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Léa Crepin

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par

Léa CREPIN

Soybean trade and imported deforestation

Directeur de thèse : **Philippe DELACOTE**

Co-directrice de thèse : **Julie LOCHARD**

Co-encadrant de thèse : **Clément NEDONCELLE**

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Membres du jury avec voix délibérative

Anne-Célia DISDIER, Directrice de recherche, INRAE

Juliano ASSUNÇÃO, Professor associado (Equiv. HDR), PUC-Rio (Brésil)

Mathieu COUTTENIER, Professeur, Ecole Normale Supérieure de Lyon

Julien WOLFERSBERGER, Maître de conférences, AgroParisTech

Présidente

Rapporteur & Examineur

Rapporteur & Examineur

Examineur

UMR PSAE - Paris-Saclay Applied Economics

AgroParisTech, 22 place de l'Agronomie

91120 PALAISEAU

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Résumé

Objet de la thèse

La déforestation importée est un enjeu crucial en matière de changement d'utilisation des terres, engendrant des répercussions considérables sur la biodiversité, le changement climatique et d'autres enjeux environnementaux majeurs (Lawrence et al., 2015). La consommation dans les pays européens, nord-américains et asiatiques exerce une pression significative sur la déforestation dans de nombreux pays exportateurs de produits agricoles. Par exemple, il est estimé que la déforestation importée représente un sixième de l'empreinte carbone du régime alimentaire d'un Européen (Pendrill et al., 2019). Face à ces défis, l'Union Européenne a adopté en 2023 une réglementation visant à éliminer l'impact de ses importations sur la déforestation (European Parliament and Council of the European Union, 2023). Parmi les produits ciblés, le soja, en particulier en provenance du Brésil, occupe une place prépondérante. En effet, l'Amazonie brésilienne constitue le principal foyer de déforestation à l'échelle mondiale, tandis que le soja est une denrée massivement exportée d'Amérique du Sud. Cette thèse s'inscrit à la croisée de l'économie de l'environnement, du développement et de l'économie internationale, pour explorer les dynamiques complexes entre le commerce international du soja et la déforestation au Brésil.

La production et l'exportation de soja sont associées à une déforestation directe et indirecte substantielle, remettant sérieusement en question leur durabilité (Jia et al., 2020). Au cours des 20 dernières années, l'expansion agricole a été l'un des principaux moteurs de la déforestation dans de nombreuses régions du monde (Curtis et al., 2018), alors même que le commerce agricole mondial ne cessait de croître. Les travaux existants qui étudient explicitement la relation entre le commerce et la déforestation demeurent relativement limités. Leblois et al., 2017 soulignent l'importance du commerce international des produits de base dans le processus de déforestation, tandis que Lopez et al., 2005 mettent en évidence le caractère non homogène de cette relation selon les pays. En adoptant une perspective historique, Alix-Garcia et al., 2018 estiment l'impact positif de la libéralisation des échanges sur la déforestation à la fin du 19ème siècle, tandis qu'Abman et al., 2020 constatent un effet positif des accords commerciaux régionaux sur la déforestation.

L'objectif général de la thèse est donc de mieux comprendre le commerce international du soja et son lien avec la déforestation au Brésil. Cette problématique générale est déclinée en plusieurs sous-questions qui font l'objet chacune d'un chapitre. L'analyse se déroule d'amont en aval du secteur du soja : elle porte d'abord sur les décisions de production et d'exportation, puis sur les réseaux de vendeurs et d'acheteurs, et enfin sur le rôle de la demande étrangère. L'approche est essentiellement empirique, en exploitant des expériences quasi naturelles et en s'appuyant largement sur la base de données TRASE, avec des racines liées à la théorie économique du commerce et des changements d'utilisation des terres.

Les décisions de production et d'exports face aux politiques environnementales

En 2004, le gouvernement brésilien a initié une série de mesures pour contrer la déforestation dans l'Amazonie Légale, rassemblées sous un plan nommé PPCDAm, pour plan d'action pour la prévention et le contrôle de la déforestation en Amazonie Légale. Une des mesures phare de ce plan est la liste prioritaire, établie pour la première fois en 2008. Cette liste définit les municipalités les plus vulnérables, c'est-à-dire sur le front de déforestation, afin de concentrer les efforts de prévention et de contrôle de la déforestation. Cette mesure a fait l'objet de nombreuses évaluations, qui s'accordent sur sa contribution au ralentissement de la déforestation en Amazonie.

Le premier chapitre de cette thèse, intitulé *Do forest conservation policies undermine the soybean sector in the Brazilian Amazon? Evidence from the priority listing of municipalities*, vise à exploiter cette expérience quasi-naturelle pour estimer les impacts collatéraux de cette politique environnementale sur le secteur du soja et les changements d'usages des sols. Cette question de recherche permet d'aborder les tensions entre conservation de la nature, développement économique et compétitivité internationale dans un contexte agricole. Elle questionne aussi les modifications des décisions de production et d'exports en présence de régulations environnementales.

Pour y répondre, les usages des sols et les exportations de soja de municipalités « traitées » (c'est-à-dire listées comme prioritaires) et avec des municipalités « témoins » (non situées dans des zones sensibles) sont comparés, avant et après la mise en place du programme. L'une des difficultés habituelles de ces méthodes est d'assurer la comparabilité des municipalités traitées et des municipalités témoins, qui sont susceptibles de différer sur plusieurs aspects. Pour contourner ce problème, nous recourons une méthode de contrôle synthétique généralisé. Celle-ci permet de recréer des municipalités « fictives » comparables, qui serviront de témoins, à partir

des vraies municipalités non traitées et de leurs caractéristiques les plus pertinentes. La base de données TRASE, qui fournit des informations détaillées concernant les exports des municipalités, ainsi que les données de recensement agricole brésilien et les données MapBiomass, qui retracent les changements d'utilisation des sols, sont mobilisées à cet effet.

Contrairement à ce que l'on pourrait anticiper, nos résultats indiquent que le secteur du soja a bénéficié de la politique en termes d'utilisation des terres, de production et d'exportations. L'inscription sur la liste prioritaire a entraîné une réduction de la production de certaines zones de production d'aliments de base, ce qui suggère une réallocation à l'intérieur du secteur agricole vers des activités à plus forte intensité en capital. Le soja a principalement remplacé d'autres cultures et pâturages. L'augmentation de la surface de soja la plus importante est observée dans les États de Rondônia et de Pará, mais nous ne trouvons pas de signes de réponses hétérogènes des municipalités aux variables testées. Cette croissance du secteur du soja en parallèle à son inscription sur la liste prioritaire peut s'expliquer de plusieurs manières. Pour se conformer à la réglementation environnementale et faire face aux coûts plus élevés de la déforestation, les grandes exploitations ont pu passer d'une stratégie d'expansion à une stratégie d'intensification vers des cultures plus rentables et à forte intensité de capital. Un effet d'éviction des petits propriétaires terriens, qui ont vendu leurs terres à des producteurs de soja plus riches, est également susceptible de s'être produit lorsque la gouvernance environnementale a engendré des difficultés économiques. Dans certains cas, il a également été rapporté que la stratégie des municipalités prioritaires pour sortir de la liste prioritaire a favorisé l'agro-industrie.

La littérature suggère que le développement du soja en Amazonie est associé à une augmentation des inégalités rurales, à la concentration des droits de propriété et à des litiges fonciers. Des recherches supplémentaires pourraient être entreprises pour étudier les conséquences distributives de l'inscription sur la liste prioritaire, sur l'emploi, les salaires et les indicateurs de développement durable.

Chocs d'approvisionnement et dynamiques des réseaux d'exportateurs

Dans un monde où les perturbations des chaînes d'approvisionnement mondiales sont de plus en plus fréquentes, notamment en raison d'événements climatiques extrêmes, il est essentiel de comprendre comment ces chaînes s'adaptent. Le deuxième chapitre de cette thèse, intitulé *Soy exporters' network and local production shocks*, se penche sur les réponses des chaînes d'approvisionnement en soja au Brésil aux chocs d'approvisionnement locaux, par exemple les sécheresses. Cela ouvre la voie à une réflexion sur les chocs réglementaires qui interdiraient l'approvisionnement

à partir de zones récemment déboisées, comme ceux générés par la nouvelle réglementation de l'Union Européenne sur la déforestation importée, et qui peuvent s'apparenter à des chocs d'approvisionnement. La question centrale est de déterminer quels exportateurs sont les plus résistants face à ces chocs et quelles sont les stratégies qu'ils adoptent pour s'adapter. Cette recherche s'inscrit dans le cadre de la littérature sur la propagation des chocs dans les chaînes d'approvisionnement, les effets des chocs climatiques sur la sécurité alimentaire et la dynamique spécifique de la chaîne d'approvisionnement du soja brésilien.

Les données utilisées comprennent des informations sur les précipitations, les transactions commerciales entre municipalités et entreprises exportatrices de soja, ainsi que les rendements du soja, fournies respectivement par Worldclim 2.1, TRASE, et l'Institut brésilien de géographie et de statistique (IBGE). Les chocs de sécheresse sont mesurés comme des anomalies de précipitations, à partir du Standard Precipitation Index, et cette mesure est complétée en robustesse par l'analyse des « killing degree days ».

Notre analyse se déroule sur trois niveaux distincts. Tout d'abord, nous évaluons l'impact des chocs sur les rendements et les exportations au niveau des municipalités productrices de soja avec pour valider notre mesure de choc. Ensuite, nous examinons l'effet des sécheresses sur les transactions entre les municipalités et les exportateurs, tant pour les transactions qui impliquent une municipalité touchée par le choc que pour celles qui impliquent un exportateur exposé à un choc, mais dans une autre commune. Cette étape permet d'identifier les transactions qui sont affectées. Enfin, nous mesurons l'effet agrégé au niveau des exportateurs, en utilisant des mesures de réseaux et en calculant un indice d'exposition aux chocs. Pour identifier ces effets, nous recourons à des régressions à multiples effets fixes, permettant de contrôler pour les facteurs temporels, spatiaux et propres aux unités d'observation.

Les résultats montrent que les chocs de sécheresse, tels qu'ils sont mesurés, entraînent une réduction des rendements, de la production et des exportations de soja. Si les transactions avec les firmes sont effectivement affectées sur la marge intensive, ce n'est pas nécessairement le cas sur la marge extensive. En d'autres termes, l'existence des relations fournisseurs - acheteurs n'est globalement pas affectée. Les firmes exportatrices exposées aux chocs sont quant à elles en moyenne peu impactées. En fait, ces firmes ont la capacité de s'adapter en augmentant leurs achats auprès d'autres fournisseurs qui ne subissent pas de chocs. Cela soulève des questions pour les politiques de régulation de la demande contre la déforestation importée, notamment en termes de concentration du marché, de frictions dans les réseaux d'approvisionnement, et de risques de

fuites vers d'autres fournisseurs.

Demandes étrangères et exports de soja : implications pour la déforestation

La lutte contre la déforestation est l'une des priorités des décideurs politiques face aux défis du changement climatique. Les politiques existantes de réduction de la déforestation s'adressent principalement aux producteurs et visent à influencer leur comportement. Cependant, ces politiques, bien que parfois efficaces, sont insuffisantes. Elles commencent à être complétées par des politiques ciblant la demande. Le rapport AR6 du GIEC souligne le potentiel des mesures axées sur la demande pour réduire les émissions de gaz à effet de serre. Le dernier chapitre de cette thèse, coécrit avec Clément Nedoncelle et intitulé *Foreign demand and soy exports: evidence and implications for deforestation*, vise à évaluer la crédibilité de ce type de politique, en se concentrant sur le secteur du soja au Brésil, qui est en grande partie destiné à l'exportation. Notre démarche consiste à estimer l'élasticité des exportations de soja par rapport à la demande étrangère de soja, en tenant compte des entreprises exportatrices dans nos analyses, et à en tirer des implications pour la déforestation. Ce chapitre contribue ainsi à la littérature sur les liens entre le commerce et la déforestation, celle sur le rôle de l'hétérogénéité des entreprises dans le commerce et à la littérature sur les effets des politiques de lutte contre la déforestation portant sur la demande.

Ce chapitre repose sur les données TRASE, que nous utilisons pour mesurer les flux commerciaux de soja depuis les municipalités productrices du Brésil et les firmes exportatrices jusqu'aux pays de destination de 2004 à 2018. Ces données sont combinées avec la base de données BACI, qui reporte les flux commerciaux entre les pays et nous permet de dériver une mesure de la demande étrangère de soja. Enfin, nous nous appuyons sur les données MapBiomas pour mesurer les changements dans l'utilisation des terres. Dans notre modèle empirique, nous estimons d'abord l'élasticité moyenne des exportations de soja en réponse à la demande étrangère, au moyen de régressions au niveau des firmes, des municipalités et des pays de destination. Des effets fixes contraignants sont utilisés pour contrôler les variations non observées. Puis, les effets différentiels des chocs de la demande sur les exportations de soja sont explorés, selon des caractéristiques spécifiques de la firme, de la municipalité et de la destination.

Nos résultats indiquent une élasticité moyenne positive des exportations de soja par rapport à la demande étrangère, ce qui confirme la crédibilité des politiques axées sur la demande. Deuxièmement, nous montrons que la réponse moyenne cache des hétérogénéités significatives entre les exportateurs et entre les municipalités brésiliennes. L'analyse met en évidence que (i) les plus grands exportateurs sont plus sensibles aux chocs de la demande de soja, (ii) une déforestation

historique plus importante réduit cette réponse, et (iii) le nombre d'entreprises exportatrices concurrentes dans la même municipalité atténue également l'impact de la demande. Enfin, nous évaluons les implications potentielles des politiques de demande sur la déforestation. Les élasticités des exportations et le potentiel d'expansion du soja sont positivement corrélés, c'est-à-dire que les zones où les exportations réagissent fortement à la demande sont également celles où il reste beaucoup de forêts. De nombreuses municipalités présentent donc un potentiel élevé de déforestation évitée. Elles sont principalement situées dans la région amazonienne. Cependant, dans certaines localités comme le sud du Mato Grosso ou le Matopiba, où le couvert forestier est encore important, la faible réaction des exportations à la demande suggère que les effets d'une politique axée sur la demande seraient moindres. À la lumière de ces considérations, on peut s'attendre à ce que les politiques de demande ralentissent la déforestation au Brésil, en particulier dans les régions proches de l'Amazonie. Une estimation plus précise de l'efficacité attendue des politiques axées sur la demande devrait tenir compte des effets d'équilibre général, qui ne sont pas pris pas en considération ici.

Discussion des résultats et perspectives de recherche

Les chapitres de cette thèse se penchent sur différents aspects des liens entre le commerce de soja et la déforestation, en adoptant une approche empirique. Ils abordent deux dimensions des liens entre le commerce de soja et la déforestation, qui se rapportent plus généralement à des questions fondamentales posées en économie internationale et en économie de l'environnement : l'impact des politiques environnementales sur la compétitivité internationale et la possibilité de substituer des politiques commerciales à des politiques environnementales.

Le premier chapitre évalue les impacts collatéraux d'une politique de conservation des forêts, la liste des municipalités prioritaires, sur la production et l'exportation de soja dans le contexte de l'Amazonie brésilienne. Le deuxième chapitre explore la résilience des réseaux d'exportation de soja du Brésil face aux sécheresses locales, utilisées comme exemple d'un choc d'offre exogène. Le troisième chapitre examine la crédibilité des politiques du côté de la demande pour freiner la déforestation liée à la production de soja, en estimant les élasticités des exportations.

Nous tirons de ces chapitres quelques enseignements transversaux. Premièrement, les politiques environnementales ne sont pas toujours préjudiciables au commerce, comme on pourrait le penser. De plus, cette thèse souligne la nécessité d'aborder de façon intégrée les politiques de production, de consommation et d'approvisionnement de part et d'autre de la chaîne de valeur.

La thèse soulève également plusieurs perspectives de recherche, y compris l'exploration des questions de justice sociale des politiques environnementales qui traitent du commerce, la coordination de ces politiques entre pays importateurs pour éviter les fuites de déforestation et la généralisation des résultats à d'autres contextes de production et à d'autres commodités.

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List of Acronyms

AR6 - Sixth Assessment Report

DD - Difference-in-Differences

EU - European Union

EUDR - EU Deforestation Regulation

FE - Fixed Effects

GSC - Generalized Synthetic Control

GDP - Gross Domestic Product

GMOs - Genetically Modified Organisms

HHI - Herfindahl–Hirschman index

IBGE - Brazilian Institute of Geography and Statistics

IHS - Inverse Hyperbolic Sine

iLUC - Indirect Land Use Change

IPCC - Intergovernmental Panel on Climate Change

LPM - Linear Probability Model

MRIO - Multi-Regional Input-Output

NGO - Non-Governmental Organization

OLS - Ordinary Least Squares

PES - Payment for Ecosystem Services

PPML - Poisson Pseudo Maximum Likelihood

REDD+ - Reducing Emissions from Deforestation and Forest Degradation

RTAs - Regional Trade Agreements

SEI-PCS - Spatially Explicit Information on Production to Consumption Systems

SPI - Standardized Precipitation Index

TOC - Theories Of Change

TRASE - Transparency for Sustainable Economies

General Introduction¹

The globalization of the food trade has been advocated as a means of fostering economic development and enhancing food security worldwide (WorldBank, 2019). While some of these objectives may have been achieved to some extent (Dithmer et al., 2017), the globalized food system as it is managed today has also given rise to numerous concerns, among which major environmental problems, contributing significantly to the climate and biodiversity crisis (Hong et al., 2022; Lenzen et al., 2012). Soy is one of the commodities that best illustrates this tension between global trade and the environment: the dramatic growth in international demand for soy has led to large-scale deforestation in South America, primarily in Brazil (Song et al., 2021). This thesis focuses on the Brazilian soy trade and its link with deforestation.

1 Setting the stage: the intercontinental soybean market

Consumption dynamics

Soy - *Glycine max* - is so versatile that it is everywhere, albeit hidden. From animal feed to cosmetics, oil to biofuels, it is consumed by almost everyone, every day, directly or indirectly. It was domesticated in China 3,000 years ago and, for a long time, it was mainly used as a rotational crop to enrich soil with nitrogen (Hymowitz, 1970). At the beginning of the twentieth century, it was the demand for industrial and then food oil that fuelled soy cultivation. Extracting oil left a by-product in the form of soy cake or meal, which rapidly became the main use for soy in animal husbandry (Norberg et al., 2023).

Today, soy is the leading source of protein for livestock production and the second largest source of vegetable oil (behind palm oil) in the world. This was far from the case less than a century ago. The rate of expansion and intensification of soybean production is historically unprecedented, raising concerns about its sustainability (Jia et al., 2020). The growth in demand for this cash crop can be explained - in part - by its particular properties (Banaszkiewicz et al., 2011;

¹Some passages in this introduction may be similar to Chapter 4 of the JRC report *Deforestation and forest degradation in the Amazon - Update for year 2022 and link to soy trade* (Beuchle et al., 2023), which was produced as part of a collaboration during this thesis.

Ramankutty et al., 2016). Soy, an oilseed and legume plant, can fix nitrogen from the air and has high protein and oil levels. Soy meals contain up to 40% of protein, enabling animals to grow and fatten quickly (Banaszkiewicz et al., 2011). In addition to its nutritional qualities, the major advantage of soy that made it such a success was its low cost (Singh et al., 2008). Therefore, soy has played a central role in reducing the cost of animal production (chicken, pork, beef, milk, eggs, aquaculture), enabling meat consumption to quadruple over the last 50 years (Norberg et al., 2023).

In turn, growing demand for meat, first in the West, then more impressively in Asia, has been the main driver of growth in soy, creating the so-called "soy-meat complex" (Escher et al., 2019). In China, for example, per capita meat consumption has increased 15-fold since 1961 (Ritchie et al., 2019). This trend is linked to demographic growth, urbanization, and increased purchasing power in Asia, all of which have led to a shift in diets. It is also linked to the lobbying activities carried out in China by transnational corporations, farmers' associations, and US officials who aimed to convince the country to intensify meat production using protein-rich soy-based animal feed (Norberg et al., 2023). Additionally, the European demand created for biodiesel since the 1990s has also encouraged the expansion of soy (Norberg et al., 2023). Growing demand for soy, combined with the liberalization of agri-food markets, has opened up new production fronts in South America (Fearnside, 2001).

Production dynamics

Satisfying the increasing international demand, soy production has undergone an unprecedented expansion, far outpacing the growth of any other agricultural crop (Norberg et al., 2023). Since 1950, production has increased 22-fold, while the world's population has tripled in the same period (De Maria et al., 2020). According to the Food and Agriculture Organization (FAO) statistics, world exports of soybeans amounted to 148 billion in 2022, representing 2% of all agricultural exports. This massive increase in soy production has involved a considerable expansion of cropland, with the area devoted to soy rising from 16.5 million hectares in 1950 to more than 127 million hectares (which is about the size of Niger) in 2020 (FAOSTAT 2022). This expansion initially occurred at the expense of other crops and pastures before spreading to border regions, displacing natural grasslands, forests, and savannahs. At the same time, improved yields through innovation in seeds, pesticides, machinery, and fertilizers have also played a key role in increasing production (Bustos et al., 2016; Carreira et al., 2024).

The United States used to dominate soy production and exports, accounting for 76% of world production in 1969. However, this share has fallen considerably, to 32% today, in the face of the emergence of new players, mainly in South America (Norberg et al., 2023). Brazil, in particular, has experienced a spectacular rise, becoming the world's leading producer in the 2000s, thanks in part to public research (incentivized by rising soy prices) that has enabled crops to be adapted to tropical and subtropical climates, as well as government support in the form of subsidized credits and export subsidies (Fearnside, 2001; Norberg et al., 2023; Ramankutty et al., 2016). This rapid growth led to soy quickly becoming the country's leading crop. First concentrated in the country's southern states, genetically modified soy and soil fertilization developments allowed the expansion into central Brazil in the 1980s and 1990s, and soy arrived in the mid-1990s in the Amazon biome (Antonio, 2013; Fearnside, 2001). The expansion of soy cultivation has spread beyond Brazil to other South American countries, including Paraguay, Argentina, Uruguay, and Bolivia. This trend consolidates the Americas' leading role in global soybean production, accounting for 85% of total production in 2022, with Brazil contributing 35% of global production and accounting for 42% of global exports (FAOSTAT 2022).

Nevertheless, this expansion and intensification of soy cultivation has resulted in major ecological risks, which are regularly the focus of NGO campaigns².

Between producers and consumers: exporting firms

The global soybean market is shaped like an hourglass, with many producers and billions of consumers, connected by a few large exporters controlling the market (De Maria et al., 2020) and coexisting with smaller traders. These traders have been central to the historical development of the soybean industry, establishing export infrastructures, processing units, and sales offices around the world (Norberg et al., 2023). In the early 2000s, ADM, Bunge, Cargill, and Louis Dreyfus already controlled 75% of soy exports (Oliveira et al., 2017). In 2018, with the addition of the Chinese giant COFCO, which has appeared in the meantime, the top five firms controlled 90% of the world market (Voora et al., 2019).

They have achieved market concentration through vertical integration, controlling credit, inputs for farmers, processing, transport infrastructure - including some ports - and exports. They have also pursued horizontal integration by acquiring local firms (Norberg et al., 2023). The growing involvement of traders in financial activities, particularly through futures markets, has

²See for example the Greenpeace report "Eating up the Amazon", published in 2006.

strengthened the power of these intermediaries, who use their information advantage to dominate the market. However, these large traders now face significant sustainability challenges, regularly being put under the spotlight for their association with deforestation in South America.

2 Environmental externalities of the soybean trade

This important rise of soy within international markets, as well as the key role played by Brazil, has resulted in significant environmental damage through increased deforestation, including greenhouse gas emissions and negative impacts on biodiversity.

Deforestation and conversion of natural ecosystems

Soybean, along with the expansion of pastureland, contributes to the ongoing deforestation of the Amazon (Barona et al., 2010). However, it is challenging to quantify precisely the contribution of the expansion of soy crops in the deforestation process. Indeed, soy is often not planted immediately after the deforestation event but after a first period of pasture, thus making it difficult to attribute the cause of deforestation to pasture or soy expansion with precision. According to Song et al., 2021, in South America, soy accounted for 5% of the 71.9 million hectares of total forest loss during this period, mostly in the Cerrado, Brazilian Amazon, and Chaco. In addition, 4% of total forest loss can be attributed to latent soybean cultivation (i.e., more than three years after clearing) between 2001 and 2016. Although the proportion might seem relatively low, most soy expansion is concentrated in active deforestation areas. The trend of soy replacing pastureland is set to continue, as soy production is expected to increase by a further 50% by 2050, and this expansion is likely to occur in South America (Alexandratos et al., 2012).

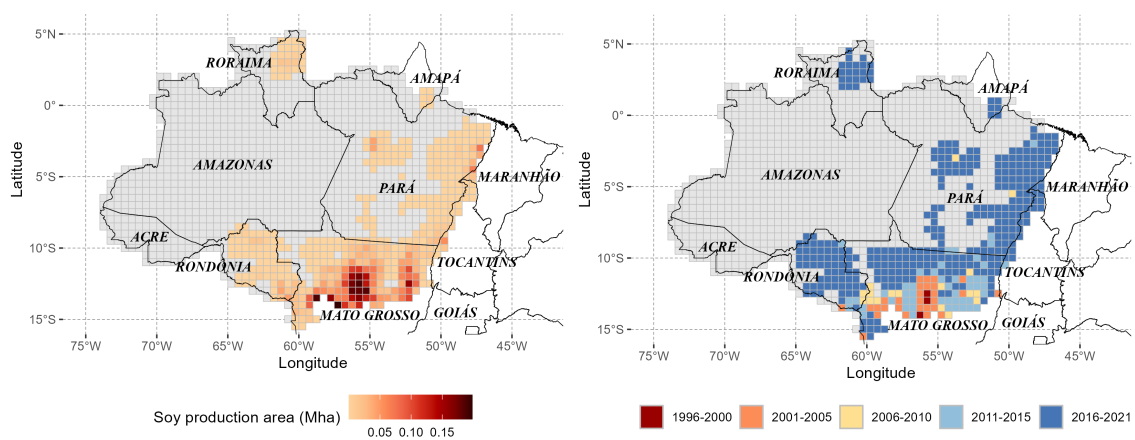


Figure 0.1: Soy expansion in the Brazilian Amazon biome

Note: Soy production area (left panel) and period of maximum expansion (right panel) for 50km X 50km grid cells, based on JRC-TMF and MapBiomas data.

Besides the encroachment of soybean on forests, the literature has demonstrated the existence of another effect, the indirect land-use change³ (iLUC). It is indeed demonstrated that mechanized agriculture encroaches on existing pastures, displacing them elsewhere to the forest frontier. Richards et al., 2014 show that in the Brazilian Amazon, between 2003 and 2008, the iLUC was large and significant (Richards et al., 2014). They estimate that a 10% reduction in soy cultivation in former grazing areas would have reduced deforestation by 40%. The expansion of soy into grazing areas in Mato Grosso has shifted beef production to Pará, contributing to deforestation in that region (Ermgassen, Godar, et al., 2020).

The impact of soy on deforestation could go beyond the direct or delayed changes in land use, as, agriculture-driven deforestation encompasses more than the direct expansion of commodity production into forests (Pendrill, Gardner, et al., 2022). Forestland prices embed a speculative part, related to the conversion to alternative land use (Miranda et al., 2019), and the expectation of a future increase in land value is a motivation to clear forests, even though soybean is planted years later. The soybean sector's ability to influence the speculative demand for rural land is a key mechanism explaining forest loss in the Amazon (Richards et al., 2014).

Land speculation and soybean expansion are also connected to infrastructure development. Agribusiness carries a significant political weight in Brazil as it prompts the government to build massive infrastructure development (railways, highways, waterways, ports) to transport crops and fertilizers. Thereafter, the public expenditures on projects stimulate private investments, including land speculation, especially in those areas where a large part of the land is suitable for soybean cultivation⁴.

Implications

The deforestation associated with soybeans has significant local and global negative externalities that are not internalized in the low cost of soy.

Local negative externalities

The encroachment and conversion of forests for soy production not only undermines the ecological integrity of these regions but also impairs the human rights of indigenous peoples (Silva-Junior et al., 2023), whose livelihoods and cultural heritage are inextricably linked to these landscapes (Fa et al., 2020). Indigenous peoples have a key role in preserving natural areas, with 40%

³iLUC are defined as "land-use change in one place caused by a land-use change in another place" (P. Meyfroidt et al., 2018).

⁴For example, the Brazilian project to build a new railroad, the Ferrogrão, is particularly controversial because of its potential impact on deforestation.

of the world's remaining intact forest landscapes located on indigenous territories (Garnett et al., 2018).

Also, deforestation has local and regional climatological effects (warming effects, reduced rainfall), which erodes the resilience of the Amazon forest and threatens to lead to permanent forest loss (Cohn et al., 2019; Maeda et al., 2021; Martinelli et al., 2017; Zemp et al., 2017). Outer forested regions are even likely to cross a bioclimatic savannization tipping point due to deforestation, which in turn endangers the soy sector (Flach et al., 2021). At least 90% of Amazonia and 40% of Cerrado should be preserved to avoid subregional bioclimatic savannization (Pires et al., 2013).

While probably less striking, local environmental impacts also exist in importing countries. As a result of the massive importation of soy from abroad, many consumer countries have turned away from producing plant proteins in favor of nitrogen-intensive crops. Such dynamic is also observed for soybean cultivation, as demonstrated by Huang et al., 2019; Sun et al., 2018. Their meta-analysis and a case study on China reveal that nitrogen pollution increased substantially in importing countries after converting soybeans to other crops. This is because soy, which fixes nitrogen from the air, requires less fertilizer. The relocation of legumes is, in fact, raised in several studies as an important option for reducing carbon emissions from agriculture. In particular, introducing more grain legumes in crop rotations and grassland could reduce the need for the application of mineral nitrogen fertilizers (and so reduce associated N_2O emissions) (Pellerin et al., 2017) with a low-cost mitigation potential (Dequiedt et al., 2015).

Global negative externalities

Deforestation, mainly due to the expansion of agricultural land (Curtis et al., 2018), contributes directly to carbon emissions and reduces future carbon storage capacity. Emissions due to land-use and land-cover changes account for 14% of global carbon emissions, which is considerable (Friedlingstein et al., 2023). Deforestation alone, which makes up the largest share of this emissions category, corresponds to an average of 1.9 Gigatons of carbon per year from 2013-2022 (Friedlingstein et al., 2023). This highlights the profound impact of deforestation on our global carbon budget. At the same time, forests are essential in the fight against climate change. Reducing deforestation and forest degradation is an effective and robust option for climate change mitigation, which would also deliver co-benefits for other ecosystem services. Deforestation would need to be curbed by 70% by 2030 and 95% by 2050 to respect the 1.5°C target (Roe et al., 2019). Emissions from deforestation are closely linked to the global food system. For example, 27% of

all land-use emissions are related to agricultural products consumed in a different country from where they were produced (Hong et al., 2022). Clark et al., 2020 demonstrates that even if we were to stop fossil fuel emissions immediately, the current trajectory of emissions from the world's food systems, a major part of which comes from land clearing, would still preclude achieving the 1.5 or 2-degree targets of the Paris Agreement.

Additionally, the erosion of biodiversity is a global environmental crisis at least as alarming as climate change, with significant repercussions on the economic system (Dasgupta, 2021). Agriculture and land conversion, notably for soy production, play a major role in the biodiversity decline (Joppa et al., 2016; Tilman et al., 2017). The expansion of soy in Brazil, taking place in areas known for their exceptional biodiversity - such as the wooded savannahs of the Cerrado or the Amazon rainforest - exemplifies this issue. Molotoks et al., 2023 quantifies biodiversity risks within the South American soy supply chain. Addressing the biodiversity erosion may thus require improving the sustainability of supply chains, recognizing the significant impact of international trade, which is responsible for 30% of global threats to species (Lenzen et al., 2012).

Facing environment/development trade-offs

Farmers are faced with contradictory injunctions between increasing production and preserving nature. The soy trade has negative effects on indigenous and local populations (through water pollution) and ecosystem services, but it also benefits living standards and incomes (Lima et al., 2011; Pellegrina, 2022). Some studies have attempted to weigh the pros and cons of commercial soy production. Boerema et al., 2016 compares trade value with the monetary valuation of environmental and socio-economic impacts. He finds that European soy imports have adverse environmental and socio-economic effects and do not benefit society at large (environmental cost calculated for 2008 amounted to 120 billion). Other studies in this field show more contrasting positive and negative impacts and that their direction varies from one region to another (Dreoni et al., 2022).

Overall, the literature shows how the international soy market is associated with substantial negative externalities, raising concerns for global environmental targets. This observation could arguably lead to a willingness to restrict soy trade. However, it should be borne in mind that limiting trade could redistribute production between nations, creating other kinds of environmental impacts. An important part of the discussion about the environmental impacts of trade is the extent to which trade and environmental policies can be mutually supportive, and what needs to change in our production and consumption systems.

3 The links between soy and deforestation

How does trade affect deforestation?

Empirical evidence

Some consensus exists that high prices stimulate deforestation (Assunção, Gandour, and Rudi Rocha, 2015) and that this effect is magnified by openness to trade (Berman et al., 2023). This highlights the importance of global market signals in deforestation decisions. Existing works that explicitly study the trade-deforestation relationship are rather limited, as causal identification is not straightforward. Using cross-country approaches, Leblois et al., 2017 emphasizes the role of agricultural trade as one of the main factors causing deforestation, especially in countries with high forest cover. Moreover, Ferreira, 2004 finds that low trade barriers are associated with higher deforestation, but only when combined with low institutional strengths. This is also found to be true in the Brazilian Amazon (Faria et al., 2016). Abman et al., 2020 exploit variations in regional trade agreements (RTAs) and show that deforestation rates increase by 19% to 26% in the three years following the ratification of an RTA, almost exclusively in tropical forests. Alix-Garcia et al., 2018 examines the impact of the Austro-Hungarian Customs Union of 1850 and concludes that it increased deforestation. However, in the context of Brazilian soy, Carreira et al., 2024 argues that the main driver of land-use change has been productivity gains rather than exposure to Chinese demand.

Mechanisms

From a theoretical point of view, the effects of trade on deforestation are difficult to predict. This is more generally true of the effects of trade on the environment (Copeland, Shapiro, et al., 2022; Grossman et al., 1991). The analysis by Grossman et al., 1991 provides a framework for examining the effects of trade on pollution. The authors distinguish three main effects. The scale effect is linked to the increase in production volume induced by trade, which mechanically increases the environmental externalities of production. In the case of soy, this can simply be translated as an increase in demand leading to more production hence more demand for land and land conversion. The composition effect is driven by the specialization resulting from trade liberalization. Countries specialize in sectors where they have comparative advantages, with different environmental effects. In a trading world, land uses are determined by structural change and comparative advantages (Farrokhi et al., 2023). For countries with favorable agricultural conditions and forestry resources, this can result in an expansion of agricultural land and a potential increase in the risk of deforestation in the absence of environmental regulations. The technical

effect, instead is linked to changes in production techniques aiming, for example, at improving yields. Technology transfers and increased pressure for a better environment can reduce the amount of polluting emissions per quantity of goods produced. The impact of trade on the environment depends on the relative importance of these three effects.

