

The sustainability of global agricultural trade:
understanding stickiness in Brazil's soy supply chain

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Foreword

I believe it is essential to offer a bit of context about this work and who I am, what I think, my origins, and thence potential biases and limitations.

For me, science is not about utopic ideals of neutrality or impartiality but rather about transparency and honesty. When I finally understood that along my academic journey, my heart and mind were enlightened. Before, researching and producing knowledge was painful because I perceived rigour and scientific methods as systems to uncover the truth. I took it seriously and suffered from never finding “the truth”. Nevertheless, when I knew this transparency nature of scientific knowledge, the research endeavours became more exciting.

Of course, there are undeniable and objective facts that can be observed through the lenses of microscopes, telescopes or satellites. However, every time we describe and interpret what we see, we impose biases and limitations. For this imposition, there is no solution except intellectual honesty and transparency. We need to ask and respond to ourselves and the public a few basic situated-knowledge questions. For example, what were we really searching for when we began looking, what transformations were we seeking to trigger, or what benefits were we expecting to reap?

In addition to that, societal problems such as poverty, famine, ignorance, human rights abuses and violations have always astonished me. As a child and even today, I keep asking myself: how come such a beautiful planet, plenished by abundant resources and beauty, with so many bright, incredible and ingenious people all over the world, still bear these tragedies? It was a hard fact to learn as I grew old that no one knows the answer. I spent many years glooming over this realisation, as probably yourself and many normative researchers like myself.

However, this inner child of myself one day decided to go out of pessimism and never grow old if this meant living in low spirits. He agreed that infinite curiosity could be a good remedy, if not to all the

Foreword

world's issues, at least for keeping me happy and alive. This child then decided to become a scientist. He understood that we will not find "the truth" but that we can learn, elicit, uncover and raise many truths, facts, beliefs and perceptions. Most importantly, this child learned that we can understand how people perceive and use things through rigorous, systematic, bold and persistent inquiry. Therefore, we can interweave these pieces together to create new mosaics and beautiful forms of knowledge. We can look from various points of view that may enlighten, or not, our existences and, perhaps, solve some of our real-world problems. I realised that science and art can walk together.

For those reasons, I came for this PhD with the spirit and intention of deeply understanding why and how we do construct or create the conditions and structures for human tragedies. I wanted to learn how to constructively transform the way we produce, trade, consume and govern our food systems, altering the current trajectory that is leading us to an impoverished, ignorant, violent and unsustainable existence.

Then you may ask: but why did you choose the soy supply chain and Brazil, amongst so many real-world issues? For finding this answer, I invite you to please take a seat, a cup of coffee or tea and enjoy the ride!

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Thanks to my co-supervisor, Tobias Kuemmerle, for offering relevant insights and guidance in this adventure and hosting me for two months in my Berlin secondment. I had the opportunity to meet other scientists and researchers to further expand my knowledge horizons. Thanks to all the lovely Biogeographers at Humboldt University, like Alfredo, Ana, Catalina, Benjamin, Arash, Teresa, Julian, Hendrik, Florian, Philippe, Mathias, Christian, including Malika and Johannes. They welcomed me warmly and contributed so much to my research.

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I. Introduction

1.1. The motivation of this thesis: setting the issue

We live in a world where multiple crises intertwine. These interconnected crises, such as global climate change, biodiversity loss, food insecurity, mass migration due to conflict, violence and absence of crucial natural resources, and a pandemic, challenge humankind on its very way of living, producing, consuming and organizing itself (Randers, 2012; Scharmer, 2016). These problems might have arisen when humans began to sedentarize, farm their food, domesticate wild animals (Brancalion et al., 2020; Diamond, 2017; Harari, 2015), or, in other words, when the humankind began harvesting the biosphere (Smil, 2012). These ingenious innovations, and resource efficiency, solved many real-world problems, such as famine and scarcity (Randers, 2012). Nonetheless, they may have also happened because of environmental and natural resources crises (DeFries, 2014).

The very way we humans interact with the earth's natural resources, the way we produce, consume and exchange food, energy, and fiber is threatening our climate stability, the world's habitats and species, water cycles, and our very capacity to feed ourselves and prevent the spread of diseases (Dobson et al., 2020; FAO, 2017; IPCC, 2014a, 2019; Tollefson, 2020). Seeking efficiency, economies of scale in the exploitation of minerals, soils, forestlands and biodiversity, impose severe threats to our global ecosystem's carrying capacity (Barry, 2007; Daily and Ehrlich, 2007; Farrell and Löw Beer, 2019). It also undermines social foundations such as human rights, gender and economic equality (Barry, 2009; Esquivel, 2016; Princen, 2003).

Nevertheless, the agricultural revolution and its efficiency gains in food production were necessary to feed almost nine billion people, decreasing the *per capita* use of arable land over time through technology (Ellis et al., 2013). Global trade and liberalism add extra pressure on this social-ecological system, arguing that more trade liberalization achieves more efficiency and economies of scale in producing and extracting commodities (Baldwin and Okubo, 2014; Krugman et al., 2012). Thus international trade may accentuate this straining relationship between humans and nature (Meyfroidt et al., 2013; Rees, 2002).

Material and immaterial flows, such as the commerce of soybeans or rice, cooperation principles and funding, financial resources, cultural values and norms connect distant landscapes, societies, places of production and consumption in a globalized world (Friis and Nielsen, 2017a, 2019; Liu et al., 2013). These linkages between different and distant places and peoples are beneficial in the sense of promoting intellectual and immaterial progress, advancing global food security, innovation, creativity for finding solutions (Egli et al., 2018; Laroche et al., 2020; Ringler et al., 2013). In contrast, the distant exchanges between places and peoples, especially trade, has also been exacerbating existing inequalities, promoting global climate change, biodiversity loss, deforestation and native vegetation conversion, fisheries depletion, *mal-* or excluding development, amongst other social-environmental outcomes (Escobar et al., 2020; Gephart et al., 2017; Green et al., 2019; Henders et al., 2015; Koberg and Longoni, 2019; Lopes et al., 2021; Pendrill et al., 2019b; Sikor et al., 2013).

At difficult times for humanity, where we find ourselves in civilizational crossroads, scientific knowledge and reasoning have been essential to expose our most fundamental trade-offs, elicit crucial facts and indicate potential solutions for our real-world problems. In this context, science contributes with systemic perspectives and collaborative thinking to find data-based solutions (Kahane, 2017; Scharmer, 2016). With this spirit and for the purposes exposed above, I believe it is crucial to investigate the relationship patterns that underpin distant material flows, which accentuate our ecological problems and social inequities. It is fundamental to inquire what social, economic, political, and cultural norms and factors drive these global exchanges between peoples and places and implicate global transformations; and how they develop and shape interacting actors and factors. Here in this thesis, I focus on the global trade of commodities, or global commodity supply chains, as a way to uncover some of these trade relationships patterns. In other words, I analyze the underlying factors that underpin the stability, rigidity or volatility of global commodity supply chains and how they may influence sustainability outcomes.

The primary question I seek to respond is ‘how can we understand and interpret global commodity supply chains to change them into drivers of positive social and environmental transformations?’ To answer this mother question, I inquire: (i) How can we analyze supply chain relationship patterns? (ii) What is the relevance of these supply chain relationship patterns for sustainability governance? (iii) How sticky, meaning stable or volatile, can these supply chain relationship

patterns be? (iv) What are the underpinning factors or predictors of this supply chain stickiness or non-stickiness? (v) What are the interactions between these supply chain relationship patterns and environmental governance? (vi) What are the implications of these supply chain relationship patterns for local development? I hypothesize that by eliciting and understanding the supply chain and trade relationship patterns, we can find elements to improve public and private sustainability initiatives, particularly land use and agriculture, and transform our global food and trade systems into drivers of positive and sustainable change.

1.2. Thesis outline and objectives

This thesis aims to increase our understanding about the relationship patterns in global commodity supply chains, developing approaches for assessing how sticky, *i.e.*, stable or volatile, supply chain relationships can be. It also aims at understanding why and how it may affect sustainability and its governance. For doing this, we first formulate a concept to assess this stability or volatility of commodity supply chains, which we call stickiness, laid out in chapter 2.

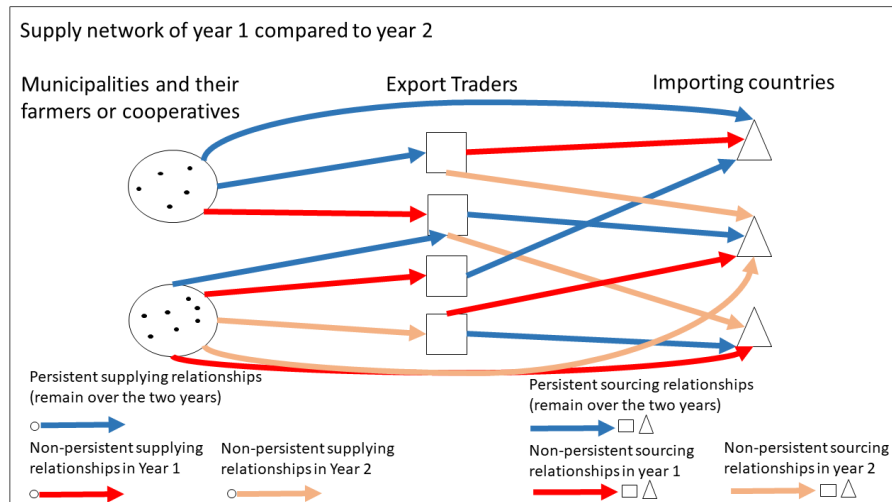
I define this stickiness in global commodity supply chains as *the maintenance and recovery, over time and through shocks, of supply chains' geographic network configurations, i.e., the network of trade linkages and flows between specific places of production and consumption, and specific actors including producers, traders, retailers, and consumers.*

I distinguish three interlinked dimensions of stickiness: (a) the persistence of supply chain configurations over time, regardless of the identification of any shock, and their (b) resistance to and (c) recovery from shocks (Chapter 2). We can use these three dimensions to characterize supply chains as a whole and specific trade relationships between actors and places in a supply chain.

By relationship patterns I mean the observable patterns emerging from all the trade relations that are embedded in global commodity supply chains, including persistence, resistance or recovery. These relations can be supplying relationships, for example, farmers supplying to cooperatives or to export traders, or cooperatives supplying to export traders, or export traders supplying to importers

and consumer countries. Alternatively, one can also look at these trade relations from the sourcing perspective, *i.e.*, export traders sourcing from farmers or cooperatives, importers sourcing from export traders, and consumer countries sourcing from importers or export traders in the producer countries (See Figure 1.1). In all situations, the agency of the trading actors is emphasized in each perspective. In other words, in supplying relationships, I emphasize the agency of farmers in deciding to supply to one or another export trader. In sourcing relationships, I look at the agency of export traders in deciding to source from one or another farmer or even from one or another region, representing a set of farmers, and a combination of logistic and edaphoclimatic conditions.

Figure 1.1 - Types of relationship in supply chains assessed in Chapter 2 and all over the thesis - relationships can have two directions: supplying if one actor or node is sending soy, and sourcing, if one actor or node is receiving soy.

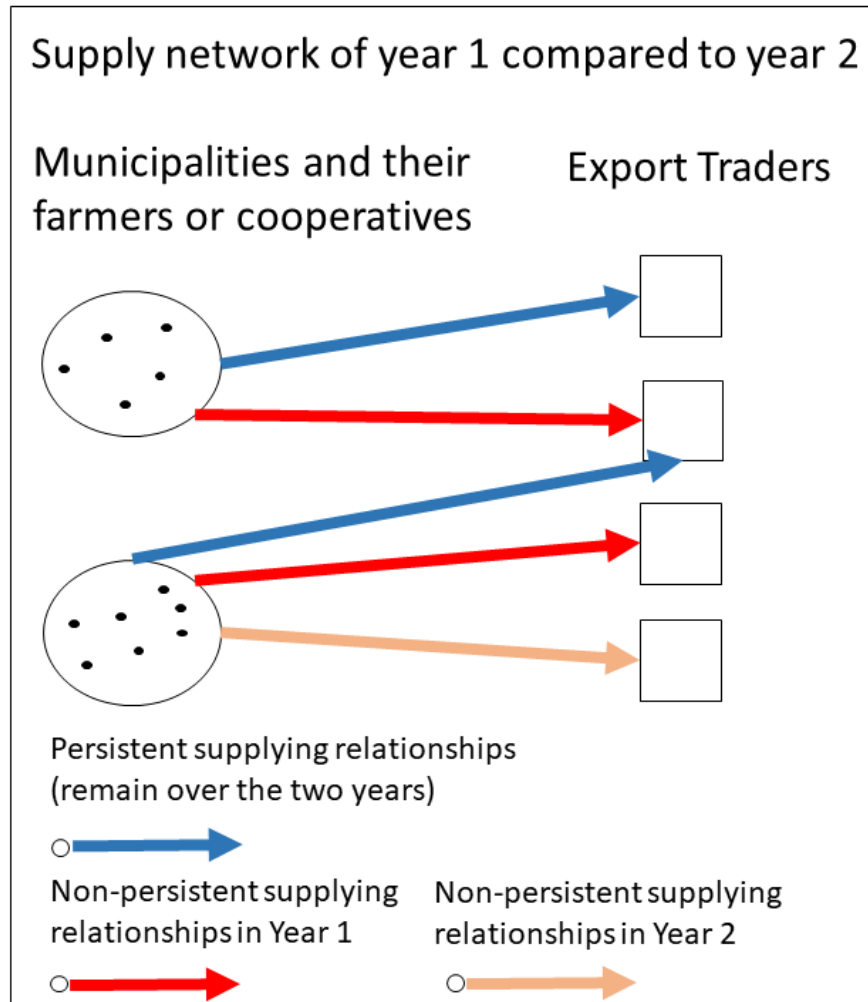


The Brazilian soy supply chain and the related sustainability issues, such as land use, deforestation and native vegetation conversion, rural development, and agricultural supply chain social networks, are the core focus of this thesis.

Still, in chapter 2, we illustrate the application of the stickiness concept to analyze Brazil's soy supply chain. We show some stability or volatility that can be measured in trade relationships in various ways, such as farmers or municipalities supplying soy exporting traders or traders sourcing from various farmers or municipalities, and the same for the relationships between traders and consuming countries. In this chapter, we assess all possible types of relationships in Brazil's soy supply chain given the available data (Figure 1.1).

In chapter 3, we conduct an exploratory analysis, combining both qualitative and quantitative methods. We elicit the underpinning or predicting factors of the stickiness measured on Brazil's soy supply chain in chapter 2. Here we inquiry the local factors that determine or influence this supply chain stickiness to decompose the elements that public or private sustainability initiatives can target for sustainability governance. Here we assess the relationship type of farmers, collectively aggregated at the municipality level or in cooperatives, supplying to export traders (Figure 1.2).

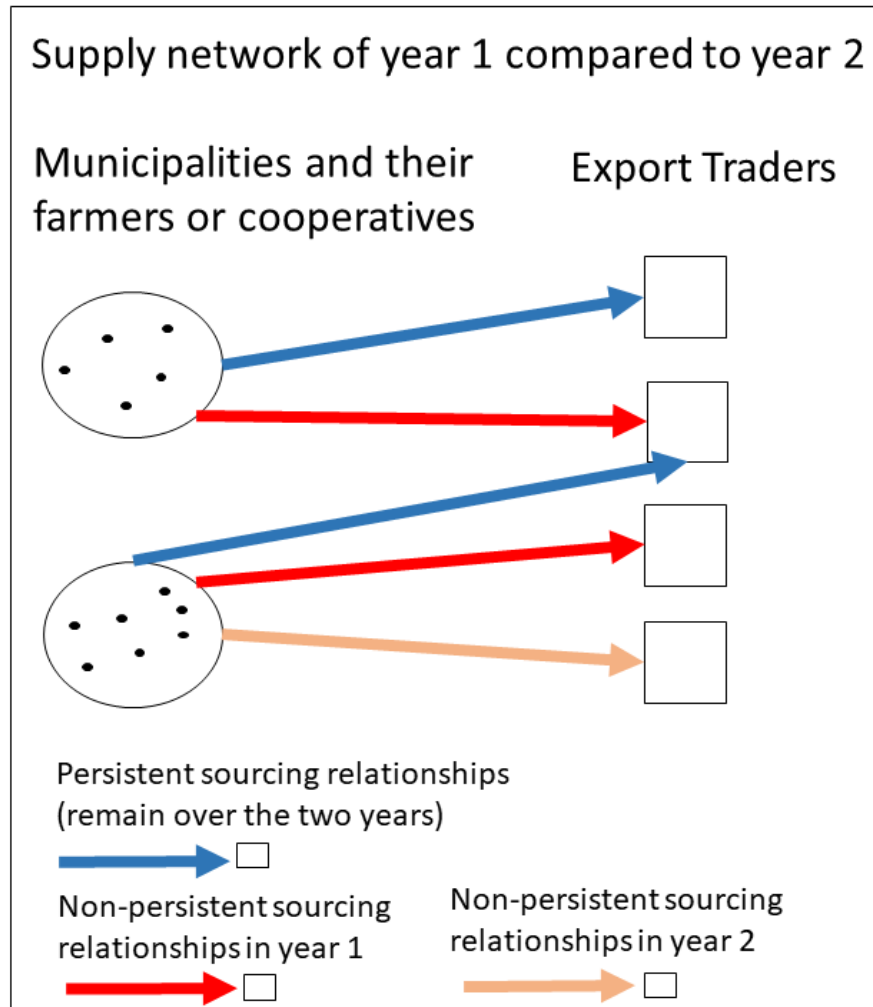
Figure 1.2 - Type of relationship in Brazil's soy supply chain assessed in Chapter 3 – farmers or cooperatives collectively aggregated at the municipality level supplying export traders.



