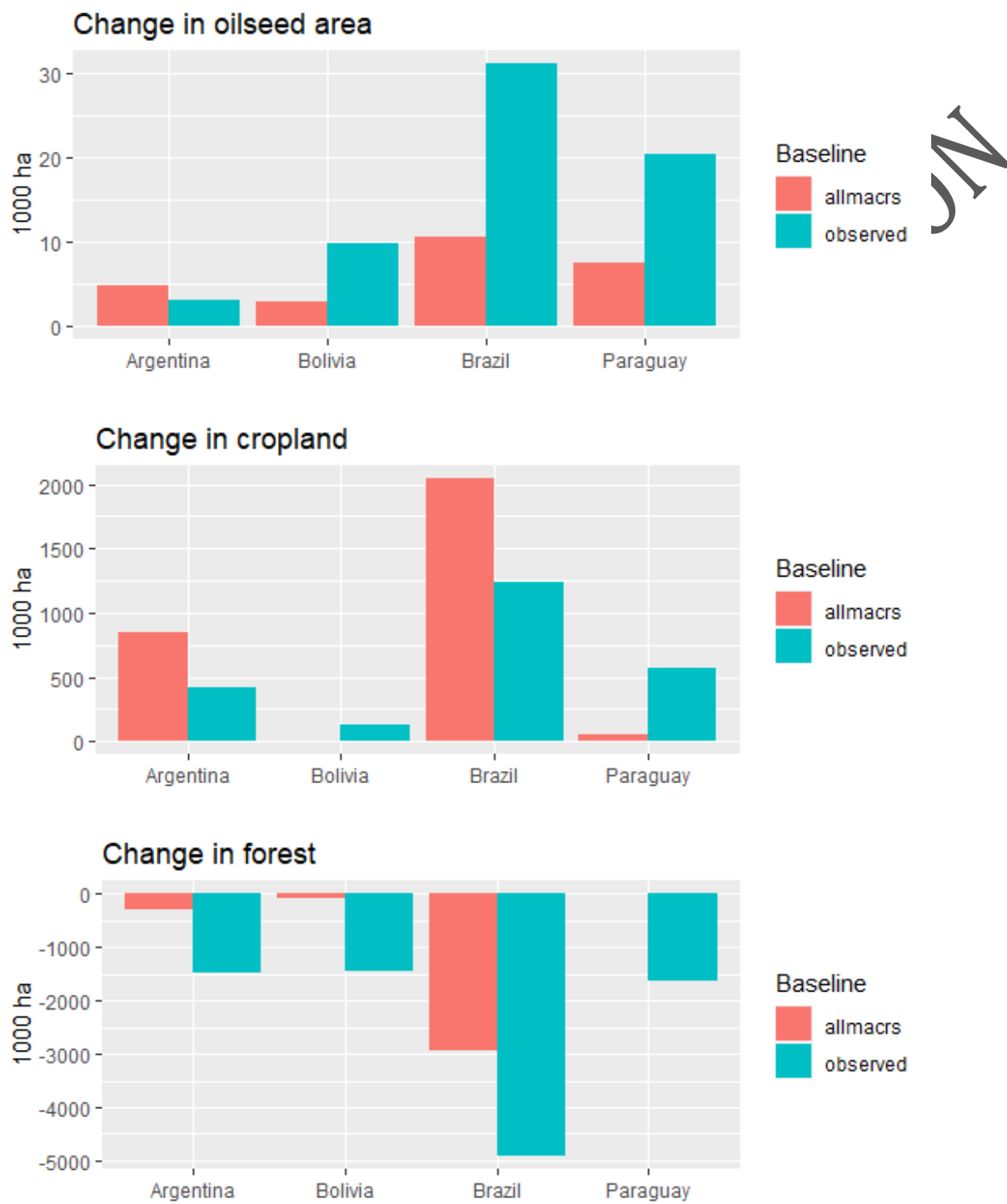
Notes: For all the variables we take the averages during 2010-2012 and 2015-2017 as endpoints of the period. Sources: FAOSTAT.