At the micro-level, deforestation mechanisms are most often studied by analyzing the decisions of farmers or forest owners. These are formed by comparing the standing value of the forest with the value of the timber harvested and the anticipated value of the alternative use of the land. A shock from the opening up of world agricultural markets can alter forest owners' decisions through several channels, summarized in Abman et al., 2020.

Firstly, the opening up of markets causes the prices of local agricultural production to converge with world prices. These are thus likely to rise or fall depending on the initial situation, which drives deforestation in the same direction (if the prices are those of commodities that can be produced in forested areas). Secondly, the price of agricultural inputs could be reduced through trade, as can the price of forest-clearing capital, increasing deforestation. Technology transfers could compound, creating productivity gains. Here again, the effect is ambiguous (Carreira et al., 2024). Productivity gains could reduce the need to increase farmland or, on the contrary, stimulate land production and consumption. Finally, the local benefits expected from alternative uses of the forest depend on prices and transport infrastructures, which are major determinants of trade flows. The effects of trade on deforestation should be expected where production can be profitable, in line with Von Thünen's theoretical models for analyzing the spatial organization of agricultural activities. In other words, trade can indeed lead to an increase in deforestation contingent on certain conditions.

Link with the forest transition theory

Forest transition happens whenever a region moves from a net loss to a net gain of forest cover (Mather, 1992). This can be achieved for several reasons, for example, as a result of the shift from an agricultural economy to a more urban and industrial one (economic development path) or as a result of policies aimed at restoring forests when they become too scarce (forest scarcity path). International forest protection policies aim to achieve a global forest transition, i.e., a net gain in forest cover at the global level (in the Glasgow Declaration on Forests at COP 26, the objective is to halt and reverse deforestation and forest degradation by 2030).

However, the net effect of countries' forestry transitions at the global level can be challenged by trade. Rather than reducing deforestation, countries might at least partially displace it to other countries through their imports of forest and agricultural products (Pfaff et al., 2010). It has been

shown that countries with net reforestation contribute to deforestation in other countries through their imports (Kastner, Erb, and Nonhebel, 2011; Patrick Meyfroidt and Lambin, 2009; Patrick Meyfroidt, Rudel, et al., 2010; Pendrill, U Martin Persson, et al., 2019a). Although not demonstrating a causal link, Pendrill, U Martin Persson, et al., 2019a quantifies that for 16 countries that have completed their transition, the deforestation caused by their imports more than offsets their reforestation. On the one hand, these facts highlight the difficulty of achieving a successful forestry transition at the global level, and on the other, the need to study the dynamics of deforestation in countries while taking into account the effect of trade.

Embodied deforestation in trade flows

The displacement of environmental pressures through trade is increasingly of interest to policy-makers, likely partly because evidence of their importance is mounting. Over the last decade, leveraging the growing availability of land use and trade data, studies have been able to track the impacts of consumption on deforestation (Henders et al., 2015; Hong et al., 2022; Karstensen et al., 2013; Kastner, Erb, and Haberl, 2014; Lathuilière et al., 2014; Pendrill, U Martin Persson, et al., 2019a; Pendrill, U. Martin Persson, et al., 2019b). They shed light on the interactions between trade and the environment. These works most often couple land-use equilibrium models with trade models. They highlight the disproportionate impact of certain commodities and actors on embodied deforestation in trade. Overall, it is estimated that between 29 and 39% of deforestation is embodied in trade flows (Pendrill, U. Martin Persson, et al., 2019b). Studies agree that soy is a major contributor to imported deforestation⁵. According to Pendrill, U. Martin Persson, et al., 2019b, this commodity represents 1/5 of the deforestation imported in trade, roughly on par with palm oil. Karstensen et al., 2013 estimates that from 1990 to 2010, 25% of Brazilian deforestation emissions were exported, with 50% through soy, and 41% of these towards China in 2018. China is the leading importing country of soy emissions, followed by the European Union.

In addition to these scientific articles, the TRASE public database has allowed considerable progress to be made in the transparency of the impact of supply chains, particularly for Brazilian soybeans. By tracing trade flows and associated deforestation from producing municipalities to importers, TRASE demonstrates the contribution of producers and importing countries, alongside the massive involvement of some international export firms in deforestation. This thesis makes extensive use of this database in each of its chapters.

⁵The terms "embodied deforestation" and "imported deforestation" are used almost indiscriminately in this thesis. The use of "imported deforestation" emphasizes the responsibility of consumer countries in the process of deforestation abroad through their consumption choices. The term "embodied deforestation" refers neutrally to deforestation contained in a final product or trade flow.

The TRASE database

"Transparency for Sustainable Economies" is a pioneering initiative co-founded by the Stockholm Environment Institute and Global Canopy in 2015. Its mission is to serve as a collaborative platform involving businesses, governments and civil society in the effort to trade commodities sustainably.

To this end, TRASE provides open data on the financing and supply chains of commodities implicated in deforestation, including soya, beef and palm oil. It connects consumer countries and commodity traders with the sub-national production regions and evaluates the risks related to deforestation, carbon emissions, and other environmental impacts.

The major innovations of TRASE compared with existing databases are the identification of exporters and the geographical precision of the place of production. The mapping of complex supply chains is achieved by an original approach, which combines various data sources and uses a material flow analysis modeling approach known as Spatially Explicit Information on Production to Consumption Systems (SEI-PCS, presented in Godar et al., 2015). It links granular production data at sub-national scales with domestic goods flows and international trade information. The model scales down country-to-country trade analyses by using either physical allocation from bilateral trade matrices or Multi-Regional Input-Output (MRIO) models.

The TRASE database has been used by governments in their strategy against imported deforestation^a, but also a number of academic articles, including Domínguez-Iino, 2023; Ermgassen, Godar, et al., 2020; Gollnow, Cammelli, et al., 2022; Silva et al., 2023; Villoria et al., 2022.

^aFurther details [here](#).

4 The way forward: public policies and regulations

The challenge of curbing deforestation, particularly when it is linked to global trade in commodities such as soy, requires a comprehensive policy approach that integrates public policy measures, international trade regulations and sectoral initiatives to combat imported deforestation. Historically, efforts to combat deforestation have focused mainly on supply-side measures. More recently, trade approaches or demand-side policies are increasingly being considered to complement supply-side policies.

Policies against deforestation

The persistent increase in deforestation rates worldwide and the variable effectiveness of existing conservation policies could cast doubt on the possibility of reducing and halting the net loss of the world's forests. The first best policy for reducing deforestation would be to impose a direct tax on producers for deforestation. However, this option is not easily feasible for political economy reasons (Balboni et al., 2023; Burgess et al., 2012). Local governments are faced with corruption, administrative constraints and weak political incentives. Understandably, local governments tend to prioritize local benefits over global consequences. In addition, it is difficult to implement such policies when property rights are poorly defined. Despite these obstacles, it is important to note that a number of other policies have proved successful, particularly in Brazil. The PPCDAm (in English, Action Plan for the Prevention and Control of Deforestation in the Legal Amazon), for example, reduced deforestation rates considerably for several years thanks to a combination of strong measures (Assunção, Gandour, and Romero Rocha, 2023; West, 2024). The plan, implemented in the Legal Amazon in 2004, included law enforcement, land tenure regularization, credit restrictions, Priority Listing of municipalities, monitoring systems, and incentives for sustainable land management practices. Protected areas, among which national parks, reserves, and conservation areas, have also demonstrated their effectiveness (Andam et al., 2008; Bebber et al., 2017; Soares-Filho et al., 2023), especially in countries with higher levels of corruption control and protection of property rights (Abman et al., 2020). Whether the effects of domestic conservation policies last, however, depends on the countries' political agendas.

As previously stated, deforestation generates global externalities, so external countries have a stake in influencing global deforestation rates. International approaches to forest conservation to circumvent local incentives in forest-rich countries exist. The most relevant financial approach to forest conservation that has emerged is REDD+ (reducing emissions from deforestation and forest degradation in developing countries), which is an international initiative aimed at reducing greenhouse gas emissions from deforestation and forest degradation in developing countries. REDD+ is a type of payment for ecosystem services. The principle is simple. The mechanism provides financial incentives for forest conservation and sustainable forest management practices. Eligible countries receive payments from National and international, public or private funds for verified emissions reductions, which can help offset the opportunity costs of forest conservation and thus promote forest conservation. REDD+ projects may involve activities such as reforestation, afforestation, improved forest management, and conservation of existing forests. However, these initiatives can only have a limited impact as long as powerful drivers such as international

demand for forest-risk commodities are not overcome. In addition, REDD+ mechanisms face constraints in terms of liquidity, embezzlement, corruption and the credibility of future payments (Jayachandran et al., 2017; Lund et al., 2017). It is, therefore, important to look for additional ways to motivate conservation without explicit payment.

Private and sectorial initiatives

Under pressure from NGO campaigns, a mosaic of sustainability governance arrangements and mechanisms has been developed to reduce the pressure of soy on deforestation. These include the Amazon Soy Moratorium, voluntary certification schemes for sustainable soy, and private commitments. While it is difficult to say whether private commitments (very heterogeneous) and certifications (low adoption) have had any effect so far on soybean-driven deforestation, wherein traders agreed not to purchase soy from recently deforested areas within the Amazon biome (Ermgassen, Ayre, et al., 2020). The literature is more optimistic about the impact of the Amazon Soy Moratorium (Heilmayr et al., 2020; Nepstad et al., 2014; Soterroni et al., 2019). The Amazon Soy Moratorium began in 2006 and has been renewed indefinitely since 2016. The Moratorium was successful over a decade, although its impact is suspected to have been partially offset by leakages (across less regulated biomes like the Cerrado and on properties towards other commodities) (Gollnow, Hissa, et al., 2018; Moffette et al., 2021). Furthermore, shifts in environmental political rhetoric have led to setbacks for the Amazon and other biomes (Ferrante et al., 2021), also for soy as there are increasing soy areas not in compliance with the Amazon Soy Moratorium (IDH, 2022). As Lambin et al., 2023 notes, supply chain initiatives currently encompass a small part of tropical deforestation and thus can only have a limited impact. They could have more leverage by covering entire biomes, corporate supply bases, and domestic and export markets while including marginal producers.

Combating imported deforestation

Recent literature has considered trade policies as alternatives to Payment for Ecosystem Services (PES) to correct the international externalities of deforestation when domestic regulations are inadequate (Balboni et al., 2023). Trade policies generally enable regulating industries operating in poorly regulated environments (Hsiao, 2022). The advantage of this type of policy is that it does not rely on the willingness and ability of domestic governments to enforce regulations against deforestation. Moreover, unlike PES, these measures are immediately scalable (Hsiao, 2022). However, the potential effectiveness of such policies is not obvious either. The literature on trade-related environmental problems has analyzed trade sanctions, border tax adjustments, and

climate clubs (Copeland, Shapiro, et al., 2022). These policies are ineffective ex-post if resources are exhaustible because once they are depleted, everyone benefits from trade. Applied to the timber case, Barbier et al., 1994 show that tariff or ban policies can increase deforestation in certain circumstances.

Studies have established the conditions under which trade policies could effectively reduce deforestation. Harstad, 2022 proposes a theoretical model to analyze the effects of trade agreements on deforestation. He finds that the negative relationship between trade and the environment can be resolved with contingent trade agreements. Tariffs would be dependent on deforestation by exporters, thereby motivating conservation. Farrokhi et al., 2023 develop a general equilibrium model and show that coordination can help resolve trade-offs between trade and environmental conservation. Hsiao, 2022, using the example of palm oil, also highlights the importance of coordination. He shows that import tariffs can almost replicate the effectiveness of a domestic first-best tax, provided that importing countries coordinate on tariffs to avoid leakages. He also stresses the need to maintain these tariffs, even when they are not statically optimal, to prevent them from declining. Domínguez-Iino, 2023 assesses the effectiveness of import tariffs by modeling the agricultural supply chain in South America with intermediaries. He concludes that tariffs are ineffective in the South American context because of leakage to unregulated countries. In line with Hsiao, 2022, the author stresses the need for coordination. He adds that the consequences for producing countries would be regressive because of the low elasticity of the supply of agricultural products in poor regions, which would therefore suffer from a greater impact of tariffs.

The need for clear theories of change

Effective policies to mitigate deforestation linked to soy or other commodities require clearly elucidating the theories of change (TOC). Identifying the underlying assumptions, facilitating conditions and blockages can, at the same time, give greater legitimacy to a policy. A TOC explains how and why a given policy intervention is expected to bring about change, detailing "who will do what differently and why". Bager et al., 2021 identified 86 public policy options for reducing imported deforestation in the EU. For all of these options, there is a significant trade-off between political feasibility (which depends on stakeholder support, the institutional framework and costs) and impact. The underlying theories of change for these policies, which aim to reduce tropical deforestation, are either to reduce demand for land for the production of forest-risk commodities or to protect existing forests. Reducing the demand for land involves reducing the demand for

forest-risk commodities, increasing the demand for free-deforestation forest-risk commodities, or increasing the production of free-deforestation forest-risk commodities. In practice, this translates into a wide variety of policy options, ranging from raising awareness to encourage consumers to change their diets, to certification, using taxes, or paying landowners for forest conservation. Importantly, some of the options are both politically feasible and impactful, among which is the due diligence of exporters.

The EU regulation on deforestation-free products

On May 31, 2023, the European Union adopted the new Regulation on “deforestation-free products” (Regulation (EU) 2023/1115), which covers seven commodities (soy, cattle, palm oil, cocoa, coffee, rubber and wood) and their derived products, such as leather, chocolate, tires, or furniture. Under the Regulation, the actors in the supply chain (e.g., operators or traders) must demonstrate that the products placed on the European market do not originate from deforested or degraded land after 31 December 2020. By institutionalizing standards, the EU regulation is expected to be a strong driver for deforestation-free supply chains, as soy producers in Brazil face demands to produce soy responsibly (Søndergaard et al., 2023).

Some studies note the risk of leakage of such policies towards unregulated importing countries. However, this should not completely offset the net forest gains in the case of Brazilian soy: eliminating deforestation from the supply chains of all companies exporting Brazilian soy to the EU or China from 2011 to 2016 could have reduced net global deforestation by 2% and Brazilian deforestation by 9% (Villoria et al., 2022).

Another major issue is the unintended consequences on the producer countries. Without adequate safeguard measures, smallholders are likely to be excluded from high-value-added supply chains, price premiums too low, and land conflicts between large-scale and small-scale farming to increase (Zhunusova et al., 2022). Small-scale farmers may indeed lack the technical capacity and financial resources to meet the compliance and traceability requirements of the regulation (Cesar de Oliveira et al., 2024). Bilateral collaboration between Brazil and the EU could help align national and demand-side legislation.

5 This dissertation

Scope of the dissertation

This dissertation comprises three empirical research papers focusing on the soybean international trade and deforestation. The overall objective of this thesis is to gain a better understanding of the international soybean trade and how it relates to Brazilian deforestation, with the hope to draw from it some insights for policies that combat trade-related deforestation⁶.

Imported deforestation is a complex process that requires understanding the interactions between local and global scales. The scientific literature of recent years has already clearly identified the link between trade and deforestation and proposed approaches such as certification to tackle the problem. However, the need for science remains strong as the phenomenon persists and consumer countries seek to implement regulations. The changes in land use involved in a globalized world still need to be fully understood. Moreover, we still need to identify more precisely the conditions that would enable measures to combat imported deforestation to be implemented more effectively and to pinpoint the best instruments for achieving this. At the same time, the remarkable development of satellite data capturing land use and the unveiling of supply chain data are creating opportunities to fill these gaps. Econometric developments are also creating new avenues for identifying causal relationships. Few economic studies consider producers, exporters and consumers simultaneously.

The thesis examines the different levels of the soy supply chain, from upstream to downstream. The main characters of Chapter 1 are producers, Chapter 2 traders, and Chapter 3 foreign demands. More specifically, the first contribution of this thesis is the analysis of producers' production and export decisions in relation to forest conservation policies (Chapter 1). One major concern of the literature on trade and the environment is the effects of environmental policies on competitiveness (Copeland and Taylor, 2004). This chapter fits into this debate, by analyzing whether the successful Brazilian Priority List distorted trade flows. The second contribution is the examination of the conditions for the successful implementation of anti-deforestation policies, addressing the issue of leakages (Chapter 2) and the role of foreign demands in deforestation (Chapter 3). This is a way to approach the question of whether trade policies could be substitutes for (or at least complements to) environmental policies. Further, the dissertation contributes to the global knowledge of the deforestation factors and is a complement to integrated assess-

⁶For data availability reasons, the focus is solely on soy originating from Brazil. Brazil is the world's largest soy producer but is by no means the only country facing trade-offs between soy exports and forest conservation.

ment models, which generally poorly represent the deforestation dynamics (Prestele et al., 2016), through exogenous deforestation rates or theory of rents (Fujimori et al., 2014).

In each chapter, the data and methods employed take advantage of the most recent innovations in research. Chapters 1 and 3, for example, draw on the MapBiomas dataset, which provides precise information on land-use transitions in Brazil, thanks to the rapid development of satellite data. This enables a more detailed study of land-use change mechanisms. In addition, all chapters rely on the TRASE database. As described above, the TRASE database provides detailed information on the value chain, including exporting firms and production municipalities. In recent years, since exporters are pivotal players in the supply chain, this database has opened up new horizons in the field of deforestation economics to which I sought to contribute. As for methods, I also benefit from frontier tools. Thus, the first chapter uses the most recent developments in difference-in-differences and generalized synthetic control methods, to ensure causal relationships. The second chapter is rooted in recent insights and methodologies that examine the propagation of shocks in supply chains.

Contributions by chapter

The **first** chapter, *Do forest conservation policies undermine the soybean sector in the Brazilian Amazon? Evidence from the Priority Listing of municipalities*, assesses the collateral impacts of forest conservation policies on soybean production and export in the context of the Brazilian Amazon. Relying on a difference-in-differences approach and a generalized synthetic control, this study examines the repercussions of the Priority Listing, a Brazilian environmental policy that targets municipalities identified for their high deforestation risk. The policy proved successful in reducing deforestation rates. Counterintuitively, findings indicate that soybean production and exports have not been adversely affected by these conservation efforts. Instead, the soybean sector appears to have benefited from the policy through shifts in land use. This chapter contributes to the literature by focusing on the soybean sector's response to forest conservation policies, in particular the Priority List (Arima et al., 2014; Assunção, Gandour, and Rudi Rocha, 2015; Assunção and Romero Rocha, 2019; Cisneros et al., 2015; Koch et al., 2019). While previous studies have extensively examined the effectiveness of the Priority List in reducing deforestation rates, this chapter offers a new perspective by examining its collateral effects on soybean production and exports, leveraging the recent TRASE database and MapBiomas data for land uses. By filling this research gap, it provides valuable insights into the trade-offs between environmental policies, trade and the agricultural sector, enriching our understanding of the agricultural dynamics in the Brazilian Amazon. In addition, this chapter introduces a methodological advance by employing the gener-

alized synthetic control method alongside the traditional difference-in-differences strategy. This innovative approach improves the robustness of the estimates and confirms the effectiveness of the Priority List in reducing deforestation.

In the [second](#) chapter, *Soy exporters' network and local production shocks*, I explore the dynamics of Brazil's soybean export networks in the face of supply disruptions, specifically local drought events. Understanding how supply chains adjust to supply shocks is key considering their growing complexity and remains an open question, particularly within the agricultural sector, which is heavily vulnerable to changing climate conditions. Besides, firms are also facing regulatory risks, which can sometimes be assimilated to supply shocks, like the new European Union Deforestation Regulation. Chapter 2 empirically estimates how the soy supply chains in Brazil respond to local supply shocks. The study highlights the existence of coping strategies among exporting companies. However, firms tend to rely on their historical partners and do not easily contract new relationships, suggesting the existence of rigidity in the soy supply chains. This chapter makes three main contributions to the literature. First, it adds to the literature on the propagation of shocks in supply chains and the mitigation strategies of firms (Acharya et al., 2023; Barrot et al., 2016; Inoue et al., 2019; Kashiwagi et al., 2021; Lafrogne-Joussier et al., 2022; Pankratz et al., 2019). We contribute to this literature by studying the specific strategies of soybean exporting companies in response to droughts. This work also advances our understanding of supply chain dynamics in the context of extreme weather events. While studies on the propagation of climatic shocks in supply chains are multiplying, few studies look specifically at the case of agricultural commodities and take into account the behavior of exporters. Yet this is one of the sectors most threatened by climate change and a key issue for global food security. Although the perception of climate risks by soy producers and exporters has been analyzed through interviews, there are no econometric studies to support the conclusions. Finally, this chapter offers a discussion on the adaptive capacity of the soy industry and the potential for network adjustment in response to demand-side deforestation regulations, complementing the literature that studies leakage from demand-side deforestation policies (Busch et al., 2022; Villoria et al., 2022).

The [third](#) chapter, *Foreign demand, soy exports, and deforestation*, is a joint work with Clément Nedoncelle. We explore the credibility of demand-side policies in curbing deforestation linked to soy production. By estimating the responsiveness of soy exports to changes in international demand, the study uncovers variations in export elasticities across exporters and municipalities. We draw some implications for the potential of demand-side measures to mitigate deforestation in some locations, especially near critical ecosystems like the Amazon. This chapter contributes

to the literature on the importance of firm heterogeneity in shaping the patterns of international trade. More importantly, it also contributes to the debate on the effectiveness of demand-side policies for environmental conservation. This chapter brings several contributions to the literature. First, it extends knowledge on the impact of foreign demand on deforestation, by specifically studying decisions at the level of traders and production municipalities in response to demand shocks and by studying the heterogeneity of these decisions. Secondly, by accounting for firm heterogeneity in the soybean market, the study quantifies the elasticity of soybean supply with respect to foreign demand, highlighting the essential role of market structure. Finally, it contributes to the literature on deforestation mitigation policies, by presenting a discussion on the differential impacts of demand policies. In particular, we show that economic differences, such as the presence of firms, can lead to geographical differences in the impact of these policies.

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Chapter 1

Do forest conservation policies undermine the soybean sector in the Brazilian Amazon? Evidence from the priority listing of municipalities

Abstract. Minimizing the trade-offs between agricultural production, development and forest conservation is key to ensure that conservation policies can achieve long-term positive impacts. Taking the case of the Brazilian Amazon in the context of the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon, I estimate the impact of the prioritizing of municipalities with high deforestation risk from soybean production (a major driver of deforestation), exports and land-use changes relying on a difference-in-differences and generalized synthetic control approach. I find that, although effective in reducing deforestation, the policy is unlikely to have undermined soybean production and exports. On the contrary, the results indicate that the soybean sector benefited from the changes in land use following the implementation of the priority list. However, I do not find evidence that land restriction triggered intensification of soybean production, which suggests that the soybean sector benefited from intra-crops reallocation and pasture conversion.

A slightly different version of this chapter is available as a working paper at https://faere.fr/pub/WorkingPapers/Crepin_FAERE_WP2022.07.pdf.

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1.1 Introduction

There is a pressing need to tackle deforestation since it has large-scale impacts on biodiversity losses, climate change, and other environmental issues (Lawrence et al., 2015), with cascading adverse effects on human societies. On the other hand, some fear that forest conservation policies could hinder economic development in food-producing countries that have heavily based their development strategy on intensive use of land. Indeed, because conversion from forests to crops and pasture remains the first driver of global deforestation by far (Pendrill et al., 2019), curbing deforestation also means slowing down agricultural expansion over land. Identifying the short-term and long-term economic and land-use adjustments that follow the implementation of forest conservation policies is crucial for shaping both efficient and fair programs that do not jeopardize social and economic development goals.

In this chapter, we estimate the impact of conservation programs on the soybean sector, focusing on a key conservation measure in Brazil, the Priority List of the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm is the acronym in Portuguese). The Priority List defines a list of the municipalities most vulnerable to deforestation in the Brazilian Legal Amazon to target their efforts to prevent and control deforestation. The measures taken towards them include enhanced environmental surveillance, severely restricted access to deforestation permits, credits and markets, and an embargo on illegally cleared areas (Fearnside, 2017). Because the PPCDAm Priority List was proven to be an essential driver of the slowdown of deforestation in the Amazon (E. Y. Arima et al., 2014; Assunção, Gandour, et al., 2015; Assunção and Rocha, 2019; Cisneros et al., 2015; Koch et al., 2019), it can be expected that the impacts on the decisions of agricultural actors will become more significant as the constraints on the land are made more stringent.

The PPCDAm has received considerable attention in recent years. It disappeared during the Bolsonaro presidency and is now being resuscitated. In particular, the Priority List is one of the major conservation policies in Brazil and an efficient measure to reduce deforestation (E. Y. Arima et al., 2014; Assunção, Gandour, et al., 2015; Assunção and Rocha, 2019; Cisneros et al., 2015; Koch et al., 2019). On the consequences of the plan, Koch et al., 2019 examine the collateral effects of the Priority List on agricultural output, demonstrating that the prioritized municipalities were paired with increases in cattle production and productivity. They do not find any consistent effect on dairy or crop production. Moffette et al., 2021 also show that the Priority List incites agricultural actors to intensify their cattle production, especially in municipalities with a high proportion

of land dedicated to large ranches. Polain de Waroux et al., 2019 is another study that focuses on the impacts of conservation policies on agriculture in South America. They find no evidence of a change in soy or pasture patterns due to changes in regulations, except within the Amazon biome, where pasture expansion slowed down and pastures intensified. This paper, more than trying to assess whether there is an increase in productivity, tries to point out whether there is a switch towards more intensive agricultural activities.

Polain de Waroux et al., 2019 shed light on international trade, another important matter when dealing with land-use change. The case of soybean is particularly relevant, as 70% of the commodity is exported worldwide. Indeed, studies suggest that as openness to trade increases, deforestation also increases in the Amazon (Faria et al., 2016). Our work relates to this literature on trade and the environment through the effects of conservation policies on exports.

The paper's contribution is to look beyond the direct effect of the policy on forests to detect its indirect effects on the soybean sector and its exports. Other land uses are examined, but only for the purpose of better understanding the origin of our soybean results. To test the relationship between conservation policies, agricultural production, and the international trade of soy, we use national surveys and the TRASE database (Trase, 2022), which traces the flows of soy between Brazil and other nations. We estimate the impact of the Priority Listing on deforestation, soy production, and exports with two econometric methods. We adopt a classical difference-in-differences strategy. Most importantly, we use the generalized synthetic control method to achieve a better control group and obtain more robust estimates. We also discuss the potential underlying mechanisms to explain our findings.

Our analysis shows that, while the Legal Amazon Priority List was responsible for a decline in the deforestation rates, the deforestation slowdown was not triggered by a reduction of land use for soybeans. On the contrary, the results of the regressions show that the production, the area, and the exports of soy increased with the implementation of the Priority List. This leads us to think that there was a reallocation of agricultural land uses in favor of soybeans. Some agricultural activities may have switched to more capital-intensive products like soybeans. Further results corroborate this specialization as one can notice a shrinkage of some staple food production areas and more pasture to soybean conversion. The largest increase of soy is observed in the states of Rondônia and Pará, but we do not find evidence of heterogeneous responses of the municipalities with the tested variables. Based on the literature, we find some possible explanations for the positive effects of prioritization on the soybean sector. The costs of compliance with the

environmental regulation may have motivated farmers to switch from an expansion strategy to an intensification strategy toward more profitable and capital-intensive agricultural activities. A crowding-out effect of smaller landowners, selling their lands to richer soybean farmers would be plausible as the environmental governance produced economic difficulties for them. The land management strategy rolled out at the municipal level as a response to being prioritized may also have triggered land-use adjustments.

The rest of the paper is organized as follows. Section 2 provides information about the background, section 3 details the data and empirical methodology adopted. Section 4 presents the land-use changes consecutive to the plan and section 5 discusses the possible mechanisms through which this has occurred, followed by conclusions. Robustness tests can be found in the appendix.

1.2 Background

1.2.1 The Priority List of the PPCDAm

As a response to the skyrocketing rates of deforestation in the early 2000s in the Amazon rainforest, the Brazilian government launched an integrated and coordinated conservation plan called the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (*Plano de Prevenção e Controle do Desmatamento na Amazônia Legal, PPCDAm*). It covers the Legal Amazon, formed by the states of Acre, Amapá, Amazonas, Pará, Rondônia, Roraima, Tocantins and Mato Grosso, and by the municipalities of the state of Maranhão located west of the 44th meridian, and contains the entire Brazilian Amazon biome and a part of the Cerrado biome. The plan deals simultaneously with monitoring, environmental control and territorial management. It has been through four phases (PPCDAm-I (2004-2008), II (2009-2011), III (2012-2015), and IV (2016-2020)), evolving to address the new patterns of deforestation. The plan's implementation was followed by a substantial decline in deforestation in the Amazon up to 2012, when the deforestation rates began to surge again (T. West et al., 2021).

Here, the focus is on one of the most emblematic measures of the PPCDAm, the Priority List, which aims to concentrate the efforts to mitigate deforestation in the most vulnerable municipalities. Decree 3621 issued in December 2007 defined 36 priority municipalities, representing 46% of the Amazonian deforestation. They were subject to more intense environmental surveillance and law enforcement, with the Brazilian Environmental Protection Agency (IBAMA) having more resources assigned to these locations. More fines were issued, and illegally cleared properties were placed under embargo. A series of administrative measures also imposed an additional cost. Li-

censing and geo-referencing requirements to demarcate legal reserves (*reservas legais* – RL) and permanently protected areas (*áreas de proteção permanente* – APP) were harsher in the prioritized municipalities and private land titles were reviewed, to gather data to enable them to be monitored to prevent the occurrence of new illegal deforestation. Credit from official public agencies was prohibited for agricultural and forestry activities related to forest burning and illegal deforestation. This applied also to all services, commercial or industrial activities that acquire, transport or sell products or by-products originating from an embargoed area (Assunção and Rocha, 2019; Bizzo et al., 2017). Additionally, the “Arco Verde operation”, as part of the PPCDAm, promoted sustainable land-based production models, particularly in the prioritized municipalities (T. West et al., 2021).

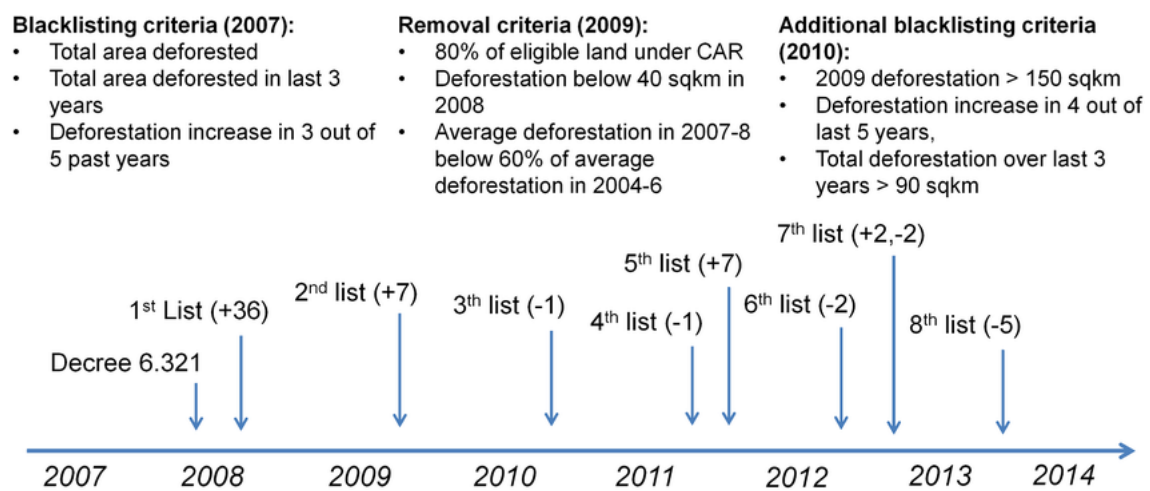


Figure 1.1: Evolution of the Priority List. Source: Cisneros et al., 2015

The municipalities were chosen according to criteria mirroring the history of their deforestation ((i) cumulative area of forest loss, (ii) area of forest loss in the last three years, and (iii) increases in deforestation in at least three of the last five years) (Fearnside, 2017). A strict threshold selection rule is followed in practice to select the municipalities, which suggests that the interference of local political influence on the list is unlikely (Assunção and Rocha, 2019). Municipalities can be removed from the list if they can demonstrate a significant reduction in deforestation.

The policy overlaps with other forest protection mechanisms, particularly interventions in the supply chain. These include the Amazon Soy Moratorium, launched in 2006, which is an agreement by grain traders not to purchase soy grown on recently deforested land (Heilmayr et al., 2020), and the G4 Cattle Agreement, launched in 2010, which excludes suppliers with post-2010 deforestation from selling to signatory slaughterhouses (Moffette et al., 2021). The Amazon Soy Moratorium proved to be complementary to the CAR (Cadastro Ambiental Rural, a legally binding document to clarify land ownership) (Heilmayr et al., 2020), while there is no evidence

that the G4 Cattle Agreement was complementary to or a substitute for the Priority List (Moffette et al., 2021).

1.2.2 Characteristics of soybean production systems

Since the second half of the twentieth century, soybean has experienced an exceptional and relentless growth in production, as a result of both improvements in yield and expansion of the harvested area. This reflects the ever-growing consumption of this crop worldwide, which is still expected to rise with the increased appetite for livestock. Soy is sometimes identified as a “flexible crop” or a “cash crop” because of its many uses. The crop is used for direct food consumption, biodiesel production, and industrial processing, but the largest share of soy use is in animal feed, both worldwide and locally (71% of the domestic consumption in Brazil) (De Maria et al., 2020). Brazil recently took the position as both the top-ranked producer and exporter of soy.

Besides the increased agricultural export revenues, this expansion has been linked with deforestation in the Amazon and Cerrado, which questions the sustainability of the soybean supply chain. The most rapid expansion of soy between 2000 and 2019 occurred in the Brazilian Amazon, where the soybean area increased more than tenfold, from 0.4 Mha to 4.6 Mha (approximately equivalent to the area of Denmark) (Song et al., 2021). This expansion of mechanized agriculture altered deforestation dynamics, both by directly increasing the conversion of forests for soy cultivation and indirectly by replacing existing cattle pasture, some of which leaked into the Cerrado regions (E. Arima et al., 2011). In response, initiatives to improve the sustainability of the soybean supply chains multiplied. Combined with public policy interventions, they triggered a decoupling of soybean expansion from deforestation after 2008 in the Southern Amazon (Macedo et al., 2012).

Soybean is a large-scale mechanized industry requiring high investments for low on-farm employment compared to ranching or other crops (R. D. Garrett and Rausch, 2016). Not only are the high levels of input (in fertilizers, pesticides, machinery) expensive, but soy also needs many supporting services (input provision, financing, marketing, distribution, and processing). Investing in planting can be risky without long-term investments and secure lands. The expansion of soy is capital-constrained and is largely driven by capital surpluses during high-price years (Richards et al., 2018). The other sources of capital are the credits provided by national and international banks or by multinationals, like Cargill or Bunge, providing credits in the form of seed, fertilizer, and chemicals in return for the soy harvested (R. D. Garrett and Rausch, 2016; Gollnow et al., 2014).

