Demand-Driven Efforts to Stop Deforestation in Brazil's Soy Sector are Unlikely to be Offset by Cross-Border Leakage

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Article

Keywords:

Posted Date: January 5th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1131832/v1

Version of Record: A version of this preprint was published at Nature Communications on September 17th, 2022. See the published version at https://doi.org/10.1038/s41467-022-33213-z.

Abstract

Supply chain policies that leverage the upstream market power of trading companies and importing countries offer great promise to address forest clearing1,2 in regions of rapid commodity expansion but weak forest governance3,4. Yet leakage—when deforestation is not eliminated but instead pushed to other regions—is a potentially major but unquantified factor that could dilute the global effectiveness of regionally successful supply chain policies5,6. We find substantial domestic leakage rates (43-50%) induced by zero deforestation policy implementation in Brazil's soy sector, but insignificant cross-border leakage (<3%) due to the interdependence of soy production in the U.S. and Brazil. Currently implemented zero-deforestation policies in the Brazilian soy sector offset 0.9% of global and 4% of Brazilian deforestation from 2011-2016. However, completely eliminating deforestation from the supply chains of all firms exporting soy to the EU or China over the same period could have reduced global deforestation by 2% and Brazilian deforestation by 9%. If major tropical commodity importers adopt policies that require traders to eliminate deforestation from their supply chains, as currently proposed in the EU, it could help bend the curve on global forest loss.

Main

Zero-deforestation (ZD) corporate policies (ZDCPs) leverage the influence of companies to enforce stringent sourcing requirements, with the hope that downstream pressure will help supplement limited public deforestation control efforts in producing regions. Starting in the mid-2000s, under duress from non-governmental environmental organizations[6], a handful of the world's largest agricultural trading companies voluntarily committed to eliminate deforestation from their supply chains[5]. For instance, signatories to the Amazon Soy Moratorium (ASM) in Brazil—the first implemented voluntary set of commitments—only buy soybeans produced in areas where forests were cleared long ago[7]. Since then, hundreds more companies in the agri-food and timber sectors have pledged to address deforestation associated with the products they handle[6].

Supply chain-based approaches to forest conservation are now being adopted by concerned importing governments. The European Union (EU) is considering legislation to allow imports of soybeans and other forest-risk commodities only by companies that can verify deforestation-free status of their products[8,9]. In the United States (US), "clean and transparent supply chains" may be required to release funds to protect the Amazon rainforest[10,11].

Eliminating deforestation embodied in supply chains starts in production regions by ensuring that no forested lands are converted to the commodity in question. Whether such land use restrictions adequately address global forest loss depends on the scale and location of their adoption[6,12] as well as the degree to which deforestation in target region supply chains is offset by the displacement or "leakage" of deforestation to other regions. Leakage is a potentially substantial barrier to ZDCP effectiveness because land conversion restrictions apply only to the fraction of production sourced by supply chains covered by

ZDCPs[5]. Yet, attributing deforestation leakage across biomes or at continental to global scales to supply chain policy changes remains a major empirical challenge due to confounding simultaneous changes in markets and governance[13,14]. Moreover, many corporate ZD policies and all proposed government regulations have not yet been implemented, limiting the use of retrospective statistical analysis. Previous ZDCP impact assessments focused on voluntary company interventions only and examined past or potential future leakage from the ASM to other regions in the Amazon[14–16] or within the Cerrado[1].

Our research substantially advances the study of ZDCPs by increasing the scope over which leakage is assessed. We assess the degree to which leakage offsets reductions in deforestation and associated greenhouse gas (GHG) emissions achieved by ZDCP implementation in the Brazilian soybean sector. In contrast to previous assessments, we evaluate leakage across all the producing regions in Brazil, and also to other countries. In addition to voluntary ZD commitments, for the first time, we include scenarios of ZDCPs derived by import regulations in the EU and China that are not yet implemented but that play an important role in current discussions about the future of ZDCPs in strengthening forest conservation in Brazil[1,8,17].

We estimate how much avoided deforestation in Brazil from 2011-2016 is displaced to neighboring agricultural forest frontiers in Bolivia, Argentina, and Paraguay ("BAP"), land-abundant countries with carbon-rich ecosystems and ample scope for further expansion of agriculture[18], and to other oil crop producing regions. We compare five ZDCP scenarios: (1) the ASM; (2) extension of the ASM to all of Brazil as per companies' pledges to global voluntary ZD commitments[19]; (3) adoption of ZDCPs by all companies that export to the EU as would be required under legislation under consideration by the EU[9]; (4) adoption of ZDCPs by all companies that export to China, the leading soybean importing nation[20] whose most important transnational soy trader has signaled possible adoption of ZD restrictions for their imports[17]; and (5) adoption of ZDCPs by all companies that export to either China or the EU. We assume that companies that sell to the regulated markets would transform their entire supply chain to be deforestation free (scenarios 3-5). This assumption is justified because supply chain differentiation within the same company requires monitoring, tracing, and certification systems with separate chains of custody. Such differentiation may be more costly than transforming only one part of the supply chain to conform with demands from a portion of the market, as demonstrated by the failure to separate transgenic and conventional soybean supply[21].