Chapter 4 assesses the interactions between the stickiness measured on the traders' sourcing relationships from Brazilian soy producing and trading municipalities and their zero-deforestation commitments (ZDC) as an example of a sustainability initiative. Here, we look at how much stickiness increase or decrease the likelihood of a company adopting a ZDC, in the first place, and then how much

stickiness may influence the overall effectiveness of these ZDCs in reducing the conversion of natural habitat (including deforestation) in Brazil. In this analysis, we consider traders association with the Amazon Soy Moratorium and their unilateral commitments. On the stickiness part, we consider all their sourcing operations in Brazil, including regions within the Amazon, Cerrado and Pantanal biomes. Here we assess the relationship type of export traders sourcing from farmers, collectively aggregated at the municipality level or in cooperatives (Figure 1.3). Note that the emphasis lies on the agency of export traders here, in contrast to Chapter 3.

Figure 1.3 - Type of relationship in Brazil's soy supply chain assessed in Chapter 4 – export traders sourcing from farmers or cooperatives collectively aggregated at the municipality level.



Chapter 5 conducts in-depth case studies of four Brazilian soy municipalities to assess how the different stickiness processes identified in Chapter 3, and operationalized in Chapter 4, influence rural development trajectories, and the role that agricultural cooperatives play in these interactions. Here we assess the relationship type of farmers supplying directly to cooperatives, and

cooperatives and farmers collectively aggregated at the municipality supplying to export traders (Figure 1.4), similar to chapter 3, but different because we conduct a more in-depth qualitative approach on the specific relations between farmers supplying cooperatives and cooperative supplying export traders. Figure 1.5 summarizes the thesis' chapters and steps described here.

Figure 1.4 - Type of relationship in Brazil's soy supply chain assessed in Chapter 5 – farmers supplying cooperatives, and cooperatives collectively aggregated at the municipality level, supplying export traders.

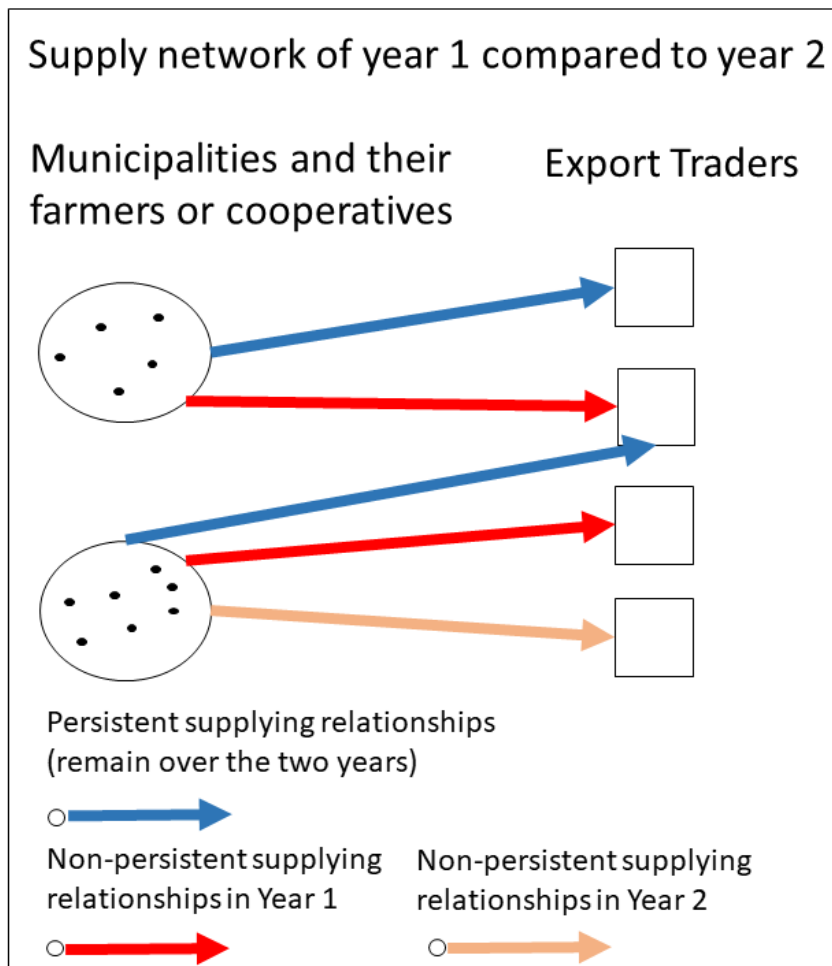
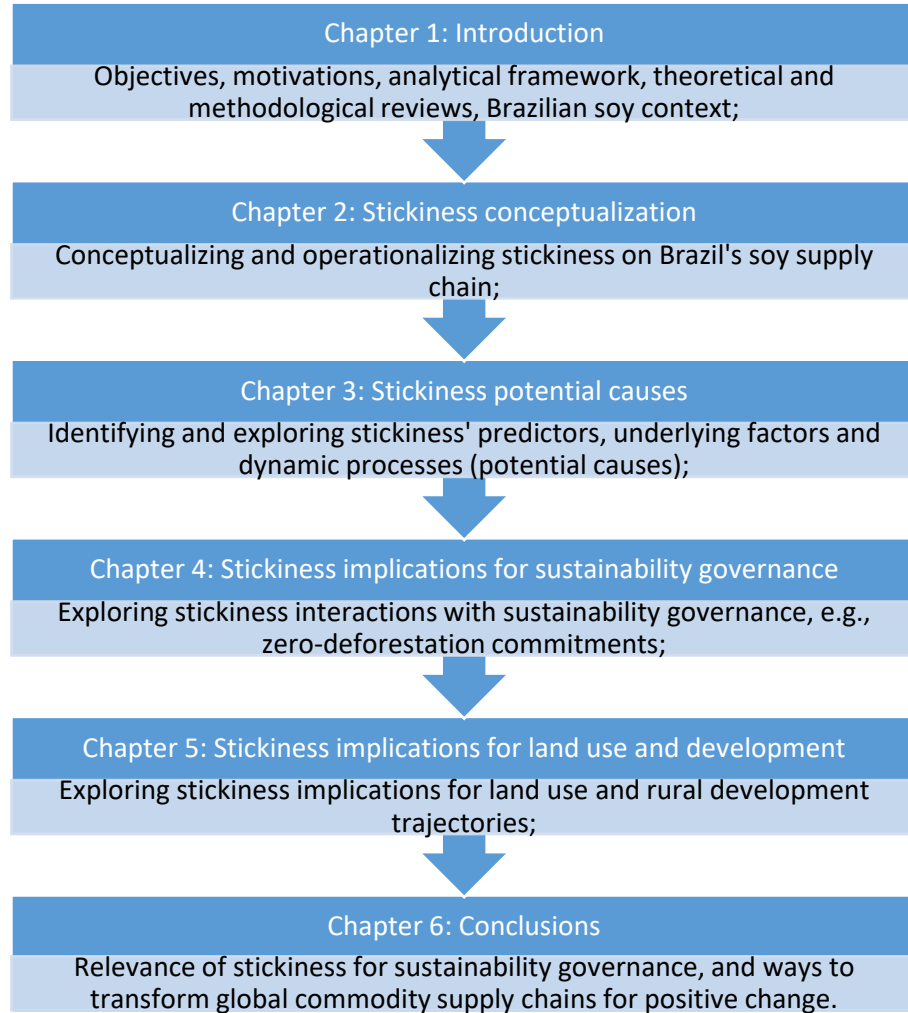


Figure 1.5 – Summary of the thesis.



1.3. Stickiness analytical framework

To investigate global commodity supply chains systematically, we propose an analytical framework as a guide. I used this analytical framework to implement this thesis. This study is limited to the Brazilian soy supply chain. Nevertheless, some lessons may be relevant and helpful in assessing other commodity supply chains.

For conducting similar appraisals in other commodity supply chains, inquirers must be aware that stickiness measurement seems more appropriate for agricultural supply chains where there is a relative facility to shift producing localities. By this, I mean that mineral commodities, for example, may be intrinsically locked to certain specific locations due to geological reasons and, therefore, a geographic stickiness assessment may not be relevant, even though a social stickiness assessment can still be relevant. Edaphoclimatic suitability and logistical conditions may also prevent agricultural commodities from moving anywhere, but still, they have more land use opportunities. Therefore, I stress that a potential stickiness analytical framework emerging from this thesis should be limited to agricultural and forestry supply chains.

The first step of the stickiness analytical framework is collecting the finest and more granular supply chain transactions data for the most extended period available—the more transactions data amongst more supply chain parts and actors, the better. This collection is conducted here in chapter 2 together with the conceptualization of stickiness. In other words, chapter 2 provides a conceptual framework for stickiness that can be transposed to other commodity supply chains. The second

step is constructing temporal networks and analyze stickiness by looking at the topological network changes over time. With this, one can measure the stickiness of nodes at any type of supply chain relationship, as described in Chapter 2.

The third step is inquiring about underlying factors and processes that may influence, predict or structurally determine stickiness at different supply chain types of relationships. In this thesis' chapter 3, looking at the Brazilian soy supply, I found several factors functioning as predictors of stickiness. I grouped them as economic incentives, institutional enablers and constraints, social and power dynamics, and biophysical and technological aspects. This framework can also be used as a reference guide for inquiring about the underpinning factors of the stickiness of other supply chains. Different factors may be encountered, but these four dimensions work as a direction. I found lock-ins effects, trust and supply chain power and agency as stickiness influencing processes. Others may be encountered in other supply chains, but these should also be regarded in other investigations.

Furthermore, more profound and robust causal methods may be employed at this stage for inquiring causality. For example, methods like the *Siena Model* for longitudinal networks, Bayesian network probabilistic models, or even structural equation modelling (SEM) apparently can be used for causal investigation in supply networks with sufficient data granularity and availability. Nevertheless, these methods are not used here.

The fourth step is assessing the interactions between stickiness and any policy, sustainability initiative or governance measure. Here in

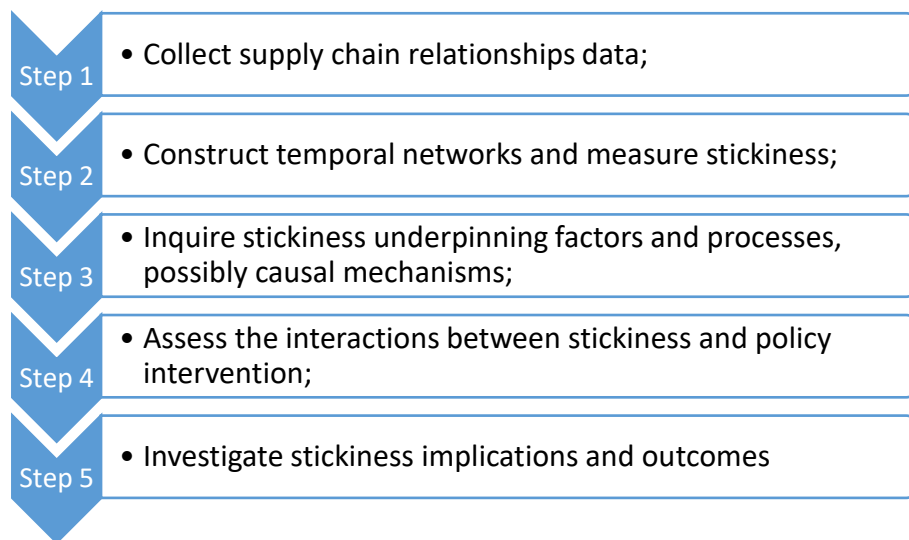
chapter 4, I analyzed the relationships, interactions and effects of stickiness on the likelihood of a soy company operating in Brazil adopting a zero-deforestation commitment (ZDC) and the effectiveness of these commitments to reduce overall deforestation. Other policies can be evaluated in light of stickiness interactions and processes in other supply chains, depending on data availability and methodological capacity to test effects, relationships and causality.

The fifth step is looking forward to investigating the potential implications and outcomes of stickiness. Here I framed this analysis on implications of rural development trajectories and land use. Other broader dimensions of outcomes can be assessed, depending on data availability, methodological design and analytical capacity to establish links and understand causal mechanisms. In this thesis' chapter 5, I used qualitative methods to investigate how stickiness may have led to different rural development trajectories, considering inclusive and excluding or *mal*-development. Spatial and quantitative methods can also be used.

A few recommendations emerge for researchers willing to use stickiness as an analytical framework to assess other commodity supply chains. First, ensuring one gets the most granular and spatial-explicit supply chain data possible. Second, ensure one uses a combination of multiple methods, preferably combining qualitative and quantitative approaches at least in the initial and exploratory phases. This recommendation for mixed methods is because stickiness is about social and commercial relationships in supply chains, underpinned by social-environmental and economic potential causes, possibly leading

to social-environmental and economic implications and outcomes. Therefore, the analysis is strengthened by methods that can capture a more comprehensive array of factors, dimensions and processes and interpret them usefully. Figure 1.6 below summarizes the stickiness analytical framework.

Figure 1.6 - Stickiness analytical framework



1.4. Theoretical review and background

Several fields may be theoretically relevant for this inquiry into global commodity supply chains and their interactions with land use in producer countries. These relevant fields of research include agricultural economics, global commodity and value chains, global production networks, social-ecological resilience and biosphere stewardship, political and social economy studies, and land system science, including economic geography.

First, agricultural economics investigates general issues as food production, consumption, international trade, and development, for example (Veeman and Veeman, 2004). The impact of trade and agricultural markets liberalization on food security, social-environmental dimensions and land-use is a recurrent topic addressed by the field (Egli et al., 2018; Gollin, 2010; van Tongeren, 2001). The field of agricultural economics is an entry point for our inquiry into supply chains stickiness, especially because it investigates trade relationships, modelling the effects of policies and other shocks into production and supply (Armington, 1969; Donnelly et al., 2004; Villoria and Hertel, 2011).

Second, research on global commodity chains (GCCs) (Bair, 2005), value chains (GVCs) (Gereffi, 2014; Gereffi et al., 2005), and production networks (GPNs) (Coe et al., 2008) provide an open theoretical framework to understand how supply chains are structured, defined and governed. The role of companies, the agency they may have in shaping land use patterns, determining landscapes and rural development trajectories by how supply and value chains are relevant theoretical aspects for our inquiry (Carodenuto and Buluran, 2021; Rueda and Lambin, 2013; van der Horst and Vermeylen, 2011).

Third, studies on social-ecological resilience and biosphere stewardship (Folke, 2006; Folke et al., 2016) have analyzed how social-ecological systems resist, adapt, transform, and recover from external shocks (Gephart and Pace, 2015; Janssen et al., 2006; Walker et al., 2004). They analyze how land use, trade, ecosystem services, ecological systems and processes, agricultural production and societal

relations interact and affect each other. These studies also consider the interconnectedness of actors, processes and biophysical factors, including through network analyzes (Bodin et al., 2019; Bodin and Crona, 2009; Bodin and Tengö, 2012; Janssen et al., 2006; Moore et al., 2016). Consequently, studies on social-ecological resilience provide not only analytical frameworks, but also methodological inspiration for this thesis.

Fourth, political economy studies on the social economy concept of embeddedness (Granovetter, 1985; Polanyi, 1944) brings to our research the deeper social knowledge of economic relations. They argue and demonstrate that subjective factors and processes such as trust, cultural norms and values, ethnic and other social ties are relevant aspects to consider when inquiring supply chain relationships (Cheng et al., 2008; Coughlin and Wall, 2011; Craviotti, 2016; Karlan et al., 2014; Prudham, 2013; Skandrani et al., 2011). Understanding the embeddedness of social relations (Krippner and Alvarez, 2007) in supply chain economic and geographic relationships is crucial to advance our research agenda.

Fifth and finally, the field of land system science, including its economic geography background and the knowledge on frontier dynamics, provides explanatory theoretical reasoning to help explain the potential causes of the supply chain relationship patterns we observe. Theoretical and empirical studies from this field show, for example, why companies and farmers cluster geographically (Dicken and Malmberg, 2001; Porter, 2000; Richards, 2018), what is the role of land institutions in driving local economic development and creating

local and regional agglomeration economies (Combes and Gobillon, 2015; Garrett et al., 2013a, 2013b; Porter, 1996). They also show what are the effects of these geographic grouping of economic factors, processes and agents that result in various frontier dynamics and outcomes (Davenport et al., 2017; Eloy et al., 2016; Jepson, 2009, 2006; Rindfuss et al., 2007).