Compared to observed exports, export predictions are highly accurate for Brazil, and to a lesser extent, Bolivia (table 6). In the case of Argentina, the sharp contraction in the observed exports obeys to producers hoarding soybean supplies during the 2016-2017 harvest as a response to delays in planned reduction of export taxes (Mergen and Sandoval 2016). In the case of Paraguay—a very marginal soybean exporter to China—the rapid growth from a very low initial value is not captured by the model. Regarding the importance of the Chinese market, 37.8% of China's soybeans imports came from Brazil in 2011, and 14% from Argentina. Bolivia and Paraguay are marginal players. The main destination of Paraguayan oilseed is Brazil. Intra-regional trade, particularly exports from Paraguay to Brazil, have exploded, increasing by 2,250% from 2011 to 2016 of 67%. Although trade is supposedly liberalized in the region, it was not until 2016 that Argentina opened up its markets to Paraguayan soybeans in order to use underutilized crushing capacity (Mergen and Sandoval 2016).

Table 6: Observed and simulated %-changes in oilseed exports from BBAP to China, from 2011 to 2016, using baseline shocks.

Region.exp	allmacrs	observed
Argentina	29.69	-27.15
Bolivia	131.95	138.54
Brazil	52.83	69.56
Paraguay	56.79	1097.28

Simulated and observed changes in oilseed, cropland, and forest area, are displayed in figure 10. The model correctly predicts the direction of changes in oilseed land use and cropland and forest covers across the BBAP region.



Notes:

Baseline = allmacrs and ETA = ex.

The comparisons of simulated and observed data in figure 10 is subject to some caveats. First, there are myriad of drivers governing land use process which our model is not designed to capture. These drivers include improvement in market access, large scale fires, deforestation decisions responding to expectations of higher prices in the future, and land property rights. In the expanding agricultural frontiers of South America, some of these factors may play an important role in changes in land cover and use. Second, the translation of changes in land use calculated by applied equilibrium models rests on assumed land productivity which are highly uncertain.

We will conduct systematically examining the robustness of our results to a different assumptions about shocks, parameters, and data assumptions in order to bound the uncertainty inherent to modeling the highly complex and dynamic process of land cover and land use in the BBAP region.

In addition to uncertainty in the ingredients of the model, the comparisons to observed data should be taken as merely referential because there are important differences in the definitions of land cover used by FAOSTAT and the definitions used in GTAP. In particular, cropland in GTAP is equivalent to the sum of the harvested areas of all the crops in the model, while FAOSTAT includes all arable lands, meadows and permanent crops. Regarding forests, the GTAP database only works with forests for which land rents can be imputed, which is a function of their accessibility (Sohngen et al. 2009). This is a subset of all the forests in a country, which is what is reported in FAOSTAT. Finally, for consistency, in GTAP, the weighted changes in land cover sum up to zero so changes in one land cover must be matched by changes in other land covers so that the total sum equals zero.

With these caveats in mind, there are still a number of important insights in figure 10. The model estimated change in Brazil's oilseed harvested area is a third of the value of the harvested area indicated by FAOSTAT. Because the simulated area is the area needed to produce the observed change in oilseed production (also from FAOSTAT, table 5), this suggests that the model is overestimating either the productivity of land or the input use response to changes in prices in Brazil (and also in Paraguay and Bolivia, but not in Argentina). Both of these responses are regulated by model parameters, and we already have or will examine the robustness of our results to plausible ranges of variation of these parameters.

In contrast, the model overestimates cropland expansion in Argentina and Brazil (and underestimates cropland expansion in Bolivia and Paraguay). The drivers of cropland change include assumptions about productivity but also depend on demand for other land-based commodities and the supply response of all the regions in the model. Below we test the sensitivity of our results to different configurations of demand and productivity shocks.

In general the model underestimates deforestation, which is not entirely surprising due to very different definitions of forests in GTAP (accessible forests for which a land rent can be imputed) which are a subset of the total forested area reported by FAOSTAT.

Sensitivity analysis

To be completed after we settle in the results and flow of the paper.

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