Market coverage influences the leverage that traders have over farmers' behaviors, including deforestation. The minimum regional market coverage by committed traders needed to achieve regional zero-deforestation crop production—defined here as cultivation of soybeans or other crops only within areas deforested before 2011 (Methods)—remains uncertain[6]. We thus examine three thresholds for compliance and report the ≥75% market coverage threshold in the main text; all thresholds result in global net avoided deforestation (Fig. 1, Methods). We circumvent the empirical measurement challenges highlighted above by applying the GTAP-AEZ database[22] with Brazil's agro-ecological zones remapped into Brazilian biomes. We determine the shares of each biome in Brazil under ZDCPs using recently available market data (Fig. 1, Methods,). This novel strategy allows us to track changes in agricultural land use and GHG emissions within and across biomes and across countries. We present our results as the difference in deforested area and GHG emissions between baseline (Supplementary Information S1) and ZDCP scenarios. Results are robust to uncertainty in the key parameters regulating land use in the GTAP-AEZ model (Supplementary Information S2).

HALF OF AMAZON SOY MORATORIUM IMPACT ABSORBED BY LEAKAGE

We find that the ASM led to 409 kha of gross avoided deforestation within the Brazilian Amazon from 2011 to 2016 (82 kha/year; Fig. 2a). This avoided forest loss rate is similar to Heilmayr et al.'s [14] lower bound estimate of ~90 kha/year (Supplementary Information S3). Around half of this avoided deforestation was offset by increases in deforestation in parts of the Amazon outside the ASM, generating a within-Brazil leakage rate of 53% (Fig. 2f). Domestic leakage was high because only 10% of Brazil's forests were in municipalities where committed soy company market share exceeded 75% (Fig. 1f).

After accounting for leakage within Brazil, net avoided deforestation in the Amazon and Cerrado biomes totaled 238 kha, about 23% of the 847 kha deforested for soy cultivation in both biomes during the same period (Supplementary Information Fig. S1). Net avoided deforestation within Brazil amounted to 194 kha (Fig. 2a), or 4% of total observed forest loss in the country[23] (Supplementary Information Fig. S4). Cross-border deforestation spillovers to the BAP region were negligible (<2 kha increase), and deforestation in the rest of the world increased by 11 kha, for a cross-border leakage rate just above 3% (Fig. 2f). Global net avoided deforestation in this scenario totaled 180 kha (Fig. 1a), 0.9% of global deforestation during 2011-2016[23], and reduced GHG emissions by 153 kilotonnes CO_2 equivalent (kt CO_2e; Fig. 2g), approximately 0.004% and 0.01% of global (4,018 megatonnes [Mt] CO_2e) and Brazil's (1,730 Mt CO_2e) GHG emissions due to land use change and forestry (LUCF) during the same period, respectively[24].

GLOBAL VOLUNTARY ZERO-DEFORESTATION COMMITMENT IMPLEMENTATION WOULD HELP PROTECT CERRADO BIOME

Implementation of all global voluntary ZD commitments including the ASM across Brazil from 2011-2016 would have increased gross avoided deforestation by 167 kha (Fig. 2b) and generated Brazil-wide gross forest savings 40% higher relative to the ASM-only scenario. Combined net avoided deforestation in the Amazon and the Cerrado represents 36% of the 847 kha of observed deforestation for soy in those biomes (Supplementary Information Fig. S1). Our finding of 39 kha (~8 kha/year) of net avoided deforestation in the Cerrado (Fig. 2b) is considerably lower than the projections by Soterroni et al.[1] of ~120 kha/year from 2020-2050. The difference is partly explained by our use of market coverage thresholds to isolate areas most likely to be impacted by ZDCPs, whereas they assume a complete and uniform application of commitments across the biome. Soterroni et al.[1] also assume high future rates of land conversion for soy in Cerrado relative to the recent past (117 kha observed during 2011-2016, Supplementary Information Fig. S1).

The leakage rate in this scenario (47%, Fig. 2f) is similar to leakage in the ASM-only scenario because the addition of global commitments only increases the proportion of Brazil's forest area subject to land use restriction from 10–13% (Figs. 1f, 1g). Net avoided deforestation in Brazil would have amounted to 306 kha, almost twice as much as in the ASM scenario and 6.2% of the total deforestation experienced by Brazil during 2011-2016 (Supplementary Information Fig. S4). Spillovers into the BAP region and the rest of the world were about 3 kha and 14 kha, respectively, for a cross-border combined leakage rate of 3% (Fig. 2f). Net global deforestation in this scenario amounted to 288 kha, 1.4% of global deforestation during the period, and avoided GHG emissions totaled 220 kt CO_2e (Fig. 2g), 0.005% and 0.01% of global and Brazil's LUCF GHG emissions, respectively.