These fields of study provided this thesis with theoretical foundations from where to seek various explanations and angles for the supply chain relationship patterns assessed here. The integration of these various theoretical and methodological fields allowed me to produce a concept, a methodological instrument, and to draw general explanations for the processes and dynamics empirically measured and observed.

1.5. Methodological review and background

For years, researchers only had available transactions and export records self-reported by countries to international databases (FAO, 2021; World Bank, 2019a, 2019b). These country-to-country datasets allowed the development and implementation of physical and monetary approaches to estimate flows and trade and their environmental footprints, including multiregional input-output (MRIO) and life-cycle assessment (LCA) methods. From these data, methodological innovations stemming from LCAs, and considering the local quantities of inputs to generate proportional outputs that were consumed distantly, allowed the attachment of ecological impacts

from production and trade (Parra Paitan and Verburg, 2019; Roux et al., 2020).

Social-ecological processes and change that were generally analyzed only at the producer-country level and territorial planning perspective began to be also assessed as a result of distant consumption (Lambin and Meyfroidt, 2011; Meyfroidt et al., 2013). Direct and indirect land use change, including deforestation and native vegetation conversion, carbon emissions, biodiversity impacts and water footprints driven by foreign and distant consumption, could be assessed (Henders et al., 2015; Pendrill et al., 2019a, 2019b; Prell et al., 2017; Steen-Olsen et al., 2012; Suweis et al., 2011; Weinzettel et al., 2019; Yao et al., 2018). Nevertheless, these analyzes remained at the international trade level, only estimating the ecological impacts of consuming countries at producer countries. They still lacked granularity and the capacity to see jurisdictional or even farm-level consequences of trade and distant consumption.

Recent data access, together with novel methods, were designed to fill this gap. They included sophisticated modelling approaches based on machine learning techniques, such as random forests (Couronné et al., 2018). They provided inquirers with the opportunity to explore trade and supply chain data at unprecedented levels and heights. These new data and methods achieved the subnational level of information, increasing the transparency of agricultural supply chains and strengthening actors' accountability on their social and environmental impacts (Gardner et al., 2019). They innovated by processing and building on national custom's, fiscal and other national,

subnational or local jurisdictions datasets like land registries, companies' accounting records and others, to model land use linked to supply chains (Godar et al., 2016, 2015b, 2015a; Trase, 2021).

With this level of spatial explicitness of land use and supply chain trade data, it became possible to link social-environmental impacts and footprints of distant consumption to local production and specific actors (Escobar et al., 2020; Green et al., 2019; Pendrill et al., 2019a). New avenues of inquiry have been open that would not be possible earlier. For example, econometric analyzes to estimate the on-the-ground effects of new policy or interventions are only possible because of new data such as Brazil's Amazon land-titling program (Probst et al., 2020) or because of the rural-environmental land registry (CAR, in Portuguese) (Azevedo et al., 2017; Sparovek et al., 2019). Also, assessing the impacts of private companies' sustainability initiatives would not be possible without these supply chain and land use novel datasets (E. zu Ermgassen et al., 2020; E. K. H. J. zu Ermgassen et al., 2020). This thesis would not be possible without the Trase (2021) dataset and recent graph theory and network analyzes (Newman et al., 2003; Newman, 2010; Schaffer-Smith et al., 2018).

Network analyzes have been used to assess primarily social networks and the effects of these embedded relationships on the behavior of actors or nodes (Borgatti et al., 2009). They have also been applied to disentangle the effects of structural ecological relationships on ecosystems, considering that the structure of network relations may be a causal factor for various outcomes (Alarcón et al., 2008). The knowledge on networks allows scientists to model how far interactions

can be and the potential outcomes of these interactions, also considering nodes in space and time (Holme and Saramäki, 2012; Nicosia et al., 2013; Tang et al., 2013). Therefore, this knowledge on temporal networks has constituted a critical methodological cornerstone in our investigation into supply chain relationships, providing the possibility of modelling and understanding these relations from a network perspective.

1.6. The Brazilian land use and soy supply chain

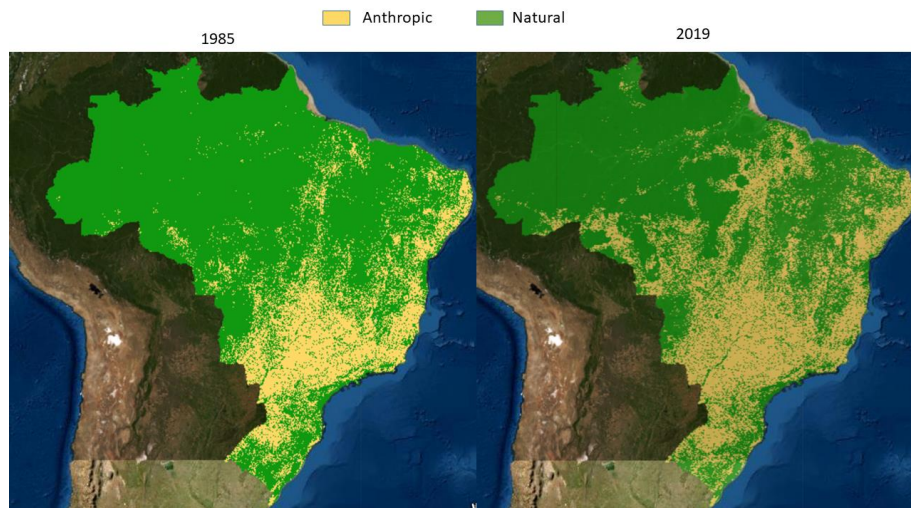
This thesis focuses essentially on the Brazilian soy supply chain, as a crucial globally traded agricultural commodity, used in as many products as biofuels, cooking oils, animal feed and some types of ink. It is also a typical example of a globalized commodity supply chain that has huge sustainability implications. As exposed above in subsection 1.5, the Brazilian soy supply chain is one the few for which highly detailed data on supply chain networks and actors are available.

Brazil has been sourcing primary commodities to the world since at least 1500 when the first Portuguese colonizers arrived in those lands. Many economic cycles based on natural resources, mineral and agricultural commodities, such as timber, gold, cocoa, rubber, coffee, sugarcane, and more recently, soy, have spurred the country's development (Prado Junior, 2012). Despite a relevant industrialization after the 1940s, Brazil has maintained a high level of commodity economic dependence. This process has been accentuating since the 2000s combined with deindustrialization (Giambiagi et al., 2016).

The Brazilian land use and cover changed significantly between 1985 and 2019 (Figure 1.6). The Mapbiomas platform shows significant changes from forestlands and other types of native vegetation into agricultural fields, mostly pasture, soybean, maize and cotton, *i.e.*, from natural to anthropic uses. Figure 1.6 highlights the rapid transformation of Brazilian natural habitats into anthropic use. In 1985, forests and non-forest natural formations occupied 655.328.927 hectares, roughly 77% of Brazil's territory. Farming occupied 177.604.109 hectares, about 20.9% of the country. The rest were

water bodies, urban infrastructure and others. In 2019, natural formations had lost 81.222.486 hectares, decreasing to 574.106.441 ha and 67.4%. The farming area, in contrast, was increased by 77.524.849 in 2019, occupying 255.128.958 hectares, 30% of the territory (Figure 1.7, Mapbiomas, 2021).

Figure 1.7 – Land use and land cover change in Brazil between 1985 and 2019, aggregate at Anthropogenic versus Natural. Source: (Mapbiomas, 2021).



Soy was the most traded agricultural commodity in the world in 2018. Total soy exports in the world accounted for roughly more than 18 billion tons (UN-Comtrade, 2019). Soy monocultures are associated with the rapid impoverishment of ecosystems, as cultivation requires vast land expanses to achieve economies of scale and profit margins in global markets (Oliveira, 2016; Trase, 2018a). In the 2017/2018 crop season, the world produced almost 340 million tons (Mt) of soy. The USA accounted for about 36%, and Brazil for 35% of this global output (USDA-FAS, 2019). Brazil was the second-largest producer but the largest exporter in 2017. Brazil supplied about 68 Mt of soy at a trade

value of 21.5 billion USD to the world (UN-Comtrade, 2019). Soybeans occupied 10.537.850 hectares in 2000 and 36.338.393 hectares in 2019. From this total expansion of 25.800.543 ha, 10.488.669 hectares (40.6%) were over forest and non-forest natural formations. Other 7.850.811 ha (30.2%) were over pasturelands (Mapbiomas, 2021).

The revealed comparative advantage (RCA) index of the Brazilian soy oil products in 2017 was at 14.7, much higher than the US at 1.35, Russia at 8.7, and China at 0.01 (UN-Comtrade, 2019, and own calculation). This significant comparative advantage against the leading competitors indicates a significant growth potential for soy production in Brazil (World Bank, 2010). The soy industry is a crucial economic driver in the Brazilian economy. In 2017, soy exports added roughly 1% to the country's GDP (UN-Comtrade, 2019; World Bank, 2019a). It is responsible for improving the country's trade surplus and driving the economic development of the countryside (Garrett and Rausch, 2016; Martinelli et al., 2017). The commercial dynamics and trading relationships developed between soy traders, production and distribution centers in Brazil and consuming countries are currently only available for the Brazilian soy supply chain, thanks to the data collection effort of the Trase (trase.earth) initiative. These commercial dynamics are the object of this empirical application of the stickiness concept.

In summary, the Brazilian soy supply chain is relevant for the empirical application of this concept for both socio and macroeconomic, global food security (Garrett and Rausch, 2016; Martinelli et al., 2017; Richards et al., 2012; Yao et al., 2018),

geopolitical (Oliveira, 2016), and social-ecological reasons (Curtis et al., 2018; Noojipady et al., 2017; Spera et al., 2016; Strassburg et al., 2017).

II. Conceptualizing stickiness in commodity supply chains

Abstract: Commodity trade is central to the global economy but is also associated with socio-environmental impacts, for example, deforestation, especially in producer countries. It is crucial to understand how geographic sourcing patterns of commodities and commercial relationships between places and actors influence land-use dynamics, socio-economic development, and environmental degradation. Here, we propose a concept and methodological approach to analyze the geographic stickiness of commodity supply chains, which is the maintenance of supply network configurations over time and across perturbations. We showcase policy-relevant metrics for all Brazilian soy exports between 2003 and 2017, using high-resolution supply chain data from www.trase.earth. We find that the Brazilian soy traders with the largest market share exhibit stickier geographic sourcing patterns, and that the supply network configurations between production places and traders become increasingly sticky in subsequent years. Understanding trade stickiness is crucial for supply chain accountability, because it directly affects the effectiveness of zero-deforestation commitments.

Keywords: stickiness; international trade; commodity supply chains; agriculture; zero-deforestation commitments; land use; soy supply chain; sustainability; temporal network analysis; telecouplings.

Adapted from: Reis, T.N.P. dos, Meyfroidt, P., zu Ermgassen, E.K.H.J., West, C., Gardner, T., Bager, S., Croft, S., Lathuillière, M.J., Godar, J., 2020. **Understanding the Stickiness of Commodity Supply Chains Is Key to Improving Their Sustainability**. *One Earth* 3, 100–115. <https://doi.org/10.1016/j.oneear.2020.06.012>.

Author Contributions

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2.1. Introduction

Over recent decades, the growth in agricultural trade has promoted economic development and food security but also resulted in negative socio-economic and environmental impacts (da Silva et al., 2017; Friis and Nielsen, 2017b; Parra Paitan and Verburg, 2019; World Bank, 2019b). Trade and consumption of agricultural commodities are critical drivers of land use change, deforestation, biodiversity loss (Curtis et al., 2018; Green et al., 2019), and carbon emissions (Meyfroidt et al., 2014; Pendrill et al., 2019a).

The production of internationally traded and financed commodities, such as soy, beef, and palm oil, dominates land use in many agricultural regions. It is responsible for over 27% of recent global forest loss (Curtis et al., 2018). Supply chain actors, such as food processors, slaughterhouses, traders, and retailers, including countries that purchase these commodities, play a crucial role in shaping land use dynamics by influencing demand, investments in infrastructure, financing, and government decisions (Folke et al., 2019; Galaz et al., 2018; Heron et al., 2018).

A growing number of governance interventions target these supply chain actors, including pushes for zero-deforestation commitments (ZDC). ZDCs aim to zero the deforestation driven by commodity supply chains, such as palm oil, beef, or soy. Individual companies and multi-stakeholder coalitions, including national and subnational governments and NGOs, sign ZDCs where each stakeholder assumes a specific role. For example, companies implement the ZDCs, NGOs monitor compliance, and governments provide the tools. Examples of

ZDCs can be in the form of sustainability roundtables (e.g., Roundtable on Sustainable Palm Oil) and broader governance fora (e.g., Tropical Forests Alliance) (Lambin et al., 2018).

The Amazon Soy Moratorium (ASM), another ZDC example, was the first voluntary ZDC in the tropics. It was a response from soy traders to pressure from retailers and NGOs, resulting in the agreement of not purchasing soy from areas deforested after July 2006 in the Brazilian Amazon. The ASM is reputed to have reduced direct deforestation to soy fields from 30% to 1% of annual soy expansion in the Brazilian Amazon (H. K. Gibbs et al., 2015). ZDCs, combined with public policies, are crucial to address deforestation, as commodity supply chains drive about five million hectares of forest loss every year (Curtis et al., 2018).

ZDCs result from consumer demand and NGO pressure (Gardner et al., 2019; Garrett et al., 2019; Lambin et al., 2018) and corporate recognition that sustainability commitments may increase both supply chain control and reputation (Dauvergne and Lister, 2013). Thus, the accountability and engagement of supply chain upstream actors are critical for these initiatives to be successful and deliver the expected impacts. For example, in agricultural supply chains, implementing ZDCs requires the engagement between food buyers, processors, and farmers (Gardner et al., 2019; Global Canopy, 2019; Meijer, 2015; E. K. H. J. zu Ermgassen et al., 2020). Understanding the geographic patterns of supply chain relationships can hold corporations accountable for what happens in the production regions to which they

are linked (Gardner et al., 2019; Nolte et al., 2018; E. K. H. J. zu Ermgassen et al., 2020).

Supply chain transparency is a prerequisite for corporate land use accountability (Gardner et al., 2019) and the monitoring of ZDCs (E. K. H. J. zu Ermgassen et al., 2020), such as through the accountability framework initiative (<https://accountability-framework.org/>). Knowledge of how much, how, and why supply chain actors engage with each other and specific sourcing regions remains limited. Moreover, we need an improved understanding of how and why actors shift sourcing locations over time and how this influences land use dynamics and socio-environmental outcomes (Bastos Lima and Persson, 2020; Garrett et al., 2019; Lambin et al., 2018; Meijer, 2015).

Researching the patterns of relationships between actors and regions over time is critical to understand different development trajectories in rural landscapes, as these trajectories are shaped by the responses of supply chain actors to biophysical, policy, logistic, or socio-economic shocks and changes (Bodin and Crona, 2009; Lambin et al., 2018; Meyfroidt et al., 2018). Examining the spatial-temporal connections between commodity buyers and sourcing regions can support governance and accountability processes. This examination can inform about the potential effectiveness of ZDCs (Garrett et al., 2019; Lambin et al., 2018) and on indirect and leakage effects where sourcing relationships are displaced in response to policy interventions (Waroux et al., 2017).

Markets are not entirely integrated and exhibit some stickiness, i.e., some trading relationships persist under changing conditions or

show inertia in responding to price and other shocks (Villoria and Hertel, 2011). This persistence is related to various factors, such as supply chain infrastructures in production regions and traders' local expertise (Garrett et al., 2013b). Agricultural traders with volatile geographic sourcing patterns likely have weaker connections, credibility, and engagement with farmers, thus less capacity to transmit the zero-deforestation signal or demand to their suppliers. Volatile traders can move from high to low-deforestation risk regions after signing a ZDC, thereby mitigating the direct risks in their supply chains, but failing to improve the overall outcome. Traders with more enduring commercial relationships may have enhanced relevance and impact in their actions. Trade persistence justifies robust accountability frameworks to reduce deforestation in specific supply chains, as it increases the likelihood that these supply chain actions will send a strong and sustained signal to the actors in the production landscapes (Dauvergne and Lister, 2013; Gardner et al., 2019; Global Canopy, 2019; Gollnow et al., 2018; Silva and Lima, 2018; E. K. H. J. zu Ermgassen et al., 2020).

Nevertheless, to date, research has focused chiefly on country-to-country persistence of trade relations. Current research lack both a clear conceptual model for defining the relationship between production landscapes, commodity traders, and consuming markets, as well as empirical measures of it, mostly because of insufficiently detailed and subnational data on supply chains.