While the soy industry contributes undeniably to growth in national export revenues and enhances rural incomes and services, the consequence of its expansion is also a decline in rural equity (R. D. Garrett and Rausch, 2016; Gollnow et al., 2014). Only farmers with very high levels of savings or leverage for obtaining a loan can afford to engage in soy production. In practice, the large soy landowners are often new South migrants with larger financial resources. Their establishment was in some cases associated with the displacement of smallholders, selling their lands to look for new opportunities in urban areas, or forced departures of vulnerable populations (traditional and indigenous landholders) where land tenure is not secure (Schilling-Vacaflor et al., 2020).

1.3 Materials and methods

The main data sources are described in 1.3.1, and we introduce our methodology in 1.3.2.

1.3.1 Data

The basis of the analysis is a panel of Brazilian municipalities from 2002 to 2012, gathering data about agriculture, forestry, and trade detailed below.

1.3.1.1 Main variables

To measure the changes in the agricultural sector following the implementation of the Priority List, we draw primarily on the standard database of the Brazilian Institute of Geography and Statistics (IBGE). The IBGE offers data series enumerating yearly agricultural production, yields and cultivated areas by crops and livestock production in the Brazilian municipalities. A full description of the variables used is provided in the appendix (Table A.1).

To analyze the changes in the productivity of cattle production and deepen the understanding of land-use changes, we also exploit the MapBiomias database¹. Compared to TerraClass, which can only provide land-use and land-cover areas for a few years (2004, 2008, 2014), MapBiomias has the advantage of providing annual land cover and land-use areas, as well as transitions between land-use and land-cover categories. The stocking rate is calculated by dividing the number of cattle (from IBGE) by the pasture area by municipality (from MapBiomias)². The pasture area for the

¹The Brazilian Annual Land Use and Land Cover Mapping Project is an initiative relying on Google Earth Engine platform and its cloud processing and automated classifiers capabilities. Though, its fully automated methodology results in some inconsistencies (Neves et al., 2020) but this data source is still better suited than TerraClass for a fine analysis of land-use transitions.

²Its correlation is low with the stocking rates provided by Cisneros et al., 2015 and Koch et al., 2019. These differences can be attributed to the difficulty of classifying land cover as pastures and the choice of the kind of pastures to calculate

calculation is defined only by the land class "pasture" and does not include the land class "mosaic of pasture and agriculture" because it was not possible to disentangle cropland from pasture land in that class. The intensity of the livestock may, therefore, be underestimated, and its trend may be inaccurate.

This data is complemented with trade data using the most recent Brazilian soybean dataset of the TRASE database (Trase, 2022). Annual data on production, exports, and associated risks at the sub-national level is linked to individual companies that export, ship, and import a traded commodity. The yearly volumes and values of exports for each municipality are calculated by aggregating the transaction data.³

The newly deforested area comes from the Brazilian National Institute for Space Research (INPE), based on its Project on Deforestation in the Amazon (PRODES), which carries out satellite monitoring of clear-cut deforestation in the Legal Amazon.

1.3.1.2 Other data

Table A.1 synthesizes the sources and definitions of the other variables of the study, used as controls in our regressions. We rely extensively on the data provided by Koch et al., 2019. Their choice reflects the changes in land management (protected areas, indigenous territories, settlements) and in local economic conditions (local prices of timber and soybean, GDP).

To explore the heterogeneities and mechanisms, we test for the influence of other variables. We use the Suitability index range for soybeans from GAEZ⁴ to account for the agro-climatic conditions. As a second indicator, we use as a proxy of the climatic conditions the 2006 mean annual precipitation, averaged by municipality. Other variables were generated to account for the connection to infrastructures to reflect the presence of an agribusiness cluster. We also compute the mean cost of transport to the nearest soy export port. The state of the connection to markets is depicted with a dummy for the most exporting municipalities and a Herfindahl-Hirschmann index⁵ to our variables to measure the market concentration of soybean traders at the municipality or state level.

the stocking rates.

³In TRASE, the exports include soybeans, cake oil and soy sauce, but they do not include more processed products such as animal feed or biodiesel (because they involve other raw products and the tracking of the supply chain would involve many other actors, which is hard to retrace). Also, 14.5% were not attributed to a municipality successfully.

⁴The Global Agro-Ecological Zoning, developed by the Food and Agriculture Organization of the United Nations (FAO) in collaboration with the International Institute for Applied Systems Analysis (IIASA), provides a standardized framework for the characterization of climate, soil and terrain conditions relevant to agricultural production. It identifies crop-specific limitations of climate, soil, and terrain resources in a consistent and empirically founded way.

⁵The index is calculated by squaring the market share of each firm in the industry and summing these squares. The result ranges from 0 to 1, with a higher HHI indicating less competition and more market power.

1.3.1.3 Estimation sample

The sample contains municipalities located in the Brazilian Legal Amazon. The period under study goes from 2004 to 2012. We choose this time window in order to keep enough years before and after the implementation of the Priority List in 2008.

We follow some exclusion rules to end with a sample better suited for the evaluation of the interaction between forest conservation policies and soybean expansion. First, following the criterion of Cisneros et al., 2015 and Koch et al., 2019, municipalities with less than 10% of forest cover remaining in 2002 (114 municipalities, none of them being prioritized) are excluded. This leaves us with some municipalities located mainly at the frontier of the Amazon biome, as illustrated in Figure 1.2. Then, we exclude municipalities that do not produce soybeans at least once in our time frame. The total “treated group” is at that point composed of 28 municipalities prioritized in 2008, five in 2009, and five in 2011. For the main specification, we keep only the 2008 treated group (by far the largest group) and exclude from the control group the municipalities treated later so that they do not serve as a comparison for the 2008-listed municipalities in the regressions. The main final sample contains 161 municipalities in the Legal Amazon, among which 28 municipalities were added to the Priority List in 2008. In the following sections, “treated municipalities” will refer to the municipalities on the Priority List, and “control municipalities” will refer to the municipalities of the rest of the sample under consideration.

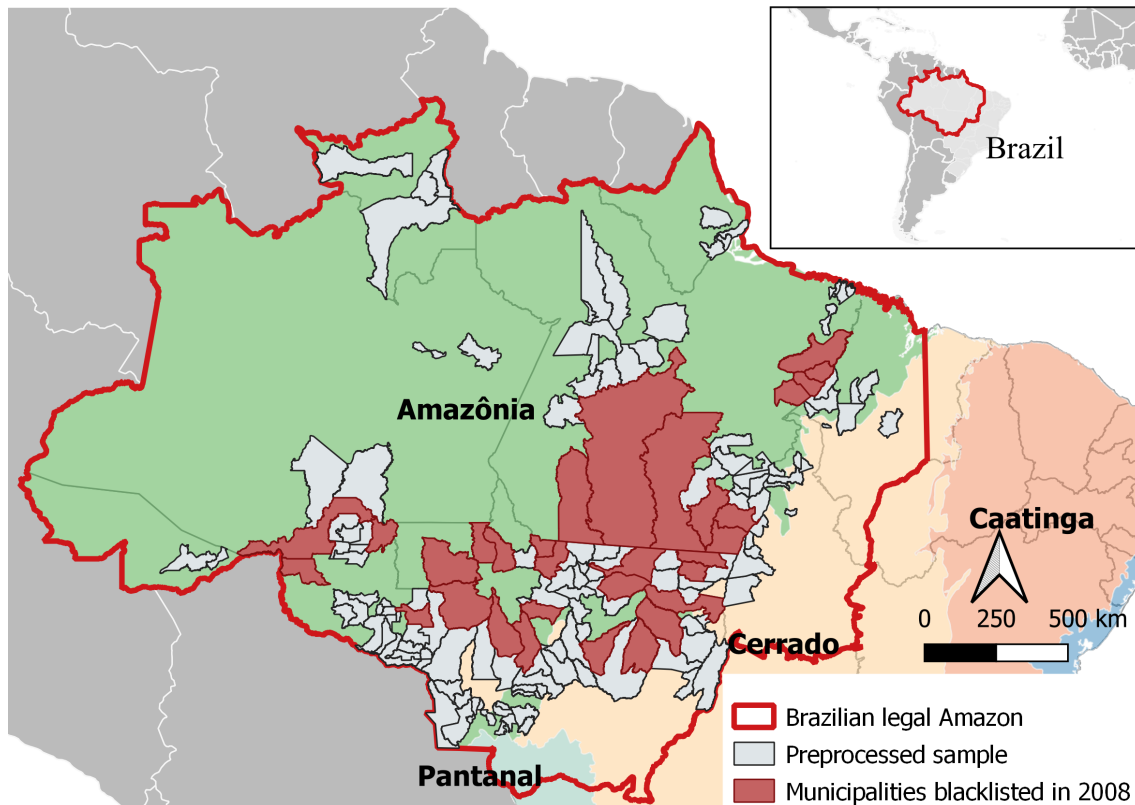


Figure 1.2: Map of the processed sample

Note: Priority municipalities in red and control municipalities in grey.

1.3.1.4 Comparison of the treated versus control municipalities

Table 1.1 summarises the statistics of some main land uses, agricultural and economic variables in 2007, right before the implementation of the Priority List. The main point on which they differ is their size. The treated communities are much larger than the control communities. They also had more remaining vegetation before the policy was implemented, but their deforestation rates were significantly higher, in line with the selection criteria of the Priority List. The treated communities tend to have less agricultural land, both for soybeans, other crops, and pasture, relative to their total area than the control communities. The pastures are less intensive. There are no striking differences in the implementation of environmental policies (considering protected areas), GDP, or suitability for soybean cultivation. The priority municipalities are more integrated in the international soybean sector and display a more concentrated soybean market.

While the levels of deforestation are different, the trends of deforestation of the two groups before the treatment show some similarities as illustrates Figure 1.3. Both groups experienced a decline in deforestation rates in 2004, consecutive to the implementation of the first phase of the PPCDAm in the Legal Amazon. In the regressions, we transform the increments of deforestation with an Inverse Hyperbolic Sine function (IHS). The evolution of the IHS-transformed variable (Figure 1.4) shows even more similar trends between the two groups. After 2008, the deforesta-

Table 1.1: Summary statistics for 2007

	Treated group N = 31		Control group (N = 160)		Comparison
	Mean	SD	Mean	SD	t-test
Land uses					
Area of the municipality	19220	28820	6360	7100	2.347 **
Remaining natural vegetation	0.6568	0.1451	0.5677	0.2253	2.644 **
Increment of deforestation	0.7728	0.5168	0.3516	0.4004	4.063 ***
Soy area	0.01571	0.03492	0.03311	0.09903	-1.607
Other crops area	0.01306	0.01594	0.03194	0.06064	-3.116 **
Soy yields	1.906	1.471	1.63	1.44	0.9035
Pasture area	0.3036	0.1578	0.3707	0.2575	-1.8
Stocking rate	0.8783	0.3641	1.137	0.5309	-3.129 **
Indigenous land	0.1185	0.1784	0.08075	0.1594	1.036
Rural settlement area	0.08609	0.1179	0.1598	0.194	-2.642 **
Strictly protected area	0.02685	0.05492	0.03277	0.09021	-0.4557
Multiple uses protected area	0.0357	0.09178	0.07319	0.1911	-1.563
Other variables					
GDP per capita	9.951	0.422	9.888	0.6051	0.6544
Soybean suitability index	0.4301	0.08048	0.4464	0.104	-0.9225
Crushing facility	0.07143	0.2623	0.08271	0.2765	-0.2048
Storage facility	0.3214	0.4756	0.3459	0.4774	-0.2469
High share of exports	0.4545	0.5096	0.3786	0.4874	0.6389
HHI by municipality	2007	3471	1490	3212	0.7258

Notes: This table reports the means and standard deviation of the main variables in 2007, just before the implementation of the policy. The treated group comprises the 2008-listed municipalities. The areas are expressed in % of the area of the municipalities, the yields in tonnes per ha, the stocking rates in cattle heads per ha. GDP per capita is in reais, while the GDP of the municipalities is expressed in 1000 Reais.

tion rates decline again, with a more pronounced pattern in the priority municipalities. We do not detect any anticipation effect before 2008. [Figure 1.3](#) also shows in parallel the changes of variations of areas of soybean and pasture. Before 2008, the increase in pasture follows the decrease in the deforestation rates for both groups, suggesting that slowing down deforestation also slowed down the pasture expansion. After 2008, the treated group even shows a net decrease in the pasture area. The variation in soybean area also follows the deforestation rates with a decrease of the rates between 2005 and 2007. Nevertheless, the soybean expansion seems to speed up again in 2008, with a steeper increase for the treated group.

1.3.2 Empirical strategy

The goal of the identification strategy is to estimate the effects of the Priority List on deforestation, agricultural production, and agricultural exports. This section proposes two main approaches. In order to point out possible heterogeneities in the treatment responses, interactions are added to the first specification (triple-differences). A possible drawback of the previous approach is the lack of comparability of the two control groups. This is why we adopt a second approach: the generalized synthetic control method.

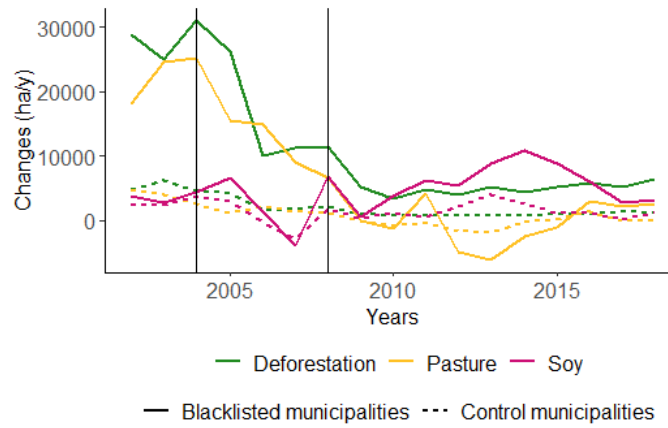


Figure 1.3: Time series of the variations of areas of deforestation, pasture and soybean

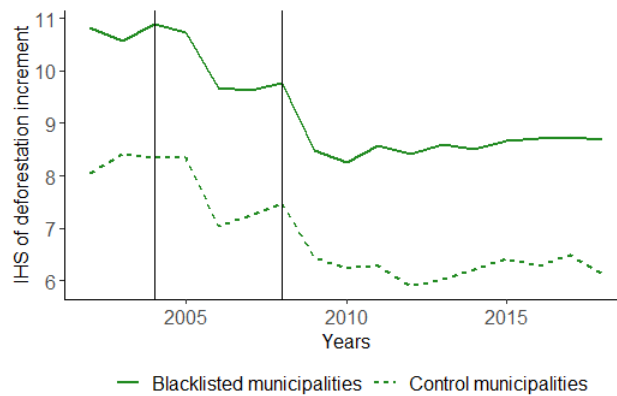


Figure 1.4: Time series of the deforestation rates (IHS)

1.3.2.1 Main difference-in-differences

We rely on a difference-in-differences approach to leverage our quasi-natural experimental design where only a few municipalities are “treated” by the environmental measures as a first approach. Indeed, the paper aims to analyze whether there is a causal effect from the environmental measures on the agricultural sector, and the difference-in-differences strategy is one of the most practical ways to identify causal effects.⁶

We estimate how the Priority List affects the production and exports of soy using the following general specification (equation 1.1). We look at different outcomes Y_{it} that characterize the sector (e.g., land use, production, exported products) and deforestation.

⁶Regression discontinuity design would have been another approach, but there are too few observations close to the threshold frontier. Moreover, the regression discontinuity would estimate the average treatment effects at the cutoff frontier, which is not the parameter we are interested in.

$$Y_{it} = \gamma + \tau_{DiD}(MP_i \cdot Post_t) + \gamma_i + \delta_t + \sum_k \gamma_k X_{it} + \epsilon_{it} \quad (1.1)$$

In Equation 1.1, Y_{it} is the outcome variable for municipality i and year t . MP_i is the dummy variable, taking 1 if i belongs to the treated group. $Post_t$ is the dummy variable taking 1 if year t is after the year treatment is imposed. The policy effect is estimated by obtaining the coefficient τ_{DiD} . In the first stage, we do not attempt to consider the different timing of the treatment. We instead simply consider the treatment in 2008 and remove the units that are listed after 2008 from the sample (10 units in total). We choose the 2008 group as the treated group because it is by far the largest group.

We control the bias from the fixed unobservable variables correlated with the policy and the outcome variables (mining, vegetation type, slope, altitude, roads, economic shock affecting the entire region, etc.) by adding municipality-fixed effects and year-fixed effects in all the specifications (γ_i and δ_t). The other issue that may arise from the difference-in-differences approach is the existence of time-varying variables correlated to our outcome variables and with prioritizing. We use covariates related to land management, agricultural and socio-economic characteristics based on the previous literature on the Priority List to control this bias. The vector of covariates X_{it} represents them in equation 1.1.

The central hypothesis for using the difference-in-differences method is to ensure that there are no unobservable variables that would influence changes in the outcome variables and the probability of being listed. To support this hypothesis, Figure 1.5 shows the trends of the outcome variables. For some outcome variables, the trends of the treated and control groups in the pre-treatment period seem parallel, but for other variables, there are some differences. This is why alternative methods are necessary.

A better solution would have been to create a control sample by propensity score matching, so as to reduce the differences between the treated sample and the control sample (also apparent in Table 1.1). However, the various matching algorithms do not give satisfactory results concerning the common support of the matched sample. This motivates us to look for another econometric specification, which addresses the differences between the treated sample and the control sample.

1.3.2.2 Heterogenous effects of the policy between the municipalities

After demonstrating the effects of the Priority List, we seek to demonstrate the heterogeneous effects of the policy across municipalities. To do so, we use a triple difference model with two

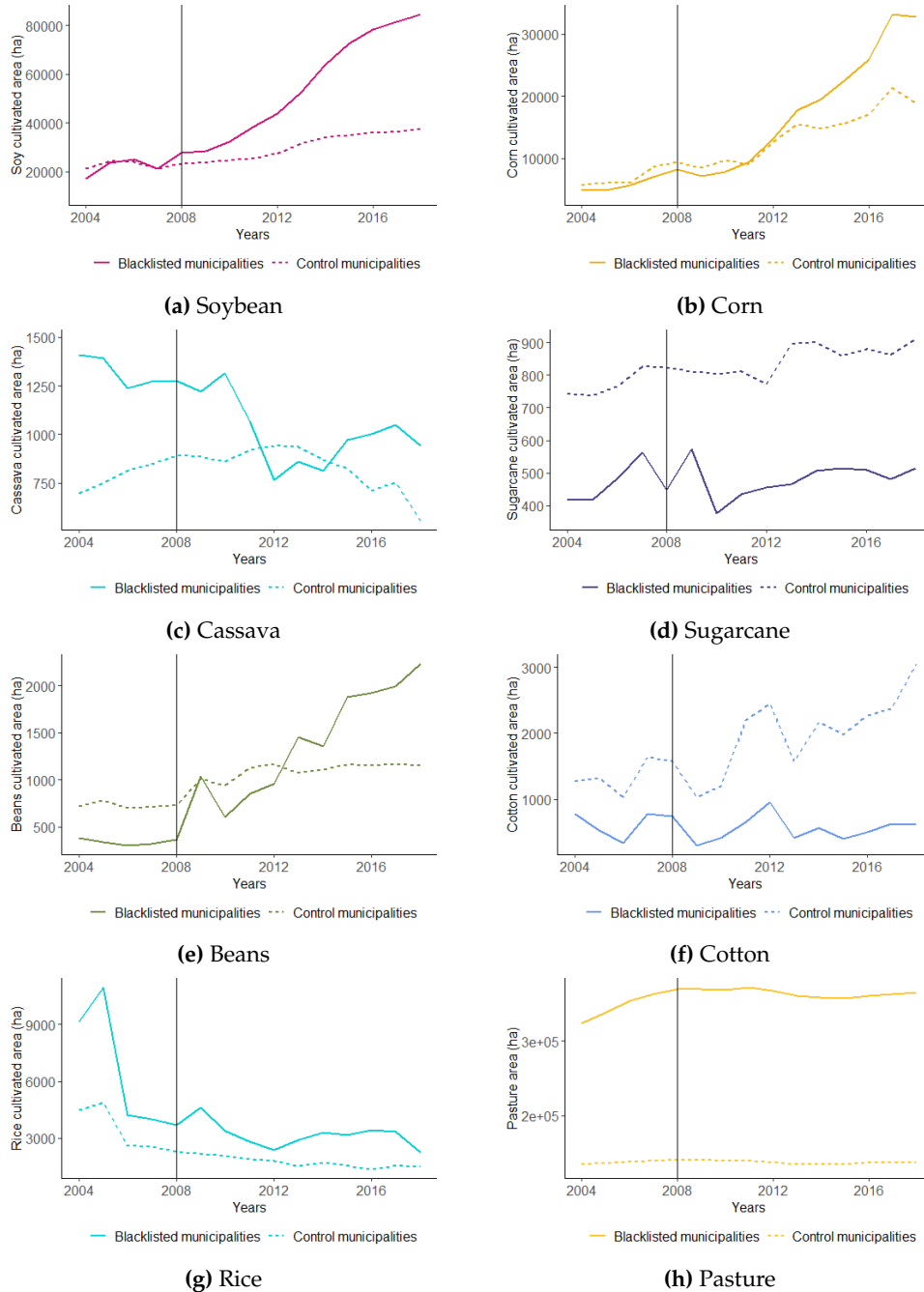


Figure 1.5: Cultivated areas and pasture area over time in prioritized municipalities in 2008 (solid line) and control municipalities (dotted line)

periods⁷. Like in the first-stage estimation, we keep only the largest treated group, the Priority List from 2008. This allows us to quantify heterogeneity in the impacts of the Priority List to help identify mechanisms that could explain the different responses to the program.

The triple difference estimator can be computed as the difference between two difference-in-differences estimators. The triple difference estimator does not require two parallel trend assumptions, but only one: the relative outcome of the two groups in the treated state must trend in the same way as the relative outcome of the two groups in the absence of treatment. The specification is the following:

$$Y_{it} = \gamma + \tau_{DiD}(MP_i \cdot POST_t) + \beta_1(MP_i \cdot d_i) + \beta_2(POST_t \cdot d_i) + \tau_{TD}(MP_i \cdot POST_t \cdot d_i) + \gamma_i + \delta_t + \sum_k \gamma_k X_{it} + \epsilon_{it} \quad (1.2)$$

Where d_i is a dummy defining the group. The parameter of interest is τ_{TD} , which isolates the deviation in deforestation rates (or soybean production, exports, or land use) that occurs in the priority municipalities presenting the characteristic d . This can be interpreted as the average treatment effect of the PPCDAm on municipalities with d .

1.3.2.3 Generalized synthetic control

The main concern of the difference-in-differences strategy is the quality of the control group. In our setup, this concern exists since the treated units are not chosen randomly and, therefore, differ by definition from the other units. The central hypothesis of the parallel trends is likely not to hold. A common method in empirical economics to relax this assumption is to rely on the synthetic control method but it requires a single, or very few, treated units. In the case of the Priority List, using this method would create some practical problems for estimation. New methods have emerged to generalize the synthetic control method to multiple treated units method (Abman et al., 2020; Y. Xu, 2017). A method that suits the setup is the generalized synthetic control method (Y. Xu, 2017), which has been recently applied in studies on forest conservation (T. A. P. West et al., 2023). This method complements and strengthens the average treatment effects estimated with the difference-in-differences method. It has the advantage of extending the synthetic control approach to scenarios involving multiple processed units, generating confidence intervals, and automatically selecting the number of factors. However, it requires more pretreatment periods than fixed-effect estimators. This method, therefore, cannot be applied to the export variables in our case, as these start in 2004. In addition, the method is more sensitive to modeling assumptions than the original synthetic matching method. Its core principle is to use control group informa-

⁷To our knowledge, the triple difference is not yet adapted to a setup with multiple time periods

tion based on a linear interactive fixed effects model that incorporates unit-specific intercepts interacted with time-varying coefficients to impute counterfactuals for each treated unit (Y. Xu, 2017). We apply this method relying on the package *gsynth*.

Let's denote Y_{it} the outcome of unit i at time t and T_0 the number of pretreatment periods. Y_{it} is assumed to be given by a linear factor model:

$$Y_{it} = \delta_{it}MP_{it} + \mathbf{x}'_{it}\beta + \lambda'_i\mathbf{f}_t + \varepsilon_{it}$$

where MP_{it} is as before the treatment, δ_{it} is the heterogeneous treatment effect on unit i at time t , \mathbf{x}_{it} a vector of observed covariates, β a vector of unknown parameters, \mathbf{f}_t a $(r \times 1)$ vector of unobserved common factors, δ_i a $(r \times 1)$ vector of unknown factor loadings, ε_{it} unobserved idiosyncratic shocks with zero mean.

The individual treatment effect on the treated unit i at time t (with $t > T_0$) is then $\delta_{it} = Y_{it}(1) - Y_{it}(0)$.

Where N_{tr} is the number of treated units and T is the set of treated units, the average treatment effect on the treated for $t > T_0$ is calculated as:

$$ATT_{(t,t>T_0)} = \frac{1}{N_{tr}} \sum_{i \in T} (Y_{it}(1) - Y_{it}(0))$$

To do so, $\hat{Y}_{it}(0)$ is imputed based on the estimated factors and factor loadings. First, the IFE model is estimated using only the data from the control group. Next, the factor loadings are estimated for each treated unit by minimizing the mean squared error of the predicted treated outcome in pretreatment periods. The latent factors capture common trends not observed in the control group. Factor loadings represent each unit's contribution to these latent factors. The underlying assumptions are the strict exogeneity (meaning that the error term of any unit at any time period is independent of treatment assignment, observed covariates, and unobserved cross-sectional and temporal heterogeneities of all units at all periods), weak serial dependence of the error terms, regularity conditions, and cross-sectionally independent and homoscedastic error terms. Here, the same vector of covariables as in the difference-in-differences method is used. Additionally, some invariant predictors that are likely to matter for the effect of the Priority List on the soybean sector are provided. They include the suitability of soybean cultivation, the distance to ports, and the share of pasture in 2007 in the municipalities.

1.4 Results

1.4.1 Impact of the policy on deforestation dynamics

As an initial check on our data and empirical approach, we test the effect of the Priority List on deforestation, which has already been demonstrated in several studies (e.g., Assunção, Gandour, et al., 2015; Assunção and Rocha, 2019; Cisneros et al., 2015; Koch et al., 2019). Some specificities of our approach could explain the different results encountered. First, our sample is generally more restricted than what was published before, as the focus here is on the municipalities that produced soybean. Second, we transform the variables with high values with an IHS function to avoid problems with log-transforming null values.

Table 1.2 displays the results. Consistent with the literature, we find that the plan provoked a decline of 37% in deforestation rates when the generalized synthetic control method is applied. This result is in line with the estimates of Assunção and Rocha, 2019, who find a -44.7% reduction in deforestation for the period 2008-2011, with Assunção, Gandour, et al., 2015 estimating a decrease of between -39.7% and -37.6% for 2008-2012, and Koch et al., 2019 who finds a reduction between -49.9 and -55.8% from 2008 to 2014. Cisneros et al., 2015 note a reduction of 13–36% on average between 2008 and 2012 (figures reported in Börner et al., 2016).

Table 1.2: Average Treatment Effect: deforestation increments

<i>Average Treatment Effects: Deforestation increments</i>			
	DD	Multiple time DD	GSC
ATT 2008-2012	-0.410*** [-0.502, -0.301]	-0.358* [-0.598, -0.118]	-0.372*** [-0.594, -0.150]
ATT 2008-2014		-0.2896* [-0.5166, -0.0615]	

Average Treatment Effect using difference-in-differences, difference-in-differences with multiple groups and timings, and the generalized synthetic control method. The dependent variable is IHS-transformed deforestation increments. Standard errors are robust and clustered at the municipality level.

*p<0.1; **p<0.05; ***p<0.01.

1.4.2 Effects on soybean: cultivated areas and exports

The previous results shed light on the shifts in deforestation dynamics within the priority municipalities. The object of the paper is to assess the impacts on the soybean segment, a pivotal component of the agricultural landscape in the region. The effects of the Priority List on the soybean sector are displayed in Table 1.3 in column 1 for the cultivated area, column 2 for the production in

quantity, and column 3 for the exports in value. The estimates indicate that a priority municipality experiences, on average, an additional expansion of its soybean-cultivated area of more than 70% compared to the unlisted municipalities (significant at 5% for the difference-in-differences). Although the trends show that the soybean area began to increase before the treatment, the generalized synthetic control seems to confirm the positive effect of the policy on the soy-cultivated area (see Table A.8 in Appendix). This effect is detected not only in land use but also in production and exports. Unfortunately, this cannot be confirmed by the generalized synthetic control, as exports are observed from 2004 onwards, leaving too few pre-treatment periods to apply this method. However, this conclusion is consistent with the findings of the working paper Damm et al., 2022 where this question is investigated.

Table 1.3: Effect on the soy sector, pasture and cultivated areas

Dependent Variables: Model:	Soy (ha) (1)	Soy (t) (2)	Soy (exports) (3)	Pasture (4)	Crops (5)
<i>Variables</i>					
Treatment effect	0.7342** (0.3626)	0.7927* (0.4141)	1.909** (0.7709)	0.0200 (0.0202)	0.0223 (0.0894)
Indigenous area (%)	-2.891** (1.297)	-3.010** (1.420)	-6.871*** (2.616)	0.0285 (0.0814)	-0.1250 (0.2941)
Settlement area (%)	-0.3233 (1.720)	-0.4244 (1.965)	-1.389 (1.823)	0.0096 (0.1111)	-0.0050 (0.3099)
Strictly protected area (%)	-5.815 (5.650)	-6.532 (6.566)	-3.440 (2.823)	0.5243* (0.3110)	-0.4307 (0.5338)
Multiple uses protected area	-2.515* (1.480)	-3.179* (1.732)	-1.201 (1.447)	0.0652 (0.0839)	-0.1330 (0.1831)
Soy price lagged	3.051*** (0.4248)	3.506*** (0.4805)	1.658** (0.6543)	0.0279*** (0.0097)	0.2209** (0.0887)
Timber price lagged	0.0375 (0.0591)	0.0357 (0.0679)	0.2660** (0.1298)	0.0017 (0.0018)	0.0207** (0.0104)
GDP per capita lagged	-0.6422* (0.3407)	-0.7430* (0.3769)	-1.102 (0.8054)	-0.0045 (0.0208)	0.0433 (0.0988)
Party affiliation	-0.9141* (0.4933)	-0.9984* (0.5578)	-0.8362 (0.8904)	-0.0181 (0.0170)	-0.1302 (0.1744)
Municipality GDP	0.2407 (0.3541)	0.2635 (0.3946)	1.088 (0.9635)	-0.0150 (0.0139)	0.6480*** (0.1025)
<i>Fixed-effects</i>					
Municipality	✓	✓	✓	✓	✓
Year	✓	✓	✓	✓	✓
<i>Fit statistics</i>					
Observations	1,449	1,449	1,449	1,449	1,449
R ²	0.879	0.871	0.745	0.995	0.947

Notes: All specifications include Municipality and Year-fixed effects and are basic difference-in-differences. Robust standard errors in parentheses clustered at the municipality level. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.

1.4.3 Effects on the main complementary land uses

How can the decrease in deforestation rates and the concomitant increase in the soybean cultivated area both be explained? The implication of those two patterns is that soybean encroaches upon some of the other land uses.

Columns 4 and 5 of Table 1.3 show the results for respectively the pasture and cultivated area. The total cultivated area is approximated by the sum of the six crops (cotton, rice, sugarcane, cassava, corn, soy, with soy alone representing 25% of the cultivated area on average in 2007). The coefficients are not statistically significant for these variables. This prompts us to take a closer look at what is happening within the cultivated areas.

To get a more detailed idea of the land uses that declined against soybeans, Table 1.4 shows the estimates of the effects on the other main crops. The regressions are performed on the har-

vested areas transformed with IHS. The average treatment effects are statistically significant for cotton (decrease of 37% in area relative to the control group), sugarcane (decrease of 76% in its area relative to the control group) and cassava (24%). These relative decreases may suggest that soybean benefited from a reallocation of land within the crops following the implementation of the Priority Listing. The policy would have spurred farmers to switch towards more intensive crops, like soybean. Indeed, the Priority List makes deforestation less attractive by increasing the costs of clearing land (no credit available, risks of fines) and reducing the benefits of clearing land (embargoes, no demand for products stemming from illegal deforestation). In doing so, the Priority List is expected to reduce deforestation and cause a substitution from land to capital, hence from land-intensive crops to capital-intensive ones (Richards et al., 2018). These results should be treated with caution, especially for differences-in-differences on cotton and sugarcane, because Figure 1.3 indicates that the trends are not parallel prior to the treatment. Furthermore, these crops do not represent a large share of the cultivated areas of the municipalities on average.

1.4.4 Intensification

Literature has emphasized the potential intensification effect of implementing conservation policies (R.D. Garrett et al., 2018). Given that we study the collateral effects of a conservation policy on the soybean sector, we cannot neglect to explore this option. In the case of the Priority List, a potential substitution from land to capital could lead to intensification processes, although it was not proven to be the case for crops (Koch et al., 2019; Moffette et al., 2021). We use three measures of the intensification processes. The productivity of pastures is measured as the number of cattle heads per hectare. Crop productivity is measured as the yields of the six main crops in tonnes per hectare. We also consider soy-corn double-cropping as a form of intensification and measure it with a cropping frequency ratio.

Pasture and crop intensification

When land clearing is no longer an option, agricultural producers are likely to intensify their production. As revealed in Table 1.5, the plan indeed triggered an increase of 2% in the productivity of pastures, while the total area of pasture remained stable. For the yields of the other crops, we find no robust evidence that the policy led to substantial increases in productivity. These conclusions are in line with the results in Moffette et al., 2021 and Koch et al., 2019, but our magnitude of the pasture intensification is much lower and is insignificant for the generalized synthetic control.

Table 1.4: Effect on the cultivated areas of the main crops

	Cotton (1)	Rice (2)	Sugarcane (3)	Cassava (4)	Corn (5)
Treatment effect	-0.374* (0.163)	0.082 (0.098)	-0.762** (0.185)	-0.258*** (0.086)	0.056 (0.102)
Indigenous area (%)	0.480 (0.551)	1.354*** (0.408)	0.075 (0.630)	0.234 (0.209)	-1.089** (0.430)
Settlement area (%)	-0.166 (0.262)	-0.227 (0.642)	-1.387 (0.986)	0.554** (0.224)	-0.096 (0.408)
Strictly protected area (%)	0.313 (0.375)	3.810** (1.805)	-0.980 (1.280)	-0.595 (0.507)	-0.607 (0.806)
Multiple uses protected area	-0.209 (0.162)	-1.095 (1.106)	-1.345 (0.931)	-0.273 (0.250)	-0.415 (0.305)
Soy price lagged	0.045 (0.110)	0.339*** (0.121)	-0.090 (0.170)	-0.113 (0.075)	0.094 (0.092)
Timber price lagged	0.023 (0.036)	0.025 (0.027)	0.043 (0.031)	-0.028* (0.015)	0.034 (0.025)
GDP per capita lagged	-0.449 (0.326)	0.077 (0.237)	-0.166 (0.237)	-0.015 (0.113)	-0.198 (0.164)
Party affiliation	0.354* (0.208)	-0.368*** (0.129)	0.507** (0.251)	0.147** (0.074)	-0.004 (0.130)
Municipality GDP	0.921*** (0.327)	0.377* (0.201)	0.133 (0.234)	0.203* (0.119)	0.664*** (0.153)
Observations	1,449	1,449	1,449	1,449	1,449
R ²	0.878	0.775	0.820	0.894	0.839

Notes: All specifications include Municipality and Year-fixed effects and are basic difference-in-differences. Robust standard errors in parentheses clustered at the municipality level. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.