MINIMAL REGIONAL DEFORESTATION LEAKAGE EXPLAINED BY DESTINATION MARKET SEGMENTATION

The low rates of deforestation leakage to the BAP region are explained by the modest effect of ZDCPs on global oil crop production and limited price transmission within the BBAP (Brazil + BAP) region (Supplementary Information S1). Intra-BBAP soybean trade volume was relatively small from 2011-2016 and remains this way (Fig. 3a). In addition, China is the main market where US and Brazil producers compete, while Bolivia and Paraguay predominately supply EU markets (Fig. 3a). This pattern of destination-market segmentation partly disconnects BAP and Brazil producers and tightly connects the supply responses of farmers in the US and Brazil[20,25] so that reduced soybean production in Brazil due to deforestation restrictions is largely absorbed by increases in US soybean area into existing farmland (Supplementary Information S4). Although additional conversion of forested lands in the US is minimal (<150 ha, Fig. S9), negative spillovers to non-forest ecosystems in the US, such as prairies and wetlands in the US, may still occur.

IMPORTER REGULATIONS COULD SUBSTANTIALLY INCREASE FOOTPRINT AND IMPACT OF SUPPLY CHAIN POLICIES

The share of Brazil's soy area where companies that export to the EU have a market share of ≥75% of soy export volumes is twice the area under voluntary global ZD commitments (52% vs. 27%, Fig. 1h). Still, only 15% of Brazil's forests would be subject to land use restrictions under a scenario in which EU regulations had been in place from 2011-2016 (Fig. 1h), generating a domestic leakage rate of 43% (Fig. 2f). In this scenario, net avoided deforestation in Brazil would have amounted to 419 kha (Fig. 2c), 8.5% of Brazil's observed deforestation during the period. This is a 37% increase in forest savings relative to the adoption of voluntary global ZD commitments. Net forest loss in the Amazon and the Cerrado would have totaled 340 kha, less than half (40%) of the observed deforestation for soy cultivation during 2011-2016 in these biomes (Supplementary Information Fig. S1).

Despite greater ZDCP coverage under this scenario (Figs. 1c, 1h), cross-border international leakage remains close to 3% (Fig. 2f) due to the destination-market segmentation discussed above. This scenario also results in 35% less GHG emissions relative to the voluntary global ZDCP scenario (-297 kt CO_2e, Fig.

2g), or 0.007% and 0.02% of global and Brazil's LUCF emissions, respectively. Worldwide net forest savings amount to 398 kha (Fig. 2c), or 1.87% of global deforestation, and a 38% increase in global net avoided deforestation relative to the adoption of global voluntary ZD commitments. The EU Commission estimates that mandatory supply chain due diligence and certification aimed at stopping deforestation driven by EU demand for six forest-risk commodities including soy[9] will avoid the deforestation of 72 kha/year starting in 2030. This estimate is far more conservative than our result of 80 kha/year considering that it covers more commodities and countries.

If the soy trading companies that export to China had imposed ZD requirements from 2011-2016, avoided deforestation and GHG emissions (429 kha of net avoided deforestation in Brazil, 408 kha net global forest savings, -300 kt CO_2e emissions, Figs. 2d, 2g) would have been similar to those stemming from EU-mandated commitments. This similarity is driven by the fact that most companies in Brazil sell to both China and the EU and is confirmed by the similarity of results from the final scenario. We find little difference in forest conservation whether zero-deforestation requirements cover all exporters from Brazil to both China and the EU (scenario 5, Fig. 2e), only exporters to the EU (scenario 3, Fig. 2c), or only exporters to China (scenario 4; Fig. 2d).

IMPORT REGULATIONS CAN HELP AVOID MORE DEFORESTATION GLOBALLY BUT COME WITH RISKS

Taking the ratio of domestic to cross-border leakage as an indicator of the effectiveness of ZDCPs, our results suggest that supply chain efforts to halt soy-driven deforestation would be substantially more effective if extended outside of the Amazon, especially if they include zero-deforestation requirements for exporting to the EU and China. Our key assumption is that such regulations incentivize traders to implement zero-deforestation policies (e.g., by strengthening monitoring systems and engaging with governments to reduce commodity-driven deforestation) across all existing and future sourcing regions rather than segregating their supply streams or leaving such demanding markets. If this assumption holds true, the current EU proposal to halt import-driven deforestation could trigger widespread structural change in the implementation of deforestation control efforts.

Scaling up zero-deforestation regulations for Brazil's soy entering the EU is not without risks. While China's share of Brazil's total soybean exports grew from 68% in 2011 to 82% in 2017, the EU's share declined from 18–9%, reducing its overall market power (Fig. 3b). In the next decade most growth in soybean demand will come from China (Fig. 3c), which is projected to be satisfied almost entirely with additional exports from Brazil (Fig. 3d). Traders may choose to drop out of the EU markets or segregate their supply chains into compliant and non-compliant streams if the benefits of selling to regulated EU markets exceed the costs of implementing zero-deforestation supply chain policies across Brazil. This would reduce gross avoided deforestation relative to our analysis and could also weaken the influence of EU-based traders on state-led forest governance in Brazil. Stringent zero-deforestation supply chain approaches may substantially impact rural livelihoods in deforestation risk areas[26] if excluding non-compliant actors is cheaper than engaging with them. Moreover, a focus on protecting forests may generate spillovers to non-forest ecosystems. Capacity building with producers to address noncompliance and improve existing agricultural practices, coupled with reducing incentives for firms to avoid non-compliant actors, may help reduce such negative spillovers from ZDCPs.