The objectives of this paper are to develop: (i) a conceptual framework to analyze the geographic stickiness in global commodity

trade, conceived as a measure of the stability and rigidity over time of supply chain configurations, i.e., of the network of trade linkages and flows between specific regions and actors; (ii) metrics to operationalise this framework and to measure stickiness empirically; and (iii) hypotheses on how stickiness influences the existence and effectiveness of supply chain zero-deforestation commitments (ZDCs), and, more broadly, the governance of supply chains for socio-environmental sustainability. We focus on agricultural commodities and their relation to land use, but the notion has broader relevance for other supply chains and sustainability issues.

Empirically, we use the first supply-chain maps linking sub-national producing regions of Brazilian soy to global markets, identifying trading companies between 2003 and 2017, developed by the Trase initiative (www.trase.earth). In the international trade of Brazilian soy, we measure the trade stickiness between specific production and distribution places, companies engaged in trading, and consumption countries (Trase, 2018b). We apply temporal network analysis to measure the similarity of the export supply chain network over time, i.e., how stable are the commercial relationships.

2.2. Results

2.2.1. *Conceptualizing stickiness in commodity supply chains*

We bridge theoretical and empirical approaches from three main fields, agricultural and trade economics, global commodity and value chains (GCCs and GVCs), and social-ecological resilience (Agcaoili-Sombilla and Rosegrant, 1994; Akkermans, 2001; Anderson et al., 2004; Antràs and Chor, 2013; Armington, 1969; Bair, 2005; Barrot and Sauvagnat, 2016; Bodin et al., 2019; Bodin and Crona, 2009; Borgatti et al., 2009; Borgatti and Li, 2009; Brun et al., 2005; Burlando et al., 2015; Coe, 2012; Coe et al., 2008; Coughlin and Wall, 2011; Demidova and Rodríguez-Clare, 2013; Disdier and Head, 2008; Donnelly et al., 2004; Fares et al., 2012; Folke, 2006; Folke et al., 2016; Garrett et al., 2019; Gereffi, 2014; Gereffi et al., 2005; Granovetter, 1985; Head et al., 2010; Heron et al., 2018; Hess, 2008; Kawashima and Puspito Sari, 2010; Kepaptsoglou et al., 2010; Krippner and Alvarez, 2007; Larsen et al., 2018; Levchenko, 2007; Mahutga, 2012; Mcdaniel and Balistreri, 2003; Melitz, 2002; Narasimhan et al., 2009; Nunn, 2007; Polanyi, 1944; Porter, 2000; Rauch, 1999; Shenton, 2017; Thorlakson et al., 2018; Turzi, 2017; Uzzi, 1997; Van Assche and Schwartz, 2010; Villoria and Hertel, 2011; Vroegindewey and Hodbod, 2018; Yu, 2010) to propose a conceptualization of stickiness in global commodity supply chains (see *Designing a conceptual framework for Stickiness in Experimental Procedures*).

Based on this, we define stickiness in global commodity supply chains as *the maintenance and recovery, over time and through shocks, of supply chains' geographic network configurations, i.e., the*

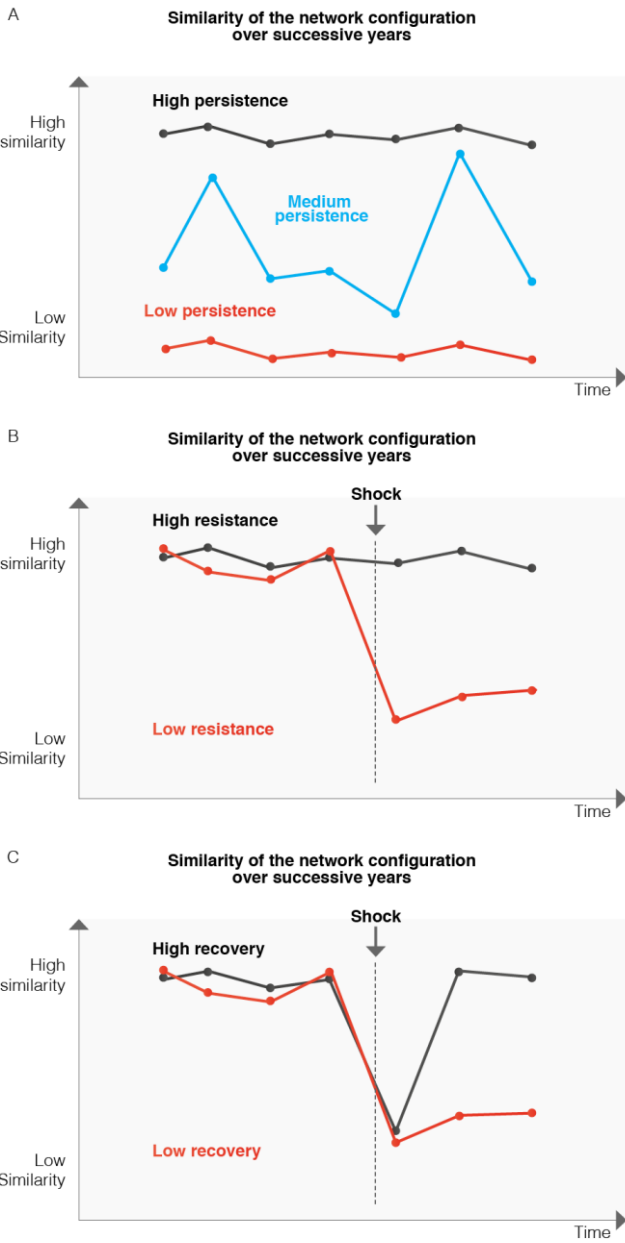
network of trade linkages and flows between specific places of production and consumption, and specific actors including producers, traders, retailers, and consumers. We distinguish three interlinked dimensions of stickiness: (i) the *persistence* of supply chain configurations over time, regardless of the identification of any shock, and their (ii) *resistance* to and (iii) *recovery* from shocks (Figure 2.1). These three dimensions can be used to characterize supply chains as a whole, as well as specific actors and places in a supply chain.

Figure 2.1 – The three dimensions of stickiness.

(A) Persistence is the property of supply chains to have trade linkage configurations that remain highly similar over time. Medium persistence may characterize networks that have a medium similarity of trade linkages over time or that oscillate between low and high similarities across pairs of successive years.

(B) Resistance is the property of maintaining linkages unaltered in relation to a given shock.

(C) Recovery corresponds to the reestablishment of stable network configurations after a shock, either with the same previous configuration or the stabilisation of a new configuration. The last two dimensions are assessed based on an identified shock.



The first dimension, *persistence*, is directly observable. In contrast, assessing *resistance* and *recovery* requires the identification of a shock affecting supply chain relationships and an analysis of their capacity to remain unaffected by it or to return to their previous state. Thus, under an initial observation, “sticky” would correspond to “persistent”. A lack of persistence likely reveals a lack of resistance. However, then, when analyzing the response to specific shocks, it is possible further to qualify the resistance or recovery to these specific shocks.

Persistence measures how much trade relations remain similar over time – *e.g.*, as traders consistently source products from the same regions and sell to the same consumer markets – or not. Persistence describes the patterns observed, absent specific knowledge about factors (shocks, perturbations) that could have affected the supply chain configuration.

Resistance measures the persistence of supply chain configurations under specific shocks or perturbations. Perturbations may affect certain places and supply chain actors. Perturbations result from policy changes, natural phenomena (*e.g.*, severe droughts, excessive rainfall), governance interventions (*e.g.*, new ZDCs), shifts in land-use decision logics (*e.g.*, exhaustion of suitable lands for expansion in a given geographical region), and market events (*e.g.*, significant changes in commodity prices), amongst others.

Recovery measures how trade relations restore after having been disrupted by shocks in two ways. First, locations and actors that had stable relations can recover the same stable configuration of relations as before. Second, these locations or actors may recover by reconfiguring their network towards another set of persistent relationships, but with a different configuration of relations with different actors and places.

2.2.2. *Metrics to assess stickiness in Brazil's soy exports*

We represent the Brazilian soy export supply chain(Trase, 2018b) as a temporal network(Büttner et al., 2016a; Nicosia et al., 2013) (see *Experimental Procedures*). This temporal network is the aggregate of soy transactions, or commercial relationships, between three levels of supply chain actors (nodes), over 2003-2017. These three levels of actors ($n=2,304$) are: logistics hubs (LHs; $n=468$), exporting traders ($n=1,709$), and importing countries ($n=127$). LHs are jurisdictions (municipalities) of soy production and trade in Brazil (See *Supplemental Experimental Procedures in Appendix 1*). LHs aggregate the behavior of soy farmers located within the logistic range of these logistics and commercial hubs for soy processing and export. They are regional market places for defining farm-gate soy prices, storage, and freight fees, acting figuratively as soy “drains”.

Traders include exporters and importers, who buy soy directly from farmers or indirectly through local small cereals warehouses and cooperatives located in these LHs or neighboring municipalities. These traders export either raw or crushed beans into oil, meal, and cake,

which are primary inputs for animal feed, biofuels, or cooking oils, for example. Our dataset comprises only export transactions, raw and crushed, thus excluding soy transactions destined to Brazil as domestic consumption (Trase, 2018b, 2018c). The dataset covers the period 2003-2017, where each year is a snapshot of the network, aggregating all individual soy transactions that occurred over that year between two actors in annual transactions. We thus represent the entire movement of the supply chain over 2003-2017 as a set of fifteen slices or snapshots. We then compare these snapshots to calculate the similarity of the supply chain network over time.

The network is directed, *i.e.*, soy only flows in one direction, from LHs to traders, and then from traders to countries. Flows are either outgoing or incoming depending on the actor's position in the supply chain, *i.e.*, while one actor is supplying soy (outgoing flow), the next one is sourcing it (incoming flow). We measure stickiness as the similarity or change in the configuration of trading partners around each actor between two points in time – *i.e.*, two snapshots – employing metrics from temporal network analysis (C_i and TC_i ; Eq.1-2 in *Experimental Procedures*). C_i is the topological overlap (Nicosia et al., 2013), which measures how much the configuration of the supply chain network changes from the first snapshot compared to the second. TC_i is the temporal average topological overlap, which is the average of several consecutive C_i s over time.

This measurement can be applied to the specific configuration of commercial relations around one specific region or actor (node), or at the overall network level. [\$C_i\$](#) , our primary stickiness metric, measures

the topological overlap – *i.e.*, how much the network configuration around each actor (node) changed between two snapshots. In other words, how much the commercial relationships of this actor changed, for example, from 2003 to 2004 (Eq.1 in *Experimental Procedures*). TC_i is the temporal average of C_i over a sequence of successive snapshots covering the analyzed period (2003-2017) for each actor or group of actors. C is the temporal correlation coefficient over the entire supply network (Eq.4 in *Experimental Procedures*), *i.e.*, the aggregation of all individual C_i s in varying time windows. A time window is an interval between two snapshots, which can be one year, e.g., 2003-2004, fourteen years, e.g., 2003-2017, or any interval in between. C measures the stickiness of the overall supply chain network over all possible time windows, *i.e.*, applied to varying time intervals between two snapshots. Eq.1-3 (*Experimental Procedures*) are steps to calculate C .

These indices vary between zero – *i.e.*, a complete reconfiguration of trade relationships between the two snapshots – and one – *i.e.*, full stickiness, all trade relations observed remain identical. Zero includes situations where the supply network has no linkages in one of the observed years. In large and complex networks, such as Brazil's soy export supply chain, we hardly find either one or zero at the whole network level, meaning that at this level, some linkages are always maintained, and new linkages always appear (Büttner et al., 2016a; Holme and Saramäki, 2012; Nicosia et al., 2013). However, when looking at specific network configurations around actors, we find zeros or ones.

From a network perspective, we decompose trade relations in commodity supply chains in “linkages” and “flows”, corresponding to the presence of a commercial relationship between two partners, and the volume of commodities exchanged between them, respectively, over discrete periods. These two approaches provide complementary information, allowing to analyze changes in the presence and intensity of trade relations and to verify whether a linkage reconfiguration is related to an increase or decrease in specific flows.

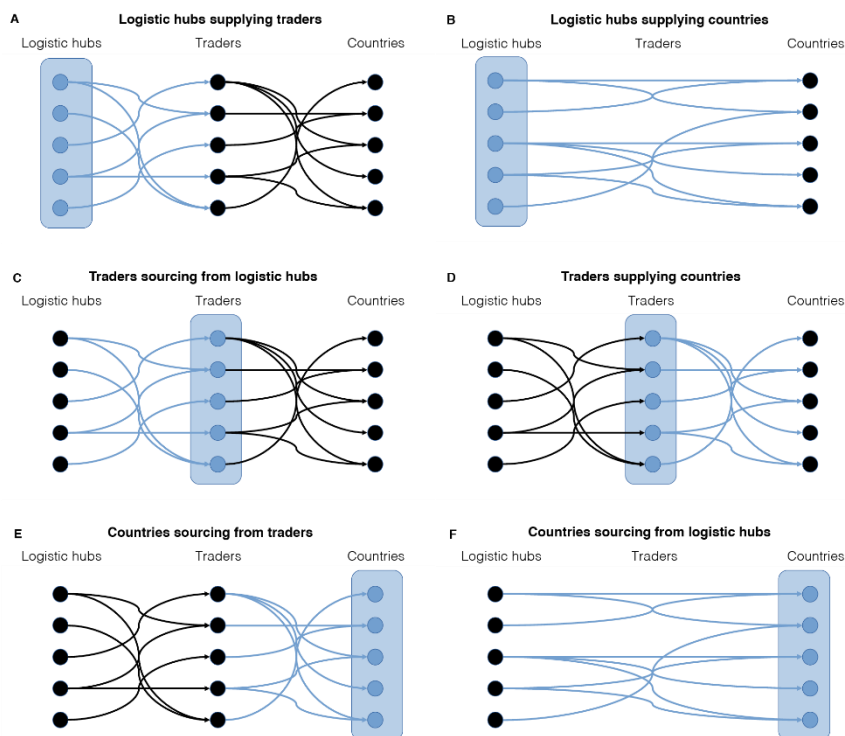
For example, a LH may trade slightly varying soy volumes every year with the same set of exporters. The stickiness measured on linkages will be one over these years, while indices on flows will be slightly below 1, as the changes in volume imply that some linkages are trading more or less of soy than the year before, thus changing flow configuration. Note that these stickiness metrics measure the absolute magnitude of changes in network configuration, notwithstanding their direction (appearance or disappearance of linkages, increases, or decreases in flows). Although this information is partly independent, changes in linkages and flows are strongly correlated (See Figure S1 in Appendix 1). For clarity, the main text presents only results on linkages. We replicate all analyzes in flows in the *Appendix 1*.

These indices are scaled from 0 to 1 and are independent of the size of the network, making it possible to compare indices within groups, *e.g.*, among traders. Although the different types of supply chain relationship have distinct nature and correspond to groups of actors with a distinct agency, the scaling of the indices make it also possible to compare the values observed across groups, *e.g.*,

comparing traders with LHs. Here, we explore the six types of supply chain relationships present in our Brazil's soy export data: (A) logistics hubs (LHs) supplying traders, (B) LHs supplying countries, (C) traders sourcing from LHs, (D) traders supplying countries, (E) countries sourcing from traders, and (F) countries sourcing from LHs (Figure 2.2). Yet, we focus our discussion on traders in their sourcing relationships with LHs and supplying relationships with countries. Other datasets might include other types of supply chain relationships, such as retailers selling to consumers or farmers buying fertilizers from input suppliers.

Figure 2.2 - The Six Types of Brazil's Soy Supply Chain Relationships.

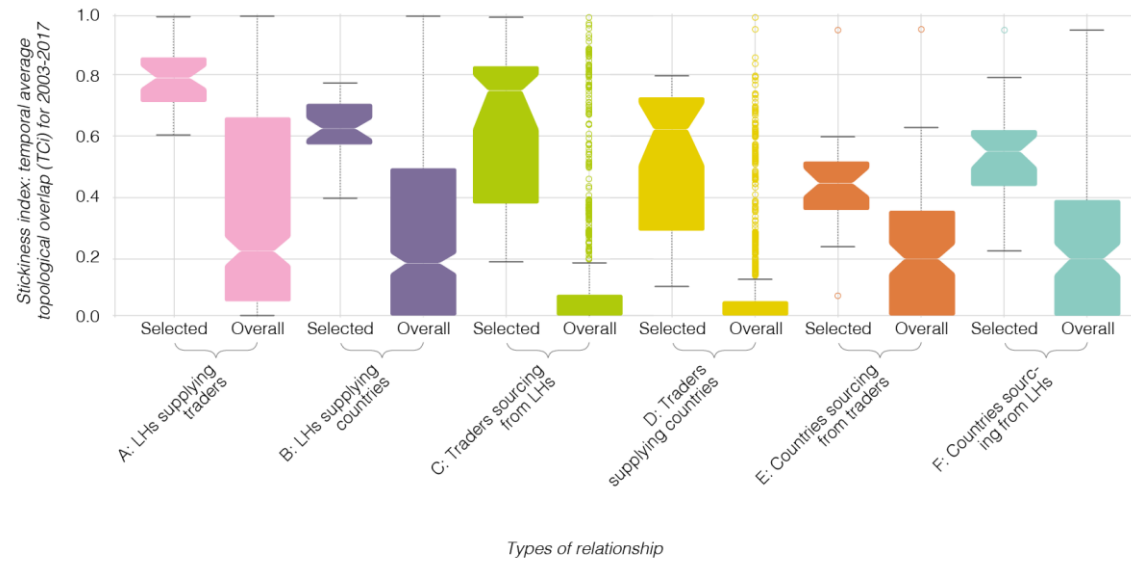
The measurement of stickiness focuses on the set of linkages and the changes in their configurations around each actor in the network. The blue colour denotes the focal group of actors (i.e., the nodes from whose perspective the analysis is being done). The blue arrows denote the linkages of the supply chain being analyzed. (A) Logistics hubs (LHs) supplying traders; (B) LHs supplying countries; (C) traders sourcing from LHs; (D) traders supplying countries; (E) countries sourcing from traders; and (F) countries sourcing from LHs.