Table 1.5: Effect on yields

Crop	Difference-in-differences	GSC
Pasture	0.0233* (0.0133)	0.0223 (0.0236)
Soybean	0.103 (0.0973)	0.111 (0.105)
Cotton	-0.0948 (0.0605)	-0.085* (0.0501)
Rice	0.0268 (0.0393)	-0.0320 (0.0438)
Sugarcane	-0.514 (0.328)	-0.566* (0.311)
Beans	-0.0534 (0.0503)	-0.0589 (0.0507)
Cassava	0.00214 (0.0394)	0.0317 (0.0371)
Corn	-0.091 (0.0845)	0.0704 (0.0474)

Notes: All specifications include Municipality and Year-fixed effects and are basic difference-in-differences. Robust standard errors in parentheses are clustered at the municipality level. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.

Intensification through double-cropping

The additional increase in the soybean cultivated land in the prioritized municipalities could hide an intensification of agriculture through double-cropping instead of a soybean land expansion in forests, pastures, or other crops as in the official records, the area in case of double-cropping is double-counted. It is worth looking at this phenomenon for three main reasons. First, because there is evidence that while cropland expansion was still the primary driver for the Brazilian grain boom, its influence has a general decreasing trend in favor of double-cropping⁸. Second, previous research has established that crop intensification with double-cropping was linked with increasing forest conservation and broader supply chain development (R.D. Garrett et al., 2018). Thirdly, the results of our regressions suggest a positive impact of the plan on the soybean production area, but no significant impact on the corn area, which represents the second main crop area after soybean in our sample. An expansion of double-cropping would be consistent with these results. We focus on soy-corn double-cropping, the most common double-cropping in Brazil, and consider the other types of double-cropping negligible, as in J. Xu et al., 2021. In this configuration, soybean is the main crop and is planted first. Corn is planted on the same land, after soybean and on a shorter period of time. We use the same data (the IBGE-PAM dataset) and method as in J. Xu et al., 2021 to build our variables to quantify the impact of the plan on soy-corn double-cropping. No double-cropping is observed in about half of the municipalities in 2010 (42 municipalities

⁸The quantitative importance of double-cropping is such as soybean-corn double-cropping would have offset 76.6 million ha of Brazilian arable land for grain production from 2003 to 2016 (J. Xu et al., 2021).

out of 119), among which 8 are priority municipalities⁹. The difference-in-differences regressions show no significant effects of the plan on the outcomes characterizing the double cropping (surface of second-season corn, cropping frequency, area increment induced by cropland expansion, and area increment induced by double-cropping).

1.4.5 Empirical challenges

1.4.5.1 Placebo tests

Our identifying assumption requires that in a counterfactual world without the Priority List, trends in the outcome variables are the same in the treatment and control groups. One important objection is that the priority municipalities are put on the list because of particularly high deforestation rates, which suggests that the land-use dynamics between the control and the treated municipalities are indeed different. A few years after the peak of deforestation, the municipalities are likely to naturally transform the new pastures into crops, and in that way, catch up with the municipalities with a longer history of intensive deforestation. Would it be the case, the effects on soybean production described in the previous sections would be overestimated.

We first run a placebo test to deal with this concern. We check for diverging trends in outcomes before implementing the policy by imposing a fictitious treatment on priority municipalities. Results are displayed in appendix (Table A.2, Table A.3, Table A.4, Table A.5). They show no evidence supporting different pretreatment trends (absence of correlation of the outcome variables with the placebo treatment).

1.4.5.2 Land-use transitions

The differences in levels of the output variables before the treatment are usually not a threat to identification when using difference-in-differences. However, in our case, they may become a concern. A well-known practice is indeed to deforest for pastures first and then to sell for high prices to soybean growers a few years later. One could thereby argue that the municipalities with high stocks of new pastures (typically the priority municipalities) would see an increase in soybean after a few years in any case. To identify whether we indeed capture the effect of the policy, or solely a different stage in the land-use chain, a solution, which is a work-in-progress, is to investigate the land-use transitions thanks to MapBiomass.

⁹Figure A.1 in appendix compares the cropping frequencies (number of harvests each year) by municipality in 2004 and 2012.

1.4.5.3 Multiples time periods

Our setup deviates from the canonical difference-in-differences setup because there are four time periods instead of only two, and potential treatment effect heterogeneity. In our case, it is worth looking at these heterogeneities to have an idea of the intensity of the effects of the policy over time and across the different waves of the Priority List. Simply extrapolating the previous methodology to the setup with the multiple groups (with a two-way-fixed-effects event-study regression, for instance) would create biases both pre and post-treatment, as Sun et al., 2020 demonstrates. The literature field of difference-in-differences has been dynamic these last years and found new estimators to circumvent these limitations (Athey et al., 2021; Callaway et al., 2020; Chaisemartin et al., 2020; Goodman-Bacon, 2021). The estimator proposed in Callaway et al., 2020 suits our needs, as their method accounts for weighting issues and has the advantages of allowing for covariates in a flexible form, proposing different estimation procedures based on outcome regression, inverse probability weighting, and doubly robust methods, proposing different aggregation schemes to further summarize the effects of the treatment and intervals of confidence, and makes minimal parallel trends assumptions. Figure A.4 reports the regression estimates. The effect of the Priority List on the soybean area is only significant for the group treated in 2008, which is not very surprising as the two other lists are composed of very few units. We also see that this effect intensifies over time. The increasing magnitude could be explained by the fact that the transition from forest requires a few years to be accomplished. On the contrary, the effect on deforestation rates weakens over time.

This section illuminated certain facts about the reactions of farmers to the Priority List. First, the policy was efficient in reducing the pressure on forests. As a result, we observe an increase in the soybean area, production, and even exports concurrent with a decrease in the dynamics of other crops like cotton or sugarcane. These changes in dynamics did not occur hand in hand with intensification processes, except for pasture. This leads us to think that the main response of the agricultural sector to the Priority List was the substitution across crops towards the capital-intensive culture of soybean. To our knowledge, these results were not documented previously and remain puzzling. Thus we explore the potential mechanisms of this shift and the heterogeneities of responses of the municipalities in the next section.

1.5 Discussion

1.5.1 Potential mechanisms

Standard microeconomic analysis looks at the maximization of profits to explain the behaviors of economic actors. Producers choose the combination of inputs and methods that maximizes their profits. In our case, environmental policies can increase the cost of access to land because the cost of clearing new land increases (no cheap credits, fines, and risks of embargoes), and new land is scarcer. In order to maximize their profits in these new conditions, farmers choose either to increase the level of the other inputs depending on their relative prices or to change their production portfolio. In the previous section, apart from livestock farming, we do not find signs of improvement in yields that would corroborate the increase of inputs (capital for machines, fertilizers, genetic improvement of cultivars, etc). This may be due to difficulties in accessing some technologies to improve yields, or due to the fact that yields are already optimized, leaving little room for improvement. Our intuition is that switching to soybean may have been a rational choice for farmers facing higher costs of access to land.

Rational economic decisions shape behaviors, but so do social forces and institutions. Two mechanisms can take place. First, farmers can reallocate their land from one crop to another. Second, there might be some land transfer towards soybean producers. Indeed, we described earlier both how the policy made access to credits harsher and how soy is a relatively expensive crop to grow. Sufficient capital and experience is necessary to engage in soy production (Rachael Garrett et al., 2022). Reduction of economic support for farmers may induce difficulties for smaller producers in investing in seeds, fertilizers, pesticides, and equipment. At the same time, increased cost of access to land where land, especially with title, is scarce and soy production profitable, can encourage smallholders to sell their land to capitalized soy farmers to find new occupations. This was pointed out in the municipality of Santarem, where soy farmers replaced smallholders after the construction of the Cargill port (Baletti, 2014; Steward, 2007; Weinhold et al., 2013) and in the case of the Priority List in the municipality of São Félix do Xingu. The environmental compliance produced economic stress pushing small and medium landowners to sell their properties (Thaler et al., 2019). The neighbors are then jointly more disposed to sell as their social network are broken, and their production can be affected by the neighboring practices (Baletti, 2014). To sum up, the winners of the Priority List could be the capitalized soy farmers who would have seized the opportunity to buy the land of smallholders growing staple food (rice, beans, cassava) in order to expand their own production. This mechanism would be difficult to test given that the

Agrocensus, which collects information on the sizes and densities of the farms, is only available in 2010 during our period of analysis.

Local governments and the private sector also have a role to play in the orientation of agriculture in the municipalities. Farmers require adequate access to dynamic input markets, dryers and silos, and transportation systems to compete in the global economy. Thus, the profitability and the expansion of soy are intertwined with the emergence of agglomeration economies (R. D. Garrett, Lambin, et al., 2013), which depends on local politics. It could be hypothesized that the strategies of the local governments in response to the Priority List benefited the soybean sector in some cases. Indeed, it is worth noting that some local governments did not stand idly by when their municipalities were placed on the list. The strategy of the 2008-listed municipality of Paragominas in Pará soon paid off and became emblematic, as the municipality became the first to exit the Priority List. The mayor formed an alliance with the local landowning elite and seized the opportunity of the Priority List to promote at the same time environmental compliance and agribusiness (Viana et al., 2016). A pact "Zero deforestation" was negotiated and signed by the main sectors, which was also the opportunity to attract new markets and investors with this Green re-branding. Although the environmental and economic objectives were reached through a boost of capitalized agricultural production, along with an expansion of soybean production, the small producers found themselves marginalized. They still relied on deforestation-dependent activities (charcoal and slash-and-burn agriculture) with few other alternatives and felt no need to register under the CAR ("rural environmental registry" or Cadastro Ambiental Rural, legally binding document to clarify land tenures) (Laurent et al., 2017; Viana et al., 2016). The strategy of Paragominas inspired the "Green Municipality Program" (or Programa Municípios Verdes) launched by the governor of Pará in 2011. It aimed at improving the local environmental governance capacity and, this way, at helping the other priority municipalities of the state to exit the Priority List or stay off it (Sills et al., 2020). There is little evidence that the program reduced further deforestation, but it benefited economic activity.

1.5.2 Heterogeneous responses of the municipalities

Finding empirical evidence of the mechanisms mentioned above is complicated by the lack of data. However, the conditions influencing the expansion of soybean can be better understood by taking a closer look at the potentially divergent land-use responses of the municipalities to the policy. The soybean sector also presents some sources of heterogeneity, in terms of production concentration, as well as allocation between local use and international trade. Hence looking for heterogeneous responses to the policy across the municipalities makes sense, all the more

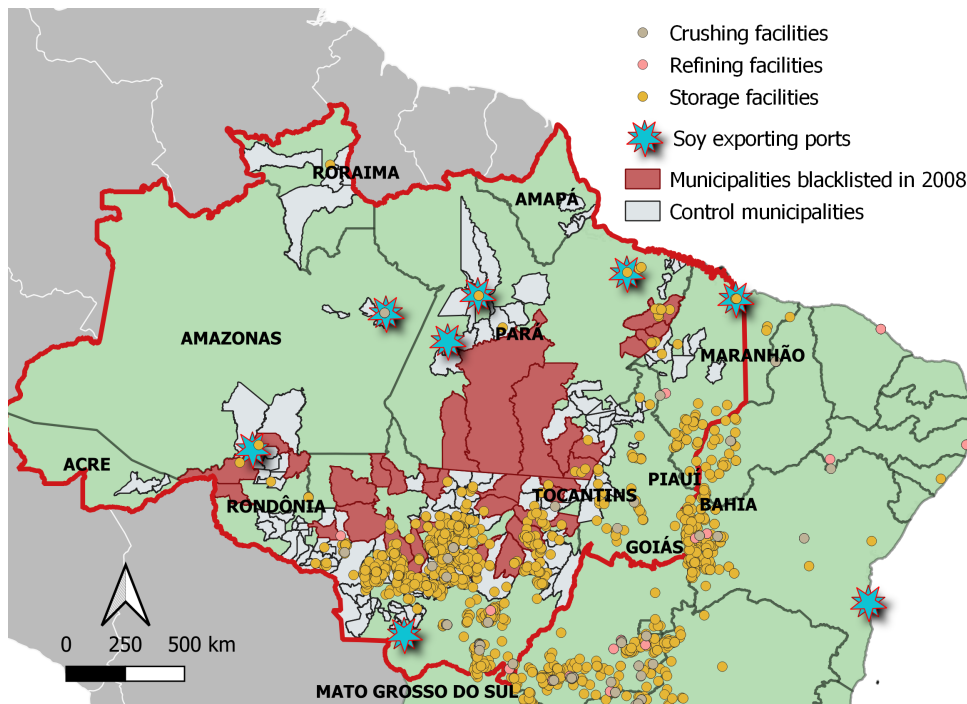


Figure 1.6: Ports and facilities of the soybean sector in the Legal Amazon

that there is a substantial level of uncertainty around the average treatment effect for most tested variables. Moreover, further statistical tests at the state level reveal that the increase in the soybean area is particularly significant in the states of Rondônia and Pará, whereas we do not observe the same statistically significant effect in the state of Mato Grosso. We investigate these heterogeneous responses using triple differences to help us identify on which population we can detect a causal effect of the policy.

More specifically, we examine the differences in responses in light of three broad categories of characteristics: the potential for soybean development, the presence of agro-business clusters, and finally, the openness to trade. Those potential heterogeneities are tested both on soybean area, but also on other soybean development characteristics, such as production, yields, and exports.

Taken together, these results suggest that there is no association between the land characteristics, the supply chain development or the trade network organization, and the soybean expansion generated by the Priority List. However, the explicative power of such regressions is limited due to the low number of municipalities and the lack of heterogeneity in our sample.

1.6 Conclusion

The Priority List curbed deforestation rates of 36% to 41% compared to the other municipalities of the Legal Amazon. This was made possible by more intense environmental surveillance, restrictions on issuing deforestation permits, the embargo of illegally cleared areas, and limited access

to credit and markets. This disruption suggests that the soybean sector, vastly established in the Brazilian Amazon and often associated with deforestation, may have been exposed to the policy. Much previous work has studied the effects of the Priority List on deforestation, ranching, and agriculture. By analyzing the response of the soybean sector and considering the trade effects, our paper deepens the analyses of the consequences of the Priority List beyond the already discussed processes of intensification. Specifically, we relate the implementation of the policy with changes in soybean production, land use, and productivity and compare it to the evolution of the other crops and pastures, using difference-in-differences and generalized synthetic control methods. Because the soybean sector presents some sources of heterogeneity that shaped its previous development, we analyze the responses of the sector according to initial patterns of agro-climatic conditions, supply chain infrastructure development, and trade network configuration.

Surprisingly, our analysis finds that the soybean sector benefited from the policy regarding land use, production, and exports. The Priority List triggered a shrinkage of the production of some staple food production areas, suggesting a reallocation inside the agricultural sector towards more capital-intensive activities. The largest increase is noted in the states of Rondônia and Pará, but we do not find evidence of heterogeneous responses of the municipalities with the tested variables. There are several possible explanations for the development of the soybean sector concomitant with the Priority List. To comply with the environmental regulation and confront the higher costs of deforestation, medium and large farms may have switched from an expansion strategy to an intensification strategy toward more profitable and capital-intensive crops. A crowding-out effect of smaller landowners, selling their lands to richer soybean farmers is also likely to have happened as the environmental governance produced economic difficulties. In some cases, it has also been reported that the strategy of the priority municipalities to exit the Priority List favored agribusiness.

The literature suggests that soybean development in Amazonia is associated with rising rural inequalities, land grabbing, concentration of tenure, and land disputes. Further research could be undertaken to investigate the distributive consequences of the Priority List on employment wages, and sustainable development indicators.

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Appendix A

A.1 Data

Suitability index. We use the Suitability index range for soybean from GAEZ (Fischer et al., 2012)¹⁰ to account for the agro-climatic conditions. The index, initially defined for 30 arc-second pixels, is averaged at the municipality level and because it initially ranges from 0 to 1000, we divide it by 1000. More specifically, the database that is used is the GAEZ v4 dataset suitability index, with the climate data source CRUTS32 on the time period 1981-2010 for soybean, rainfed and with high input levels. Variables were also computed for the same database for rainfed crops, but the results are not displayed here.

Precipitation and temperature. Temperatures and precipitation are the year (in 2006) and municipality averages.

Infrastructures of the soy supply chain. We account for the presence of infrastructures in the neighborhood in order to represent the presence of agribusiness clusters. It has been previously observed that the soy processing facilities are correlated with other soy supply chain variables (R.D. Garrett et al., 2018). They can, therefore, be used as indicators of the presence of a well-developed soy cluster. Here, we compute dummies for each municipality across time that take value 1 if there is any facility within 100km of each polygon based on the storage facilities (to store the soybean grains) and crushing facilities (to process soybean into soybean meal or soybean oil) mapped in TRASE.

Cost of transport to ports. The mean distance through roads from the centroid of each municipality to the nearest active soybean port is computed as a proxy of the transportation costs. The distance is calculated for the years 2000, 2005, and 2010, based on the costs of transportation from Victoria et al., 2021. The initial maps in Victoria et al., 2021 were calculated taking into account the evolution of the road network and differential costs for paved roads, unpaved roads, and the absence of a road network. More information on their methodology can be found here <https://data.mendeley.com/datasets/6xbjzyz3th/2>.

Openness to trade. We differentiate the municipalities that are the most integrated in the international soybean trade with a dummy variable, taking 1 if the municipality under consideration has the highest share of exports than the median of the municipalities in 2006.

Herfindahl-Hirschmann index. This variable is used to measure the market concentration of soybean traders at the municipality or state level. The higher the index is, the more the market

¹⁰The Global Agro-Ecological Zoning, developed by the Food and Agriculture Organization of the United Nations (FAO) in collaboration with the International Institute for Applied Systems Analysis (IIASA), provides a standardized framework for the characterization of climate, soil and terrain conditions relevant to agricultural production. It identifies crop-specific limitations of climate, soil, and terrain resources in a consistent and empirically founded way.

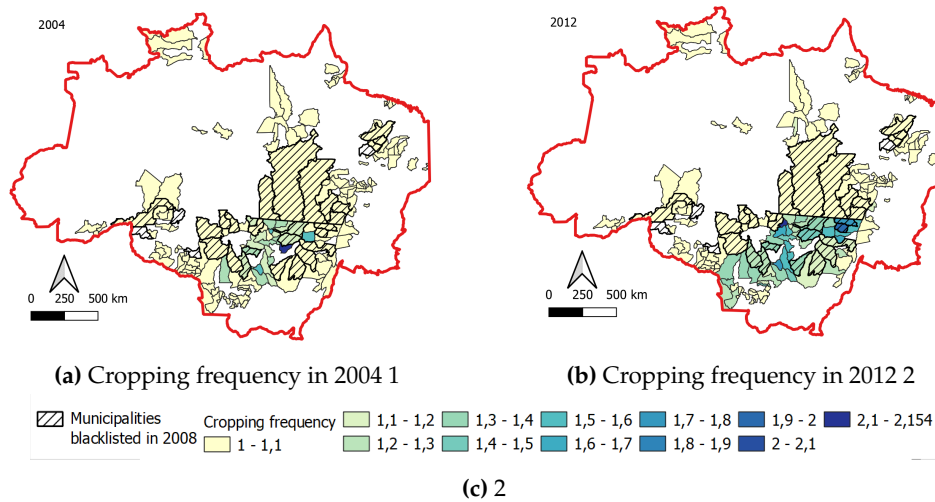


Figure A.1: Soy-corn cropping frequency in 2004 and 2012

is concentrated in the hands of a few traders. Both variables are calculated from the TRASE database.

Double-cropping. We use the same data (the IBGE-PAM dataset) and method as in J. Xu et al., 2021 to build our variables to quantify the impact of the plan on soy-corn double-cropping. The IBGE-PAM dataset contains separate records for first-season and second-season corn. We preprocess the dataset by (1) excluding the municipalities with more than three years of repeated values, because we consider that there might contain artificial data (2) by selecting only the municipalities with more than 4 years of consecutive records (for the validity of linear regression) (3) we exclude second season corn from municipalities where soybean is not planted (because considered not to be soybean-corn) (4) in the North-East, double-cropping is not possible due to unfavorable climate conditions, and the cropping season is late, so we move their second season corn recordings to the first season corn recording. Cropland expansion is defined as the increase in the harvested areas of main-season crops (soybean and first-season corn). A cropping frequency of 1 means that there was no double cropping, while a cropping frequency of 2 means that the entire soy production was in double cropping systems.

Table A.1: Description and data sources of the variables used in the model

Variable	Description	Unit	Time frame	Source
MPi	Intercept dummy for the presence in the Priority List	-	-	MMA
Def_area	Yearly increment of deforestation	m2	2002-2012	INPE/PRODES
Planted_area	Area planted with soybean, corn, cassava, rice, sugarcane, cotton, beans		2002-2012	IBGE/PAM
Prod_vol	Volume of production for the seven main crops	t	2002-2012	IBGE/PAM
Yield	Yields for the seven main crops	t/ha	2002-2012	IBGE/PAM
Cattle_heads	Number of heads of cattle	-	2002-2012	IBGE/PPM
Stocking_rate	Number of heads of cattle per hectare	heads/ha	2002-2012	IBGE/PPM and MapBiomass
Exp_soja	Volume of exports for soybean	t/yr	2004-2012	TRASE
Exp_soja_large	Volume of exports for soybean through large trading firms	t/yr	2004-2012	TRASE
upi_parea	Share of district area covered by strictly protected reserves	-	2002-2012	Cisneros et al., 2015
uus_parea	Share of district area covered by multiple use protected reserves	-	2002-2012	Cisneros et al., 2015
ind_parea	Share of district area covered by indigenous territory	-	2002-2012	Cisneros et al., 2015
settle_parea	Share of district area covered by settlement projects	-	2002-2012	Cisneros et al., 2015
soy_price_l1	lagged real local soy price	Reais	2002-2012	Cisneros et al., 2015
timber_price_l1	lagged real timber price	Reais	2002-2012	Cisneros et al., 2015
gdpcc_l1	lagged GDP per capita of the previous year	Reais	2002-2012	Cisneros et al., 2015 (IBGE)
muni_GDP	Municipal GDP	1000 Reais	2002-2012	Koch et al., 2019 (IBGE)

Table A.1 continued from previous page

Variable	Description	Unit	Time frame	Source
SL_soy	Suitability index for Soybean	-	-	GAEZ v4
PT	Precipitation x Temperature	mm/an.°C	-	
d_storage	Intercept dummy for the presence of soy storage facility within 100km	-	2004-2014	TRASE
d_crushing	Intercept dummy for the presence of soy crushing facility within 100km	-	2004-2014	TRASE
dist_ports	Cost of transport to the nearest port	-	2000, 2005, 2010	Victoria et al., 2021
d_open	Intercept dummy for the municipalities exporting the most	-	2006	TRASE
HHI	Herfindahl-Hirschmann index	-	2004-2014	TRASE

A.2 Placebo tests and linear time-trend correction

Beyond the visual support for the assumption of parallel trends, we employ a more formal approach to provide additional support. A placebo treatment test is conducted on the pre-policy data on all the tested outcomes. The policy timing is falsified and imposed in 2005, 2006 or 2007. Apart from that, the specification is the same as in the difference-in-differences exposed earlier, using fixed effects and covariates. There should be no significant treatment effect to ensure that the trends between the two groups were the same before the policy intervention. For all variables except pasture area and rice area, we fail to reject the parallel trends in the pre-period. Of course, this is not enough to establish the validity of the assumption of parallel trends. But we have other reasons to think that there are no factors that could have differentially affected each group. Besides the levels of deforestation, the municipalities are not that different. The restriction on the municipalities producing soybeans in the Legal Amazon region is likely to have selected more similar municipalities, and they are mostly all located in the area of deforestation. The main concern that remains is the stock of pasture which is likely to be higher in the prioritized municipalities and could affect the future dynamics of land uses. There is a higher potential for prioritized municipalities for soybean expansion. To account for that, we run the same difference-in-differences regression and add initial conditions interacted with a time linear trend. As initial conditions, we use the soil suitability to grow soybean and the shares of land used as pastures and soybean in 2006. We find consistent results (Table A.6 and Table A.7).

Table A.2: Pre-treatment ‘Common Trends’ test: deforestation and soy

	Deforestation	Soybean area	Soybean volume	Soybean exports	Soybean yields
Treated Group x Year=2005	-0.0643 (0.128)	0.76 (0.533)	0.818 (0.533)	0.594 (1.08)	0.096 (0.131)
Treated Group x Year=2006	0.00704 (0.129)	0.56 (0.425)	0.582 (0.481)	0.691 (1.49)	0.0579 (0.1)
Treated Group x Year=2007	-0.126 (0.149)	0.0221 (0.558)	-0.0044 (0.641)	0.686 (1.03)	-0.0338 (0.143)
Nobs	644	644	644	644	644

Table A.3: Pre-treatment 'Common Trends' test: deforestation and soy: pasture and cultivated area

	Pasture area	Crops area	Crops without soybean area
Treated Group x Year=2005	0.0514*** (0.0159)	0.0301 (0.0914)	-0.047 (0.101)
Treated Group x Year=2006	0.04*** (0.0129)	0.00633 (0.0901)	-0.12 (0.102)
Treated Group x Year=2007	0.0283** (0.0128)	-0.0215 (0.081)	-0.0755 (0.0812)
Nobs	644	644	644

Table A.4: Pre-treatment 'Common Trends' test: crops

	Cotton	Rice	Sugarcane	Cassava	Corn
Treated Group x Year=2005	0.0789 (0.298)	-0.19 (0.124)	0.0574 (0.185)	-0.049 (0.197)	0.127 (0.15)
Treated Group x Year=2006	-0.17 (0.267)	-0.294** (0.129)	0.318 (0.265)	-0.108 (0.182)	0.132 (0.144)
Treated Group x Year=2007	0.104 (0.27)	-0.222* (0.114)	0.27 (0.247)	-0.123 (0.161)	0.106 (0.122)
Nobs	644	644	644	644	644

Table A.5: Pre-treatment 'Common Trends' test: yields

	Pasture	Cotton	Rice	Sugarcane	Cassava	Corn
Treated Group x Year=2005	-0.00838 (0.0243)	0.0514 (0.0668)	0.00428 (0.0488)	-0.0124 (0.136)	0.0349 (0.0619)	-0.0175 (0.0379)
Treated Group x Year=2006	-0.00597 (0.026)	-0.0493 (0.0769)	-0.0322 (0.0424)	0.0768 (0.21)	0.0416 (0.0488)	0.00653 (0.0376)
Treated Group x Year=2007	-0.00885 (0.0382)	0.0296 (0.0751)	-0.0355 (0.0421)	0.144 (0.12)	0.0417 (0.047)	0.011 (0.037)

Table A.6: Regression of IHS-transformed deforestation rates and cultivated areas of the main crops - with time linear trend correction

	Def (1)	Pasture (2)	Crops (3)	Other crops (4)	Soy (5)	Cotton (6)	Rice (7)	Sugarcane (8)	Cassava (9)	Corn (10)
did	-0.498*** (0.114)	0.008 (0.021)	0.039 (0.092)	-0.077 (0.078)	0.798** (0.388)	-0.383** (0.176)	0.036 (0.131)	-0.738** (0.371)	-0.275* (0.155)	0.060 (0.198)
Observations	1,449	1,449	1,449	1,449	1,449	1,449	1,449	1,449	1,449	1,449
Adjusted R ²	0.856	0.994	0.942	0.923	0.862	0.879	0.777	0.820	0.894	0.847

Note: * p<0.1; ** p<0.05; *** p<0.01

Table A.7: Regression of IHS-transformed yields of the main crops and stocking rates - with time linear trend correction

	Cotton (1)	Rice (2)	Sugarcane (3)	Cassava (4)	Corn (5)	Soja (6)	Stocking rate (7)
did	-0.099 (0.062)	0.024 (0.040)	-0.530 (0.331)	0.008 (0.039)	0.075 (0.049)	0.108 (0.099)	0.026 (0.024)
Observations	1,449	1,449	1,449	1,449	1,449	1,449	1,449
Adjusted R ²	0.822	0.649	0.768	0.744	0.772	0.733	0.918

Note: * p<0.1; ** p<0.05; *** p<0.01

A.3 Generalized Synthetic Control

Table A.8: Average Treatment Effects using difference-in-differences and generalized synthetic control. Dependent variable: Agricultural areas

<i>Dependent variable: agricultural areas</i>				
	Pasture	Crops	Soybean	Other crops
	(1)	(2)	(3)	(4)
<i>Difference-in-differences</i>	0.0200	0.0223	0.734*	-0.091
	(0.0214)	(0.0948)	(0.385)	(0.0845)
R2	0.994	0.94	0.862	0.917
Obs	1449	1449	1449	1449
GSC	0.0485**		0.782*	
	(0.0245)		(0.400)	

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Regressions with controls, municipality fixed effects and year fixed effects.

Robust standard errors in parentheses are clustered at the municipality level.

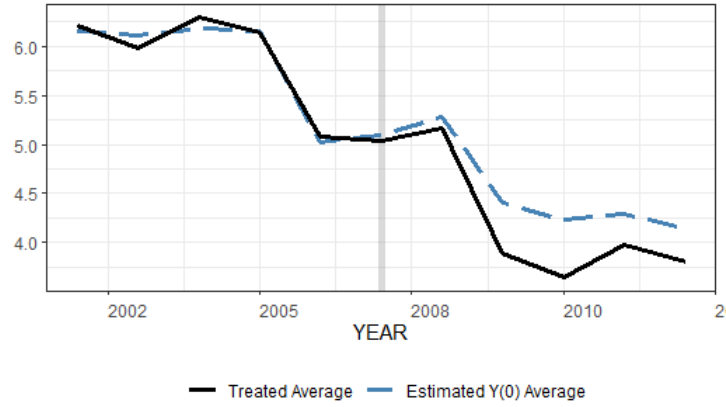


Figure A.2: Generalized synthetic control counterfactual for deforestation rates

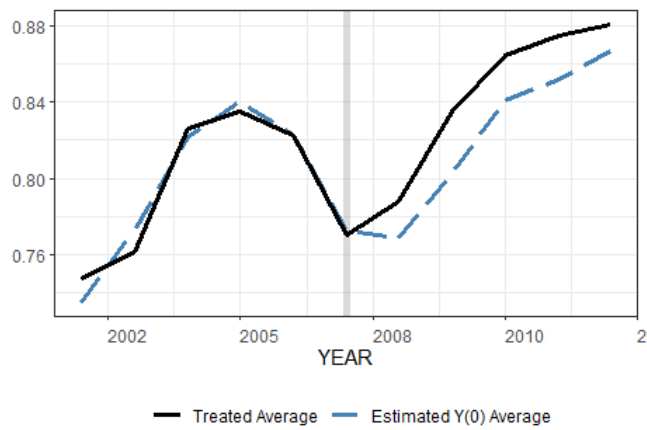


Figure A.3: Generalized synthetic control counterfactual for stocking rates

A.4 Multiple time periods

We leverage the Callaway et al., 2020 estimator to estimate the effect of the Priority List on the soybean area across time and different waves of treated groups. The control group is the "not-yet-treated units" instead of "never-treated units" to leverage most of our sample, meaning the municipalities prioritized in 2009 and 2011 belong to the control group before their year of treatment.

In the case of the difference-in-differences with multiple time periods, the identifying assumptions are (Callaway et al., 2020):

- Irreversibility of the treatment. In our case, this does not hold, as there is the possibility to be removed from the Priority List. This is the case for 6 municipalities from the 2008 group. One is removed in 2010, one is removed in 2011 and four others are removed in 2011. However, we can suppose that once a municipality is removed from the Priority List, there is still enhanced monitoring from the local authorities to prevent returning to the list. Also, to get out of the list, the licensing and geo-referencing requirements were already accomplished, and may have lasting effects. Finally, the potential supplementary measures taken by governments, like local plans for sustainable production, are likely to be still up to date., random sampling, limited treatment anticipation ¹¹
- Conditional Parallel Trends based on a "Never-Treated" Group or based on a "Not-yet-Treated" Group (which is a generalization of the two-period parallel trend assumption). It states that conditional on covariates, the average outcomes for the group first treated in period g and for the never-treated / not yet treated group would have followed parallel paths in the absence of treatment
- Overlap: a positive fraction of the population starts treatment in period g , and that, for all g and t , the generalized propensity score is uniformly bounded away from one.

¹¹The criteria are based on the past three years, so there is little room for anticipation. Moreover, the trends in deforestation rates do not suggest any anticipation effect.

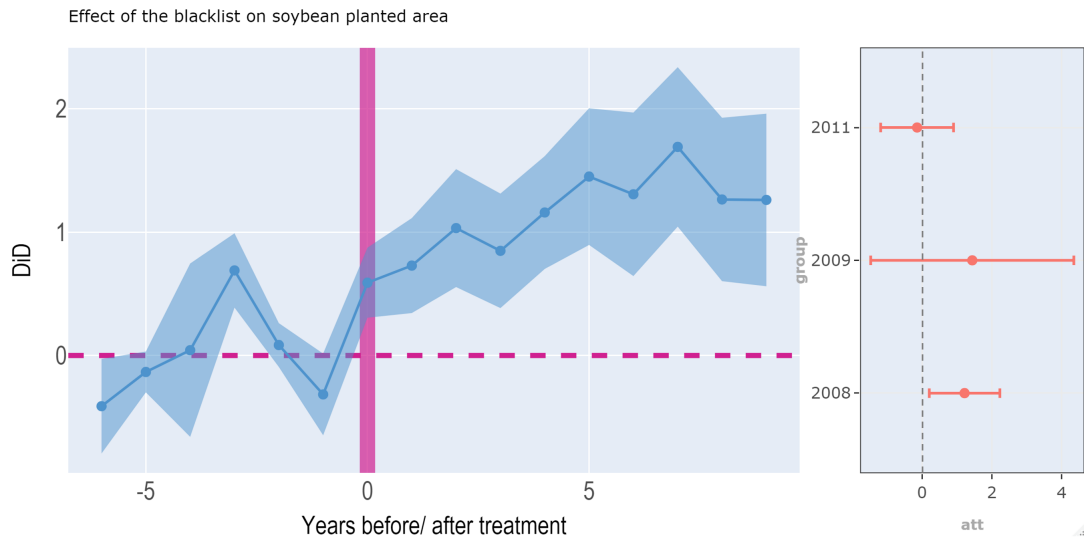


Figure A.4: Average treatment effect on soybean area across time and treated groups with the Callaway et al., 2020 estimator

A.5 Leakages

The program may lead to leakage to neighboring municipalities. The program could either deter deforestation because it could be more easily detected by the authorities, or it could push deforestation pressure back into neighboring municipalities. The accompanying effect on soybeans could also go both ways. Leakages need to be measured to ensure the effectiveness of the policy and to verify that our estimates are not over- or underestimated by these potential effects. This is done by using the neighboring communes of the target communes as the treated units, and by removing the prioritized municipalities from the sample. The results are presented in Table A.9. No significant effect is found. It can, therefore, be assumed that the policy did not lead to a leakage effect.