Conclusion

Given the market segmentation of the world's major soy deforestation-risk regions, there is ample scope to eliminate soy-driven deforestation by extending ZDCPs within Brazil without significantly threatening forests elsewhere or disrupting international markets. Yet, due to this market segmentation, the low leakage associated with soy ZDCPs may not apply to other deforestation-risk commodities. For instance, oil palm is largely restricted to climates that also support humid tropical forests and cross-border leakage rates are substantially higher that what we found for Brazil[27]. However, our findings provide hope that extension of ZDCPs to more regions and supply chains could protect tropical forests with low risk of global deforestation leakage.

Methods

Modeling framework

We used an open source, fully documented, and publicly available medium run applied general equilibrium (AGE) model[28] with explicit treatment of subnational land markets divided in Agroecological Zones (AEZ), nicknamed GTAP-AEZ[22]. The GTAP-AEZ framework is based on decision nests at which agricultural producers decide on land cover conversions (Supplementary Information Fig. S2), for example, from pastures to cropland, and then on the allocation of individual crops within the cropland. As producers in different AEZs are connected through land, labor, and capital markets, competition among land uses, and supply chains, the GTAP-AEZ model is ideally suited to study within-country changes in 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, soybean, and oilseed markets, and the effects of productivity gains during the Green Revolution[25,27,29,30].

We updated the standard GTAP-AEZ model to include a nesting structure that separates the decision to convert forest to agricultural land from the decision to convert pasture to cropland, which is justified by the observation that deforested lands transition first into pastures, and then onto cropland[31]. This nesting structure applies to all the regions. We also adopted regional elasticities of transformation, from natural covers to agricultural land, and between pastures and cropland, calibrated based on recent historical changes[31]. We further updated the income elasticities of demand for agricultural and food products to reflect the latest work in this area[32]. 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. Another key assumption in the GTAP-AEZ model is the response of yields to changes in commodity and input prices[33]. For both we use the assumptions in the original GTAP-AEZ model[22]. Given the uncertainty regarding these parameters, we conduct extensive systematic sensitivity analysis of our results to alternative parametric configurations (Supplementary Information S2).

Underlying the model there is a database that consistently represents production, consumption, and trade patterns of 140 regions and 57 sectors in year 2011[34]. To make solution times and model output manageable, we aggregated the model into 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 collapsed the 57 commodity sectors into 18 sectors (i.e., paddy rice, wheat, coarse grains, oilseeds, raw sugar, grazing livestock, non-grazing livestock, forestry, extractive industries, processed livestock, vegetable oils, processed rice, processed sugar, other processed food, chemicals, manufactures and services). For Brazil, we considered the GTAP aggregate oilseed commodity as soybeans because soybeans account for more than 96% of oilseed production in Brazil[35]. 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 representative of 2011[36].

Spatial Footprint Scenarios (SFS) and Market Share Thresholds of Zero Deforestation Corporate Policies (ZDCPs)

The SFS (Fig. 1) are designed to assess how much deforestation would be avoided by implementing different configurations of the company- and importing country-led ZDCPs. Except for the ASM, most ZDCPs–either voluntary or imposed—have not been implemented[6,8,11,17]. Therefore, the SFS are counterfactual, non-observed states of the world. We estimate changes in deforestation and other economic outcomes as the difference between the counterfactual SFS and a baseline (as explained below). The baseline includes patterns of land use, land cover, and other economic outcomes obtained by letting the model simulate the changes in equilibrium as the economy responds to a set of drivers of land use during the period 2011-2016, without any land restriction to land expansion in Brazil. The baseline is therefore a plausible representation of the world in the absence of any type of ZDCPs.

We chose 2011 as our initial year because this is the most recent year for which we have the consistent snapshot of the world economy, including land use and land cover—GTAP Database and AEZ Database, V9[34,36] —needed to calibrate the GTAP-AEZ model. We stop in 2016 as we seek to understand a “medium run” time horizon whereby global production, consumption and trade have enough time to adjust to an equilibrium that includes all the economic effects of the modeled ZDCPs. The ASM was in place during our period of study, and it should be considered a baseline relative to further hypothetical policy developments analyzed here. The drawback of including the ASM in the baseline is that we would not be able to report the ASM outcomes, which, by virtue of its pioneering status, is a natural benchmark of future ZDCPs in Brazil’s soybean sector. For this reason, we exclude the ASM from the baseline by not imposing land restrictions in the Amazon.