2.2.3. *The stickiness of Brazil's soy export supply chain*

Observing the first dimension of the stickiness (i.e., persistence) of different sets of actors in the Brazilian soy export supply chain reveals that traders overall have relatively low stickiness. LHs and import countries have somewhat moderate stickiness levels. However, each group is heterogeneous (Figure 2.3). The soy supply chain is highly concentrated, with 31 traders (out of 1,709 in total) accounting for 82% of the total soy traded. Traders with the largest market shares have higher average stickiness (Figure 2.3, t-test p-value = $9.107e-13$). A large group of small traders (1,678 companies) is comparatively non-sticky and represents 18% of the total soy exported. A few LHs ($n=35$) were the source of 62% of the total exported soy volume, while the 29 largest consuming countries imported 97% of total soy in the analyzed period. Both groups have higher average stickiness than the average LHs (t-test p-value < $2.2e-16$) and countries (t-test p-value = $2.208e-14$) analyzed here (Figure 2.3).

Figure 2.3 - Overall Distribution of the First Dimension of Stickiness (Persistence). Measured on the configuration of commercial linkages (TCi, Equation 2 in Experimental Procedures). Over the whole dataset (“Overall”), traders are the least sticky group in the Brazilian soy supply chain. “Selected” includes only logistics hubs and traders that commercialized at least 1% of the total soy volume in any year after 2008 and countries that imported at least 0.5% of the total soy volume in the same period. These selected traders, logistics hubs, and countries are stickier overall. (See the equivalent on flows in Figure S2, Appendix 1). The bars in the boxplots represent quartiles. The horizontal bar inside the colored range indicates the median. The upper and lower ranges indicate the 25% and 75% quartiles, respectively. The upper and lower black lines indicate the max and min values.



We correlated the temporal average stickiness (TC_i) with soy deforestation risk from Trase (Trase, 2018b; E. K. H. J. zu Ermgassen et al., 2020). “Soy deforestation risk (hectares) is the soy deforestation allocated to the actors along the supply chain in proportion to the volume of soy that they export from a given jurisdiction, relative to the total production of soy (by all producers) in the same jurisdiction. Deforestation risk for a given year of export is based on deforestation that occurred in the previous five years, during which time the soy that is being exported was planted and harvested” (Trase, 2018c).

When observing the network of traders sourcing from logistics hubs and supplying countries (see Figure 2.2-A and B), we found that stickier traders also exhibit higher soy-deforestation risk ($r=0.22$ and 0.27 , t-test p-value $< 1.98E^{-09}$, and $< 1.51E^{-14}$, respectively). This correlation suggests that traders who have been stably sourcing from a set of logistics hubs or supplying to a stable set of countries also present higher soy-deforestation risks. Moreover, the stickiness measurements on these two types of supply chain relationships, *i.e.*, traders sourcing from logistic hubs (Figure 2.2-C) and supplying countries (Figure 2.2-D), are also strongly correlated ($r=0.95$ and p-value < 0.001), indicating that traders who have stable relationships with their suppliers also have stable relationships with their customers. This association suggests a high potential for signal transmission from consumers to producers in the supply chain, including a signal demanding to reduce deforestation.

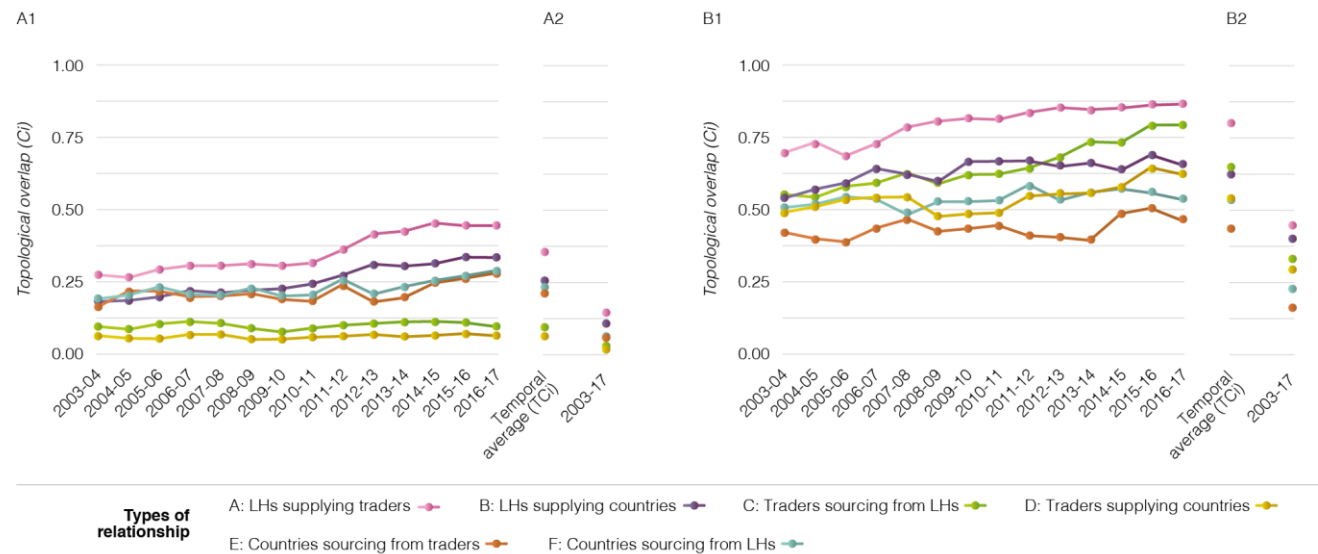
Testing the difference in the temporal average stickiness (TC_i) between ZDC signatory and non-signatory traders (E. K. H. J. zu

Ermgassen et al., 2020), we found that ZDC traders are significantly stickier than non-ZDC, both when measuring their stickiness in sourcing from LHs (Figure 2.2-C; t-test p-value = $1.042e^{-08}$) and in supplying countries (Figure 2.2-D; t-test p-value = $1.765e^{-08}$).

A temporal profile of stickiness between consecutive snapshots also confirms that traders and LHs with large market-shares (Figure 2.4 - B1, B2) are stickier than their respective overall groups (Figure 2.4 – A1, A2).

Figure 2.4 - Temporal Stickiness Profile in the First Dimension of Stickiness (Persistence) on linkages.

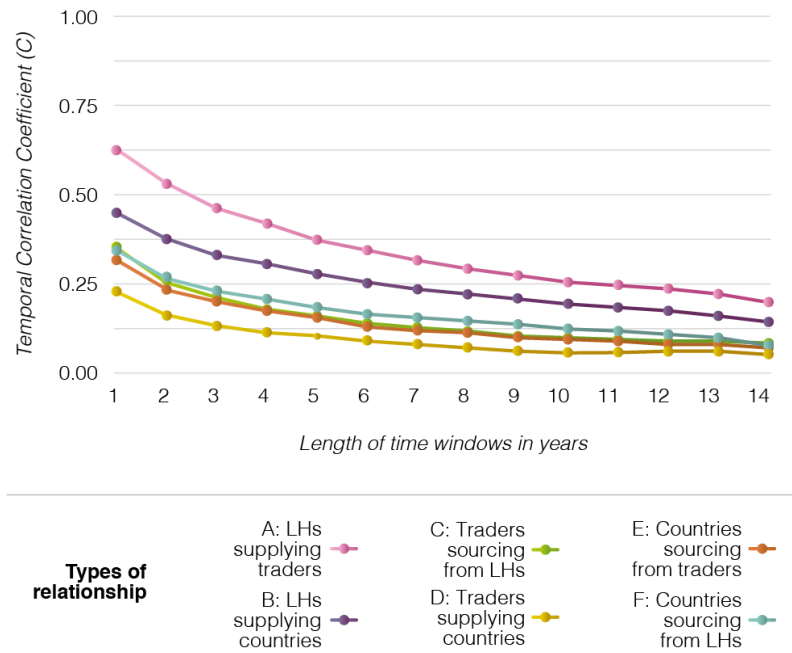
Measured on the configuration of commercial linkages (C_i and C_m ; Equations 1 and 3 in Experimental Procedures (2.5)). In (A1) and (A2), LHs are stickier than other actors' group in both types of relationships. Nonetheless, in (B1) and (B2) the selected traders sourcing from LHs show higher stickiness than the overall group in (A). (A2) and (B2) complement the temporal profiles by showing the temporal average (TCi; Equation 2) and the C_i calculated for the comparison directly between 2003 and 2017, instead of for each consecutive biannual snapshots compared. See the equivalent figure measured on flows in Figure S3 (App. 1). Also see a complementary Figure S4 (Appendix 1) zooming in on the relationships of different categories of traders (overall, small, and large).



For most types of supply chain relationships, especially the linkages between LHs and traders (Figure 2.2-A and C), the inter-annual stickiness increases over time. When comparing the 2003 snapshot directly with 2017, all relationships become less sticky (Figure 2.4 - A1, A2, and B1, B2). Thus, even if supply chain configurations appear relatively stable year-to-year, small step-by-step reconfigurations over short time intervals lead to major overall changes in the long term.

This difference in the measured time frame may reflect various processes, including expansion into new frontiers, and newcomers. Calculating the temporal correlation coefficient (C ; Eq.1-4 in *Experimental Procedures*, 2.5) shows that, when observing the mean value of stickiness for all possible time windows, the overall stickiness of the entire supply chain network decreases the longer the time window is (Figure 2.5). For example, the stickiness will be higher when comparing the supply network over two consecutive years, such as 2003 versus 2004, in contrast with comparing more temporally distant configurations, such as 2003 versus 2017.

Figure 2.5 - Overall Stickiness (Persistence) of Brazil's Export Soy Supply Chain. Calculated over all different configurations of comparisons between years separated by increasing time intervals.

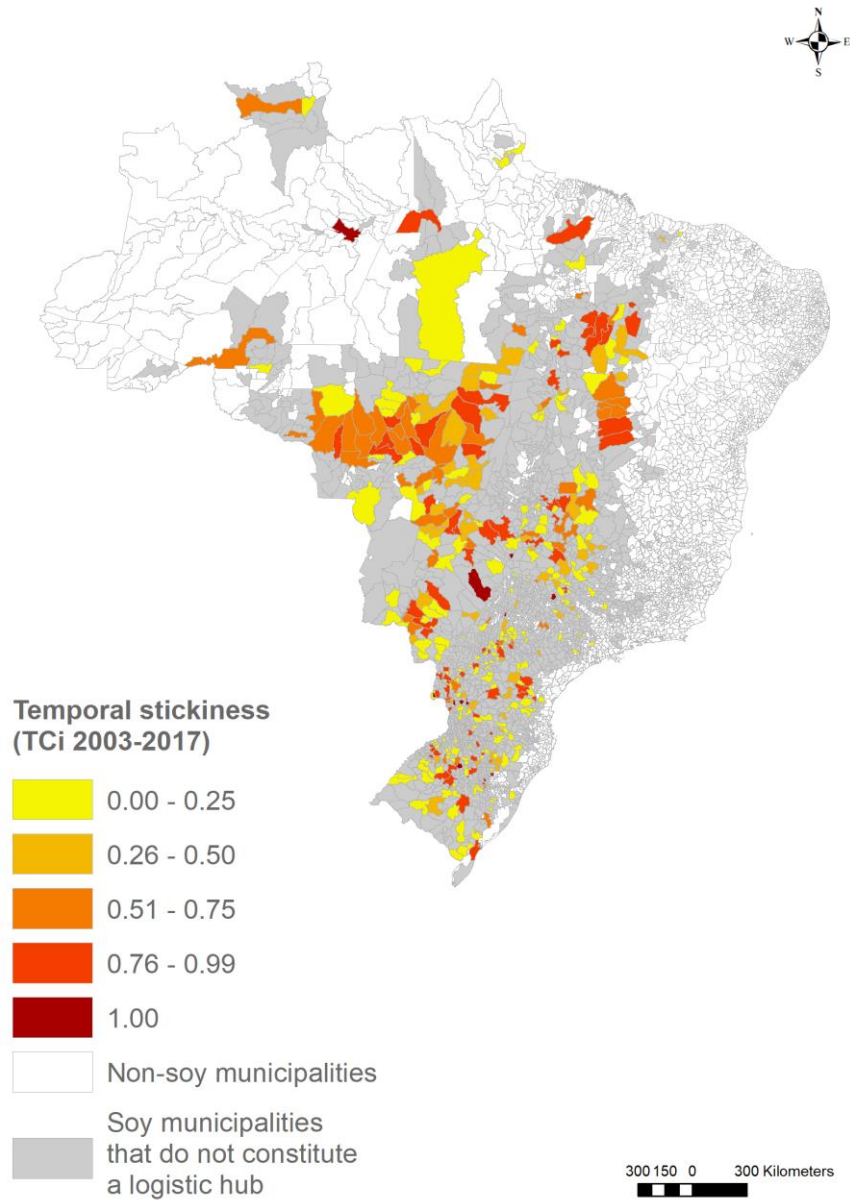


The geographic analysis of the stickiness of LHs in their supplying relationships with traders shows that certain LHs have been supplying soy to exactly ($TC_i=1$, $n=13$) or mostly the same ($0.76 \leq TC_i \leq 0.99$, $n=75$) set of traders over time (Figure 2.6). Showing the various levels of engagement between regions of production and distribution and soy traders reveals the potential land use accountability of traders operating in these places. Some LHs in two important agricultural frontiers in Brazil – Northern Mato Grosso and the “Matopiba” (Maranhão, Tocantins, Piauí, and Bahia) frontier in the Cerrado – present high stickiness with traders, suggesting that impacts of soy

production and trade can be consistently associated with these specific traders in those regions.

Figure 2.6 - Spatial Distribution of Stickiness (Persistence) of Traders to Sourcing Areas.

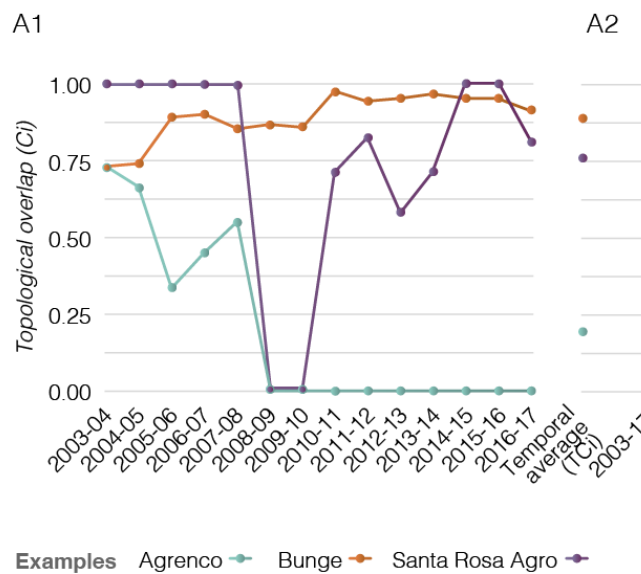
A map with stickiness measured on soy flow configuration displays similar patterns (Figure S5, App. 1). Municipalities in gray produce soy, but this soy is bought by traders through one of the logistics hub municipalities. Note that local soy transactions destined for local consumption in poultry or pork facilities are not captured by this dataset.



2.2.4. Stickiness dimensions in Brazil's soy exports

Here, we illustrate how the three dimensions of stickiness (persistence, resistance, and recovery) manifest in relation to shocks and other factors using exemplary cases in traders (Figure 2.7). We use the stickiness of soy linkages (C_i), the temporal average stickiness (TC_i), and the stickiness measured on the longest time window (2003's supply network configuration compared to the 2017's) (see Experimental Procedures). Formally, attributing causal relation to specific factors requires further analyzes beyond the scope of this paper.