Table A.9: Estimations of the leakages of IHS-transformed deforestation rates and cultivated areas of the main crops - with time linear trend correction

	Def (1)	Pasture (2)	Crops (3)	Other crops (4)	Soy (5)	Cotton (6)	Rice (7)	Sugarcane (8)	Cassava (9)	Corn (10)
Treatment effect	0.037 (0.149)	0.003 (0.020)	0.066 (0.125)	-0.014 (0.106)	0.114 (0.349)	0.349 (0.363)	-0.444 (0.286)	0.033 (0.238)	0.007 (0.113)	0.382* (0.206)
Observations	1,197	1,197	1,197	1,197	1,197	1,197	1,197	1,197	1,197	1,197
Adjusted R ²	0.813	0.993	0.942	0.927	0.861	0.886	0.773	0.840	0.904	0.860

Note: *p<0.1; **p<0.05; ***p<0.01

Chapter 2

Soy exporters' network and local production shocks

Abstract. Understanding how supply chains adapt to supply shocks is essential given their increasing complexity and remains an open question, particularly in the agricultural sector, which is yet highly vulnerable to extreme weather events. Additionally, companies also face regulatory risks, which can sometimes be assimilated to supply shocks, such as the new European Union regulation on deforestation. This chapter examines whether and how exporters adjust their trading networks in response to supply disruptions. To do so, we use the Standardized Precipitation Index, panel data regressions and network analysis at the municipality, transaction and firm levels. Exporters rely on established relationships to mitigate losses, but the supply chain as a whole exhibits some rigidity, with limited adjustments on the observed extensive margin. We draw implications for possible network adjustments for firms facing regulatory risks related to the sustainability of their soybean supply chains.

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2.1 Introduction

The disruptions of supply chains for critical goods and resources is one of the most cited expected global risks -led by extreme weather events- in the World Economic Forum's Global Risk Perception Survey 2023-2024 (World Economic Forum, 2024). Indeed, the growing complexity of supply chains means that supply shocks can have global consequences. Particularly since COVID, this has become the subject of a growing number of articles in the economic field. The profound effects of supply shocks on production networks have been illustrated in a series of events, including the Fukushima tsunami, earthquakes, floods, pandemic, heatwaves (Boehm et al., 2015; Castro-Vincenzi et al., 2024; Chacha et al., 2024; Inoue et al., 2019; Kashiwagi et al., 2021). Understanding how supply chains adjust to supply shocks is key and remains an open question, particularly within the agricultural sector, which is heavily vulnerable to changing climate conditions.

Besides, firms are also facing regulatory risks, which can sometimes be assimilated to supply shocks. The new European Union Deforestation Regulation (European Parliament and Council of the European Union, 2023), for instance, compels traders to prove that their supplies are deforestation-free. This requirement effectively introduces regulatory-induced supply shocks, as firms are now prohibited from sourcing from areas deforested after the cut-off date. The adjustments of the production networks generated by this new class of forest conservation policies will be a decisive factor in their success. Observing how supply chains adapt to shocks provides information about such potential network dynamics, which could, in the end, result in leakages, threatening the net effect on deforestation (Meyfroidt et al., 2018; Stokeld et al., 2023; Villoria et al., 2011).

This paper aims to empirically estimate how the soy supply chains in Brazil respond to local supply shocks. Insights about which supply chains are resilient to shocks, why, and who are the actors benefiting or losing from it could guide policymakers in their regulations on sustainable supply chains. To do so, we leverage the occurrence of droughts as an example of exogenous supply disruptions. To lessen the impact of supply shocks on their business, trading firms can either reallocate their purchases by leveraging a diversified network or relocate their operations to new municipalities. For firms, the costs of switching suppliers can be substantial (Barrot et al., 2016; Moxnes et al., 2018). It sometimes entails finding new commercial partners and new logistical routes to deliver merchandise to ports. This process takes time and contributes to the inertia of the supply chain.

Our paper is connected to three strands of the literature. First, it adds to the literature on the propagation of shocks in supply chains and the mitigation strategies of firms (Acharya et al., 2023; Barrot et al., 2016; Inoue et al., 2019; Kashiwagi et al., 2021; Lafrogne-Joussier et al., 2022; Pankratz et al., 2019). The ability of firms to cope with shocks depends on the specificity of the inputs (Barrot et al., 2016). Firms can use inventories as buffers against adverse shocks (Lafrogne-Joussier et al., 2022) and geographic diversification of input purchases (Castro-Vincenzi et al., 2024; Todo et al., 2014). We contribute to this literature by investigating the particular case of the exporting firms of the soybean supply chain in response to droughts. We also relate to the literature that addresses the effect of climate shocks on international supply chains and their effect on food security. Using trade network models, this literature demonstrates that the structure of commodity trade is key to the propagation of shocks and has major consequences for food security (Burkholz et al., 2019; Fair et al., 2017; Torreggiani et al., 2018). The articles rely mostly on trade between countries and do not consider the role of firms in the propagation of shocks. The third strand of literature this paper is connected to is the literature on the dynamics of the soybean supply chain (T. Reis, Ribeiro, et al., 2023; T. N. d. Reis et al., 2020). The authors of the TRASE database studied the “stickiness” - the stability in trading relationships between supply chain actors - of the soybean supply chain in Brazil (T. N. d. Reis et al., 2020). They find that stickiness differs substantially across traders in the soybean markets. Stickier traders are more likely to adopt zero-deforestation commitments, but the effectiveness of such commitments for stickier traders is lower (Leijten et al., 2022). A qualitative interview-based study by T. Reis, Bastos Lima, et al., 2024 describes the extent to which soybean supply chains differ in Brazil. In particular, the authors distinguish the strategies of farmers in consolidated regions, more capitalized and bound to cooperatives, in Southern Brazil, from those of farmers in frontier regions, more reliant on credit and commodity traders. They also point out that exporting firms tend to diversify their supply zones to mitigate climate risks. Instead of focusing on the dynamics of the supply chain in general, we focus on the response of the soy supply chain to exogenous shocks.

The present study is based on monthly precipitation data, land cover data from MapBiomas v.2., and on trade data at the municipality- and exporter-level originating from TRASE. We employ panel data regressions to estimate the effect of droughts on municipal agricultural production, trade flows and exporting firms exposed to shocks. The geographical variations of droughts are leveraged to identify the effects on the supply chain. Our weather shocks indicator is based on monthly negative precipitation anomalies and accounts for the shocks' timing. Firms differ in their exposure to extreme weather events as a result of the size and geography of their sourcing

network. We measure firm exposure to weather shocks using the past sales-weighted-average of the weather anomalies across all their locations. The effect of the shock on firms is measured along two dimensions: whether production or purchases drop and whether supplier links are maintained. To do this, simple network measurements are adopted, such as the number of lost links and the number of new links.

We confirm that droughts negatively affect soybean yields, leading to a decline in production. Our main finding is that this in turn has downstream effects on the soybean supply chain, with implications for the network dynamics of exposed exporting firms. Exporters engage in mitigation strategies to cope with the losses. They rely on established relationships in their network to compensate for volume losses. However, the buyer-seller network shows some inertia, with adjustments occurring mainly at the intensive margins between suppliers and exporters. The results indicate that exporting firms do not easily enter into new contracts, suggesting that there is some friction in the soybean supply chain. This has implications for the potential trade adjustments following concerns on suppliers' compliance with anti-deforestation trade regulations.

The rest of the article is organized as follows. Section 2 presents the context and the data and explains how weather shocks are computed at the municipality level. Section 3 explains the identification strategy. Section 4 presents and analyses the results of the panel estimations for the municipalities affected by the shocks and for the trading firms directly exposed to the shocks. Section 5 discusses the results and concludes.

2.2 Data and context

2.2.1 Case study

Brazil's rural landscapes have seen an impressive expansion in soybean area, in response to booming demand from countries like China. This expansion, which has made Brazil the world's leading soybean producer since 2019, has come partly at the expense of the Amazon rainforest and the Cerrado. This has brought sustainable development concerns of large trading firms into the spotlight, particularly with regard to deforestation. As a prominent example, in May 2023, the European Union adopted the new Regulation on "deforestation-free products" (Regulation (EU) 2023/1115), which covers seven commodities, including soy, and their derived products. Under the regulation, the actors in the supply chain (e.g., operators or traders) must demonstrate that the products placed on the European market do not originate from recently deforested or degraded land. In the context of a changing regulatory landscape, the difficult trade-off of traders between

maintaining supplier relationships and adapting their sourcing network to new regulatory risks is a key issue. Some traders claim in their ESG reports their commitment to working alongside with suppliers, thus ensuring compliance of suppliers to regulations and preserving access to some foreign markets.

The Brazilian soybean market is characterized by an oligopolistic structure, with many farmers and a few dominant traders. Some large traders have established a stable supplier base, anchored by financial commitments such as credit to farmers, investment in infrastructure, and future contracts. At the same time, there is an emerging class of volatile traders operating on the spot market. Securing a reliable and stable supply chain is crucial for traders, who are increasingly seeking to minimize the climatic risks associated with their sources of supply (T. Reis, Bastos Lima, et al., 2024).

Indeed, recently Brazil has been increasingly affected by more frequent and intense droughts. These shocks can be attributed to climate change, local climate effects of deforestation, and the occurrence of the El Niño and La Niña phenomena (Getirana et al., 2021; J. A. Marengo et al., 2022; Rodrigues, 2023), which have contrasted effects on the Brazilian soy production (Iizumi et al., 2014). About 90% of the soy cultivated area in the Amazon and Cerrado region is rainfed (Rattis et al., 2021), leaving production unprotected from drought events. Several droughts have already lowered Brazilian soybean yields in the past years, and these risks are set to increase in the future (Rattis et al., 2021). Climate change, particularly in the form of extreme events, is a major factor in the perception of risk among soy producers in Brazil (Dou et al., 2023; D. S. Silva et al., 2023). According to (Stokeld et al., 2023), there are a number of possible outcomes if a soy farmer is unable to fulfill a contract he has already signed with a trader, and these depend very much on the relationship with the trader. The contract could be renegotiated, soy farmers could go into debt, pay a fine or the cost of soy on the market, the contract could be postponed until the following year, or farmers could face legal action.

2.2.2 Local weather anomalies

We construct weather shock time series, aggregated at the year-level and municipality-level.

The rainfall data are obtained from Worldclim 2.1. (Fick et al., 2017). This database provides monthly precipitation data (along with maximum and minimum monthly temperatures) with a resolution of 2.5 minutes (~ 21 km² at the equator), from 1970 until 2018. We use the Standardized Precipitation Index (SPI) as an indicator for drought hazard, as it is one of the most common

methods used. The first step is to calculate the average and the standard deviation of monthly climate data for the period 1970-2000. They serve as a reference for the calculation of weather anomalies. Monthly negative anomalies are dummies calculated as follows for each grid cell and each month of 2004-2018. A negative precipitation anomaly, represented by a dummy equal to one, corresponds to a deviation from the historical means toward drier conditions.

$$prec_{i,m,t} < mean(prec_{i,m,1970-2000}) - 2 * sd(prec_{i,m,t}) \quad (2.1)$$

where i is the pixel, t the year and m the month.

Rattis et al., 2021 show that precipitations (along with Vapor Pressure Deficit) explain a large portion of the variability in soybean historical yields in Brazil, which justifies using precipitation as an indicator for agricultural weather shocks. Weather shocks are relevant for our analysis only if they affect soy production. They can affect soybean yields if they occur during the growing or flowering seasons. That is why we retain only the shocks occurring during these periods of the development of the plants. To determine the relevant shocks for soybean production, we use agricultural calendars provided by the Agricultural Market Information System¹ and keep the months between September and March.

The rest of the data is defined at the municipality level. We therefore need to aggregate the weather data at this level. We follow Rorato et al., 2023 and aggregate the anomalies in space by calculating the average area of a municipality affected by a weather anomaly for each month between September of year $t - 1$ and March of year t . To aggregate the shock across time, we sum the weather anomalies, following Kuwayama et al., 2018, in order to make the indices easier to interpret. The resulting weather shock measure is a continuous variable, representing the number of months of the soy cultivation season in which a municipality experiences dry weather shock, weighted by the share of the area of a municipality affected that month. A value of 7 therefore indicates that the entire municipality was affected by a weather anomaly for each month from September in $t - 1$ to March in t . This situation is extremely rare, especially as we consider a high threshold to define a drought (below 2 standard deviations, while the literature sometimes uses 1.5 as a threshold). For this reason, the maximum observed in our sample is 3.85. When positive, the average anomaly value is 0.77 (equivalent to a situation where at least 77% of a municipality experiences an extreme weather event every month). 1100 of the 2392 soy-producing municipalities have been affected at least once by a negative precipitation anomaly between 2004

¹The Agricultural Market Information System data can be retrieved at the following <https://www.amis-outlook.org/amis-about/calendars/soybeanca1/en/>

and 2018, affecting 13% of the production and exports.

2.2.3 Trade data

The weather shocks are coupled with data recording the transactions of soy between municipalities and exporting firms in tons and value, stemming from TRASE (Godar, 2018).

TRASE² is a unique dataset that has the great advantage of presenting the soy supply chains from Brazil across years, including the exporting firms and consumer countries (and their associated deforestation). The data are freely available and record the yearly values and volumes of soy transactions in Brazil from sourcing municipalities to exporters, importers, and destination countries. We use the data from 2004 to 2018 in our analysis. One limitation of this dataset is that it is partially modeled. While the route from the logistic hubs to destination countries is data-driven (until 2017), the part of the route from the production municipality to the port is model-driven, using the SEI-PCS methodology, typically based on trade costs, optimization methods, known assets, and facilities. Also, a share of the soy trade is not attributed (12%). In the sample, from 2004 to 2018, there are 2496 soy-producing municipalities (among the 5570 Brazilian municipalities), 2392 soy-exporting municipalities and 864 exporting firms during the period.

2.2.4 Other data

We also rely on the soy yields reported at the municipality level by the Brazilian Institute of Geography and Statistics (IBGE) for our analysis. It is likely that soy producers are heterogeneously exposed to weather shocks over time and space, due to differences in technological adoption (GMOs, tractors, etc.), or the incidence of disease or pests. Unfortunately, we cannot take this into account because, to the best of our knowledge, no such data are available at the municipal level and throughout the years. Nevertheless, the analysis includes a heterogeneity analysis based on the MAPSPAM database (Ru et al., 2023), which presents agricultural techniques used in Brazil in 2010, with maps, including input intensity and irrigated area.

2.2.5 Summary statistics

Table 2.1 reports some facts about the extreme weather events regarding precipitation deficits. For each year, we observe a weather shock, although the extent of it varies considerably across the years. In 2009, 417 soy-producing municipalities and 17% of the exports were affected by a shock, while in 2014, only 20 municipalities and less than 1% were hit. In the scientific literature, it is documented that the Cerrado region experienced severe droughts in 2007 and 2017, and the

²The TRASE data can be retrieved at the following <https://trase.earth/open-data>

Amazon region in 2005, 2010 and 2015 (Jimenez et al., 2016; J. Marengo, 2015; Panisset et al., 2017; Rattis et al., 2021). It should be noted that Table 2.1 assigns the shocks from September to December to the following year, in which harvesting potentially takes place.

Table 2.1: List of droughts

Year	# of mun.	# of mun. with soy	Prod. affected (%)	Exports affected (%)	# of exporters
2004	197	197	0.13	0.13	68
2005	335	310	0.20	0.19	97
2006	48	39	0.05	0.06	46
2007	21	18	0.02	0.02	55
2008	159	151	0.26	0.25	171
2009	458	417	0.20	0.20	141
2010	44	34	0.09	0.11	75
2011	14	12	0.04	0.06	56
2012	79	67	0.03	0.04	65
2013	208	188	0.32	0.32	271
2014	20	17	0.04	0.06	65
2015	211	187	0.15	0.16	177
2016	391	349	0.27	0.23	224
2017	37	29	0.04	0.04	49
2018	51	44	0.06	0.07	83

Notes: List of the weather anomalies (negative precipitations). The table describes the number of affected municipalities, the number of affected municipalities producing soybean, the share of the affected production, the share of the affected exports, and the number of affected exporters. Shocks occurring between September and December are reported the following year.

Figure 2.1, showing the regional distribution of the frequency of weather shocks, suggests that weather shocks do not hit regions randomly. Most municipalities witnessed at least one weather shock during the period. Some municipalities were hit by a shock nearly every year. In order to account for the non-random distribution of the shocks, we follow Borusyak et al., 2020 and include a counterfactual shock.

Table 2.2 provides descriptive statistics for the three samples at the municipality-level, exporter-level, and municipality-exporter level. The firm or a municipality enters the sample when it is active for the first time. In the export year dataset, removing observations prior to market entry reduces the number of observations from 15660 to 8629. The municipality sample contains 2392 municipalities, the exporter sample contains 864 firms and the exporter-municipality sample contains 13158 municipality-firm pairs. The high number of zeros in the table indicates that actors do not always remain active in the soy market from one year to the next.

Cleaning the trade data

Table 2.2: Descriptive statistics

	Obs.	Mean	Sd	p10	p50	p90
<i>Municipality sample (2392)</i>						
Production (t)	27302	36964.81	102819.27	0	7194.95	83528.31
Exports (t)	27302	26068.94	88909.88	0	1827.60	59081.67
Yield (ton/ha)	25427	2.72	0.68	1.80	2.80	3.50
# customers	26094	1.04	1.24	0	1	2
Dummy shock	27302	0.08	0.28	0	0	0
Shock	27302	0.07	0.14	0	0	0
<i>Exporter sample (864)</i>						
Exports (t)	3859	181407.92	903522.76	0	1495.98	173822.97
# suppliers	3859	6.59	28.40	0	1	10
# new suppliers	3737	4.06	17.10	0	0	6
Duration of rls. with supplier	2253	3.59	2.91	1	2.85	8
Firm shock dummy	3859	0.14	0.35	0	0	1
Firm shock	3859	0.07	0.14	0	0	0
<i>Exporter-municipality sample (13158)</i>						
Exports (t)	93019	7525.92	33243.21	0	0	15855.30
Own shock (dummy)	93019	0.08	0.27	0	0	0
Own shock	93019	0.07	0.14	0	0	0
Peer shock (dummy)	93019	0.15	0.35	0	0	1
Peer shock	93019	0.28	0.97	0	0	0.62

Notes: Summary statistics of the variables used in the analysis. The sample is restricted to the period 2004-2018.

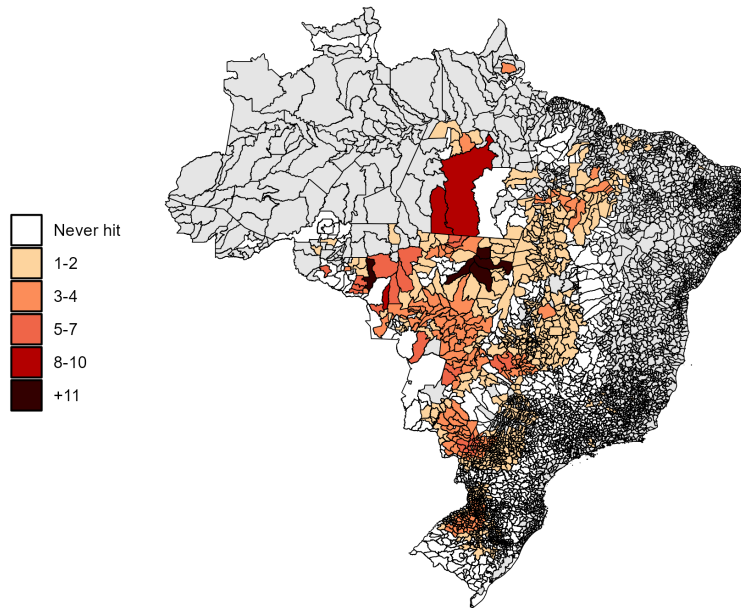


Figure 2.1: Frequency of extreme weather events in Brazilian municipalities (2004-2018)

The first concern relates to the high volatility of the soy supply chain. 376 of the 864 firms trade only one year; 479 less than 2 years; 558 less than 3 years; 614 less than 4 years. This considerably narrows the potential for analyzing firm behavior over time. To address this feature, we restrict the sample to firms trading for at least three years over the period. In the initial dataset, there are 161,154 transactions, whereas in the processed dataset, the number of transactions is reduced to 93,019. This represents 19% of the traded volume withdrawn from the sample.

Note also the large coverage trading firms that rely on very few suppliers. This limits the relevance of the analyses on interactions between suppliers of the same firm when a shock occurs. 113 firms have ten or more suppliers, while 832 firms have less than 3 suppliers in a single year.

2.3 Identification strategy

2.3.1 Supply shocks and potential responses of exporters

Our main research question is the response of supply chains to supply shocks. This involves examining the effects of droughts at different levels. Figure 2.2 summarises the various effects tested. Our experimental design implicitly assumes that droughts do indeed create a supply shock for soy harvests and thus affect the ability of farmers to export. The indicator of drought may be inappropriate, there may be effective farming strategies to adapt to weather shocks, such

as changes in sowing dates, or the shock may be too small to cause disruption to the downstream network. Our first step is, therefore, to validate this hypothesis by measuring the direct adverse effect of the shock on municipalities (number 1 in Figure 2.2, subsection 2.3.2 for the description of the identification strategy).

Identifying the reaction of exporters to supply shocks also assumes that there is a disruption in trade flows from the affected suppliers. In fact, the expected effect is not straightforward. The literature describes various types of lock-in between farmers and exporting companies, due to relationships of trust, ownership of infrastructure or technological and financial contracts (T. Reis, Ribeiro, et al., 2023). These could justify maintaining relations even in the event of shocks. Farmers can prioritize selling their grains to certain powerful traders with whom they have long-term contracts or a solid relationship. We investigate the direct effect on the trade flows and associated heterogeneities (number 2 in Figure 2.2, strategy described in subsection 2.3.3).

Next, we aim to validate the idea that supply shocks are transmitted downstream by examining the impact on exporters at the aggregate level (number 3, subsection 2.3.4). The transmission of shocks is theoretically ambiguous. Exporters can dissipate the effect of a shock by resorting to multiple sourcing (Acharya et al., 2023) or inventories (Lafrogne-Joussier et al., 2022). On the other hand, exporters who depend on a few suppliers or who sell specific products (Barrot et al., 2016) could be indirectly affected.

Last, we consider the coping strategies of firms. There are two testable strategies for offsetting the impact: relying on historical suppliers (number 4, subsection 2.3.3), by increasing supplies from these municipalities; or turning to new suppliers.

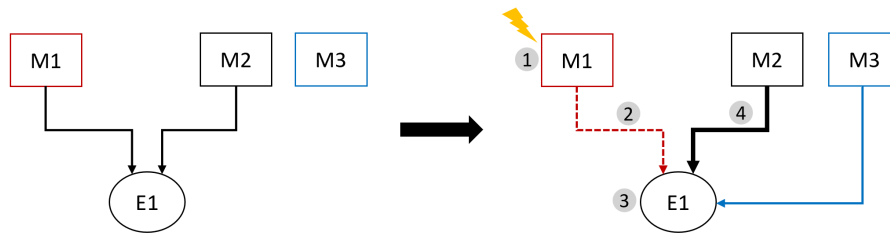


Figure 2.2: Tested effects of a supply shock

Note: M denotes the municipalities and E the exporters. In this example, M1 is affected by a drought while M2 and M3 are not.

2.3.2 Measuring the effect of weather shocks on suppliers

We employ panel regression methods to identify the effect of weather shocks on municipalities.

We test the effect on yields, levels of production, and exports using the following model:

$$y_{m,t} = \alpha_0 + \alpha_1 \text{shock}_{m,t} + \alpha_2 \sum_{l=t-4}^{t-1} \text{shock}_{m,l} + \sum_j \beta_j X_{m,t} + \mu_m + \pi_t + \epsilon_{m,t} \quad (2.2)$$

for municipality m in year t . The municipality fixed-effects (μ_m) control for unobserved, time-invariant characteristics of each municipality that might influence its vulnerability to weather shocks, such as soil quality or access to irrigation. The year fixed-effects (π_t) absorb general trends affecting all municipalities, such as changes in agricultural technologies or global soy prices. The regression therefore captures the variations of y within municipalities over time.

When the dependent variable is the yields, y is log-transformed and an OLS estimator is used for the equation 2.2. For production and exports, we employ a PPML estimator to estimate the equation 2.2, following the standard procedure for analyzing trade flows (J. M. C. S. Silva et al., 2006), which accounts for zero-trade flows.

We control for the past weather shocks to account for their potential lasting effects on current agricultural outcomes and thus isolate the impacts of the current weather shock. We also incorporate controls for extreme temperature anomalies and positive precipitation anomalies, following the method exposed in section 2.2.2. These controls ensure that our estimates of the impact of droughts are not confounded by other climatic variables, which are also likely to affect agricultural outcomes. Standard errors are robust and clustered at the municipality level. The coefficient α_1 captures the effect of the drought on the agricultural outcomes, and we expect it to be negative.

The identification rests on the assumption that rainfall and temperature in a given year are random after controlling for municipality and year effects, which is likely to hold. But it also makes the assumption that the effect of droughts is uniform in time and space, which is less

realistic. The production of municipalities with high rainfall in ordinary times, when faced with a negative precipitation anomaly compared to their historical average, is likely to be less affected. One way to tackle this would be to use new methods controlling for heterogeneous treatment effects (e.g. Chaisemartin et al., 2022).

2.3.3 Measuring the effect of weather shocks on trade flows

Affected trade flows

We then turn to our main focus, which is not the disruption to the suppliers themselves, but rather the impact on the trade relations. We identify the effect of direct shock on trade flows by relying directly on the database of the transactions. We use the following regression, where δ captures the effect of the shock and is expected to be negative.

$$y_{f,m,t} = \alpha_0 + \delta * \text{shock}_{m,t} + \alpha_2 \sum_{l=t-4}^{t-1} \text{shock}_{m,l} + \alpha_f + \mu_m + \pi_t + \epsilon_{f,m,t} \quad (2.3)$$

The firm fixed-effects absorb differences in levels of exports across firms (f), the municipality fixed-effects absorb differences in levels of exports across municipalities and year fixed-effects absorb general trends in exports across years. Standard errors are robust and clustered at the municipality level. We use a PPML model when $y_{f,m,t}$ is the level of exports and a linear probability model when $y_{f,m,t}$ is a dummy representing the existence of a trade relationship.

"Peer" shock

We then turn to the examination of the firm adaptation strategies consecutive to weather shocks. To see if there are positive spillovers within a firm's existing network, we examine the sales from a municipality to a firm after the other suppliers of the same firm were hit by a shock. In other words, we investigate whether exporters compensate for the loss of production by increasing their purchases from other suppliers of their network. The regression takes the following form:

$$y_{f,m,t} = \delta * \text{Peer Shock}_{f,m,t} + \alpha_f + \alpha_{m,t} + \epsilon_{f,m,t} \quad (2.4)$$

This linear regression measures the impact of a "peer shock" ($\text{Peer Shock}_{f,m,t}$) on the volume of purchase of firm f from municipality m at t ($y_{f,m,t}$). Firm fixed effects (α_f) absorb differences in sales between firms, while municipality and year fixed effects ($\alpha_{m,t}$) absorb fluctuations at the municipality level that can impact a municipality's export levels over time (including weather variations). Thus, the sales of a supplier affected by a peer shock to an affected buyer are compared to the sales of this same supplier to an unaffected buyer. The first transaction from the

supplier is affected by a "peer shock", while the second is not. Standard errors are clustered at the municipality level. If positive spillovers on the "peer" suppliers are detected, δ should be significant and positive. Following prior studies on firm networks (Acharya et al., 2023), the peer shock is defined as:

$$\text{Peer Shock}_{f,m,t} = \log\left(1 + \sum_{m' \neq m} \frac{\text{Volume}_{f,m',t-2}}{\text{Volume}_{f,m,t-2}} \text{shock}_{m',t}\right) \quad (2.5)$$

Its value is 0 when m is the only supplier of f (in that case, there is indeed no peer shock), or when there is no supplier which is affected by a shock. This variable takes higher values when the historically important sourcing municipalities of the firm (compared to municipality m) are affected by a shock. Because the peer shock is computed using the transactions two years before the shock as a reference network, the first two observations of each firm are removed from the sample.

2.3.4 Measuring the aggregate effect on trading firms

Once an effect is confirmed and quantified at the municipality and trade flow level, we explore whether an aggregate effect can be detected at the aggregate firm-level i.e., across all suppliers.

To do so, we need to define who the affected customers are. An exporting firm is affected by a disaster if a significant share of its suppliers is hit by a weather shock. Hence, we define the exposure of a firm f to a weather shock in t as the fraction of its traded volume in the past years coming from municipalities affected by a shock in t . There are several possibilities to calculate the fraction. We choose to define the share as the average share of the volume traded by the firm from a supplier in the first three years before³.

$$E_{f,t} = \sum_{i=1}^N s_{f,i,t-4:t-1} \text{shock}_{i,t} \quad (2.6)$$

$s_{f,i,t-4:t-1}$ represents the volume of purchases that firm f makes from municipality i , relative to firm f 's total purchases. N is firm f 's total number of suppliers. $\text{shock}_{i,t}$ is the same variable as in 2.3.2. The index is standardized in order to be easier to interpret.

The effect of weather shocks on exporting firms is determined along two dimensions: how volumes of exports vary and how firms change their sourcing patterns in response to the events. The volumes of exports are the transactions' volumes aggregated at the year and firm level. The network modifications are simply measured as the number of total relationships, terminated re-

³Other specifications are tested in the robustness section (2.4.5).

relationships and new relationships. In both cases, we estimate the following relationship for firm f at year t with PPML models.

$$y_{f,t} = \alpha_0 + \alpha_1 E_{f,t} + \alpha_2 \sum_{l=t-4}^{t-1} E_{f,l} + \alpha_3 Eplac_{f,t} + \mu_f + \pi_t + \epsilon_{f,t} \quad (2.7)$$

α_1 is the coefficient of interest. The firm fixed effects capture fixed differences in the behavior of each firm since T. N. d. Reis et al., 2020 shows that there are substantial differences across firms in their trade persistence. The year-fixed effects capture common time-specific shocks in the Brazilian soybean sector, which include, for example, changes in prices or demand. We control for the past firm exposure to weather shocks and cluster standard errors at the firm level.

The regression model includes the term $\alpha_3 Eplac_{f,t}$. This term represents a counterfactual shock aimed at mitigating the potential bias arising from the non-random exposure of firms to weather shocks. Indeed, as depicted in Figure 2.1, weather shocks are not uniformly distributed across regions. Municipalities in the Mato Grosso region, for instance, tend to experience more frequent shocks than others. Consequently, firms may be non-randomly exposed to weather shocks based on their geographical location. Intuitively, a bias could emerge because certain firms are systematically more exposed to exogenous shocks, leading them to exhibit different behaviors not solely due to the shock itself but rather due to their exposure. The confounding factor here is the expected treatment. Borusyak et al., 2020 propose a solution to avoid the omitted variable bias. The idea is to specify valid counterfactual exogenous shocks and recalculate the instrument using them. The treatment with these counterfactual shocks is then averaged for each observation. The expected treatment can also be incorporated as a control.

We adopt a similar approach in our study. Municipalities are categorized into five classes based on the frequency of shocks they experienced over the period. For each year, we randomly shuffle the weather anomalies among the municipalities within the same class. This process yields 250 counterfactual shocks for each year and municipality. The municipality-level counterfactual shock is computed with the same "shares" as in equation 2.6 multiplied by the average of the 250 counterfactual shocks. This counterfactual shock serves as a control.

To take the analysis a step further and understand which type of firm is most affected, we then perform heterogeneity analyses. We interact the shock with selected firm characteristics C and run the following regression.

$$\begin{aligned}
y_{f,t} = & \alpha_0 + \alpha_1 E_{f,t} + \gamma_1 E_{f,t} \cdot C_{f,t-1} + \alpha_2 \sum_{l=t-4}^{t-1} E_{f,l} + \alpha_3 E_{plac_{f,t}} \\
& + \alpha_4 E_{plac_{f,t}} \cdot C_{f,t-1} + \mu_f + \pi_t + \epsilon_{f,t}
\end{aligned} \tag{2.8}$$

2.4 Empirical results

2.4.1 Direct effect on agricultural production of the municipalities

Our first objective is to ensure that our shock measurement is valid. To do this, we verify that yields are adversely affected by drought shocks.

Table 2.3 reports the direct effect of the shocks on the yields, production and exports. The yield variable is extracted from the IBGE database and is detrended so that the technological progress is not captured in the coefficient. We find that yields decrease by 6% for each additional month of drought that would affect the entire municipality during the cultivating period, using a threshold of 2 for the calculation of the SPI. This justifies using the precipitation anomaly variable as a shock degrading soy production. This result is consistent with that of Rattis et al., 2021, who report that, in the same period, droughts decreased crop yields in both rainfed and irrigated systems in Brazil (although on a more modest scale). Figure 2.3 reports the estimates and corresponding 95% confidence interval for a severe drought in blue (used in the estimations below) and a less severe drought in orange (threshold of definition of 1.5). The magnitude of the effects of an additional month of drought on each dependent variable, namely yields, production, exports and domestic share, are higher for a severe drought. For severe drought, all coefficients are statistically significant. Notably, the shock deteriorates both production (-6% for an additional month of severe drought) and export quantities (-12%). The effects are stronger for these variables than on yields. This can be partly explained by the interruption of soy production and exports in municipalities affected by droughts. Also, the negative effect is stronger on exports than on production, suggesting a possible production shift towards the domestic market. This is confirmed by the positive coefficient for the share of the production destined for the domestic market.

Table 2.3: Impact on municipality production and exports (severe drought)

Dependent Variables:	Yield	Production	Exports	Domestic share
Model:	(1)	(2)	(3)	(4)
	OLS	PPML	PPML	OLS
<i>Variables</i>				
Neg prec anomaly	-0.0626*** (0.0052)	-0.0646*** (0.0156)	-0.1256*** (0.0256)	0.0398*** (0.0111)
Positive Prec.	0.0040*** (0.0013)	-0.0366*** (0.0063)	-0.0387*** (0.0114)	-0.0113*** (0.0033)
Positive Tmax	-0.0191*** (0.0012)	-0.0245*** (0.0052)	-0.0339*** (0.0088)	0.0142*** (0.0026)
Negative Tmin	-0.0051 (0.0135)	0.0959** (0.0443)	0.0772 (0.0833)	0.0888** (0.0345)
Past shocks (-5:-1)	0.0021 (0.0013)	-0.0084 (0.0148)	-0.0081 (0.0211)	0.0108* (0.0061)
<i>Fixed-effects</i>				
Municipality	✓	✓	✓	✓
Year	✓	✓	✓	✓
<i>Fit statistics</i>				
Observations	25,162	27,302	27,302	27,302
R ²	0.637			0.418

Notes: Estimates based on equation 2.2. Yields are in log and the other variables are in levels. Columns (1) and (4) are OLS and columns (2) and (3) are PPML. Yields (column 1) are detrended by municipality. Domestic share (column 4) is the share of production that is sold on the domestic market. The shock Neg prec anomaly are negative precipitation anomalies (or standardized precipitation index) calculated with a threshold of 2 in equation 2.1. Other controls include other anomalies in precipitation (positive) and in temperatures as well as past negative precipitation anomalies. All specifications include Municipality and Year-fixed effects. Robust standard errors in parentheses clustered at the municipality level. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.