The SFS we evaluate are as follows:

1. **Amazon Soy Moratorium.** This scenario uses the spatial footprint in the Brazilian Amazon of the companies that implemented the moratorium in 2006. These companies are: 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, and Selecta. Other companies that are part of the ASM do not export soybeans from the Amazon are: Binatural, JBS, Oleos menu, Agribrasil, and Culturale. The duration of the ASM has been extended indefinitely[14].
2. **Global voluntary ZD Commitments + Soy Moratorium.** This scenario includes the ASM companies above and adds all Global ZDCPs as if they were implemented in 2011. The Global ZDCPs have been adopted by a subset of the companies that agreed on the ASM. These are (pledge year and in parentheses): ADM (2015 company pledges); Amaggi (2017 company pledges), Bunge (2015 company pledges) Cargill (2014 New York Declaration on Forests); Louis Dreyfus (2018 company pledges); Cofco (2019 Soft Commodities Forum); Glencore (2019 Soft Commodities Forum); and Denofa do Brazil (2014 New York Deforestation of Forests).
3. **Import restrictions imposed by the European Union (EU).** Agriculture-driven deforestation has become an increasingly polarizing issue between the EU and Brazil, and is a central issue in a potential trade agreement between the EU and the MERCOSUR, a trade bloc agreement among Argentina, Brazil, Paraguay, and Uruguay[37]. We therefore also explore the effects of the adoption by the EU of mandatory rules currently considered by the European Parliament that would de facto impose ZDCPs on the companies sourcing soybeans from Brazil[8]. We consider 155 traders exporting to EU plus Switzerland and the United Kingdom that would only procure their soybeans from areas already converted to agriculture prior to 2011. The EU countries appearing as importers consist of Belgium, Bulgaria, Croatia, Cyprus, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, and Sweden.
4. **Hypothetical import restrictions imposed by China, assumed to be similar to those being currently evaluated by the EU** [17] . We consider 140 traders that export to China including Hong Kong (in addition to the ASM) that would only procure their soybeans from areas already converted to agriculture prior to 2011.
5. **Hypothetical import restrictions imposed by both China and the EU.** These simulations provide an upper bound estimate of the ZCDPs.

In the SFS 3-5 (scenarios 3-5 in the main text) we assume that if a company supplying either EU or Chinese markets decides to produce deforestation-free soybean to preserve market share in one destination, the company 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[21,38].

Market Share Thresholds

Uncertainties exist regarding the critical market share (i.e., the percentage of total regional market share held by corporations with ZDCPs) needed to discourage farmers from selling soybeans produced in recently cleared land to non-committed traders[6]. If no soybean buyers within a region have a ZDC, farmers have no incentives to avoid forest for soybean clearing. Alternatively, if only committed traders buy soybeans within a region, producers should be forced to comply with the ZDCP land use restrictions to sell their soybeans. In many Brazilian regions, traders with and without ZDCPs purchase soybeans, thus producers with soybeans that are not deforestation free can typically sell their products. We posit that with increasing regional ZDCP market share, the difficultly of selling non-compliant soybeans increases. At some critical market share threshold, farmers may be completely disincentivized from producing soybeans on non-compliant lands that were recently deforested due to the difficulties in selling their product [39,40].

We bound the uncertainty about the competition structure needed to ensure compliance through three market share thresholds built using the export market shares of all the companies active in the Brazil's soybean market from the Trase v2.4 database [41]:

1. The most restrictive market share thresholds requires that at least 75% of the soybeans exported from a given municipality are bought by companies with voluntary ZD commitments. In this scenario, 10% of the area under soybeans in Brazil is subject to the ASM (Fig. 1f). By adding pledged global voluntary ZD commitments in other biomes to the ASM, 27% of Brazil's soybean area would be under agreements to halt forest conversion for soy production (Fig. 1g).
2. A less conservative market share thresholds requires an export threshold of 50%. Under this scenario, the area under soybeans that is affected by global voluntary ZD commitments under the current pledges amount to 48% of Brazil's total soybean area (Fig. 1g).
3. The least restrictive scenario requires at least one committed company to be present in the municipality (>0% of market share covered by voluntary ZD commitments). Under global voluntary ZD commitments, 75% of Brazil's soybean area would be subject to ZDCPs (Fig. 1g).

Land Cover Definitions

We use two different definitions of forests in Brazil to accommodate different biome characteristics and ZDCP targets [42]. Definition A was exclusively based on mapped forest cover. Definition B included natural grasslands outside the Amazon Biome, which may have high conservation value and are included in some traders ZDCP definition [e.g., "Transforms our supply chain to be deforestation free while protecting native vegetation beyond forests." [43]]

- Forest definition "A": Forest is defined as forest only, as mapped by PRODES for the Amazon [44] and by Mapbiomas for other biomes [Mapbiomas v4 [45], classes 1, 2, 3, 4, and 5]. Forest area was derived excluding forest regrowth, with forest base year of 2006 [45]. We used PRODES for the Amazon biome, because PRODES deforestation maps define the baseline for ASM monitoring, implementation, and enforcement. We used Mapbiomas outside the Amazon Biome. To our knowledge, Mapbiomas provides the most accurate and consistent large scale land use and land cover classification for Brazil.

- Forest definition “B”: Forest is defined as forest only in the Amazon biome, as mapped by PRODES, and forest and grasslands in all other Brazilian biomes, as mapped by Mapbiomas.