Figure 2.7 - Temporal Stickiness (Persistence) Measured on Selected Traders. Traders' sourcing linkages from logistics hubs. See the same graphs with measurements on trade flows in Figure S6, App. 1. (A2) complements the temporal profiles by showing the temporal average stickiness (TCi; Equation 2, Experimental Procedures, 2.5) and the Ci calculated for the direct comparison between 2003 and 2017, instead of for each subsequent biannual snapshot.



Bunge, the single largest soy trader in Brazil, had a persistent configuration of soy linkages from LHs (Figure 2.7). In contrast with Santa Rosa Agroindustrial and Agrenco, Bunge also appears to have had a more resistant configuration to the various shocks that occurred during 2008-2010, including the global financial crisis and the Amazon Soy Moratorium (ASM), which all three companies signed in 2006. Santa Rosa Agroindustrial had a persistent pattern until 2008, and then experienced a profound reconfiguration of its sourcing linkages, with a period of high instability between 2008 and 2010, and then recovered a sticky pattern from 2011 onwards. Despite the collapse of Santa Rosa's linkages configuration in 2008-2010, the configuration of

the first snapshot (2003) and the last (2017) were quite similar (index ~ 0.62) (Figure 2.7, A2). This long-term similarity indicates that after having been disrupted for several years, Santa Rosa Agroindustrial recovered a similar network of sourcing logistics hubs, to a greater extent than Bunge. Agrenco, in contrast, exemplifies a non-persistent pattern, with stable linkages configurations sometimes lasting for two consecutive years, but then strongly reorganizing, and being unable to recover any stable sourcing pattern after 2009.

A proper causal analysis to explain why different traders present distinct patterns is beyond the scope of this paper. Nevertheless, these examples illustrate that small local traders like Santa Rosa Agroindustrial are subject to particular circumstances that may affect the observed stickiness patterns. Depending on market circumstances, these small local traders may venture into direct exports. However, they may also decide to sell their stocks for other traders to export or for local demand, thereby disappearing from the export registry in a given year. Indeed, Santa Rosa appears with zero export in 2009, leading to the stickiness metric dropping to zero when comparing the similarity of Santa Rosa's supply network in 2008 with 2009. In 2010, Santa Rosa resumed exporting, so that this new network configuration also produced a stickiness value of zero when comparing 2009 to 2010. Then the 2010-2011 measurement goes up to 0.7, indicating that the supply network of 2011 was around 70% similar to that in 2010.

2.3. Discussion

2.3.1. Stickiness as a conceptual and methodological tool

Our results reveal key insights into Brazilian soy supply chains: stickiness is higher for large traders, and increases over time, which may reflect the progressive consolidation of the relationships between traders and specific regions of production through investments in infrastructures or business relations. Further, stickiness typically decreases when the time interval observed becomes longer. From one year to the next, the configuration of the Brazilian soy network presents only small changes. However, these changes accumulate over time so that within the fifteen years covered by our assessment, the supply chain has substantially reconfigured, as observed for a pig supply chain in Germany (Büttner et al., 2016a).

Our results reflect three characteristics of Brazil's soy supply chain: (i) Market concentration, including potential infrastructure lock-in of large traders in some regions, *e.g.*, through the ownership of port terminals and export corridors; (ii) The strategy of large traders to diversify their sourcing regions to mitigate supply risks, and therefore a tendency to have relatively high stickiness given their ubiquity; (iii) The existence of many small traders (1,678 companies) that engage in intermittent trading and brokerage, without strong geographical dependency, following market circumstances and opportunities.

Our proposed metrics allow characterizing the whole network, specific linkages, and flows, as well as the behavior of actors – *i.e.*, decision-making entities (companies and regions of production, distribution, and consumption, representing the aggregate of

individual producers' and consumers' trade behaviors). These metrics can apply to different types of relations across supply and value chains – *i.e.*, material flows such as soy volumes here, but also financial flows or others – to investigate the existence and changes in linkages configuration and their intensity (*e.g.*, volumes traded). Examples from the Brazilian soy supply chain suggest that the three dimensions capture the dynamics of trade relationships and can be approached with our method.

Beyond our set of indices (Eq.1-6 in *Experimental Procedures*), other metrics can be used to measure the similarity of the network around specific nodes over time or the frequency or persistence of specific linkages. Our dataset on Brazilian soy has a fine granularity (*i.e.*, subnational production areas and distribution points, importing and exporting companies), but the same approach can also be applied over country-to-country data or other levels of detail.

Further methodological research would help to refine the indices and their information content, the measurement of the different stickiness dimensions and quantitative thresholds to characterize them, and specific procedures for supply chains covering distinct products, scales, and types of flows. Additional investigations are needed to formally define and identify shocks and analyze their impacts on trade linkages and flows (Bodin et al., 2019). The stickiness concept can further our understanding of various processes across commodity supply or value chains ranging from development (Gibbon, 2001), macroeconomics, and political economy (Garrett and Rausch, 2016) to supply chain management and business strategies (Lee et al.,

2012). Here we focus on appraising the potential effectiveness of supply chain zero-deforestation commitments (ZDCs) and other similar interventions (Garrett et al., 2019).

2.3.2. Understanding stickiness for sustainability governance

Analyzing stickiness in commodity trade can contribute to improve territorial and supply chain governance for sustainability, including reducing deforestation, carbon emissions, and biodiversity loss.

First, understanding stickiness can contribute to explaining and projecting the restructuring of trade flows under changing governance contexts or other shocks (Waroux et al., 2017). Past stickiness patterns can inform on which trade relations are more likely to persist over time, be resistant to shocks, or recover from them. Changes in deforestation regulations alter soy and cattle expansion and exports, but the mediating role of specific supply chain actors remains unclear (Waroux et al., 2017). Identifying areas and actors with low stickiness can help to understand their instability under changing policy or market conditions, as well as supply chains', companies', or regions' vulnerabilities to shocks such as newcomers or climatic changes.

Second, there is a growing momentum of supply chain interventions, such as ZDCs, to improve the sustainability of land use and other dimensions of supply chains (Lambin et al., 2018; Thorlakson et al., 2018). In 2006, Greenpeace launched a campaign blaming McDonald's consumers in Europe for causing deforestation in the Brazilian Amazon (H. K. Gibbs et al., 2015). In response, soy companies

and environmental NGOs established The Amazon Soy Moratorium (ASM) to address this growing awareness of corporate accountability for unsustainable commodity production and tackle reputational risks (Dauvergne and Lister, 2013; H. K. Gibbs et al., 2015). Other related initiatives ensued, including the New York Declaration on Forests, the Amsterdam Declarations, Tropical Forests Alliance 2020, and companies' pledges (Lambin et al., 2018). Assessments of the effectiveness, coverage, and benefit to corporate actors of these zero-deforestation initiatives (FAO, 2018; Garrett et al., 2019; Lima et al., 2019; Meijer, 2015; Soterroni et al., 2019) rest on a poor understanding of how strongly actors are connected to production places and how supply chain configurations are affected by these initiatives. We hypothesize that the relations between stickiness and supply chain governance are multiple. If supply chains are not geographically sticky, these commitments may be less effective, as traders will lack a sufficient engagement with producing regions to influence changes in their suppliers. In the reverse direction, supply chain interventions can also create, increase, or decrease stickiness.

We hypothesize that the ASM may have consolidated the export relationships between places with already deforested available lands, signatory traders, and European countries. However, it may have also created instability in other places by creating market space for non-signatory traders supplying the growing Chinese soy demand from municipalities where expansion was still occurring. About 350,000 tons of soy were harvested in the 2016/2017 season in violation of the ASM (Silva and Lima, 2018), suggesting that non-signatory companies

entered this market and bought this soy. We speculate that the entry of these non-signatory companies decreased stickiness in these municipalities.

Consequently, the strength of actor-geography connections is likely to have important implications for actors' accountability. Traders sourcing in spot markets with low stickiness may more hardly be held accountable for the impacts associated with soy production than actors with consistent sourcing patterns may. Further, stickiness may not only influence the effectiveness of ZDCs and other interventions but also condition their emergence and signing in the first place. Our results show that ZDC signatories, for example, also have the largest market-shares and the highest stickiness scores to their sourcing places and supplying countries. This higher stickiness may reflect not only the investments and facilities installed in these places but also the long-term trust relationships and the role of embeddedness (Uzzi, 1997) in shaping social-economic relations. Traders with such embeddedness and long-term engagement may be in a favorable position to sign and implement ZDCs.

Monitoring the stickiness and deforestation-risk exposure of each company over time (E. K. H. J. zu Ermgassen et al., 2020) allows for targeted efforts on specific regions in the supply chain. Companies with non-sticky patterns may require more robust monitoring and verification tools than sticky companies sourcing consistently from the same locations. In contrast, sticky actors may constitute stronger levers to influence their sourcing regions with more additionality in curbing deforestation, not only in their direct suppliers (Gardner et al.,

2019; Garrett et al., 2019; H. K. Gibbs et al., 2015; Heron et al., 2018; E. K. H. J. zu Ermgassen et al., 2020).

Stickiness may also affect the mechanisms through which interventions are transmitted along supply chains: strategies of sticky and non-sticky traders to achieve a ZDC may differ, with different overall impacts on the sector. Non-sticky traders may easily achieve targets related to their own embedded deforestation by shifting their sourcing to compliant suppliers. Nevertheless, this approach may have less effect on territorial deforestation overall, in contrast with sticky traders that have to steer changes on the ground to achieve a commitment (Gollnow et al., 2018). These different approaches may have distinct implications for socio-economic development and the spatial distribution of ZDC effectiveness.

Stickiness reflects stable long-term relations between actors. We hypothesize that the level of stickiness may thus also relate to and inform on the level of trust between regions of production and distribution, traders, and consuming countries (Krippner and Alvarez, 2007). Trust may be crucial for the success of supply chain interventions, and gaining insights on this level of trust may thus inform the sustainability strategy to be implemented and the likelihood of its success. Further works could explore these various hypotheses empirically.

Third, by informing on how supply chains behave, adapt over time, and react to shocks, analyzing stickiness can further our understanding of deforestation leakage and other complex land-use spillover dynamics stemming from territorial interventions and other

regulatory changes(Gollnow et al., 2018; Lima, 2019; Meyfroidt et al., 2020; Silva and Lima, 2018). The stickiness of consolidated traders in already-cleared regions in the Amazon may have facilitated their decision to sign the ASM agreement, acknowledging that they could expand into the neighboring Cerrado(Lima et al., 2019; Noojipady et al., 2017; Soterroni et al., 2019).

Leakage across supply chains – *e.g.*, deforestation being displaced from soy to beef(Gollnow et al., 2018; Richards et al., 2014) – and regions – *e.g.*, displacement of deforestation from the Amazon to the Cerrado –(H. K. Gibbs et al., 2015; Soterroni et al., 2019) is likely to follow the patterns of sticky relationships(Villoria and Hertel, 2011). Traders facing an intervention that curbs deforestation and agricultural expansion – *e.g.*, in the Amazon – may seek room for expansion in regions unaffected by the intervention – *e.g.*, in the Cerrado – where they already have sticky relationships. Stickiness analyzes might have informed on which Cerrado municipalities were more likely to experience increased soy deforestation after the ASM implementation(Soterroni et al., 2019).

Stickiness levels can also result from anticipation behaviors. Companies can enhance their fluidity by building new assets in places they expect to remain unaffected by interventions, or outsourcing logistics and storage services in locations targeted by interventions. In ASM procedures, soy purchased by indirect suppliers in the Amazon, *i.e.*, local cooperatives or small grain warehouses, are not subject to the verification procedures applied when traders source directly from farmers(Imaflora, 2016). Traders have thus an incentive to become

more fluid and outsource their facilities, while possessing physical assets in places targeted by interventions may become a competitive hindrance.

Fourth, stickiness can inform on trade dependency and market concentration. At the country level, dependency theory suggests that developing countries face reinforcing feedback loops between the creation of strong export linkages with wealthy countries and the expansion of land use with detrimental environmental impacts (Prell et al., 2017). Stickiness concept and method can improve the understanding of how agricultural supply chains and land use determine each other. This reciprocal dynamic includes legacies of past investments, infrastructure decisions (Meyfroidt et al., 2018), corporate strategies to increase market share, and positioning in distinct market segments (Garrett et al., 2013c).

2.3.3. A research agenda on stickiness in commodity trade

Two key questions may constitute a research agenda for stickiness in commodity supply chains, particularly concerning sustainability.

First, how sticky are various trading relationships, and what are the factors and mechanisms that explain variations in stickiness between specific actors and locations? These factors likely vary at different levels (e.g., company to company, or country to country), and steps in the supply chain. The concept of territoriality, i.e., how global production networks are spatially dispersed, can contribute to explaining the level of supply chain stickiness, as clustered actors tend

to have more rigid relationships than dispersed ones(Dicken and Malmberg, 2001).

Producer-driven commodity chains – *i.e.*, those in which large transnational manufacturers or processors play the central roles – are expected to have high barriers to entry for new producers, such as the soy industry for new producers of soy outputs like oil and cake(Bair, 2005; Gereffi, 2014; Turzi, 2017). These high barriers, due to the need for appropriate capital and expertise, may lead producer-driven chains to be relatively sticky, as downstream actors such as feed companies and food retailers depend on a concentrated set of processors. In contrast, buyer-driven chains, such as vegetables retailed by supermarkets, have lower barriers to entry and may be less sticky. In this case, large-branded supermarkets can easily change their suppliers drawing from a dynamic pool of vegetable producers. New buyers can also enter the market and compete for a pool of producers by offering more advantageous purchasing conditions(Gereffi, 1994).

The governance structure of value chains – *i.e.*, how authority and power relationships, such as through market shares and price-setting power, determine the allocation of benefits and resources across chains – also influences the options and bargaining power of actors and thus their stickiness(Gereffi et al., 2005). Social networks and embeddedness(Boekema and Rutten, 2004) also likely influence stickiness. Geographic factors, including the availability of land for further expansion, may influence the involvement of supply chain actors with specific places. Producers' stickiness can be tied to the presence of infrastructures from one versus different companies, or

preferential contracts, while consumers' stickiness depends on their attachment to brands(Antràs and Chor, 2013).

Countries may shift sourcing across other countries while a local trader may be tied to a place where it has a silo or other infrastructure. Stickiness may also be influenced by policies that increase traceability or compliance with specific sanitary norms or preferences – such as the EU refusal of genetically-modified crops – or provide preferential market access(Garrett et al., 2013c; Kawashima and Puspito Sari, 2010). Over the long term, environmental and other policies affect infrastructure development and production factors such as labor force, which in turn determines land-use displacement across geographies(Meyfroidt et al., 2018).

Second, how does an actor's stickiness influence patterns of land use in the geographies where they engage, and more broadly, the socio-environmental impacts of commodity production? Further, how does stickiness interact with various governance interventions, *i.e.*, territorial or jurisdictional interventions, supply chain, or public policy interventions, aiming to manage land use more sustainably, and does this influence their effectiveness?

Formulating and testing more specific hypotheses relating to the relationship between stickiness and land-use governance can help to design more effective interventions. In the specific context of ZDCs, we propose that (i) stickier companies are more likely to implement zero-deforestation commitments by requesting changes in their suppliers' practices as opposed to shifting their sourcing patterns, and (ii) interventions on stickier companies or territories are less likely to

result in leakage. Testing these hypotheses requires further work beyond the scope of this study.

2.4. Conclusion

We presented the notion of stickiness to measure and characterize the level of stability and rigidity of supply chain relations, decomposed into the persistence, resistance, and recovery of these relations. Metrics from network analysis can measure these dimensions for both the presence of linkages and the intensity of flows.

Understanding stickiness can inform policies and initiatives to address deforestation, in particular, to assess the potential effectiveness of supply chain zero-deforestation commitments. If supply chains are not geographically sticky, these commitments may be less effective, and less likely to be signed, as companies may lack the capacity to influence their suppliers downstream. This relationship between stickiness and zero-deforestation commitments requires further investigation.

Analyzing stickiness revealed insights into the behavior of production places and traders active in the Brazilian soy supply chain. Brazilian soy traders with the largest market share and with ZDCs exhibit stickier geographic sourcing patterns. Soy-deforestation risk among traders is correlated with stickiness. The linkages between production places and traders become increasingly sticky over time. Specific regions, in particular current agricultural and deforestation frontiers, have higher stickiness. The cause-effect relationships behind these patterns require further investigations.

Further research could improve the methodological tools for empirically assessing the different dimensions of stickiness, especially related to the identification of supply chain shocks and their effects. These improvements can enhance our understanding of the factors that influence stickiness patterns, the impacts of supply chain dynamics, and the mediating role of actors on socio-environmental dimensions. Research on stickiness can inform the development of solutions for curbing deforestation and promoting sustainable land use and supply chains.