2.4.2 Direct effect of the shock on the transactions between municipalities and exporters

We now examine the direct effect of shocks on transactions between producing municipalities and traders. Figure 2.4 presents the main findings, while Table 2.4 provides the detailed regressions. These results show a significant negative impact of shocks on the level of export transactions, with an additional month of severe drought linked to a 0.11% reduction in transaction volumes between affected municipalities and exporters. We then break down the results between the intensive (column 2) and extensive (column 3) margins and find that adjustments predominantly occur at the intensive margin. While the volume of exports decreases, there is no significant effect detected on the extensive and the coefficient is near zero.

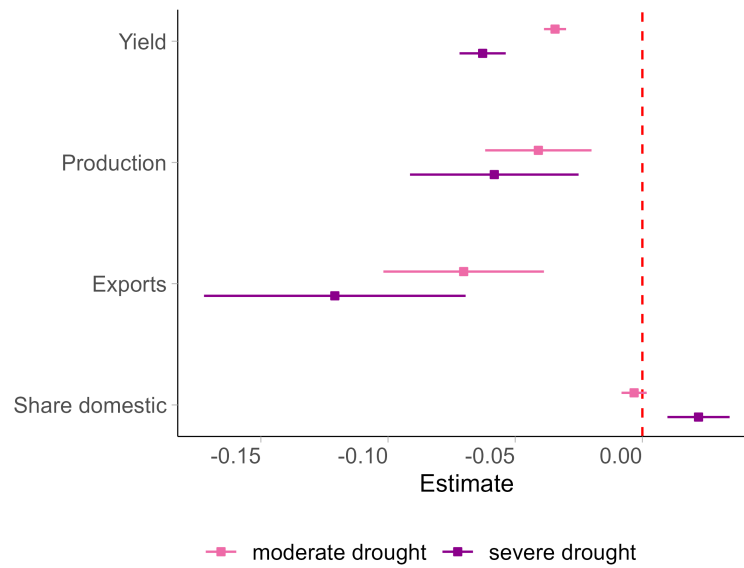


Figure 2.3: Estimated direct effects on municipalities.

Notes: The plot shows the coefficient estimates and corresponding 95% confidence intervals for α_1 from Equation 2.2. Full results are displayed in Table 2.3.

The resilience of trading relationships, despite supply shocks, can be attributed to several factors identified in the literature, including trust, financial commitments, infrastructure, and product specificity. Table 2.5 aims to explore these heterogeneous effects of shocks on transactions at the intensive margin, where the adjustments occur. We use as a proxy for trust the duration of the transaction (column 1), for infrastructure, the transportation costs (column 4) and for the specificity of the product, the zero-deforestation commitments of traders. Furthermore, we explore the shock effects differentiated by firm types, distinguishing the largest traders (column 2) and cooperatives⁴ (column 3), because the type of contract with suppliers is likely to differ. Overall, the results point to some extent to heterogeneous effects: they reveal that for non-cooperatives and traders without zero-deforestation commitments (ZDC), the impact of the shock is highly negative on export amounts (coefficients of the Shock variable). However, for cooperatives and those with ZDC, the impact is weaker (even positive for cooperatives). This result is unsurprising for cooperatives, which are often rooted in their territory and work closely with producers. Regarding zero deforestation commitments, the attenuated effect of the shock that is observed could be interpreted as a consequence of the specificity of the product traded, which would justify privileged links with producers.

⁴They are identified using the names of the firms, and thus this variable may be subject to uncertainty.

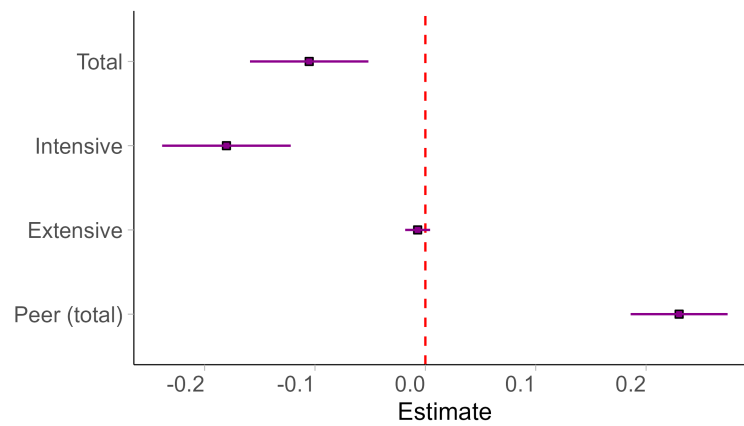


Figure 2.4: Estimated direct effects on transactions and estimated effects on peer transactions. *Notes:* The plot shows the coefficient estimates and corresponding 95% confidence intervals for α_1 from Equation 2.3 and Equation 2.4.

Table 2.4: Impact on transactions

Dependent Variables:	All Exports	Exports > 0	1(Exports)
Model:	(1)	(2)	(3)
	PPML	PPML	OLS
<i>Variables</i>			
Shock	-0.1053*** (0.0274)	-0.1802*** (0.0297)	-0.0070 (0.0058)
Positive Prec.	-0.0308** (0.0124)	-0.0135 (0.0122)	-0.0004 (0.0016)
Positive Tmax	-0.0417*** (0.0093)	-0.0320*** (0.0086)	-0.0007 (0.0014)
Positive Tmin	0.0422 (0.0864)	-0.0055 (0.0836)	-0.0167 (0.0200)
Past shocks (-5:-1)	0.0266 (0.0262)	-0.0764*** (0.0237)	-0.0033 (0.0035)
<i>Fixed-effects</i>			
Exporter	✓	✓	✓
Municipality	✓	✓	✓
Year	✓	✓	✓
<i>Fit statistics</i>			
Observations	93,019	26,873	93,019
R ²			0.234

Notes: Estimates based on equation 2.3. The first column is the total impact of the SPI on the transactions and is a PPML. The second column is also a PPML and represents the intensive margin. Column 3 is a LHS model and quantifies the extensive margin. Controls include other anomalies in precipitation and in temperatures and past negative precipitation anomalies. All specifications include Exporter, Municipality, and Year-fixed effects. Robust standard errors in parentheses clustered at the municipality level. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.

Table 2.5: Impact on transactions - intensive margin

Dependent Variable:	Exports > 0				
Model:	(1)	(2)	(3)	(4)	(5)
<i>Variables</i>					
Shock	-0.1782*** (0.0430)	-0.2078*** (0.0456)	-0.1871*** (0.0359)	-0.1435*** (0.0383)	-0.3365*** (0.0626)
Shock × Duration Relationship	0.0135 (0.0103)				
Shock × Top Traders		0.0923 (0.0612)			
Shock × Cooperative			0.3321*** (0.1204)		
Shock × Close to Port				-0.1118 (0.0754)	
Shock × Zdc					0.2566** (0.1216)
<i>Fixed-effects</i>					
Exporter	✓	✓	✓	✓	✓
Municipality	✓	✓	✓	✓	✓
Year	✓	✓	✓	✓	✓
<i>Fit statistics</i>					
Observations	25,448	26,873	26,873	26,635	10,283
R ²	0.686	0.677	0.677	0.678	0.721

Notes: The characteristics are lagged by one year, and are, in order, the length of the relationship, a dummy variable for the largest traders, a dummy variable for whether the company is a cooperative, a dummy variable for municipalities close to ports (the definition threshold is the median), and a dummy variable for whether the company has zero-deforestation commitments. All specifications include Exporter, Municipality, and Year-fixed effects. Robust standard errors in parentheses clustered at the municipality level. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.

2.4.3 Reallocation within the network

What are the coping strategies of the multi-location firms? Firms are either likely to rely on their past suppliers or to find new contracts to compensate for their losses.

We quantify the effect of a peer shock on transactions between suppliers and exporters to explore the effect on peer suppliers. Municipalities are considered as "peers" to affected municipalities if they served the same exposed exporter two years before. Table 2.6 reports the effect estimate in the first column. They suggest a positive spillover effect of the shock on peer suppliers. This means that when some suppliers are hit by a shock, their peers may benefit indirectly. Exporters, seeking to compensate for the loss of production, increase their purchases from other suppliers of their network. So while the shock may be negative for some suppliers, it may create opportunities for others within the same network. This highlights that the network structure matters for the effect of a supply shock.

The following columns analyze whether this effect varies according to certain supplier characteristics: exporter size, yield and presence of irrigation infrastructure. We classify municipalities into two groups according to whether they are below or above the median. The results, presented in Table 2.6, indicate that exposed firms tend to source more from larger suppliers, with higher yields and irrigation infrastructure within their network.

2.4.4 Indirect aggregate effect on exposed exporters

Is the shock large enough to affect the exports and/or the network of downstream exporters? When suppliers are hit by a shock and their production declines, their customers could see their own sales also affected by the shock if the shock is large enough. This is what we try to find out by measuring the effect on the aggregate volume of exports of the exposed exporters.

Table 2.7 reports the results on the aggregate exports of firms. The estimated coefficients, therefore, include any coping strategies that the exporters might implement. We do not find any significant effect, even when analyzing the differential effect on exports for firms with a single supplier in the pre-shock period, which may be more vulnerable.

A possible strategy for exporters could be to adapt their sourcing network and find new suppliers. If this is the case, it should manifest in changes to network measures, such as the number of lost relationships and new relationships. Table 2.7 displays the impact of the exposition to shocks on some network variables. The results are not very conclusive since most effects are not significant. It is important to interpret these results with caution, as it is possible that the calculated measure of exposure does not fully capture the true extent of the vulnerability of firms to supply

Table 2.6: Impact on peer transactions and heterogeneity

Dependent Variable:	All All Exports (t)			
Model:	(1)	(2)	(3)	(4)
<i>Variables</i>				
Peer shock	0.2299*** (0.0224)	0.1139*** (0.0246)	0.1292*** (0.0292)	0.1753*** (0.0345)
Peer shock × large prod.		0.3578*** (0.0518)		
Peer shock × high yield			0.2100*** (0.0432)	
Peer shock × equipment				0.0916* (0.0469)
<i>Fixed-effects</i>				
Exporter	✓	✓	✓	✓
Municipality-Year	✓	✓	✓	✓
<i>Fit statistics</i>				
Observations	71,227	65,978	68,773	71,227
R ²	0.453	0.448	0.451	0.454

Notes: Clustered (Municipality) standard errors in parentheses. Column 1 presents the basic estimation, and columns 2, 3 and 4 present the estimations augmented with interactions with characteristics. Characteristics are dummies defined with the median as the threshold for: municipalities that are large producers, have high yields, and use irrigation and high inputs. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.

shocks. More research is required to better understand what strategies can be implemented by heterogeneous firms.

Table 2.7: Impact on exporters - exports and network dynamics

Dependent Variables:	All Exports		Total rls.	Lost rls.	New rls.	Exit
Model:	(1)	(2)	(3)	(4)	(5)	(6)
	PPML	PPML	PPML	PPML	PPML	OLS
<i>Variables</i>						
Shock exposure	-0.1598 (0.1780)	-0.1617 (0.1815)	0.2207 (0.1924)	-0.0553 (0.2518)	0.2405 (0.4033)	0.0399 (0.0433)
False shock	0.0086 (0.1216)	0.0131 (0.1244)	0.0089 (0.0917)	-0.2451** (0.0964)	0.0338 (0.1635)	-0.0124 (0.0138)
Past shocks (2) (-5:-1)	0.1155 (0.0934)	0.1157 (0.0934)	0.3140* (0.1660)	0.2815* (0.1437)	0.4496** (0.1989)	0.0072 (0.0173)
Shock exposure × Single		0.0584 (0.3087)				
False shock × Single		-0.1473				
<i>Fixed-effects</i>						
Exporter	✓	✓	✓	✓	✓	✓
Year	✓	✓	✓	✓	✓	✓
<i>Fit statistics</i>						
Observations	3,859	3,859	3,299	3,628	2,195	3,859
R ²						8.721e-4

Notes: Estimates based on equation 2.7 and 2.8 for column 2. The first column is the effect of the exposure to a shock on the total exports of a firm. Column 2 differentiates the effect depending on whether the firm has a single supplier or many suppliers. They are both PPML and the variables are in levels. Columns 3, 4 and 5 detail the effect of the exposure to a shock on the network dynamics of a firm: the number of total relations, the number of lost relations, the number of new relations (all PPML estimators). Exit is a dummy whose value is 1 if the exporting firm stops importing (temporarily) after the shock. Controls include a counterfactual shock to account for the non-random exposure to the shock. All specifications include Exporter and Year-fixed effects. Robust standard errors in parentheses clustered at the exporter level. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.

2.4.5 Robustness

We perform several robustness tests to ensure that our main results are not sensitive to our modeling choices.

First, we test another common approach to analyzing the impact of weather shocks on soy crops, which is using killing degree days. Killing degree days could capture different variations than the Standardized Precipitation Index because it quantifies extreme heat. We adopt similar regressions as in (Annan et al., 2015; Kuwayama et al., 2018) and run the same principal estimations as before. More details on the approach are given in the Appendix B.3. We test whether our findings on the impact of supply shocks on the soy network remain robust to a different type of shock and different estimation specifications (Tables B.5, B.6, B.7, B.8). Overall, the direction of the effects remains consistent with those obtained using the Standardized Precipitation Index shock. The main discrepancy lies in the significance of the effect at the transaction and exporter levels. For transactions, the effect is weaker than for the intensive margin, but significant and negative for the extensive margin (column 3 of table B.6), suggesting changes in relationships that we have not captured with the SPI. For the aggregate effect at the exporter level, the effect on exports remains insignificant, but the regressions show that extreme heat leads to more interrupted relationships (column 4 of table B.8) and more suppliers in general (column 3), presumably to compensate for losses.

The first step in the study was to clean the dataset by removing exporters with less than three transactions. We test the sensitivity of the transaction-level results to this criterion in table B.2. Panel A includes firms with at least two transactions and panel B includes firms with at least four transactions. Overall, we observe the same effects, with the exception of the extensive margin, which becomes significant and negative in Panel B, although with a very small coefficient.

A strong assumption for firm-level estimates is the measurement of indirect exposure to shocks. Table B.3 shows the sensitivity of our results to different measures of the exposure of trading firms to a shock. In all three cases, the overall effect on firms' exports is insignificant, as in our main estimation. The only difference is in columns (4) and (5), where we detect a negative significant coefficient for the lost relationships.

Table B.4 shows that the definition of peer shock (depending on the year of reference used to define the municipalities in the network of a trader and the weights chosen) mostly does not generally affect the results of network spillovers. We also find a positive significant effect on peer relations, except when equal weights for all peer municipalities are employed (column 3).

2.5 Discussion / Conclusion

This article provides an empirical analysis of the response of exporting firms in response to exogenous supply shocks. To provide causal evidence, we leverage the temporal and spatial variability of droughts. Previous studies have highlighted the importance of drought for soybean production in Brazil in the coming decades (Rattis et al., 2021), as well as the role of climatic risks for traders' strategies in Brazil (T. Reis, Bastos Lima, et al., 2024; Stokeld et al., 2023). These are just additional arguments for using drought as an example of a supply shock. From there, a secondary objective of this paper was to approach the problem of leakages in the regulations against imported deforestation, which explicitly targets trading firms.

Our findings demonstrate that droughts negatively affect soybean yields, leading to a decline in production. This, in turn, has downstream effects on the soybean supply chain, with repercussions on the transactions between municipalities and exporters. The results also reveal that exporters engage in strategies to cope with the shocks. Exporting firms draw on established relationships in their network to compensate for volume losses. The findings indicate that the exporting firms do not easily enter into new contracts, and we do not find evidence that the existence of transactions is disrupted in the event of a shock, suggesting the existence of some friction and rigidity in the soybean supply chain.

These results corroborate the previous observations of T. Reis, Bastos Lima, et al., 2024, whose qualitative research finds that some large traders keep sourcing and maintain the costs of empty silos in slow years, because of long-term contracts with farmers and due to infrastructural, financial and technological lock-in. However, we do not find evidence of the existence of small and opportunist exporters, trading on the spot market, which would harvest profits only in prosperous years, perhaps as a result of our choice of sample. The lock-in to large traders that emerges from our analysis also questions farmers' potential adaptation to climate change. Dou et al., 2023 report that farmers cannot adjust their planting behavior in the face of an extreme event or its forecast because they are tied to powerful supply chain actors (through credit or future contracts) to whom they are beholden to sell their crops. Future work based on the same analysis could include the more downstream effects of soybean supply shocks on intermediate and final consumers, especially on prices. Indeed, there is evidence that such shocks can have significant effects on, for example, livestock farmers abroad (West et al., 2021). The longer-term effects of droughts on exporters' adaptation strategies also merit further study.

Taken together, these results reveal something about the dynamics of the Brazilian soybean

supply chains in response to supply shocks, and we can draw some implications from these results for demand-side regulation against deforestation. First, an important distinction has to be made between large and smaller firms. Indeed, larger trading firms can switch sourcing patterns more easily. One could thus expect that more stringent sourcing liabilities related to deforestation-free demand policies would increase market concentration, to the benefit of the largest firms. Secondly, to cope with a shock, trading firms tend to rely on their other sourcing locations. While this may be an option for traders with diversified supplier portfolios, it may not be possible for companies that source exclusively from locations that have experienced deforestation after the cut-off date. Due to network frictions, the regulations could pose problems even for large companies in the short term if they display high-risk suppliers. Finally, it should not be forgotten that demand-side policies are only implemented by certain importing countries. Some traders exposed to regulations on deforestation are likely to reduce their purchases from "hit" suppliers, and others, which are not subject to such regulations because serving consumer countries without regulations, could take their place. This would jeopardize the net effectiveness of these policies on forests. This underlines the need for cooperation from importing countries on demand-side regulations.

The generalization of these results is subject to certain limitations. For example, production shocks cannot be assimilated to regulation shocks. The latter are probably longer-term and producers are responsible for the non-compliance, unlike droughts, which are uncontrolled risks. Moreover, we do not consider leakage between producing countries, nor leakage between consumer countries. We abstract totally from the global reorganization of the trade patterns following the implementation of demand-side anti-deforestation policies. To develop a full picture of the leakages, additional studies are needed to explore the leakages between destinations, which are likely to be much more important.

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Appendix B

B.1 Data

Table B.1: Sources of Variables

Variable Names	Variable Description	Data Sources
Neg prec anomaly	Precipitation anomalies	https://www.worldclim.org/data/worldclim21.html and own calculation for the SPI and the aggregation
Positive Tmax	Temperature anomalies	https://www.worldclim.org/data/worldclim21.html and own calculation for the anomalies and the aggregation
Peer shock	Peer shock	Own calculations from Worldclim 2.1 and TRASE
Exp. Shock	Firm exposure to shock	Own calculations from Worldclim 2.1 and TRASE
Yield	Yield	https://www.ibge.gov.br/en/statistics/economic/agriculture-forestry-and-fishing
Prod.	Production	https://www.ibge.gov.br/en/statistics/economic/agriculture-forestry-and-fishing
Exports (Municipalities)	Exports municipalities	TRASE aggregated at municipality-level
Exports (Transaction)	Exports transaction	TRASE aggregated at municipality-exporter level
Exports (Trader)	Exports trader	TRASE aggregated at exporter level
# Suppliers	Number of suppliers	Calculated from TRASE
Age transaction	Age transaction	Calculated from TRASE
Distance to ports	Distance to ports	Calculation using Victoria et al., 2021
ZDC	Zero deforestation commitment	TRASE, includes soy moratorium signatories and private commitments
Irrigation	Surface irrigated and input intensity in 2010	Calculations using MAPSPAM database (Ru et al., 2023)
Cooperative	Cooperative	Own classification using the names of Exporters in TRASE
KDD	Killing degree days	Own calculations using Brazilian Daily Weather Gridded Data (BR-DWGD) (Xavier et al., 2022) and Google Earth Engine
Drought EMDAT	Drought EMDAT	EM-DAT (Delforge et al., 2023)

B.2 Robustness tests

Table B.2: Robustness: Different samples

Dependent Variables:	Transactions			Exporters		
	All Exports	Exports > 0	1(Exports)	Exports	Lost rls	New rls.
Panel A						
<i>Variables</i>						
Neg prec anomaly (2)	-0.1011*** (0.0273)	-0.1772*** (0.0295)	-0.0073 (0.0055)			
Shock exposure				-0.1505 (0.1770)	0.1316 (0.3088)	0.4149 (0.2808)
<i>Fixed-effects</i>						
Exporter	✓	✓	✓	✓	✓	✓
Municipality	✓	✓	✓			
Year	✓	✓	✓	✓	✓	✓
<i>Fit statistics</i>						
Observations	97,862	27,799	97,862	5,319	5,049	4,448
R ² adj		0	0.239			
Panel B						
<i>Variables</i>						
Neg prec anomaly (2)	-0.1053*** (0.0274)	-0.1854*** (0.0303)	-0.0113* (0.0063)			
Shock exposure				-0.1989 (0.1792)	-0.0803 (0.2475)	0.4071 (0.2654)
<i>Fixed-effects</i>						
Exporter	✓	✓	✓	✓	✓	✓
Municipality	✓	✓	✓			
Year	✓	✓	✓	✓	✓	✓
<i>Fit statistics</i>						
Observations	93,019	25,646	86,384	2,918	2,714	2,394
R ² adj			0.228			

Notes: This table shows the robustness of the results at the transaction- and municipality level to the choice of the sample. Panel A displays the results of a sample with firms trading at least two times, while panel B displays the results on a sample where firms trade at least 4 times (the baseline in the main text was 3 times). Robust standard errors in parentheses clustered at the municipality level. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.

Table B.3: Robustness - exposure

Dependent Variables:	All Exports (t)			Lost rls.			New rls.		
Model:	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
<i>Variables</i>									
Exposure: t0:t0+2	-2.045			-2.931**			1.297		
	(1.250)			(1.426)			(1.938)		
Exposure: t0		-0.8803			-2.213**			1.927	
		(0.7195)			(1.005)			(1.416)	
Exposure: t-1			0.2899			0.1700			2.510
			(1.109)			(1.428)			(1.626)
<i>Fixed-effects</i>									
Exporter	✓	✓	✓	✓	✓	✓	✓	✓	✓
Year	✓	✓	✓	✓	✓	✓	✓	✓	✓
<i>Fit statistics</i>									
Observations	3,859	3,859	3,859	3,628	3,628	3,628	3,191	3,191	3,191

Notes: Different choices of measurement of the exposure of firms to shocks compared to equation 2.6. In the first row, the share is defined as the average between the three first years, the share in the second row is defined in the first year, and the share in the third row is defined as the year before. Robust standard errors in parentheses clustered at the exporter level. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.

Table B.4: Robustness: different measures of peer shocks

Dependent Variable:	All Exports		
Model:	(1)	(2)	(3)
<i>Variables</i>			
Peer shock: t-1	0.5158***		
	(0.0321)		
Peer shock: t-3		0.1395***	
		(0.0204)	
Peer shock: equal weight			4.088
			(4.378)
<i>Fixed-effects</i>			
Exporter	Yes	Yes	Yes
Municipality-Year	Yes	Yes	Yes
<i>Fit statistics</i>			
Observations	105,114	105,114	105,114
R ²	0.438	0.434	0.433

Notes: Clustered (Municipality) standard errors in parentheses. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.

B.3 Other shocks

Another common approach to analyzing the impact of weather shocks on crops is to use killing degree days, which could capture different variations than the Standardized Precipitation Index because it quantifies extreme heat. We test whether our findings on the impact of supply shocks on the soy network remain robust to a different type of shock and different estimation specifications.

Killing degree days are calculated on Google Earth Engine based on the Brazilian Daily Weather Gridded Data (BR-DWGD) (Xavier et al., 2022). Following Hamed et al., 2023, we define a critical temperature threshold for soy as 35°C. Killing degree days are calculated for each pixel using the formula:

$$KDD = \sum_{i=1}^n \max(0, T_{\max_i} - T_c) \quad (\text{B.1})$$

where T_{\max_i} represents the maximum temperature on the day i , n denotes the number of days suitable for soy cultivation, and T_c is the critical temperature threshold. The soy cultivation period for year t spans from November of year $t - 1$ to May of year t , following the approach of D. S. Silva et al., 2023. The computed killing degree days for each cell are then averaged within each municipality to obtain municipality-year data.

For the empirical analysis, we adopt a similar specification to previous studies studying the economic impacts of weather shocks on soybean (Annan et al., 2015; Kuwayama et al., 2018).

Total precipitation during the growing season (also derived from BR-DWGD) and squared total precipitation are included as covariates in both municipality and transaction-level specifications. To assess exposure to shocks, we use the same methodology and specifications as described in Section 2.3.4.

Tables B.8, B.5, B.9, B.6, B.7 present the results. Overall, the direction of the effects remains consistent with those obtained using the SPI shock. The main discrepancy lies in the significance of the effect at the transaction and exporter levels.

Table B.5: Impact on municipality production and exports (extreme heat)

Dependent Variables:	Yield	Production	Exports	Domestic share
Model:	(1)	(2)	(3)	(4)
	OLS	PPML	PPML	OLS
<i>Variables</i>				
KDD (hundreds)	-0.4459*** (0.0270)	-0.6722*** (0.1285)	-1.071*** (0.1747)	0.0596*** (0.0083)
Prec. (meters)	0.0990*** (0.0077)	-0.0006 (0.0790)	0.1201 (0.1053)	0.0090 (0.0056)
Prec. squared	-0.0121*** (0.0016)	0.0108 (0.0171)	-0.0132 (0.0220)	-0.0015 (0.0009)
<i>Fixed-effects</i>				
Municipality	✓	✓	✓	✓
Year	✓	✓	✓	✓
<i>Fit statistics</i>				
Observations	29,035	39,520	37,536	89,008
R ² adj	0.650			0.448

Notes: Yields are in log and the other variables are in levels. Columns (1) and (4) are OLS and columns (2) and (3) are PPML. Yields (column 1) are detrended by municipality. Domestic share (column 4) is the share of production that is sold on the domestic market. KDD represents hundreds of killing degree days. Other controls include precipitation and squared precipitation. All specifications include Municipality and Year fixed effects. Robust standard errors in parentheses clustered at the municipality level. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.

Table B.6: Impact on transactions (extreme heat)

Dependent Variables:	All Exports	Exports > 0	1(Exports)
Model:	(1)	(2)	(3)
	PPML	PPML	OLS
<i>Variables</i>			
KDD	-1.075*** (0.1594)	-0.8214*** (0.1829)	-0.1119*** (0.0224)
Prec. (meters)	0.1705 (0.1069)	0.8587*** (0.0987)	-0.0097 (0.0184)
Prec. squared	-0.0222 (0.0225)	-0.1407*** (0.0215)	-0.0022 (0.0038)
<i>Fixed-effects</i>			
Exporter	✓	✓	✓
Municipality	✓	✓	✓
Year	✓	✓	✓
<i>Fit statistics</i>			
Observations	93,019	26,873	93,019
R ² adj			0.233

Notes: The first column is the total impact of the KDD on the transactions and is a PPML. The second column is also a PPML and represents the intensive margin. Column 3 is a LHS model and quantifies the extensive margin. All specifications include Exporter, Municipality, and Year-fixed effects. Robust standard errors in parentheses clustered at the municipality level. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.

Table B.7: Impact on transactions (extreme heat)

Dependent Variable:	All Exports				
Model:	(1)	(2)	(3)	(4)	(5)
<i>Variables</i>					
KDD	-0.7947*** (0.2126)	-0.3695 (0.2252)	-1.094*** (0.1616)	-0.9791*** (0.1841)	-1.024*** (0.2657)
KDD × Duration Relationship	-0.1035* (0.0535)				
KDD × Top Traders		-1.108*** (0.3505)			
KDD × Cooperative			1.100 (1.237)		
KDD × Close to Port				-0.5762** (0.2815)	
KDD × Zdc					0.3224 (0.5276)
<i>Fixed-effects</i>					
Exporter	✓	✓	✓	✓	✓
Municipality	✓	✓	✓	✓	✓
Year	✓	✓	✓	✓	✓
<i>Fit statistics</i>					
Observations	91,440	93,019	93,019	92,254	22,547

Notes: The table displays the coefficients for the interactions only. All specifications include Exporter, Municipality, and Year-fixed effects. Robust standard errors in parentheses clustered at the municipality level. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.

Table B.8: Impact on exporters - exports and network dynamics (extreme heat)

Dependent Variables:	All Exports		Tot. rls	Lost rls	New rls	Exit
Model:	(1)	(2)	(3)	(4)	(5)	(6)
	PPML	PPML	PPML	PPML	PPML	OLS
<i>Variables</i>						
Firm shock	0.0184 (0.6551)	0.1027 (0.6811)	1.654* (0.9516)	2.563*** (0.7801)	-0.3268 (2.319)	0.4205*** (0.1456)
Firm shock × Single		-1.773 (1.406)				
<i>Fixed-effects</i>						
Exporter	✓	✓	✓	✓	✓	✓
Year	✓	✓	✓	✓	✓	✓
<i>Fit statistics</i>						
Observations	3,859	3,859	3,299	3,628	2,195	3,859

Notes: The first column is the effect of the exposure to a shock on the total exports of a firm. Column 2 differentiates the effect depending on whether the firm has a single supplier or many suppliers. Columns 3, 4 and 5 detail the effect of the exposure to a shock on the network dynamics of a firm: the number of total relations, the number of lost relations, and the number of new relations (all PPML estimators). Exit is a dummy whose value is 1 if the exporting firm stops importing (temporarily) after the shock. All specifications include Exporter and Year-fixed effects. Robust standard errors in parentheses clustered at the exporter level. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.

Table B.9: Impact on peer transactions and heterogeneity (extreme heat)

Dependent Variable:	All Exports (t)		
Model:	(1)	(2)	(3)
<i>Variables</i>			
Peer shock	0.1361*** (0.0199)	0.1171*** (0.0235)	0.1574*** (0.0280)
Peer shock × large prod.	0.2687*** (0.0417)		
Peer shock × high yield		0.2208*** (0.0338)	
Peer shock × equipment			0.1049*** (0.0379)
<i>Fixed-effects</i>			
Exporter	✓	✓	✓
Municipality-Year	✓	✓	✓
<i>Fit statistics</i>			
Observations	65,978	68,773	71,227
R ²	0.449	0.452	0.455
Within R ²	0.007	0.007	0.005

Notes: Clustered (Municipality) standard errors in parentheses. Column 1 presents the basic estimation, and columns 2, 3 and 4 present the estimations augmented with interactions with characteristics. Characteristics are dummies defined with the median as the threshold for: municipalities that are large producers, have high yields, and use irrigation and high inputs. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.

Chapter 3

Foreign demand and soy exports : evidence and implications for deforestation

co-written with Clément Nedoncelle (INRAE, PSAE)

Abstract. The current paper aims to assess the credibility of demand-side policies to curb deforestation. We tackle this question focusing on the Brazilian soy sector, as conversion from forests to soy-producing areas is a major driver of deforestation. We estimate a firm-level gravity model relating soy exports to destination-specific soy demand. First, we estimate a positive elasticity of soy exports to foreign demand, which confirms the credibility of demand-side policies. Second, we document that the average response hides significant heterogeneities across exporters and across municipalities. Combining export elasticities with soy expansion possibilities, we conclude that demand-side policies could hence avoid aggregate deforestation, particularly in regions proximate to the Amazon.

This chapter is available online as a working paper at <https://ideas.repec.org/p/hal/wpaper/hal-04312450.html>.

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3.1 Introduction

Tackling deforestation is among the top priorities of policymakers in light of climate change issues. Existing policies include soy moratorium, blacklisting of particular municipalities and firms, implementation of protected areas, monitoring, and changes in access to credit, among others. The common characteristic of these policies is that they are supply-side policies. Indeed, these policies target producers and intend to affect deforestation through producers' behavior. Whereas these policies can be effective (Assunção et al., 2020; Heilmayr et al., 2020), policymakers have recently considered complementary actions. The AR6 report of the IPCC underscores the potential impact on mitigation of demand-side and material substitution measures for the agriculture, forestry, and other land-use sector. These measures could contribute to reducing emissions by 2.1 [1.1–3.6] GtCO₂-eq per year (IPCC, 2022). There are many international and national initiatives to implement demand-side policies to curb deforestation. For instance, the European Green Deal includes measures to favor sustainable supply chains. In France, a strategy to fight against “imported deforestation” has been set up, and actions include the relocation of plant protein production on the national territory, i.e. relying on locally available proteins instead of on imported proteins.¹ All in all, reducing the import demand of forest-risk commodities is envisaged by policymakers.

The general objective of the current paper is to assess the credibility and the potential effects of these demand-side policies. To provide some insights on this important issue, we tackle this question focusing on the soy sector. Indeed, conversion from forests to soy-producing areas (potentially indirectly through conversion into pastures first) is a major driver of deforestation (Pendrill et al., 2019; Song et al., 2021). Lowering demand for soy could thus curb land conversion and deforestation rates. Whereas soy supply is responsible for deforestation, the quantitative role of foreign demand for soy remains an open question.

To answer this question, we use data covering the universe of soy exports from Brazil and estimate the elasticity of exports to soy foreign demand. Most of the soy produced in Brazil is for exports (75% in our dataset): exports and production patterns are hence very close. As a result, changes in soy production could plausibly be driven by changes in foreign demand. Our analysis combines location and firm-specific soy export data with aggregate trade data informing on soy demand (imports) by destination. In this context, we estimate a firm-level gravity model relating firm-municipality-destination export flows to destination-specific soy demand and to standard

¹<https://www.deforestationimportee.ecologie.gouv.fr/en/sndi/article/sndi>

firm-level trade determinants. Combined with demanding fixed effects, identification relies on the exogeneity of demand from abroad faced by soy exporters. Indeed, as we rely on micro-level export flows, foreign demands are plausibly exogenous from firm-specific or municipality-specific decisions.

Our analysis delivers the following conclusions. First, we estimate an average micro-level elasticity of soy exports to foreign demand of around 0.2. On average, exporting firms increase their exports by 0.2% for a 1% increase in foreign demand. This result is robust to including a wide array of potentially omitted variables, alternative estimations, and measurement issues. This positive average elasticity confirms the credibility of demand-side policies, even though the magnitude of the effect remains small.

Second, we document that the average response hides significant heterogeneities across exporters and across municipalities in Brazil. If changes in demand affect soy exports, the response varies across places and across exporting firms. In particular, our analysis highlights (i) that the largest exporters are more sensitive to soy demand shocks, (ii) that higher past deforestation patterns reduce the response, and (iii) that the number of competitors in the same municipality also dampens the impact of demand. Changes in demand, hence, mainly affect large exporters and municipalities with less competition and low soy expansion possibilities. We also document no heterogeneity across the origin of the import demand. Taking these results at face value, demand-side policies – regardless of their origin– could effectively curb soy production but would imply reallocations of soy production across places and firms. These reallocations are important as they would redistribute exports and production in favor of the smallest exporters but not necessarily into deforestation-prone places.