Land Use and Land Cover Databases: In addition to the data on soybean export market share and forests, we gathered municipality-level data on agricultural land cover from Mapbiomas v4 [45]: total cropland [classes 18-20] and pasture area [class 15], soybean area (ha), soybean production (tonnes), areas with both maize and soybean (ha), maize second harvest area (ha), calculated as the area of second harvest maize that is greater or equal to the area of soy harvested [46], and cattle headcount (heads)[47]. These data were used to build the different versions of the GTAP-AEZ database, as explained below.

The supply-side spatial footprint scenarios, market share thresholds, and forest definitions give rise to thirty different databases with land use and land cover in each Brazilian municipality (five SFS * three market share thresholds* two Forest Definitions = thirty databases.) We use these land use/land cover databases to build biome-specific distributions of land cover and soybean production with and without ZDCPs that can be used to calibrate the counterfactual experiments using the GTAP-AEZ model.

Model calibration

We use the databases discussed in Supplementary Information S1 to recalibrate the GTAP-AEZ model so that Brazil is split into biomes instead of the standard AEZs. This requires rebuilding the original GTAP and GTAP-AEZ databases. The algorithm to split Brazil’s agricultural output values into biomes proceeds as follows. For each ZDC spatial configuration, market share threshold, and forest definition, we use the following algorithm

1. Overlay the AEZ map used in the GTAP-AEZ database[36] on a municipality-level map of Brazil[48]. In case that a municipality is split across more than one AEZ, assign the municipality to the AEZ with the largest intersection.
2. Overlay a biome map over the AEZ and municipality maps for Brazil. The biomes generally encompass several AEZs and the same AEZ can occur in different biomes. Biomes other than the Amazon and Cerrado are in an “Other” category. In case that a municipality is split across more than one biome, we assign the municipality to the biome with the higher ZDC implementation stringency, prioritizing the Amazon, second the Cerrado, and all other.
3. Each municipality receives a unique id for each biome-AEZ combination, for example: AEZ5 becomes AEZ5-Amazon, AEZ5-Cerrado, and AEZ5-Other.
4. Compute compliant market share thresholds for each municipality (using pledges as of 2017), and then categorize the biome-AEZ ids into compliant and non-compliant based on the SFS. For example: AEZ5 becomes AEZ5-Amazon-ZDC, AEZ5-Cerrado-ZDC, and AEZ5-Other-ZDC, and AEZ5-Amazon-Non-ZDC, AEZ5-Cerrado- Non-ZDC, and AEZ5-Other-Non-ZDC.

5. Use aggregate municipality-level land cover (cropland, pasture, and forest area) and land use (soybean area, soy production, areas with both maize and soy, cattle headcount) to assign land cover and land use areas to each biome-AEZ-market share thresholds level.
6. For all regions other than Brazil, build a conventional GTAP-AEZ database representative of 2011. This step uses a database of land use and land cover areas at the level of AEZs [36,49] to split the country-level output value of relevant products (crops, grazing livestock, and forestry) in the standard GTAP database [34] into AEZs.
7. For Brazil, we use the AEZ-Biome area and production shares created in steps 1-4 to split the aggregate output values of oilseeds, coarse grains, grazing livestock, and forestry into biomes. Each new database represents a counterfactual year 2011 in which some of the area in each AEZ-BIOME was under a ZDCP commitments pledged before 2020. The simulations answer the question: how different area, production, and consumption would have been in 2016 if the pledged ZDC had been in place since 2011.
8. The area of the crops other than oilseeds and coarse grains (paddy rice, etc.) are shared out in each biome-AEZ in proportion to the cropland.

In each experiment we halt land conversion between forest and agriculture in the areas assumed under ZDCs by way of a subsidy that compensates producers for the economic losses of not transforming forests on to agriculture.

Deforestation Leakage Rates

Following the literature on carbon leakage[50], we define the deforestation leakage rate as the increase in deforestation in regions without restrictions (*No ZDCP*) induced by the measures taken in regions with ZD policies (*ZDCP*) as a percentage share of the absolute value of deforestation in regions with ZDCP. Formally

$$DeforestationLeakageRate = \frac{\Delta Deforestation_{NoZDCP}}{|\Delta Deforestation_{ZDCP}|} \times 100.$$

Where Δ denotes the difference between deforestation outcomes in the baseline and counterfactual scenarios, and

$$\Delta Deforestation_{Global} = \Delta Deforestation_{ZDCP} + \Delta Deforestation_{NoZDCP}.$$

Greenhouse Gas Emissions

Greenhouse gas emissions (GHGs) from the changes in land cover associated with the different experiments are calculated using the also open-source AEZ Emission Factor (AEZ-EF) Model[51]. 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[52]. It also includes data on carbon remaining on harvested wood products, non-CO_2 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 CO_2 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[27,53].

Declarations

Acknowledgments: Authors acknowledge funding from US National Science Foundation grant # 1739253 (NV, RG, KC, FG), US Department of Agriculture, National Institute of Food and Agriculture, Hatch Project HAW01136-H (KC), McIntire Stennis Project HAW01146-M, managed by the College of Tropical Agriculture and Human Resources (KC), National Socio-Environmental Synthesis Center (SESYNC) - U.S. National Science Foundation award DBI-1052875 (NV, RG, KC, FG), NASA Land-Cover and Land-Use Change Program (Grant # 80NSSC18K0315) (FG), U.S. Department of Agriculture, National Institute of Food and Agriculture, Multistate Research Project S1072 (NV).