2.5. Experimental Procedures

2.5.1. Designing a conceptual framework for Stickiness

Several fields have explored how to describe the stability and rigidity of supply chain patterns and trade networks, and the processes that underpin them. First, agricultural economics investigates stickiness in international trade, showing, under the so-called “Armington assumption”, that in global markets with free trade, agricultural products from one place are not fully substitutable with products from another place, even after accounting for price differences (Armington, 1969; Villoria and Hertel, 2011). The often-used gravity model explains the amount of country-to-country flows as a function of economy sizes, *i.e.*, GDP and geographic distance (Brun et al., 2005; Kepaptsoglou et al., 2010). However, this literature says little about geographic stickiness between places and actors, except for clustering in manufacturing supply chains (Porter, 2000), and lacks explicit articulation of the role of stickiness in sustainability

governance of supply chains, particularly for ZDCs (Garrett et al., 2019). Second, research on global commodity chains (GCCs) (Bair, 2005), value chains (GVCs) (Gereffi, 2014), and production networks (GPNs) (Coe et al., 2008) show how actors, including raw material producers, traders, and retailers, create and maintain specific trade networks. This research remains based on specific case studies, lacking the large datasets linking localized production, supply chain actors, and consumption places that are necessary to explore quantitatively how supply chain configurations react to various changes in markets and policies (Larsen et al., 2018). Third, studies on social-ecological resilience and biosphere stewardship (Folke, 2006; Folke et al., 2016) have analyzed how social-ecological systems resist, adapt, transform, and recover from external shocks (Gephart and Pace, 2015; Janssen et al., 2006; Walker et al., 2004). They distinguish the two dimensions of *resistance* – *i.e.*, the ability of a system to withstand shocks by maintaining its functions – and *recovery* – *i.e.*, the ability of a system to bounce back to its previous state after being perturbed (Bodin et al., 2019; Bodin and Tengö, 2012; Janssen et al., 2006). In the next paragraphs, we explain in more detail how these three streams of literature contribute to designing a conceptual framework for stickiness.

Agricultural economics studies show that in global markets with free trade, agricultural products from one place are not fully substitutable with products from another place, even after accounting for price differences (Agcaoili-Sombilla and Rosegrant, 1994; Donnelly et al., 2004; Kawashima and Puspito Sari, 2010; Mcdaniel and

Balistreri, 2003). Standard econometric studies and economic models use empirically-calibrated “Armington trade substitution elasticities”(Armington, 1969). These studies account for the differentiation of products based on production place, and for the fact that price shocks occurring in one country do not spread homogenously in the global market, but predominantly affect the key trade partners of that country (Anderson and van Wincoop, 2004; Armington, 1969; Barrot and Sauvagnat, 2016).

For example, a drought in a few specific municipalities of Brazil, as a soy exporting country, will affect local producers and traders by impairing their capacity to deliver future contracts. As a result, this local shortage of supply may increase regional soy prices, but this will not affect global markets, as most traders can change sourcing to other regions not affected by this local shock. In global commodities, for global prices to be affected, there need to be higher scale shocks. In this sense, a local price shock caused by local climate variability will differentiate soy according to its production location because municipalities that did not suffer from this drought will have more supply and lower prices to feed global demand.

For supply chains at firms level, the economic literature identifies some factors influencing stickiness, mainly input and output specificity (Barrot and Sauvagnat, 2016; Van Assche and Schwartz, 2010). Input and output specificity refers to the properties and characteristics of materials used in manufacturing and the resulting products that differentiate them. For example, soy farmers who use specific breeds of genetically modified (GMO) seeds are highly sticky to the companies

that supply the specific set of agrochemicals that function with those seeds. By acquiring certain types of GMO seeds, a farmer may establish an enduring commercial relationship with the suppliers of an adequate and specific set of inputs (Garrett et al., 2013c; Turzi, 2017).

The actor's relative position in the supply chain, which is dependent on the elasticity of demand faced by the consumer-facing company (Antràs and Chor, 2013; Heron et al., 2018; Thorlakson et al., 2018), also influences stickiness because of the embeddedness nature of some commodities in food systems (Heron et al., 2018). For example, soy is used for multiple purposes that are opaque to consumers, such as animal feed and biofuel; only a small fraction of soy goes to direct human consumption. This opacity means that it is relatively easy for intermediate companies, such as traders and processors, to be non-sticky with their suppliers. These intermediate companies have a distant relative supply chain position from end consumers. This distance implies they can shift sourcing places from time to time, as they do not receive direct consumer pressure for accountability.

Geographic proximity influences the country-to-country trade patterns (Disdier and Head, 2008; Rauch, 1999; Villoria and Hertel, 2011) significantly. However, the literature also shows other more qualitative factors influencing international trade, such as ethnic networks (Coughlin and Wall, 2011), colonial linkages and common language (Head et al., 2010; Rauch, 1999), piracy (Burlando et al., 2015), governance regimes (Yu, 2010), institutional quality and differences between countries (Levchenko, 2007), and the countries'

capacity to enforce contracts (Nunn, 2007). The social economy concept of embeddedness (Granovetter, 1985; Polanyi, 1944) complements our review of stickiness by acknowledging the social structure and trust of interfirm networks and commercial relationships (Uzzi, 1997). Understanding the embeddedness of social relations (Krippner and Alvarez, 2007) in supply chain economic and geographic relationships is crucial to advance the stickiness research agenda.

Lock-in effects are equally important factors of stickiness in supply chains, mainly technological (Fares et al., 2012), the fixing of relative preferences over time (Akkermans, 2001), social dependence, and investments (Narasimhan et al., 2009). The gravity model explains the amount of country-to-country flows as a function of economy sizes, i.e., GDP, and geographic distance (Brun et al., 2005; Kepaptsoglou et al., 2010), which can also partially explain stickiness or, in other words, why some country-to-country flows persist over time. Furthermore, the Melitz model (Melitz, 2002) suggests that stickiness depends on a country's exposure to international trade, where more productive firms would access foreign markets, thus having more volatile supply chains. In contrast, less productive firms would be sticky to domestic consumers. Varying levels of trade openness would cause different supply chain responses and more or less volatility in sourcing and supplying patterns (Demidova and Rodríguez-Clare, 2013).

These economic studies focus on providing robust estimates of trade substitution elasticities for different commodities, and on explaining stickiness in inter-firm and country-to-country trade. Nonetheless, they say little about geographic stickiness between

places and actors, except for clustering in manufacturing supply chains (Porter, 2000). This literature also lacks explicit articulation of the role of stickiness in sustainability governance of supply chains, particularly for zero-deforestation commitments (ZDCs) (Garrett et al., 2019).

Research on global commodity chains (GCCs) (Bair, 2005) and value chains (GVCs) (Gereffi, 2014) provides a complementary perspective. They move beyond structural country-to-country relations and show that various actors such as raw material producers, traders, processors, and retailers play a role in creating and maintaining specific trade networks. The notion of global production networks (GPNs) (Coe et al., 2008) highlights that companies and non-state actors exercise power and agency to shape the legal, governance, and policy frameworks and contexts in which they operate (Coe et al., 2008; Gereffi et al., 2005; Hess, 2008; Mahutga, 2012). Most quantitative research on supply chain configurations investigates structural factors at the country-to-country level (Coe, 2012). As far as we see, research on GCCs, GVCs, and GPNs remains based on specific case studies. It lacks the large datasets linking localized production, supply chain actors, and consumption locations that are necessary to explore quantitatively how supply chain network configurations react to various changes in markets and policies (Larsen et al., 2018).

Here, we bridge these theoretical and empirical approaches by analyzing supply chains as a network (Borgatti and Li, 2009; Shenton, 2017). We extend the notion of stickiness formulated in economics through the analysis of supply chains as proposed in GCC, GVC, and GPN research. We consider stickiness as a moderating factor of the

existence, and the potential effectiveness, of supply chain sustainability initiatives (Garrett et al., 2019), particularly ZDCs. The notion of resilience in social-ecological systems and biosphere stewardship (Folke, 2006; Folke et al., 2016) inspires us to define the dimensions or characteristics of stickiness, namely resistance and recovery. The extensive inquiry on network approaches (Bodin et al., 2019; Bodin and Crona, 2009) and in supply chains (Vroegindewey and Hodbod, 2018) are also crucial for our stickiness approach. Nonetheless, here we do not aim to characterize all the aspects of resilience of production, consumption locations, and networks, as well as of actors in the supply chains, and the capacity of these actors to adapt and transform. We simply aim at providing a concept and methodological approach to initiate those types of enquiring.

2.5.2. Assessing stickiness in the Brazilian soy supply chain

Network analyzes are applied to various sustainability issues, including social-ecological, biological, food webs (Dunne et al., 2002), supply chain (Kim et al., 2011), land acquisitions (Seaquist et al., 2014), and virtual water trade (Carr et al., 2013). In many cases, they aim to describe and understand the persistence and reconfigurations of these networks. These studies offer inspirations for our methodology for characterizing trade stickiness.

The Brazilian soy trading data from Trase version 2.3 (See Supplemental Experimental Procedures, Appendix 1) includes transactions of soy exported as raw beans, oil, meal, or cake (Trase, 2020a) . We assembled this dataset as a network linking logistics hubs,

traders, and countries of consumption. We did not measure stickiness on all soy-producing municipalities. The allocation of soy flows from the logistic hubs (LHs) to the municipalities of production in the Trase data is the result of linear programming. This method may create artifacts in the measurements of the inter-annual stability of the network configuration at the municipality level (Trase, 2018c). LH-level data rely directly on official trade records, and are representative of a set of soy farms within the municipal boundaries in which they are located, but also for neighboring municipalities, as these LHs gather soy produced in a surrounding region with viable logistic connectivity. We also clarify that we do not consider trade linkages with local feed companies and processors that supply soy for Brazilian domestic consumption. All soy consumed internally is treated as a single node called “domestic consumption” in the logistics hubs and traders network levels, and as “Brazil” in the country destination network level.

We transformed the raw data (in the format of edges lists) into adjacency matrices. Each aggregate year of trade data between 2003 and 2017 became one adjacency matrix, representing one snapshot of the network. We call each year's aggregate transaction data a snapshot because our network comprises fifteen snapshots or annual aggregate transaction data. Each stickiness measurement implies comparing two snapshots. In one set of adjacency matrices, we replaced entries by 1, representing the existence of a linkage between two adjacent nodes, and 0 when no link existed, thus creating an unweighted adjacency matrix (or binary interaction matrix). We used

this to measure stickiness on trade linkages. All measurements presented here in the main text use this unweighted adjacency matrix. In the second set of matrices, we maintained the entries with the original values representing the volumes of soy traded. With this, we measured stickiness on trade flows. The measurements on flows that are equivalent to those on linkages presented here are shown in the SI. Both measurements, on soy trade linkages and flows, are highly correlated.

They are complementary indicators. While the measurements on linkages allow us to identify overall changes in the configurations of commercial relationships, the measurements on flows allow us to qualify these changes by indicating whether the configuration of volumes traded through each linkage increased or decreased.

For stickiness in trade linkages (unweighted networks), we used the temporal correlation coefficient (C) (Büttner et al., 2016a; Nicosia et al., 2013) and its intermediary steps for directed, temporal, and unweighted networks (as adapted by (Büttner et al., 2016b; Pigott and Herrera, 2018)). These intermediary steps are the topological overlap (C_i), the temporal average topological overlap (TC_i), and the graph average topological overlap (C_m ; Eq.1-4). C_m is the average topological overlap, calculated not over time as TC_i , but over groups of nodes. It is a necessary step to see the overall stickiness across groups and to calculate C . For stickiness in trade flows (weighted networks), we adapted the topological overlap (C_i) to analyze directed, temporal, and weighted networks, transforming it into what we call

weighted persistence of trade flows (WPI) and the temporal average weighted persistence (TWPI; Eq.5-6).

Metrics used for stickiness in linkages

The temporal correlation coefficient and its intermediary steps were first designed as metrics for undirected and unweighted networks. Further adjustment corrected and adapted the metric for directed networks (Büttner et al., 2016b, 2016a; Pigott and Herrera, 2018). The temporal correlation coefficient “measures the overall average probability for an edge to persist across two consecutive snapshots”(Büttner et al., 2016a; Nicosia et al., 2013; Tang et al., 2010). The topological overlap (C_i) of the surrounding links around a node in two-time points is the first step to measure the temporal correlation coefficient (C) of a network. The C_i allows us to quantify the temporal changes in the configuration of trading linkages of an actor in the supply chain.

We present the C_i equation below, where C_i is the topological overlap (Nicosia et al., 2013) of links around node i . t_m is the first snapshot of the temporal network, for example, the configuration of trade linkages of the soy supply chain in 2003. t_{m+1} is the second snapshot, in the same example, the configuration of trade linkages in 2004, the subsequent year with available data. We used the same metric to compare non-successive years, *i.e.*, comparing the network configuration in 2003 with that of 2017. a_{ij} is a value (1 or 0) in the adjacency matrix representing the network. With the C_i (Eq.1), we can observe and measure temporal changes in two snapshots with the

selected time interval, in the trading relationships around any specific actor in the supply chain.

$$Ci(t_m, t_{m+1}) = \frac{\sum_j a_{ij}(t_m) a_{ij}(t_{m+1})}{\sqrt{[\sum_j a_{ij}(t_m)][\sum_j a_{ij}(t_{m+1})]}} \quad (Eq. 1)$$

The Ci in biannual snapshots allows observing the changes in the trade linkages configuration over two subsequent years around each node, e.g., 2003-2004, 2004-2005, ..., 2016-2017. Based on this, we then computed the temporal average topological overlap (Büttner et al., 2016a) of the nodes (TCi , Eq.2) for all snapshots, where M is the total number of considered snapshots. In our study, the maximum snapshots we can have is 15, each year from 2003 to 2017.

$$TCi = \frac{1}{M-1} \sum_{m=1}^{M-1} Ci(t_m, t_{m+1}) \quad (Eq. 2)$$

In practical terms, Eq.1 is calculated over two snapshots that may be successive years (e.g., 2003-2004) or non-successive years (e.g., 2003-2017), and Eq.2 is the mean of several Cis over time. Eq.2 shows the average variation in stickiness for every node in the complete length of the analyzed period and considering all biannual changes in between. With this Ci temporal average (TCi), we can see the average changes in the trading relationships around any specific actor or region

over a longer period, acknowledging several or all subsequent snapshots in between.

In the third step, we grouped the trade relationships in six types: logistics hubs (LHs) supplying (A) traders and (B) countries; (C) traders sourcing from LHs, and (D) supplying countries; (E) countries sourcing from traders, and (F) from LHs (Figure 2.2). We then calculated the mean of the biannual C_i s for each type of relationship. Having the C_i s of nodes, we also calculated the average topological overlap of the graph (entire supply network) (Büttner et al., 2016b) for two consecutive snapshots (C_m , Eq.3). The C_m is different from C_i temporal average because TC_i focuses on the trade linkages configuration around each node, while C_m describes the changes in the whole network configuration. The C_m is an intermediary step to get to the temporal correlation coefficient (C). Therefore, we did not present the results here. The equation used is:

$$C_m = \frac{1}{\max[A(t_m), A(t_{m+1})]} \sum_{i=1}^N C_i(t_m, t_{m+1}) \quad (Eq. 3)$$

In this equation, $\max[A(t_m), A(t_{m+1})]$ denotes the maximum number of active nodes of the graph at t_m and t_{m+1} . A node i is called “active” at time t_m if it has an edge with any other node (Büttner et al., 2016a). This equation was presented by (Büttner et al., 2016b; Pigott and Herrera, 2018), modifying Nicosia et al.’s (Nicosia et al., 2013) equation to acknowledge only active nodes in the calculation rather than all nodes, i.e., even inactive nodes that did not trade anything in the two snapshots considered. We subset the network to

compute C_m for specific groups of edges or, in our case, trade relationships, as described above.

Finally, the temporal correlation coefficient (C) (Eq.4) measures the overall average probability of an edge to persist between two consecutive snapshots (Büttner et al., 2016a; Nicosia et al., 2013; Tang et al., 2010). It is the fourth step after computing C_i and C_m . M is the total number of considered snapshots. C is calculated as follows:

$$C = \frac{1}{M-1} \sum_{m=1}^{M-1} C_m \quad (Eq.4)$$

The temporal correlation coefficient (Eq.4) summarizes the C_m s, which we grouped by type of supply chain relationship, to demonstrate how much the trade configuration changes overall with the length of the timeframe observed.

All these four metrics generate values ranging from 0 to 1, 0 being a complete change, and 1 a complete maintenance of the trade configuration. As an illustration, if one actor in the supply chain displays C_i or $TC_i = 1$, it means that this actor kept precisely the same trade linkages configuration throughout the period assessed. On the contrary, if the value is 0, the trade linkage configuration changed utterly. Any value in between implies some degree of reconfiguration. Looking at C_m and C , 1 means that the whole trade network remained completely unchanged over the assessed period, while 0 means a complete change. As can be expected, the longer the time interval, the more likely the network is to change, and therefore the less sticky it appears (Figure 2.4). Büttner et al. (2016a) found a slightly different trend in their pork supply chain analysis, as C increases sharply in the

initial increments of the timeframe, and then starts to fall slowly as timeframe increases. Their time steps were very short (days) compared to ours, so their supply chain appears much more volatile in comparison to our soy supply chain, which is less volatile and measured in years.