Third, we assess the potential benefits of the envisaged demand-side policies. The main metric of interest is the avoided deforestation. In our case, it measures the amount of deforestation that would have occurred to produce the avoided exports. This metric combines the avoided exports and expansion possibilities at the municipality level. In empirical terms, it combines (i) observed soy expansion possibilities with (ii) the estimated elasticities of exports from the gravity model and using observed firm size, competition, and recent deforestation patterns as determinants. In the cross-section of municipalities, avoided exports and soy expansion possibilities are positively correlated: places with high export response to demand are also places with a lot of remaining forests. This underlines both the risks generated by the current global increase in demand and the potential effectiveness of policies to reduce deforestation, on the side of consumer countries. Many municipalities have a high potential for avoided deforestation. These are mainly located in the Amazon region. However, in certain localities, such as southern Mato Grosso or Matopiba,

which still have significant forest cover, the weak response to exports suggests that the effects of a demand-driven policy would be lower.

Related Literature This paper builds upon and contributes to three strands of the literature. Firstly, it adds to the growing body of research on the link between trade and deforestation. While previous studies have identified several channels through which trade openness may affect deforestation, including agricultural market prices (Berman et al., 2023), land-use value, imported agricultural input costs, and productivity (Abman et al., 2020), empirical evidence of the effect of trade on deforestation has been limited (Balboni et al., 2023). However, recent studies have provided new insights into this relationship. Abman et al., 2020 shows that deforestation increases following regional trade agreements and that this effect is mediated by agricultural trade. Tracking the deforestation in trade flows, Pendrill et al., 2019 shows that a large part of tropical deforestation can be attributed to foreign consumer countries, especially soybean. Also, the recent microdata of the supply chains document the involvement of transnational firms in this process (Trase, 2018). This paper builds on this literature by quantifying the heterogeneous effects of changes in foreign demand on supply and deforestation, considering geographic and firm-level characteristics. We also build on the international economics literature that considers the importance of firm heterogeneity in shaping the patterns of international trade (Bernard et al., 2012; Melitz, 2003). Here, we empirically show how the heterogeneity in firms in the soybean market affects the elasticity of supply to foreign demand and how this heterogeneity matters for the effect of demand-side policies on deforestation. Finally, this paper adds to the growing body of literature on policies to slow the rate of deforestation. Recent research has considered trade policies as instruments to encourage conservation in countries that may otherwise deforest their territories (Balboni et al., 2023). While some studies have proposed import tariffs as a means of reducing deforestation (Domínguez-Iino, 2023; Harstad, 2022) and others have examined the efficiency of bans (Busch et al., 2022; Villoria et al., 2022), the effectiveness of these policies remains controversial. This paper contributes to this literature by examining how changes in foreign demand can be transmitted heterogeneously to deforestation through firms and how these changes could translate into a decrease in deforestation. Our results on demand-side policies suggest that, although acting on foreign demand would not transmit homogeneously across the market, the adaptation of the supply to the changes in demand could indeed slow down the deforestation process in producing countries.

The rest of the article is organized as follows. The next section details the data sources and

presents the main variables used in the empirical analysis. Section 3 provides an overview of the empirical methodologies employed. Section 4 describes the main results of the analysis. Section 5 presents the implications of our results for deforestation patterns. The final section concludes and discusses the results.

3.2 Data and context

3.2.1 Data Sources

We use data covering the universe of soy exports, soy production, and foreign demand from 2004 to 2017.

Soy firm-level exports To identify soy export flows, we rely on the TRASE database (Godar, 2018). This database is constructed from customs records and maps trade flows (in physical quantities and port of export FOB values) from source cities to destination markets and the agribusiness firms intermediating the transactions. The unit of observation in our analysis is at the exporter group \times municipality (of production) \times final destination country \times year level.

Indeed, exporters (mainly multinational firms) mainly buy soy from individual or collective producers (farmers, cooperatives) which are located in different municipalities. TRASE hence identifies the origin municipality (where the soy is grown).²

Firms characteristics The TRASE database allows us to identify exporters' characteristics. Namely, we can measure total firm exports, the number of destinations each firm serves, as well as the number of source municipalities. The TRASE dataset also allows us to measure many aggregates informing on the market structure and which may be driving forces behind the main elasticity. We compute by municipality, the number of exporters (sourcing from this specific municipality, eventually serving a specific destination), the average exports of these firms, the rank of each firm in the hierarchy and other aggregates.

Soy demands measures We measure the soy demands arising in importing countries using the BACI Database. BACI is an international trade database stemming from the harmonization of the COMTRADE database, in which the trade flows reported by exporting and importing countries sometimes differ (Gaulier et al., 2010). We select the bilateral trade flows of the six-digit Harmonized System products associated with soybeans (HS6 120100, Soya beans; whether or not broken) and aggregate by destination d and year t the total soy trade flows imported from all ori-

²TRASE also identifies the main exporting port (where soy is shipped) but we do not use this information in this research.

gins o : $SoyDemand_{dt} = \sum_o X_{odt}^{soy}$. This measure represents to total amount (in value and volume) of soy entering a destination d , independently of the origin. As Brazil represents around 40% of soy exports worldwide, excluding export flows from Brazil for the computation would amount to introduce a bias in the foreign demands.

Municipality characteristics We also collected some municipality-specific time-varying variables, which can be determinants of firm-specific and aggregate trade. Among others, we use data on municipality GDP, population, distance to the main port, and other variables from the Brazilian National Institute of Geography and Statistics (IBGE).

Deforestation Patterns To measure deforestation, we rely on the MapBiomas database (Souza et al., 2020), aggregated at the municipality-year level³. Because most of the soy expansion takes place in the Cerrado (an ecosystem of tropical savanna not included in the forest definition), we extend the analysis beyond deforestation and consider more broadly the effects of the changes in demand on the changes in natural vegetation. This ecosystem, with low legal protection compared to the Brazilian Amazon, is currently experiencing high conversion rates (five times as high as deforestation rates in the Amazon before the Soy Moratorium) in which soy plays a direct and significant role (Rausch et al., 2019).

3.2.2 Stylized facts

Fact 1: Increasing soy demands. Figure 3.1 underscores a consistent pattern of growth in international demand for soy, illustrating how the world demand for soybeans increased dramatically during the sample period. Soy exports worldwide tripled during 2005-2015, in line with an increasing global import demand. In this context, Brazil is a major exporter of soybeans: around 40% of total soy exports are from Brazil origin. Brazilian soy exports follow the same increasing trend.

Fact 2: China and the EU are the top destinations. Figure 3.2 plots the main destinations of Brazilian soy, from the TRASE dataset. The figure provides the average share of each destination in the sample. The distribution of exports is skewed across destinations. China is the main importing country of soybeans, and the EU is second⁴. These two destinations account for 80% of total flows.

³MapBiomas was chosen as the main data source because of its complete coverage and detailed classification of land use and land cover in Brazil, which includes forests and natural grasslands. Unlike PRODES, which focuses solely on forest cover in the Amazon region, and the Hansen dataset, which identifies the tree cover loss and therefore does not identify forests or wider natural vegetation, MapBiomas provides a more detailed representation of land use across the country. In addition, MapBiomas is widely used in research on land-use change in Brazil (e.g. Villoria et al., 2022)

⁴We aggregate all EU countries in this Figure only, for clarity and for exposition. In the estimations, we account for the demand of each EU country separately.

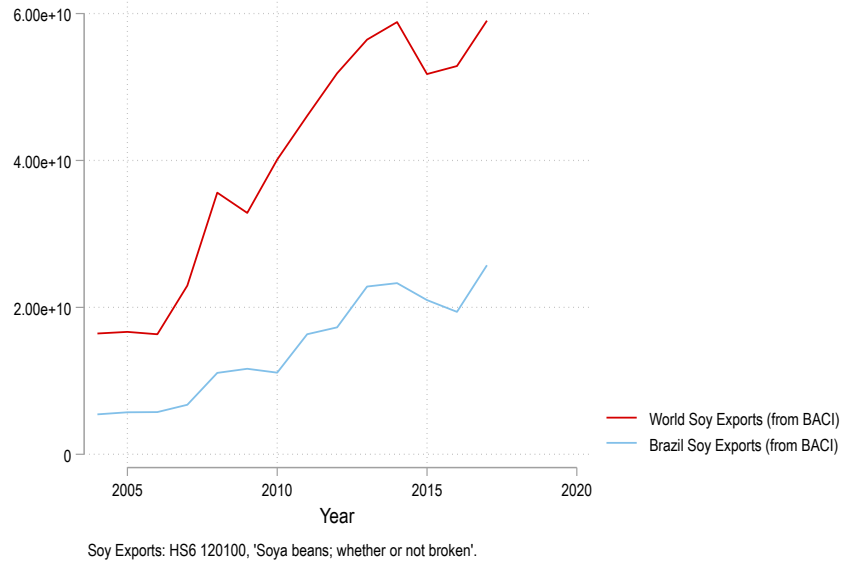


Figure 3.1: Demand from BACI trade flows

Exporters and municipalities typically serve multiple destinations. Over our period (2004 to 2017), municipalities served on average 18 countries, whereas a typical exporter serves 6 countries. Exporters and municipalities therefore face multiple demand shocks from various importing countries.

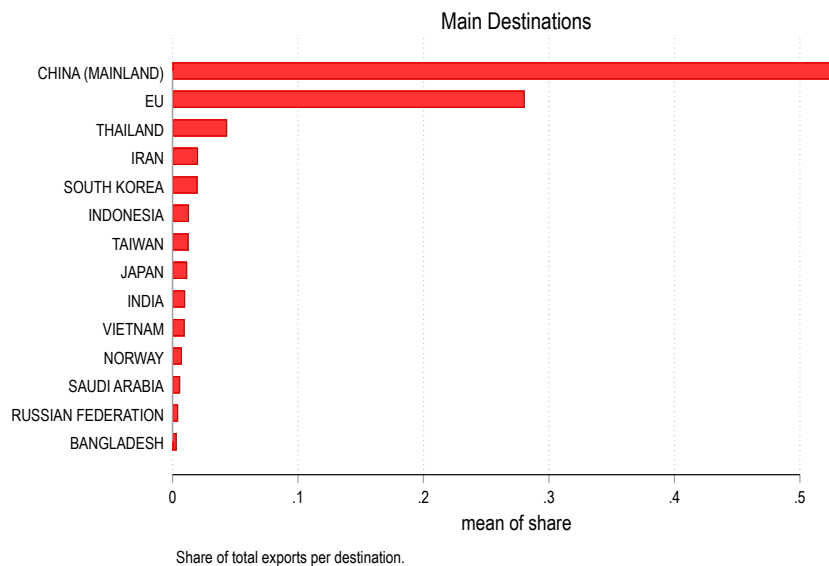


Figure 3.2: Distribution of export destinations of soybeans

Fact 3: Exporters distribution is highly skewed. Our main estimation sample contains 327 distinct exporters. However, a few firms dominate the market. Figure 3.3 shows the average share of the top 25 firms. In line with anecdotal evidence, exporter distribution is highly skewed as well. There are a few but very large trading firms. In particular, existing literature highlights

the major role played by the ABDC traders: ADM, Bunge, Cargill, and Louis Dreyfus (Clapp, 2014; Clapp, 2015). These four firms alone control more than half of the soybean export market in Brazil, and this figure does not vary over time. On average, they source from many municipalities and present a high market share in their sourcing municipalities compared to smaller firms. This particular market structure implies that there may be some strategic interactions between these firms. These firms are so large that their presence should impact other firms' export behavior. We account for this feature by computing an index of competition, which is the number of top 4 firms by municipality-destination-year.

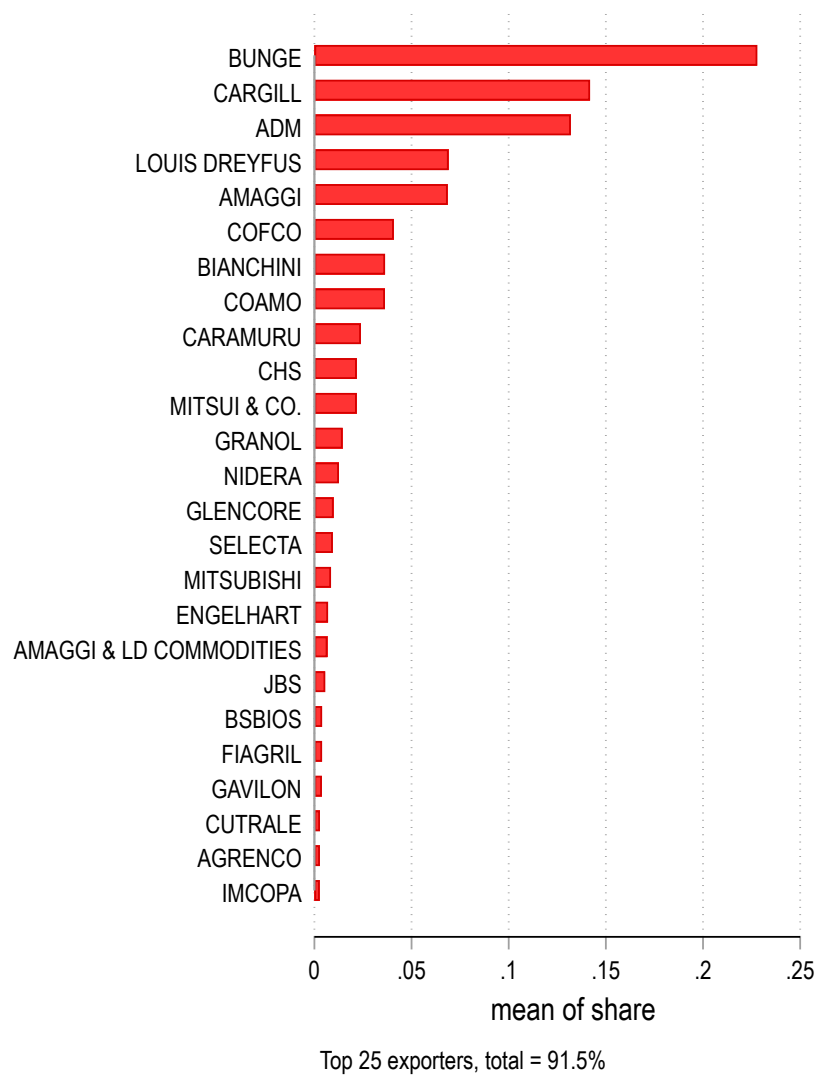


Figure 3.3: Distribution of exporters in sample

3.3 Empirical models

3.3.1 Average elasticity

Our main estimation strategy of the micro-level elasticity is based on regressions of soybean exports per firm – municipality - destination on the soybean demand from a destination country. We choose this level of analysis to estimate the reaction of a firm sourcing from a municipality to a demand shock from a destination country. At this level, foreign import demands are plausibly exogenous from firm-specific export flows. In formal terms, the regressions follow the equation:

$$\text{Exports}_{fmdt} = \lambda_{fmd} + \lambda_{fmt} + \alpha \text{Soy Demand}_{dt} + \beta \text{Controls}_{dt} + \varepsilon_{fmdt} \quad (3.1)$$

where Exports_{fmdt} is the value of the soy exports of firm f from municipality m to destination country d in year t , Soy Demand_{dt} is the total soy imports by destination d from anywhere in the world, including Brazil, from BACI. We do not consider the EU as a group (as in Figure 3.1) but rely on each country's demand.

Controls_{dt} is a vector of time-varying destination-specific trade determinants such as destination observables: foreign GDP and population, both to measure market size. We include a small set of control variables, to avoid over-fitting and bad controls problems. Besides, given the demanding fixed effects structure, most of the variance should be controlled.

Our specification also includes a set of fixed effects. The main results are obtained using firm-municipality-destination fixed effects (λ_{fmd}) and firm-municipality-year fixed effects (λ_{fmt}). The former set of fixed effects absorbs variance across individuals. Coefficients are thus identified from variation across years for a given individual (i.e. an exporter-source municipality-destination country group). These fixed effects absorb the effect of many time-invariant determinants of trade, such as the distance from the destination country (as all exporters are located in Brazil) and the pre-existence of a relationship between a firm and a destination country. It also absorbs trade determinants that do not vary in our sample period, such as the existence of a regional trade agreement between Brazil and a destination (as Brazil did not sign any new agreement between 2004 and 2017 with soy export destinations).

Firm-municipality-year fixed effects control for time-varying heterogeneity across cities (such as GDP per capita, the share of agriculture in local GDP, ...) as well as across firms (such as total firm exports, number of destinations, number of sources, etc.). This set of fixed effects first controls for aggregate and local supply shocks: both local, country-wide, or international supply shocks (a technology shock, for instance) are absorbed in this measure. It also excludes the potential non-random selection of sourcing cities at the firm level: estimations are performed within a

given firm network of sourcing and destination at the firm level. All the adjustments must therefore take place within a given network. Crucially, the firm-municipality-year fixed effects also control for changes in both the international and local prices of soy. As a result, we focus on the residual effect of demand, after accounting for price changes. These fixed effects finally control for the so-called outward multilateral resistance terms in gravity frameworks as they absorb the exporter-year dynamics (whether it is at the national or firm levels).

Our coefficient of interest is α , which we expect to be positive as exports and demand should go in the same direction. All explanatory variables are in logs, except dummy variables. This α coefficient hence captures the average elasticity of exports to demand. Beyond significance, the value of α will inform the credibility of demand-side policies. Indeed, these policies would have any effect only if α is large enough and to a larger extent as long as the cost of the policy is not too high. Regarding inference, ε_{fmdt} is a random error term. We allow errors to be correlated within groups of destination-year and cluster the standard errors at this level (which is also the level of the demand shocks).

We estimate equation (1) using a PPML estimator, as standard practice regarding trade flows (Silva et al., 2006), including zero-trade flows. We will check the sensitivity of results when using alternative estimators (OLS) and specifications.

3.3.2 Differential effects

After estimating the average export elasticity of firms sourcing from a municipality to a demand shock from a destination country, we investigate the heterogeneous response across firms, municipalities, and destinations. We estimate some interaction models of the following general form:

$$\begin{aligned} \text{Exports}_{fmdt} = & \alpha \text{Soy Demand}_{dt} + \beta \text{Controls}_{dt} + \delta_1 (\text{Soy Demand}_{dt} \times \text{Controls}_{ft}) \quad (3.2) \\ & + \delta_2 (\text{Soy Demand}_{dt} \times \text{Controls}_{mt}) \\ & + \delta_3 (\text{Soy Demand}_{dt} \times \text{Controls}_{dt}) \\ & + \text{FE} + \varepsilon_{fmdt} \end{aligned}$$

where the set of δ captures the differential effects of the same soy demand shock across firms, municipalities, and destinations. Regarding interpretation, conditional on a positive α in the previous estimations, a positive δ will mean that the same demand shock will generate increased exports for firms, municipalities, and destinations with bigger controls.

First, to identify which exporters capture the changes in demand, we condition the impact of the demand shocks on observables at the firm level (Controls_{ft}). Variables include the lagged total exports, lagged total number of destinations, and lagged the number of sourcing municipalities

per firm. Overall, these variables intend to capture exporter size. This dimension of heterogeneity is supposed to capture a large part of the variance in the reaction across firms. Many recent papers argue that firms react differently to foreign demand shocks depending on their size (Bernard et al., 2012; Bricongne et al., 2022; Chowdhry et al., 2023), in line with theoretical arguments (Edmond et al., 2015; Melitz and Ottaviano, 2008).

Second, to determine *where* the additional demand is satisfied from, we focus on the interaction between demand shock and municipalities' characteristics (Controls_{mt}). These characteristics include the GDP of the sourcing municipalities, their population, the number of top-4 competitors in the municipality (see previous discussions), as well as its past deforestation levels. In line with economic geography arguments (Desmet et al., 2015; Redding et al., 2015), these variables are supposed to capture differences across cities and will inform on the differential pattern of soy exports across municipalities (Garrett, 2013).

Finally, to explore whether the response is shaped by destination characteristics, we interact soy demand with controls at the destination-year level (Controls_{dt}). These controls include country dummies (as for China or the EU) and destination time-varying characteristics, such as GDP and population, to investigate whether foreign market size shapes the elasticity.

In formal terms, we will use a wide array of fixed effects (denoted FE) to use the correct identifying variation and control for many unobserved shocks. For instance, when investigating the variation across firms, we will use (at least) a municipality-destination-year fixed effect to account for observables and unobservables at this level and use the remaining variation across firms only. Note also that the whole set of fixed effects will also absorb most of the unconditional effects of variables of interest. For instance, the unconditional effect of firm size on soy exports will be captured in the firm(-city)-year fixed effect. Importantly, we will use a destination-year fixed effect: this will absorb the unconditional effect of the demand shock (acting as if all firms faced the same demand shock) but the interaction between demand and observable will remain identifiable. Note also that as some specifications include a set of destination-year fixed effects, they control for the inward multilateral resistance terms.

3.4 Results

3.4.1 Effect of foreign demand on soy exports

Benchmark results are displayed in Table 3.1. Column 1 includes firm-municipality-destination and year fixed effects, whereas columns 2 and others consider a more demanding fixed effects structure, including a firm \times municipality \times year fixed effect absorbing the major trade determinants at both the firm and the aggregate levels.

The results in columns 1 and 2 point towards a 0.2 average elasticity. The larger the soy demand in a destination, the larger the export flow. Using this 0.2 elasticity, a 10% increase in foreign soy demand increases soy exports (in value) by 2% on average. One standard deviation of soy demand (2.32) is related to a 0.5% increase in exports in our sample. This value is the average effect of changes in demand across firms and municipalities. The positive elasticity is independent of the set of fixed effects included in the estimation and of the subsequent change in samples (excluding singletons in the fixed effect dimensions). Comparing columns 1 and 2, in particular, excludes that the main effect is solely driven by composition effects. Regarding control variables, GDP has a positive impact on soy exports, in line with the gravity literature (Head et al., 2014). We, however, find no significant and robust pattern regarding the impact of population – capturing the market size – on soy exports.

Table 3.1 further decomposes the average elasticity of soy exports to demand into an intensive (col. 3) and an extensive (col.4) margin of trade. Indeed, the baseline sample includes both zero trade flows and strictly positive flows. As for the intensive margin, we estimate equation (1) on the sample of positive trade flows. As for the extensive margin, we regress a dummy equal to 1 if the trade flow is positive, and we use a linear probability model (denoted LPM in the table). We estimate that soy demands affect soy exports through both trade margins. In quantitative terms, both trade margins are at play: it implies that soy demand changes affect soy exports not only through the level of exports, conditional on presence but also through changes in the presence of an exporter, i.e. entry and exit of the export market.

3.4.2 Differential effects across firms, municipalities and destinations

Turning to heterogeneity, we now document the differential effect of the demand shocks across firms, across municipalities, and depending on previous deforestation patterns.

3.4.2.1 Heterogeneity across firms

Using variation across firms, holding municipality-destination-year observables constant (thanks to the fixed effects, reducing sample size however), Table 3.2 finds robust differential effects of increased demand across exporters. We differentiate firms along four measures of size: lagged total exports (col.1), lagged number of foreign destinations (col.2), lagged number of sourcing municipalities (col.3), and “being a top-4 firm” dummy (col.4). All those measures are documented to be proxies for firm size (Bernard et al., 2012; Melitz and Redding, 2014). We find that all interactions between soy demand and lagged firm size proxies are positive. When foreign demand increases, larger exporters capture most of this additional demand. In particular, the large differential impact of the top-4 dummy suggests that these top firms capture almost all the additional

Table 3.1: Average Effects

Dep. Variable:	Firm-level Exports (X_{fmdt})			$1(X > 0)$
	(1)	(2)	(3)	(4)
Log Soy Demand	0.188*** (0.036)	0.191*** (0.033)	0.085*** (0.027)	0.023*** (0.005)
Log Dest GDP p.c.	1.788*** (0.107)	2.363*** (0.140)	1.941*** (0.240)	0.170*** (0.023)
Log. Dest. Pop.	0.482 (0.738)	1.343* (0.725)	-0.382 (0.680)	0.152 (0.110)
Observations	199895	110855	56840	191024
Firm-Muni-Dest. FE	✓	✓	✓	✓
Firm-Muni-Year FE		✓	✓	✓
Year FE	✓			
Cluster Level: Destination-Year	✓	✓	✓	✓
Sample	Full	Full	Exports>0	Full
Estimator	PPML	PPML	PPML	LPM

Standard errors in parentheses

* p<0.1, ** p<0.05, *** p<0.01

demand. One additional result is that the firm size premia on exports is not driven by the firm's access to storage and crushing facilities (col.5) as the differential effect of firm size is not affected by this augmented set of interacted controls. Overall, this exporter size premium over demand variations is in line with recent evidence on the topic, relying on heterogeneous elasticities across firms (Bricongne et al., 2022; Chowdhry et al., 2023; Melitz and Ottaviano, 2008).

Table 3.2: Heterogeneity across Firms

	Dep. Variable: Firm-level Exports (X_{fmdt})				
	(1)	(2)	(3)	(4)	(5)
Log Soy Demand \times Log Firm Exports (t-1)	0.053*** (0.007)				0.056*** (0.008)
Log Soy Demand \times Log Nb Dest. (t-1)		0.099*** (0.020)			
Log Soy Demand \times Log Nb Sources (t-1)			0.051*** (0.008)		
Log Soy Demand \times Dtop4				0.109*** (0.021)	
Log Soy Demand \times Dstorage					-0.471*** (0.110)
Log Soy Demand \times Dcrushing					-0.339*** (0.055)
Observations	19942	19942	19942	21847	19942
Muni-Dest.-Year FE	✓	✓	✓	✓	✓
Firm-Muni-Year FE	✓	✓	✓	✓	✓
Cluster Level: Destination-Year	✓	✓	✓	✓	✓

Standard errors in parentheses

* p<0.1, ** p<0.05, *** p<0.01

3.4.2.2 Heterogeneity across municipalities

Next, changes in foreign demand have a different impact across soy-producing municipalities. Table 3.3 controls for firm-destination-year fixed effects and the identifying variation is hence across cities. Results support strong and robust differential effects of increased demand across soy-producing municipalities.

Conclusions are threefold. First, we estimate that conditional on the soy demand change, the impact is larger in cities with smaller GDP per capita (measured in 2004 to avoid endogeneity)

(col. 1). The larger the GDP in 2004, the lower the elasticity to soy demand changes. This effect is almost offset by population: large municipalities capture and absorb more the demand shock. This effect may partly be driven by cities closer to ports (col. 2). Distance to ports could capture within-Brazil trade costs such that the pro-trade effect of increased foreign demand could favor places with lower relative trade costs within the country.⁵ Second, competition drives a large part of the differential effect. We measure competition by counting the number of top-4 firms serving the same destination-year from the same municipality. We estimate that, conditional on soy demand changes, the larger effects are observed in municipalities with a low number of top 4 firms that were present in the previous year (col.3). This competition channel appears to be quantitatively an important driver of the differential effect across municipalities, as other determinants are estimated insignificant in column 3 onward. The export response seems to be driven much more by competition than by local economic conditions. This is in line with anecdotal evidence on the importance of these top firms (in an oligopoly setup, with a fringe of small firms) and of their strategic interactions. Firms sourcing from municipalities with fewer competitors yield higher elasticities. Third, recent deforestation patterns also shape the potential export response. Indeed, we find that the elasticity of exports to demand is larger in places with lower recent deforestation. Most of the action seems to be at play in places with lower recent deforestation patterns. Indeed, low levels of recent deforestation are correlated to potentially large deforestation in the past and thus a path-dependence pattern. Overall, a smaller GDP, fewer competitors in the municipality, and lower recent deforestation patterns dampen the impact of demand changes on soy exports.

3.4.2.3 Heterogeneity across destinations

Finally, the origin of the shock in demand plays no role in the patterns of exports. Table 3.4 displays models including an interaction term between soy demand and dummies characterizing the origin country. On average, firms do not particularly react to demand originating from China (compared to other countries altogether, in col. 1), nor from the EU (col. 2). More generally, destination GDP per capita and destination population (market size) do not shape the elasticity. This absence of differential effect along the origin of the demand shock is important for the implications of our exercise: it will allow us to remain agnostic on the origin of the shock, and estimated implied exports and deforestation effect will have external validity, independently of the source of the demand shock.

3.4.3 Robustness checks

Conclusions are robust to many robustness checks detailed in this subsection.

⁵Recall that distance with the final destination of the good is absorbed in the destination fixed effect.

Table 3.3: Heterogeneity across Municipalities

	Dep. Variable: Firm-level Exports (X_{fmdt})			
	(1)	(2)	(3)	(4)
Log Soy Demand \times Log GDP 2004	-0.029*** (0.010)	-0.023** (0.010)	-0.023 (0.017)	-0.008 (0.018)
Log Soy Demand \times Log Population (city) (t-1)	0.029*** (0.010)	0.024** (0.011)	0.025 (0.017)	0.003 (0.016)
Log Soy Demand \times Log Distance to Port		-0.025* (0.014)	-0.013 (0.017)	0.021 (0.018)
Nb Top 4 firms (t-1)			2.181*** (0.282)	1.972*** (0.295)
Log Soy Demand \times Nb Top 4 firms (t-1)			-0.110*** (0.018)	-0.097*** (0.019)
Log Soy Demand \times Deforestation (t-1) (Mapbiomas)				-0.007*** (0.001)
Log Soy Demand \times Deforestation (t-2) (Mapbiomas)				-0.007*** (0.002)
Observations	133753	133753	46211	37555
Firm-Dest.-Year FE	✓	✓	✓	✓
Muni.-Year FE	✓	✓	✓	✓
Cluster Level: Destination-Year	✓	✓	✓	✓

Standard errors in parentheses

* p<0.1, ** p<0.05, *** p<0.01

Table 3.4: Heterogeneity across Destinations

	Dep. Variable: Firm-level Exports (X_{fmdt})				
	(1)	(2)	(3)	(4)	(5)
Log Soy Demand	0.193*** (0.033)	0.220*** (0.038)	0.220*** (0.037)	0.307 (0.195)	-0.433* (0.246)
Log Dest GDP pc.	2.084*** (0.241)	2.281*** (0.145)	2.025*** (0.245)	2.559*** (0.389)	2.145*** (0.155)
Log Dest. Pop.	1.473** (0.728)	1.145 (0.730)	1.272* (0.730)	1.304* (0.723)	0.900 (0.732)
Log Soy Demand \times China=1	0.147 (0.137)		0.137 (0.138)		
Log Soy Demand \times EU=1		-0.118 (0.072)	-0.113 (0.072)		
Log Soy Demand \times Log Dest GDP pc.				-0.013 (0.022)	
Log Soy Demand \times Log Dest. Pop.					0.035** (0.014)
Observations	110855	110855	110855	110855	110855
Firm-Muni-Dest. FE	✓	✓	✓	✓	✓
Firm-Muni-Year FE	✓	✓	✓	✓	✓
Cluster Level: Destination-Year	✓	✓	✓	✓	✓

Standard errors in parentheses

* p<0.1, ** p<0.05, *** p<0.01

3.4.3.1 Outcomes: Exports measures

Exports in quantities, and unit values First, we replicated the estimations using firm-level exported quantities. Results are presented in Table C.1. Second, we replicated our main estimation on unit values (defined as the ratio of export values over exported quantities). Results are presented in Table C.2. The average effects occur regarding quantities, whereas prices (approximated by unit values) are mainly unaffected.

3.4.3.2 Main determinant: Soy Demands measures

Excluding supply shocks As the main measure of soy demand is a trade flow measure, we cannot exclude that this measure captures supply effect rather than demand variations. This concern is partly addressed by our estimation strategy, which captures the supply-side determinants: in the worst case in which the measure is solely a supply effect since our fixed effects absorb variations between suppliers, results would go to zero, i.e, estimating no effect of the soy demand.

We now check that our measure and estimation results resist to the potential bias introduced by supply shocks. Supply shock can arise in every production country of soy, not only in Brazil⁶. That implies we can decompose the observed trade flows in the following manner:

$$X_{odt}^{soy} = \eta_{ot} + \eta_{dt} + \eta_{od} + \varepsilon_{odt} \quad (3.3)$$

in which η_{ot} are the supply shocks. Purging the observed trade flows X_{odt}^{soy} from the supply shocks (estimated in η_{ot} in eq. 3.3) yields the supply-corrected demand for soy. We denote this value as the "purged" demand, which we then use in the benchmark estimations. Results are presented in Table C.3. Results confirm the benchmark conclusions: on average, demand slightly affects soy exports but favors the largest firms, with a minor role for (economic) geography.

Soy Demand in volume Conclusions are unaffected by our choice of soy demand measures. Indeed, Table C.4 presents results when using world soy demand in quantities (from BACI) instead of the benchmark export values, without affecting our conclusions.

3.4.3.3 Estimation issues

OLS estimation Table C.5 shows results when estimating equation 3.1 with the log of exports as the dependent variable and using an OLS estimator. Focusing on the universe of positive trade flows only, Table C.5 supports that the main elasticity value is affected by the choice of the

⁶Once again, we could exclude Brazil as a potential source of soy exports in our main measure. However, as Brazil represents around 40% of soy exports worldwide, excluding export flows from Brazil for the computation amounts to introduce another bias in the foreign demands: what we would identify from this measure would probably not be the exact demand faced by Brazilian exporters.

estimator and lies on average around 0.1. This is about half the value of the benchmark estimates. One way to interpret this result is: the OLS estimates capture the effect of demand on exports at the intensive margin only, whereas the PPML estimates identify the effects at both the intensive and extensive margins of trade. Hence, it is not surprising to obtain smaller point estimates.

Clustering of standard errors The inference is robust to the use of alternative standard error clustering levels: whereas benchmark results were based on destination-year clustering, the inference is confirmed when municipality-year clustered errors (Table C.6) or with two-way municipality-year and destination-year clusters (Table C.7). Table C.8 also shows results when clustering the standard errors at the logistic hub-year level (at the intensive margin of trade only, hence reducing sample size, however).

3.4.3.4 Placebo: other-than-soy exports

Finally, we do not capture a general trend toward Brazilian goods or other trends in import behavior. We first computed the total imports of agricultural goods from Brazil and excluded soy. We then regressed the firm-level soy exports on this demand that is unrelated to soy. In table C.9, plugging this non-soy demand in the estimations provides mainly non-significant coefficients, as expected.

3.5 Implications for deforestation

So far, we have examined how certain firms and municipalities heterogeneously capture demand variations. Building on this previous result, the final section of this paper discusses the implications of this result for the potential effect of demand-side policies on deforestation.

3.5.1 Background

Studies of forest conservation policies generally quantify their effectiveness in terms of avoided carbon emissions or avoided deforestation, which is the gap between the observed deforestation and a counterfactual value Alix-Garcia et al., 2017; Combes Motel et al., 2008; Delacote et al., 2016. To answer our specific research question, we need to examine the amount of forest that would remain intact when implementing a policy that reduces foreign demand for soy, compared to a business-as-usual scenario.

The effects of changes in foreign demand on deforestation can be decomposed into two distinct dimensions. First, the previous section provided an elasticity of exports to demand, that varies across municipalities and firms. Consequently, a demand reduction affects exports differently depending on location and market structure. Second, whether this change in exports will result

in deforestation depends on the potential for soybean expansion into forests: how much forest would have been affected in order to produce the (avoided) exports? Obviously, this is also highly location-dependent since some regions have much greater residual forest cover than others. We take both these dimensions into account in our discussion. As a result, avoided deforestation is the combination of avoided exports on the one hand and soy expansion possibilities on the other hand.

3.5.2 Avoided Exports

To estimate avoided exports, we rely on the previous empirical models and predict the observed export response to a marginal 1% increase in foreign demand. They have been generated from a regression of exports on foreign demands at the firm and municipality level, interacted with all firm-specific and municipality-specific variables used in the above analysis (see section on heterogeneity).