Author contributions: NV, RG, KC, FG conceptualized the article, developed the methodology, conducted the analysis, and wrote the article.

Competing interests: Authors declare that they have no competing interests.

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Figures

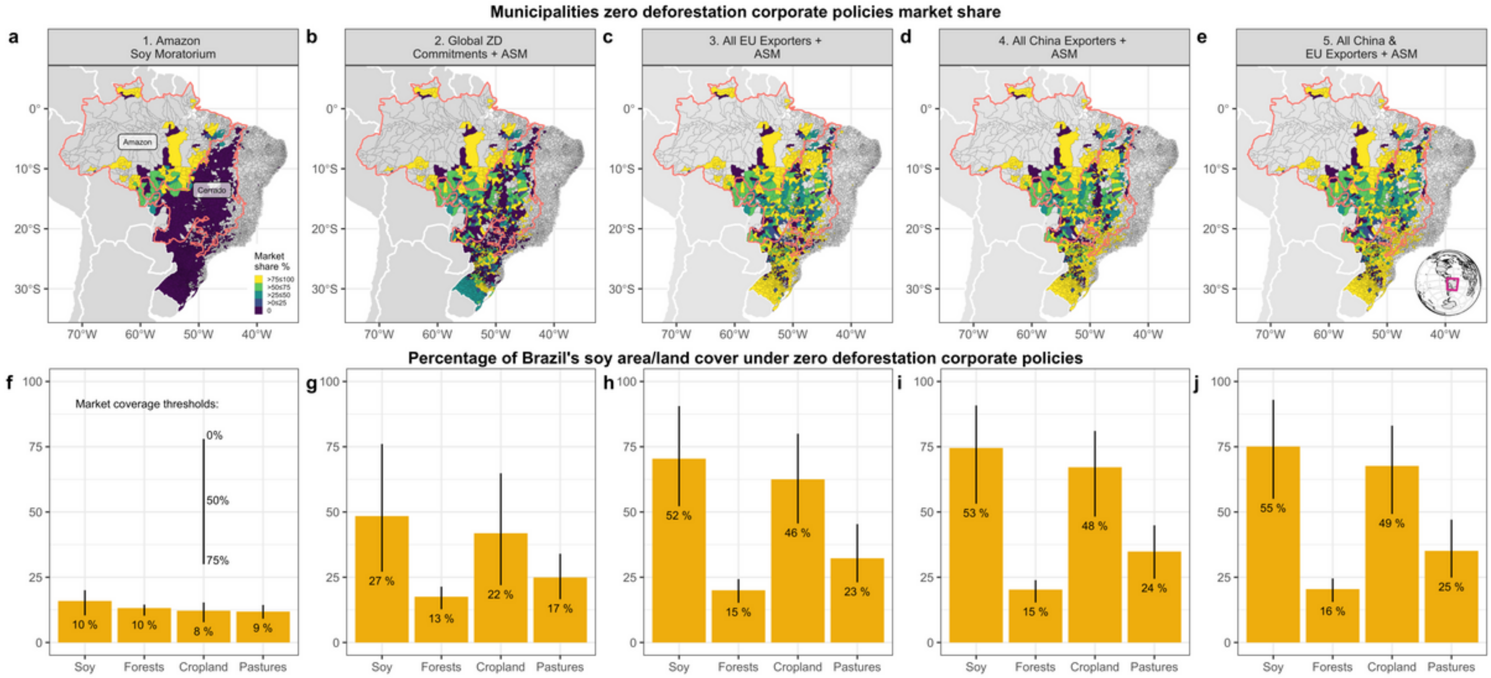

Figure 1

Spatial footprint of Zero Deforestation Corporate Policy (ZDCP) scenarios. a-b: Municipality-level market shares of companies with voluntary ZDCs [Amazon Soy Moratorium (ASM) and Global ZDCs]. **c-e:** Municipality market shares of companies that export to the EU (**c**), China (**d**), or both (**e**). Panels **f-j** depict the percentages of Brazil's soy and land covers subject ZDCPs. For instance, under the most restrictive market coverage threshold (≥75%), in the ASM scenario, 10% of Brazil's forests (located in the municipalities with a ≥75% market share in panel **a**), cannot be converted to agriculture. In the ASM scenario, changes in soy area (10% of Brazil's soy area) would occur either in the surrounding cropland (8% of Brazil's total cropland) or pastures (9% of Brazil's total cropland), or elsewhere in the world. Sources: TRASE[41] and Mapbiomas[45].

Figure 2

Changes in forest area and greenhouse gas emissions relative to a baseline without land use restrictions. **a-e:** Changes in forests. Positive values in indicate avoided deforestation while negative values are displaced deforestation. **f**: Deforestation leakage rates defined as the ratios of displaced deforestation within Brazil and to the rest of the world as percentages of the avoided deforestation from ZDCPs (Methods). **g:** Changes in emissions from land use change (Methods). In all cases the height of the bars corresponds to the difference between counterfactual and baseline values obtained under the market share threshold (≥50%). The displayed values in all the plots are for the most restrictive scenario (≥75% market share). BAP = Bolivia, Argentina, Paraguay; ROW = rest of the world.

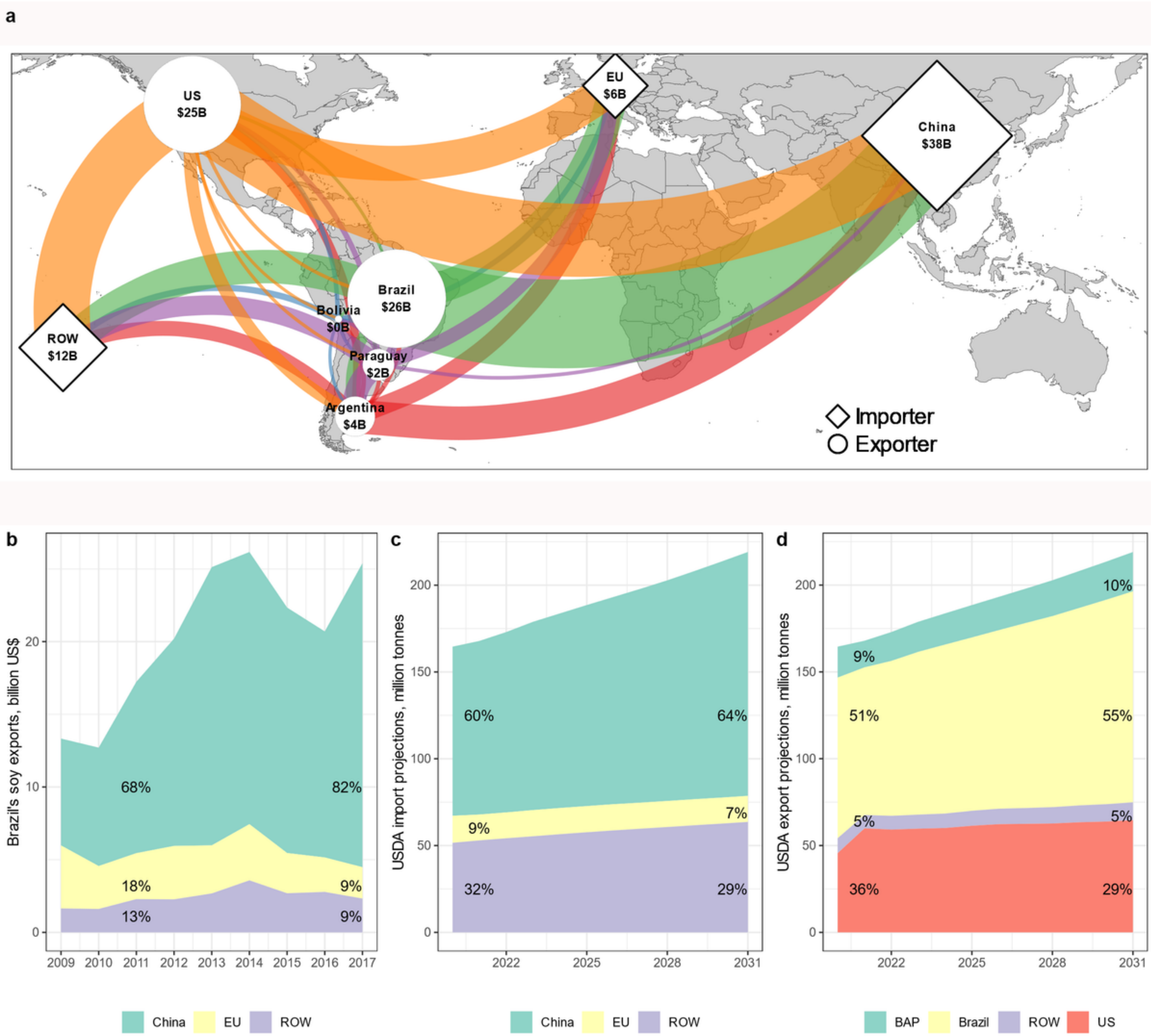

Figure 3

Illustration of China's increasing dominance in global soy markets. a: Main international soy trade flows (average 2017-2018**)** indicate that world trade is highly concentrated with China importing 68% of global exports, 93% of which come from the US and Brazil. **b:** The main destinations of Brazil's soy exports (2009-2017) indicate that China's importance in Brazil's soy exports has grown rapidly, from 68% in 2011 to 82% in 2017, while the EU's share of Brazil's soy exports has decreased, from 18% to 9%. **c-d:** Sources of long-term (10-year) soy import demand (c) and export supply (d) indicate strengthening demand in China, which will be mostly satisfied by Brazil. Sources: a-b[54], c-d[55]. BAP = Bolivia, Argentina, Paraguay; ROW = rest of the world.

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