Figure 3.4 illustrates the estimated elasticities at the municipality level. The map displays the weighted average elasticity of exports to demand in each municipality. Dark areas correspond to large elasticities. The larger the elasticity, the larger the soy export response of the municipality. Brighter areas correspond to lower elasticities and imply no change in exports despite a change in soy demand.

A cluster of municipalities whose exports are most responsive to demand seems to emerge towards the east of the Amazon. Other small municipalities located in the south of the country also display relatively high elasticities. Surprisingly, municipalities in Matopiba, a region west of the Cerrado currently being extensively converted to soybean production, exhibit low elasticity.

Two points are worth highlighting. First, we found no significant effect of the origin of the demand shock. We can thus remain agnostic and predict the impact of a change in demand regardless of its origin. It also implies that policies that end up reducing imports (or reducing import growth) will have the same export effect regardless of whether the EU or other countries drive it. Second, avoided exports measure the "costs" of having a 1% increase in demand.

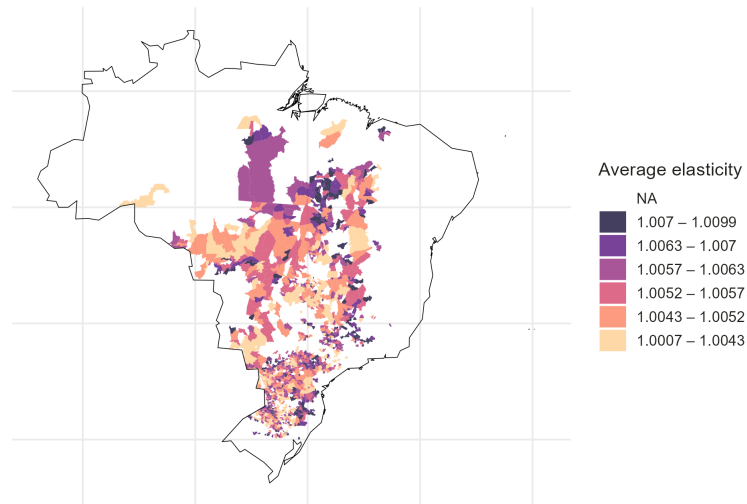


Figure 3.4: Average elasticities of exports in municipalities

3.5.3 Avoided deforestation

We now combine these elasticities with soy expansion possibilities at the municipality level. We measure soy expansion possibilities by computing the share of remaining forest cover out of the total area per municipality from MapBiomas data.⁷

First, in the cross-section of municipalities, avoided exports and soy expansion possibilities are positively correlated but with a low magnitude: we estimate a pairwise correlation of 0.14. It implies that places with high export response to demand are also places with a lot of remaining forests. This positive correlation supports the direct relationship between foreign demand and deforestation. This also underlines both the risks generated by the increasing trend in global demand and the potential effectiveness of policies to reduce deforestation on the side of consumer countries.

Figure 3.5 (left) plots the hierarchy of the estimated avoided deforestation. Darker areas represent places with large avoided deforestation. To decompose the total effect into the two components, Figure 3.5 (right) decomposes this index into the two components (red for exports elasticity and green for soy expansion possibilities). A dark color indicates a high percentage of remaining forest coupled with a high elasticity. This corresponds to areas where demand-side policies result in large avoided deforestation. This map reveals that many municipalities have a high potential for avoided deforestation. These are mainly located in the Amazon region. However, in certain localities, such as southern Mato Grosso or Matopiba, which still have significant forest cover, the weaker response to exports suggests that the effects of a demand-driven policy would be lower.

⁷It only includes forest formations and therefore excludes savannah-type vegetation, for example.

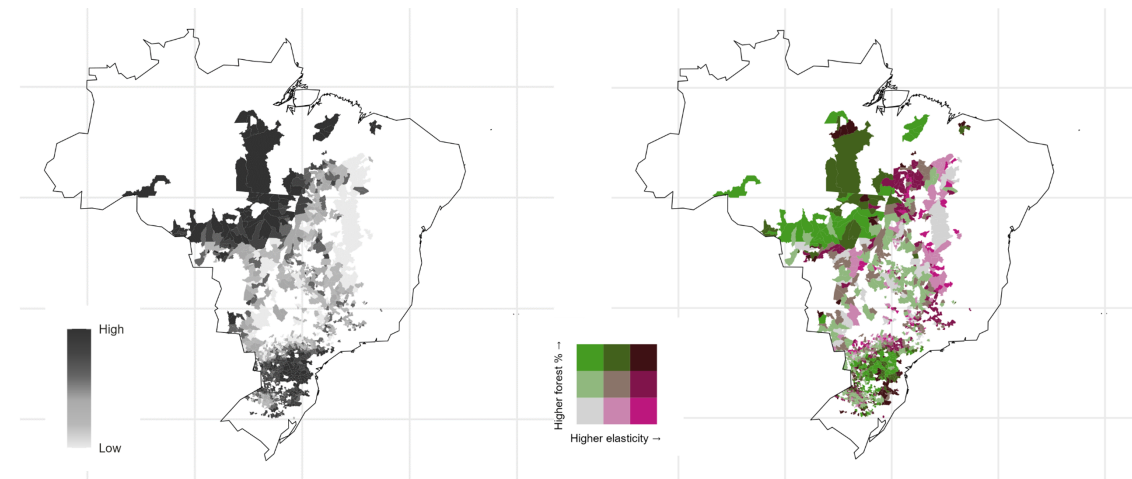


Figure 3.5: Potential of demand-side policies to avoid deforestation

3.6 Conclusion and Discussion

The current paper aims to assess the credibility of demand-side policies to curb deforestation. Are changes in consumer demand related to deforestation? To provide some insights on this important issue, we tackle this question focusing on the soy sector. Indeed, conversion from forests to soy-producing areas is a major driver of deforestation. We estimate a firm-level gravity model relating firm-municipality-destination export flows to destination-specific soy demand and to standard firm-level trade determinants.

Our analysis delivers the following conclusions. First, we estimate a positive average micro-level elasticity of soy exports to foreign demand, which confirms the credibility of demand-side policies. Second, we document that the average response hides significant heterogeneities across exporters and across municipalities in Brazil. Our analysis highlights (i) that the largest exporters are more sensitive to soy demand shocks, (ii) that higher past deforestation patterns reduce the response, and (iii) that the number of competitors in the same municipality also dampens the impact of demand. Third, we assess the potential benefits of the envisaged demand-side policies. In the cross-section of municipalities, export elasticities and soy expansion possibilities are positively correlated: places with high export response to demand are also places with a lot of remaining forests. Many municipalities have a high potential for avoided deforestation. These are mainly located in the Amazon region. However, in certain localities, such as southern Mato Grosso or Matopiba, which still have significant forest cover, the weak response to exports suggests that the effects of a demand-driven policy would be lower. In light of these considerations, one may anticipate that demand-side policies may slow down deforestation in Brazil, particularly in regions proximate to the Amazon.

Estimating the effectiveness of demand-side policies remains challenging and warrants fur-

ther investigation. The analysis carried out here does not consider general equilibrium effects, and the findings are contingent upon the assumption of symmetry between the impacts of rising and falling foreign demand. These aspects could be explored in future research projects to gain a more nuanced understanding of the dynamics surrounding demand-side policies and their implications for deforestation in tropical countries such as Brazil. Finally, how to reduce import soy demand remains a challenging question. First, increased meat and soy-based product consumption and population growth are fueling growth in soy demand worldwide, and trends are not likely to reverse in the short-run. Second, substituting soy with local protein crops is still challenging, and the search for alternatives requires attention to avoid creating additional environmental impacts.

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Appendix C

Table C.1: Firm-level exports in Quantities

	Dep. Variable: Firm-level Exports Volumes Q.			
	(1)	(2)	(3)	(4)
Log Soy Demand	0.197*** (0.039)			0.576** (0.229)
Log GDP pc (Dest.)	2.431*** (0.173)			3.027*** (0.449)
Log Dest. Pop.	1.296* (0.751)			1.224* (0.733)
Log Soy Demand × Log Firm Exports (t-1)		0.048*** (0.008)		
Log Soy Demand × Log 2004-GDP (city)			-0.010 (0.017)	
Log Soy Demand × Log Population (city) (t-1)			-0.002 (0.016)	
Log Soy Demand × Log Distance to Ports			0.020 (0.018)	
Nb. Top-4 (t-1)			1.975*** (0.323)	
Log Soy Demand × Nb. Top-4 (t-1)			-0.096*** (0.021)	
Log Soy Demand × Deforestation (t-1)			-0.006*** (0.001)	
Log Soy Demand × Deforestation (t-2)			-0.006*** (0.001)	
Log Soy Demand × GDP pc (Dest.)				-0.040 (0.025)
Observations	110855	21765	37555	110855
Firm-Muni.-Year FE	✓	✓		✓
Firm-Muni.Dest FE	✓			✓
Firm-Dest.-Year FE			✓	
Muni.-Dest.-Year FE		✓		
Muni.-Year FE			✓	
Cluster Level: Destination-Year	✓	✓	✓	✓

Standard errors in parentheses

* p<0.1, ** p<0.05, *** p<0.01

Table C.2: Unit Values

	Dep. Variable: Firm-level: Unit Value			
	(1)	(2)	(3)	(4)
Log Soy Demand	-0.006*			0.025
	(0.004)			(0.021)
Log GDP pc (Dest.)	-0.020			0.033
	(0.025)			(0.041)
Log Soy Demand × Log Firm Exports (t-1)		-0.002***		
		(0.001)		
Log Soy Demand × Log 2004-GDP (city)			-0.001	
			(0.001)	
Log Soy Demand × Log Population (city) (t-1)			-0.001	
			(0.001)	
Log Soy Demand × Log Distance to Ports			-0.009***	
			(0.003)	
Nb. Top-4 (t-1)			0.067	
			(0.053)	
Log Soy Demand × Nb. Top-4 (t-1)			-0.004	
			(0.003)	
Log Soy Demand × Deforestation (t-1)			-0.000	
			(0.000)	
Log Soy Demand × Deforestation (t-2)			0.000	
			(0.000)	
Log Soy Demand × Log GDP pc (Dest.)				-0.003
				(0.002)
Observations	56840	8633	15639	56840
Firm-Muni.-Year FE	✓	✓		✓
Firm-Muni.Dest FE	✓			✓
Firm-Dest.-Year FE			✓	
Muni.-Dest.-Year FE		✓		
Muni.-Year FE			✓	
Cluster Level: Destination-Year	✓	✓	✓	✓

Standard errors in parentheses

* p<0.1, ** p<0.05, *** p<0.01

Table C.3: Demand purged from supply shocks

	Dep. Variable: Firm-level Exports (X_{fmdt})			
	(1)	(2)	(3)	(4)
Log Purged Demand	0.068** (0.029)			-0.040 (0.199)
Log GDP pc (Dest.)	2.649*** (0.134)			2.440*** (0.417)
Log. Dest. Pop.	2.342*** (0.744)			2.380*** (0.754)
Log Purged Demand \times Log Firm Exports (t-1)		0.057*** (0.009)		
Log Purged Demand \times Log 2004-GDP (city)			-0.003 (0.020)	
Log Purged Demand \times Log Populaton (city) (t-1)			-0.002 (0.020)	
Log Purged Demand \times Log Distance to Ports			0.033 (0.022)	
Nb Top4 (t-1)			2.555*** (0.403)	
Log Purged Demand \times Nb Top4 (t-1)			-0.136*** (0.027)	
Log Purged Demand \times Deforestation (t-1)			-0.008*** (0.002)	
Log Purged Demand \times Deforestation (t-2)			-0.007*** (0.002)	
Log Purged Demand \times Log GDP pc (Dest.)				0.012 (0.022)
Observations	110819	21763	37555	110819
Firm-Muni.-Year FE	✓	✓		✓
Firm-Muni.Dest FE	✓			✓
Firm-Dest.-Year FE			✓	
Muni.-Dest.-Year FE		✓		
Muni.-Year FE			✓	
Cluster Level: Destination-Year	✓	✓	✓	✓

Standard errors in parentheses

* p<0.1, ** p<0.05, *** p<0.01

Table C.4: Soy Demand: Quantities

	Dep. Variable: Firm-level Exports Values			
	(1)	(2)	(3)	(4)
Log Soy Demand (Q)	0.168*** (0.030)			0.252 (0.180)
Log GDP pc (Dest.)	2.394*** (0.138)			2.552*** (0.382)
Dest. Pop.	1.426* (0.728)			1.394* (0.732)
Log Soy Demand (Q) × Log Firm Exports (t-1)		0.052*** (0.007)		
Log Soy Demand (Q) × Log 2004-GDP (city)			-0.009 (0.017)	
Log Soy Demand (Q) × Log Population (city) (t-1)			0.003 (0.016)	
Log Soy Demand (Q) × Log Distance to Ports			0.021 (0.017)	
Nb. Top-4 (t-1)			2.021*** (0.308)	
Log Soy Demand (Q) × Nb. Top-4 (t-1)			-0.095*** (0.019)	
Log Soy Demand (Q) × Deforestation (t-1)			-0.007*** (0.001)	
Log Soy Demand (Q) × Deforestation (t-2)			-0.006*** (0.002)	
Log Soy Demand (Q) × Log GDP pc (Dest.)				-0.009 (0.020)
Observations	110855	21765	37555	110855
Firm-Muni.-Year FE	✓	✓		✓
Firm-Muni.Dest FE	✓			✓
Firm-Dest.-Year FE			✓	
Muni.-Dest.-Year FE		✓		
Muni.-Year FE			✓	
Cluster Level: Destination-Year	✓	✓	✓	✓

Standard errors in parentheses

* p<0.1, ** p<0.05, *** p<0.01

Table C.5: OLS

	Dep. Variable: log Firm-level Exports			
	(1)	(2)	(3)	(4)
Log Soy Demand	0.085*** (0.027)			0.258 (0.182)
Log GDP pc (Dest.)	1.941*** (0.240)			2.216*** (0.381)
Log Dest. Pop.	-0.382 (0.680)			-0.462 (0.680)
Log Soy Demand × Log Firm Exports (t-1)		0.041*** (0.007)		
Log Soy Demand × Log 2004-GDP (city)			0.018 (0.015)	
Log Soy Demand × Log Population (city) (t-1)			-0.018 (0.015)	
Log Soy Demand × Log Distance to Ports			0.004 (0.019)	
Nb. Top-4 (t-1)			0.968** (0.402)	
Log Soy Demand × Nb. Top-4 (t-1)			-0.043 (0.027)	
Log Soy Demand × Deforestation (t-1)			-0.003** (0.001)	
Log Soy Demand × Deforestation (t-2)			-0.003*** (0.001)	
Log Soy Demand × Log GDP pc (Dest.)				-0.019 (0.020)
Observations	56840	8633	15639	56840
R ²	0.848	0.794	0.726	0.848
Firm-Muni.-Year FE	✓	✓		✓
Firm-Muni.Dest FE	✓			✓
Firm-Dest.-Year FE			✓	
Muni.-Dest.-Year FE		✓		
Muni.-Year FE			✓	
Cluster Level: Destination-Year	✓	✓	✓	✓

OLS estimations. Standard errors in parentheses.

* p<0.1, ** p<0.05, *** p<0.01

Table C.6: Alternative clustering: municipality-year

	Dep. Variable: Firm-level Exports			
	(1)	(2)	(3)	(4)
Log Soy Demand	0.191*** (0.021)			0.307** (0.134)
Log GDP pc (Dest.)	2.363*** (0.111)			2.559*** (0.249)
Dest. Pop.	1.343*** (0.463)			1.304*** (0.465)
Log Soy Demand × Log Firm Exports (t-1)		0.053*** (0.007)		
Log Soy Demand × Log 2004-GDP (city)			-0.008 (0.021)	
Log Soy Demand × Log Population (city) (t-1)			0.003 (0.022)	
Log Soy Demand × Log Distance to Ports			0.021 (0.022)	
Nb. Top-4 (t-1)			1.972*** (0.426)	
Log Soy Demand × Nb. Top-4 (t-1)			-0.097*** (0.028)	
Log Soy Demand × Deforestation (t-1)			-0.007*** (0.002)	
Log Soy Demand × Deforestation (t-2)			-0.007*** (0.002)	
Log Soy Demand × Log GDP pc (Dest.)				-0.013 (0.015)
Observations	110855	21765	37555	110855
Firm-Muni.-Year FE	✓	✓		✓
Firm-Muni.Dest FE	✓			✓
Firm-Dest.-Year FE			✓	
Muni.-Dest.-Year FE		✓		
Muni.-Year FE			✓	
Cluster Level	by municipality-year			

Standard errors in parentheses

* p<0.1, ** p<0.05, *** p<0.01

Table C.7: Two-way clustering: municipality-year + destination-year

	Dep. Variable: Firm-level Exports Values			
	(1)	(2)	(3)	(4)
Log Soy Demand	0.191*** (0.035)			0.307 (0.205)
Log GDP pc (Dest.)	2.363*** (0.157)			2.559*** (0.399)
Dest. Pop.	1.343* (0.738)			1.304* (0.733)
Log Soy Demand × Log Firm Exports (t-1)		0.053*** (0.009)		
Log Soy Demand × Log 2004-GDP (city)			-0.008 (0.023)	
Log Soy Demand × Log Population (city) (t-1)			0.003 (0.023)	
Log Soy Demand × Log Distance to Ports			0.021 (0.023)	
Nb. Top-4 (t-1)			1.972*** (0.387)	
Log Soy Demand × Nb. Top-4 (t-1)			-0.097*** (0.026)	
Log Soy Demand × Deforestation (t-1)			-0.007*** (0.002)	
Log Soy Demand × Deforestation (t-2)			-0.007*** (0.002)	
Log Soy Demand × Log GDP pc (Dest.)				-0.013 (0.023)
Observations	110855	21765	37555	110855
Firm-Muni.-Year FE	✓	✓		✓
Firm-Muni.Dest FE	✓			✓
Firm-Dest.-Year FE			✓	
Muni.-Dest.-Year FE		✓		
Muni.-Year FE			✓	
Cluster Level	by municipality-year and destination-year			

Standard errors in parentheses

* p<0.1, ** p<0.05, *** p<0.01

Table C.8: Alternative clustering: by logistic hub-year

	Dep. Variable: Firm-level Exports Values			
	(1)	(2)	(3)	(4)
Log Soy Demand	0.095*** (0.026)			0.476*** (0.137)
Log GDP pc (Dest.)	1.971*** (0.136)			2.605*** (0.273)
Log Soy Demand × Log Firm Exports (t-1)		0.042*** (0.007)		
Log Soy Demand × Log 2004-GDP (city)			0.022 (0.018)	
Log Soy Demand × Log Population (city) (t-1)			0.000 (0.020)	
Log Soy Demand × Log Distance to Ports			0.071*** (0.021)	
Nb. Top-4 (t-1)			1.238*** (0.369)	
Log Soy Demand × Nb. Top-4 (t-1)			-0.059** (0.025)	
Log Soy Demand × Deforestation (t-1)			-0.004*** (0.002)	
Log Soy Demand × Deforestation (t-2)			-0.005*** (0.001)	
Log Soy Demand × Log GDP pc (Dest.)				-0.041*** (0.015)
Observations	56840	8633	15639	56840
Firm-Muni.-Year FE	✓	✓		✓
Firm-Muni.Dest FE	✓			✓
Firm-Dest.-Year FE			✓	
Muni.-Dest.-Year FE		✓		
Muni.-Year FE			✓	
Cluster Level	by logistic hub - year			

Standard errors in parentheses

* p<0.1, ** p<0.05, *** p<0.01

Table C.9: Placebo: other-than-soy exports

	Dep. Variable: Firm-level Exports			
	(1)	(2)	(3)	(4)
Log Non-Soy Demand	0.071 (0.051)			0.885*** (0.305)
Log GDP pc (Dest.)	2.559*** (0.155)			3.939*** (0.566)
Log Dest. Pop.	2.349*** (0.743)			2.379*** (0.732)
Log Non-Soy Demand × Log Firm Exports (t-1)		0.016 (0.011)		
Log Non-Soy Demand × Log 2004-GDP (city)			0.029* (0.017)	
Log Non-Soy Demand × LogPopulation (city) (t-1)			-0.026* (0.015)	
Log Non-Soy Demand × Log Distance to Ports			-0.023 (0.023)	
Nb. Top-4 (t-1)			1.931*** (0.308)	
Log Non-Soy Demand × Nb. Top-4 (t-1)			-0.097*** (0.021)	
Log Non-Soy Demand × Deforestation (t-1)			-0.005*** (0.001)	
Log Non-Soy Demand × Deforestation (t-2)			-0.005*** (0.002)	
Log Non-Soy Demand × Log GDP pc (Dest.)				-0.090*** (0.034)
Observations	110855	21765	37555	110855
Firm-Muni.-Year FE	✓	✓		✓
Firm-Muni.Dest FE	✓			✓
Firm-Dest.-Year FE			✓	
Muni.-Dest.-Year FE		✓		
Muni.-Year FE			✓	
Cluster Level: Destination-Year	✓	✓	✓	✓

Standard errors in parentheses

* p<0.1, ** p<0.05, *** p<0.01

General Conclusion

4.1 Main findings

This thesis provides some insights on the intersection between trade and the environment, using the international soy trade and its relationship with deforestation as a case study. The growing concern about the interaction between trade and deforestation stems from the fact that deforestation has both local and global consequences, notably on climate and biodiversity. Preserving forests is, therefore, essential to achieving global climate and biodiversity targets. The attention given to the effects of trade on deforestation also reflects the growing awareness that consumers participate in deforestation abroad through their consumption of agricultural products. As a result, international attention is increasingly focused on the role of demand and foreign trade, particularly in tropical deforestation. This evolution from a local resource management issue to an international policy concern is illustrated by initiatives such as the EU Regulation on 'deforestation-free products' (Regulation (EU) 2023/1115), which aims to tackle deforestation linked to the imports of products such as soy.

The three chapters proposed in this essay all focus on the Brazilian soy trade and its links with deforestation, adopting an empirical approach. Where possible, they consider several actors in the soy value chain, namely producers, exporters and destination countries. They look successively at different levels of the supply chain, from upstream to downstream. Two aspects of the

links between soy trade and deforestation are explored, which relate more generally to fundamental questions raised in international economics and environmental economics: the impact of environmental policies on international competitiveness and the possibility of substituting trade policies for environmental policies. The first chapter explores the effects of a Brazilian forest conservation policy on the soy trade. The second and third chapters examine the credibility of trade policies in halting deforestation.

More specifically, the first chapter assesses the collateral impacts of a forest conservation policy, the Priority List, on soybean production and export in the context of the Brazilian Amazon. Findings reveal that the policy successfully reduced deforestation rates using difference-in-differences and a generalized synthetic control. Counterintuitively, findings also indicate that soybean production and exports have not been adversely affected by these conservation efforts. Instead, the soybean sector appears to have benefited from the policy through shifts in land use. In the second chapter, we explore the resilience of Brazil's soybean export networks in the face of supply disruptions, specifically local drought events. The analysis reveals how these shocks differentially impact exporters, depending on their sourcing strategies. The study also highlights the existence of coping strategies among exporting companies. However, firms tend to rely on their historical partners and do not easily contract new relationships, revealing the existence of rigidity in the soy supply chains.

The third chapter investigates the credibility of demand-side policies in curbing deforestation linked to soy production. By estimating the responsiveness of soy exports to changes in international demand, the study uncovers variations in export elasticities across exporters and municipalities. We draw some implications for the potential of demand-side measures to mitigate deforestation in some locations, especially near critical ecosystems like the Amazon.

4.2 Transversal policy implications

This dissertation yields several lessons. The first one is that supply-side policies are not always detrimental to trade, contrary to what might be assumed. Some supply-side policies in Brazil have not only succeeded in curbing deforestation but have also managed to do so without any adverse effects on trade. This is important because it suggests the possibility of combining apparently contradictory interests, namely increasing production while preserving natural resources. Naturally, this may not work in other contexts. Brazil's current inefficiencies in land use, particularly its extensive grazing lands, suggest considerable room for improvement and that sustainable

intensification of agricultural production could be a credible option. The first chapter of the thesis is a reminder that Brazil has already implemented ambitious forest conservation policies in the past, with great success achieved through the synergy of various instruments. The country is mature compared to other countries regarding forest regulations: there are already well-proven forest monitoring, traceability, and rural land registry systems. Given these favorable conditions, we can expect synergies with the European Union's new EUDR regulation, which could create opportunities for the agro-industrial sector⁸. Additionally, the chapter highlights intracrops reallocations, emphasizing the importance of targeting multiple products or addressing deforestation comprehensively, rather than focusing solely on individual commodities.

Our second conclusion is that demand-side policies could contribute to curbing deforestation rates. To make a real dent in global deforestation, policies must be aligned and synergized to achieve a single vision for the desired European agricultural model. Currently, policies in France are fragmented, with disjointed approaches to issues such as protein self-sufficiency, limiting imported deforestation, Mercosur free trade agreements and unclear views on shifting diets away from meat consumption. This silo approach could compromise the achievement of their objectives. The challenges of reducing the dependence on soy from deforestation are real, as the livestock industry relies heavily on soybean imports, which calls for coherent, multidimensional policies. This dependence, coupled with the consolidation of feed production by multinational companies, has marginalized domestic protein sources in Europe (Skoufos, 2014). On the other hand, reducing reliance on imported soy provides an opportunity to mitigate the environmental impacts of agriculture abroad and domestically. Encouraging the cultivation of local protein crops like lupin, peas or sunflower seeds, and promoting more efficient protein use are key strategies. This is not an easy path, as the question of the viability and feasibility of switching to local protein sources remains open, given Europe's agro-climatic constraints. To be self-sufficient in soy, Europe would need to devote 9-12% of its arable land to soy (Guilpart et al., 2022). This is yet another reason to promote dietary changes to reduce demand for soy and, hence, deforestation abroad. In pursuing sustainable alternatives, careful consideration is needed to avoid unintended environmental consequences.

4.3 Research perspectives

Some aspects raised in this thesis exceed the scope of the three chapters, but open new exciting avenues for research.

⁸<https://www.climatepolicyinitiative.org/publication/brazilian-environmental-policies-and-the-new-european-union-regulation-for-deforestation-free-products-opportunities-and-challenges/>

An under-explored aspect of this thesis concerns the social justice dimension of environmental trade policies, particularly regarding stakeholder compensation. Given that the imported deforestation policies emanate from developed countries with a history of deforestation and are imposed on developing countries, the potential distributional disparities these policies may create merit close scrutiny. Policies aiming at curbing deforestation can potentially exacerbate inequalities within and between countries, leading to winners and losers in the process that require equitable compensation. For instance, unintended effects could be the exclusions of indigenous people and local communities from high-value supply chain of commodities, land conflicts between large-scale and small-scale agriculture (Grabs et al., 2021; Zhunusova et al., 2022). Resolving these equity issues is essential to foster international cooperation and ensure equitable policy outcomes (Cesar de Oliveira et al., 2024).

Indeed, the main pitfall of demand-side policies is the issue of coordination and leakage (Harstad, 2022; Hsiao, 2022; Villoria et al., 2022). Although we indirectly address the leakage problem between suppliers and traders, we do not consider leakage between countries. Yet, this is a central issue in discussions on trade and deforestation. A sufficient number of importing countries is necessary to encourage changes in production models and avoid leakage. This applies to all policies to combat climate change, which are international in nature. The crucial coordination issue naturally leads us to consider the possibility of global governance of land-use trajectories. For this reason, the role of the soil sector in climate negotiations is another fertile area for research. We need to study the conditions under which such agreements can be concluded and the political economy obstacles.

Next, the question of the generalizability of the results presented in this thesis to other contexts and other commodities remains open and deserves further exploration. Given that the empirical studies presented in this dissertation are based on the specific context of soy in Brazil and measure marginal effects in past situations, their conclusions are inherently limited. For example, other products linked to deforestation, like palm oil or cocoa might be very different stories. Because no 'one size fits all' approach to trade-related deforestation can deliver results in various landscapes, research efforts should focus on identifying the optimal policy mix for different jurisdictions through field studies that involve all stakeholders and develop tailored theories of change (Lambin et al., 2023). These approaches could be complemented by other research methods, which would allow broader conclusions to be drawn, such as land-use and trade models for prospective analysis, or lab experiment studies to study consumers' behaviors (Disdier and S. Marette, 2012; Disdier, Stéphan Marette, et al., 2013).

Furthermore, the agri-food systems of the major soy-importing countries deserve much more attention than they receive in this dissertation. Further research is needed to find the right in-

struments to encourage plant protein relocation while ensuring farms' economic and ecological viability. Moreover, there is a pressing need to explore avenues for reducing meat consumption and promoting alternative protein sources to alleviate the pressure on global soy demand.

Finally, in the policy implications section, we mentioned the importance of addressing food, agricultural production and trade policies as a whole. From a research perspective, this could translate into studies at the macroeconomic level, looking at the implications of combined policy scenarios for the economy and the environment. Such research could refine the estimates of climate change mitigation potential for agricultural and food policies, which are currently subject to significant uncertainties.

To conclude, trade policies against deforestation, especially when imposed on other trading partners, need a rigorous scientific basis to be credible. Science is essential to support the development, implementation, and monitoring of these policies. Each of these research areas (in economics, but also agricultural development) is fundamental to inform policymakers. With vast areas of forest still standing around the world, there are still many opportunities to implement effective forest protection measures.

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Title: Soybean trade and imported deforestation

Keywords: Soybean, Imported deforestation, Brazil, Trade

Abstract:

The growth in international soy trade is giving rise to mounting concern about its impact on deforestation, and consequently on climate and biodiversity. The role of foreign consumers through their demand for agricultural products is crucial, revealing the considerable weight of foreign trade in deforestation. These findings mark a shift in the way we approach deforestation, from a local resource management issue to an international concern. The concept of imported deforestation illustrates this change in perspective. This thesis aims to shed light on the links between trade and deforestation by focusing on the soy trade in Brazil. Using an empirical approach, it explores these links at different levels of the supply chain, from upstream to downstream.

The first chapter analyses production and export decisions by examining the effects of a Brazilian forest conservation policy on the soy sector. In 2008, the government drew up a list of municipalities most vulnerable to deforestation in order to target efforts to prevent and control deforestation. We draw on this quasi-natural experience to estimate the collateral impacts of this policy on the soy sector and changes in land use. This research question addresses the tensions between nature conservation, economic development and international competitiveness in an agricultural context. To answer this question, we use double difference and synthetic generalized control methods. Our results indicate that the soybean sector has benefited from the policy in terms of land use, production and exports.

In a world where disruptions to global supply chains are becoming increasingly frequent, it is essential to understand how these chains adjust. The second chapter of this thesis looks at how soybean supply chains in Brazil respond to local supply shocks, using droughts as an example. The results indicate that these shocks lead to a reduction in soybean yields, production and exports at the level of the producing municipalities. Although transactions with exporting firms may be affected at the intensive margin, this does not necessarily affect the existence of relationships between suppliers and buyers. Exporting firms exposed to these shocks show, on average, some resilience by increasing their purchases from other unaffected suppliers. This raises questions for policies against imported deforestation, particularly with regard to market concentration, frictions in supply networks, and the risks of relocation to other suppliers.

Finally, the third chapter investigates the credibility of demand policies in the fight against deforestation linked to soy production, by analysing the links between foreign demand and production, and drawing implications for deforestation. We find a positive average elasticity of soy exports with respect to foreign demand, which confirms the effectiveness of demand-side policies. However, this average response conceals heterogeneities among exporters and among Brazilian municipalities. Export elasticities and the potential for soy expansion are positively correlated, meaning that the places where exports respond strongly to demand are also those where there are still large areas of forest. Thus, many municipalities have a high potential for reducing deforestation. From this perspective, it is reasonable to expect that demand-side policies will help to slow deforestation in Brazil.

Titre : Commerce du soja et déforestation importée

Mots-clés : Soja, Déforestation importée, Brésil, Commerce international

Résumé :

L'essor du commerce international du soja suscite une inquiétude croissante quant à son impact sur la déforestation, et par conséquent sur le climat et la biodiversité. Le rôle des consommateurs étrangers par le biais de leur demande de produits agricoles est crucial, ce qui révèle le poids considérable du commerce extérieur dans la déforestation. Ces constats marquent un changement dans la manière dont nous abordons la déforestation, passant d'un problème de gestion des ressources locales à une préoccupation internationale. Le concept de déforestation importée illustre ce changement de perspective. Cette thèse vise à éclairer les liens entre commerce et déforestation en se focalisant sur le commerce de soja en provenance du Brésil. À travers une approche empirique, elle explore ces liens à différents niveaux de la chaîne d'approvisionnement, de l'amont à l'aval.

Le premier chapitre analyse les décisions de production et d'exportation en examinant les effets d'une politique brésilienne de conservation des forêts sur le secteur du soja. En 2008, le gouvernement a établi une liste des municipalités les plus vulnérables à la déforestation pour cibler les efforts de prévention et contrôle de la déforestation. Nous utilisons cette expérience quasi-naturelle pour estimer les impacts collatéraux de cette politique sur le secteur du soja et les changements d'usages des sols. Cette question de recherche permet d'aborder les tensions entre conservation de la nature et compétitivité internationale. Pour y répondre, nous recourons à des méthodes de double différences et de contrôle généralisé. Nos résultats indiquent que le secteur du soja a bénéficié de la politique en termes d'utilisation des terres, de production et d'exportations.

Dans un monde où les perturbations des chaînes d'approvisionnement mondiales deviennent de plus en plus fréquentes, il est essentiel de comprendre comment ces chaînes s'ajustent. Le deuxième chapitre de cette thèse se penche sur la manière dont les chaînes d'approvisionnement en soja au Brésil réagissent aux chocs d'offre locaux, en prenant pour exemple les sécheresses. Les résultats révèlent que ces chocs entraînent une diminution des rendements, de la production et des exportations de soja au niveau des municipalités de production. Bien que les transactions avec les entreprises exportatrices puissent être affectées sur la marge intensive, cela n'impacte pas nécessairement l'existence des relations entre fournisseurs et acheteurs. Les entreprises exportatrices exposées à ces chocs montrent, en moyenne, une certaine résilience, en accroissant leurs achats auprès d'autres fournisseurs qui ne sont pas affectés. Cela soulève des questions pour les politiques contre la déforestation importée, notamment en ce qui concerne la concentration du marché, les frictions dans les réseaux d'approvisionnement, et les risques de délocalisation vers d'autres fournisseurs.

Enfin, le troisième chapitre évalue la crédibilité des politiques de demande dans la lutte contre la déforestation liée à la production de soja, en analysant les liens entre demandes étrangères et production, et en en tirant des implications pour la déforestation. Nous constatons une élasticité moyenne positive des exportations de soja par rapport à la demande étrangère, ce qui confirme l'efficacité des politiques centrées sur la demande. Cependant, cette réponse moyenne dissimule des hétérogénéités entre les exportateurs et entre les municipalités brésiennes. Les élasticités des exportations et le potentiel d'expansion du soja sont positivement corrélés, ce qui signifie que les endroits où les exportations réagissent fortement à la demande sont également ceux où il reste encore de vastes étendues forestières. Ainsi, de nombreuses municipalités présentent un potentiel élevé de réduction de la déforestation. Dans cette perspective, on peut s'attendre à ce que les politiques basées sur la demande contribuent à ralentir la déforestation au Brésil.