Metrics used for stickiness in flows

Despite the robustness of C and its sequential steps to measure stickiness in trade relationships, one primary limitation of this metric is its inability to account for the changes in volumes traded, as it was designed for unweighted networks (binary set of linkages). The C_i is calculated over a list of binary edges or pairs of adjacency matrices, where nodes are either connected by a trade relationship (1) or not (0). For our stickiness analysis of commodity trade, it is also important to gauge the variations in flows, i.e., the volumes of product traded in tons over the years through the linkages. Therefore, we devised an additional index modifying the C_i and C steps. The weighted persistence index (WPI) is the ratio between the absolute changes in the trade flows of a node i and the total volume of soy produced or distributed (if the node is a logistic hub), traded (if it is a trader) or imported (if it is a country) by this node i in the observed time window. The same interpretation of C_i applies to the WPI index, i.e., an actor having $WPI = 1$ reveals that, overall, its in - or outflows - of commodities remained unchanged over the observed period, whereas 0 indicates a complete change in flows. We calculated the weighted

persistence (WPI, own formulation) as:

$$WPI(t_m, t_{m+1}) = 1 - \frac{\sum_j |a_{ij}(t_m) - a_{ij}(t_{m+1})|}{\sum_j a_{ij}(t_m) + a_{ij}(t_{m+1})} \quad (Eq. 5)$$

$$TWPi = \frac{1}{M-1} \sum_{m=1}^{M-1} WPI(t_m, t_{m+1}) \quad (Eq. 6)$$

With these two equations, we demonstrate a way to measure stickiness and its three dimensions in commodity trading. Other metrics and approaches could be used. The WPI is only applicable to edges or flows aggregated by nodes or by types of trading relationships.

Measuring the three dimensions of stickiness

Based on these indices, we explored the three dimensions of stickiness empirically, using the soy data, through the following questions (Figure 2.7):

Persistence: which actors and locations have trade linkages and flows that are persistent over time? To answer this, we can look at trade linkages and flows with C_i , TC_i , WPI , and $TWPI$ close to 1. Those who kept biannual C_i s and WPI s at high values over the whole observed period are the most persistent. Actors and places that have values for these metrics closer to 0 have low persistence for the period considered.

Resistance: which actors and locations have trade linkages and flows that are resistant over time? To answer this, we need to identify

a potential or known shock, which can, among other things, be a drought, a new trade policy, a ban or moratorium, a sudden increase or decrease in global demand. Once we have identified a shock, we look at trade linkages and flows that are subject to this shock and observe how their persistence (as measured by C_i for linkages and by WP_i for flows) performed during the shock period. The trade linkages and flows that maintained C_i s and WP_i s, respectively, at values that are high and similar to the period before the shock can be characterized as resistant. Those who experience a substantial change are less resistant, and those who break linkages and flows and experience a sudden drop in their indices are non-resistant. Note that proper attribution of the changes in network configuration to the identified shocks requires applying appropriate causal inference approaches that we did not do here. (Figure 2.7).

Recovery and reconfiguration: which actors and locations have trade linkages and flows that recover and reconfigure a stable situation over time? For this question, we look at linkages and flows that are affected by a shock, *i.e.*, show decreasing C_i s and WP_i s during the shock period, but which afterward reconfigured their connections and flows in a way that it returned to a similar trade configuration as before the shock. Here we make two subdivisions. The first entails the recovery towards the same previous stable configuration, *i.e.*, after breaking linkages and flows, they recover to the same old partners and stabilizes. The second entails linkages and flows that recover, but in a new configuration, *i.e.*, it creates new linkages with new partners and then maintains this stable new configuration. Here we did not analyze

causal explanations of this dimension, only observed it empirically (Figure 2.7).

These three dimensions can be illustrated by first identifying a shock and how the *Cis* and *WPis* drop in the period after the shock. If it recovers during subsequent snapshots, it means the linkages and flows were re-established in a more stable configuration. If we increase the analyzed timeframe, for example, instead of 2007-2008 we look at *Cis* and *WPis* for 2007-2012 and see unchanged high *Cis* and *WPis*, it means that not only were the supply chain actors able to re-establish stable relations, but these relations were similar to those prior to the shock - *i.e.*, that the network restored to its previous configuration. In contrast, if *Cis* and *WPis* for 2007-2012 are low, it means that over this longer period, they changed the configuration significantly, so the network has reconfigured.

It is essential to highlight that here we do not define numeric boundaries or thresholds to determine when the stickiness of a trade linkage or flow is resistant or recovering, or not. So far, this is done simply in terms of comparison with previous patterns. In other words, if the stickiness index of a specific node varies between, for example, 0.7 and 0.9 for a period, then it drops to 0.1 in a biannual timestamp, to go up again back to the 0.7 and 0.9 range, we can point out its recovery. More empirical analyzes and stickiness observations are needed so that we can start considering the establishment of numeric boundaries and thresholds for each dimension.

The sustainability of global agricultural trade: understanding stickiness in Brazil's soy supply chain

After conceptualising stickiness in global commodity supply chains from theory, formulating a method to quantify stickiness as a pattern in trade relationships using temporal network analyzes, empirically demonstrating the viability of this method and concept on Brazil's export soy supply chain, and discussing some of its potential influencing factors and implications for sustainability governance, it is time to deepen the analysis. The next chapter seeks predictors, underlying influencing and determining factors and processes of stickiness through quali-quantitative analysis of Brazil's soy supply chain.

The sustainability of global agricultural trade: understanding relationship patterns in Brazil's soy supply chain

III. Explaining the stickiness of supply chain relations in Brazilian soybean trade

Abstract: The global trade of agricultural commodities has profound social-ecological impacts, increasing overall food availability and potentially agricultural efficiency, displacing local communities, incentivizing deforestation, and causing biodiversity losses. However, our understanding of how supply chain actors, including traders, food processors, and consumer countries, develop, maintain or shift trading relationships geographically remains limited. Understanding stickiness, i.e., the stability in sourcing and trading relationships, is crucial to identify entry points for private sector sustainability initiatives, to assess the effectiveness of such supply chain interventions, to project the restructuring of trade flows, and for territorial planning that considers the geographic sourcing patterns of supply chain actors. Here we use data on the Brazilian soy supply chain to explore the agency of supply chain actors and structural factors that influence the stickiness in the commercial relationships between places of production and supply chain actors over time. We find that economic incentives, institutional enablers and constraints, social and power dimensions, and biophysical and technological conditions influence stickiness and may thus underpin the stability or volatility of relationships between regions and supply chain actors.

Keywords: Stickiness, commodity supply chains, random forests, agricultural trade, Brazilian soy production, tropical deforestation.

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Author Contributions

Conceptualization, T.N.P.R., P.M., R.D.G., T.K.; Methodology, T.N.P.R., P.M., V.R.; Software, T.N.P.R., V.R., P.R, Validation, P.M., T.K., R.D.G., V.R.; Investigation, T.N.P.R., V.R.; Resources, T.N.P.R., V.R., V.G.F., P.A.; Data Curation, T.N.P.R., V.G.F., P.R., V.R.; Writing, T.N.P.R., P.M., R.D.G., T.K., P.A., P.R.; Supervision, P.M., T.K., R.D.G.; Funding Acquisition, P.M., T.K.

3.1. Introduction

Land use, agriculture, and forestry are at the heart of many urgent global sustainability challenges. This sector contributes to about 25% of the world's greenhouse gas emissions and offers crucial opportunities for climate change mitigation and adaptation (IPCC, 2014b). Land-use change is the primary driver of ongoing massive biodiversity loss (Díaz et al., 2019). It also interacts with water cycles, food security, and international trade of agricultural commodities, resulting in consequences that affect beyond producer localities (Graesser et al., 2018; Henders et al., 2015; Leite-Filho et al., 2019; Liu et al., 2013; Meyfroidt et al., 2016; Sun et al., 2018). Therefore, understanding what underpins land-use change is essential for addressing many global sustainability and environmental challenges.

Land use patterns and governance in many regions are increasingly impacted by a handful of companies associated with the production, trade, and processing of key global agricultural commodities (Curtis et al., 2018; Escobar et al., 2020; E. K. H. J. zu Ermgassen et al., 2020). Corporations have been re-shaping the global patterns of agricultural production and, consequently, its social, economic, and environmental outcomes in producer countries (Cattaneo et al., 2010; Curtis et al., 2018; Dauvergne and Lister, 2013). The agency of global companies in producer countries may have bigger impacts on local landscapes than governments (Thorlakson et al., 2018; Vatn, 2018). The lack of political will or capacity for effective environmental governance in some national or subnational governments (Scott, 1998) contributes to this increasing role of companies (Bernauer and

Betzold, 2012; Levy and Newell, 2002; Schwab, 2008). Yet, the power of corporations can also be an opportunity. Targeting companies is increasingly seen as essential leverage for sustainability (Folke et al., 2019). Steering this leverage requires a better understanding of their agency. More specifically, knowledge is needed on where companies choose to locate and source commodities, why these geographic sourcing behaviors and patterns remain stable or change over time, and conversely, whether certain landscapes are influenced over time by the same or different companies.

Through their supply chains, companies interact with diverse actors and institutions in production regions, all of which have their agency concerning receiving and responding to signals from distant consumer markets. These signals can be marketing or governance signals, such as demand preferences for certification, and institutional and regulatory constraints, such as environmental criteria in trade agreements (Brack, 2013; Dauvergne and Lister, 2013; Gardner et al., 2019; Heron et al., 2018; Kehoe et al., 2020). In some cases, actors in the producing regions may have agency over which companies they would like to interact with, which could moderate any demand-side efforts to affect changes on the ground in the production region through international levers (Garrett et al., 2013b; Garrett and Rausch, 2016; Gollnow et al., 2018). Understanding the factors and processes underlying supply chain actors' relationships is essential for designing more targeted and precise supply chain sustainability interventions.

Some studies have analyzed trade patterns using multiregional input-output models and human appropriation of net primary

production, elucidating the role and impacts of trade on producer-countries landscapes and ecosystems (Henders et al., 2015; Pendrill et al., 2019b, 2019a; Prell et al., 2017; Roux et al., 2020; Schaffartzik et al., 2015; Schröter et al., 2018). Other set of studies have assessed the quality, scope, and the effectiveness of a type of sustainability initiatives relevant for land use and our study, namely zero-deforestation commitments (ZDCs) made by companies and industry coalitions to remove deforestation from their supply chains (Garrett et al., 2019; H. K. Gibbs et al., 2015; Holly K. Gibbs et al., 2015; Lambin et al., 2018; Leijten et al., 2020; Meijer, 2015; E. K. H. J. zu Ermgassen et al., 2020). However, these studies say little about how the relationship patterns between actors and regions change or maintain over time in commodity supply chains, i.e., what has been described as the level of “stickiness” in supply chain relations (Reis et al., 2020).

Understanding what determines the stability or volatility in trade relations is unclear, including why companies and producers choose to interact with each other in various spatial-temporal patterns. Knowledge about this stickiness of trading relations can help us understand how persistent certain intervention points for sustainability might be if certain global or local conditions change (i.e., if these trade relations are affected by shocks). In addition, we need to know how the agency of actors and various structural factors influence this stability and change.

Previous work has adapted the concept of stickiness in global commodity supply chains from the notion of trade substitution elasticities, or Armington assumption, which was proposed to

understand the substitutability of commodities and origin bias in the context of liberalizing international trade (Armington, 1969; Kawashima and Puspito Sari, 2010; Mcdaniel and Balistreri, 2003). The Armington assumption has been developed and applied to measure stability in bilateral trade (Agcaoili-Sombilla and Rosegrant, 1994; Villoria and Hertel, 2011). A previous study used this notion to conceptualize and measure actor-geography relationships patterns (Reis et al., 2020; Villoria and Hertel, 2011). There, stickiness is defined as *“the maintenance and recovery, over time and through shocks, of supply chains’ geographic network configurations, i.e., the network of trade linkages and flows between specific places of production and consumption, and specific actors including producers, traders, retailers, and consumers”* (Reis et al., 2020). This study operationalized a stickiness index, measuring the overall stickiness of the trade relationships between Brazilian municipalities of soy production and trade (known as logistics hubs – LHs), traders, and country destinations (Reis et al., 2020). Nevertheless, a deeper inquiry about the underlying and influencing factors of stickiness in supply chain relationships is still lacking.

The Brazilian soy export supply chain is interesting to understand the drivers of stickiness because it is a market-governed global value chain (Gereffi et al., 2005), where trade relations are dynamic, rationally-driven but also embed social and cultural norms and values coupled with economic, institutional and infrastructural factors (Bair, 2008; Craviotti, 2016; Garrett et al., 2013b; Henderson et al., 2002; Waroux et al., 2017). Soy constitutes a critical global supply chain for

food security, geopolitics, and social-environmental aspects (Garrett et al., 2018; Oliveira, 2016; Sun et al., 2017). Soybeans and their direct derivatives (i.e., oil, cake, and meal) were the most traded agricultural commodities globally in 2018. In the 2017/2018 crop season, the world produced almost 340 million tons (Mt) of raw soybeans (that later were processed into oil, cake, and meal), with the USA and Brazil accounting for 36% and 35% of this global output, respectively (USDA-FAS, 2019). Brazil was the second-largest producer but the largest exporter in 2017. Brazil supplied about 68 Mt of raw soybeans at a trade value of 21.5 billion USD to the world (UN-Comtrade, 2019).

The soy industry is a crucial economic driver in the Brazilian economy. In 2017, soy exports directly added roughly 1% to the country's GDP (UN-Comtrade, 2019; World Bank, 2019a). It is responsible for improving the country's trade surplus and driving the economic development of the countryside (Garrett and Rausch, 2016; Martinelli et al., 2017). The Brazilian export soy supply chain has the most extended data time series available for the market dynamics and trading relationships developed between soy traders, production and distribution centers, and consuming countries (Trase, 2020a).

Specifically, earlier work has shown that between 2003 and 2017, the soy traders with the largest market share in Brazil exhibited stickier trading relationships with production and trading municipalities, which means that they sourced continuously from the same set of places. These stickier traders are also the signatories of ZDCs and showed a higher soy deforestation risk. Moreover, the sticky traders to their supplying regions are also sticky to their destination markets,

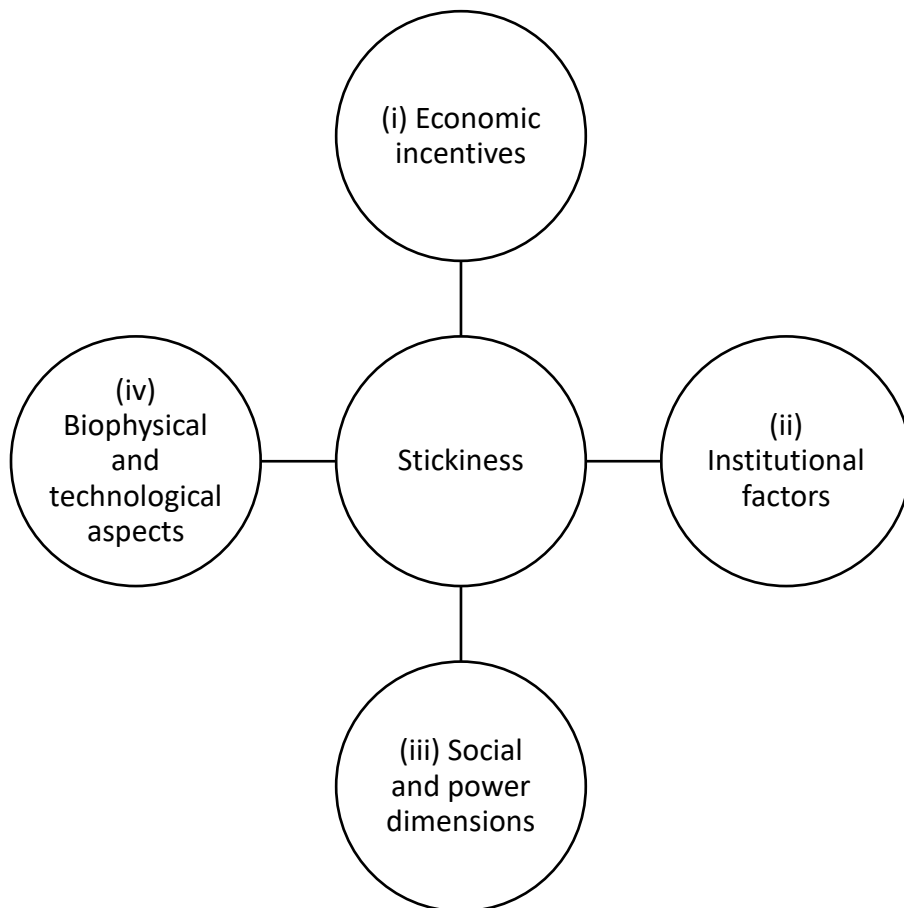
suggesting a potential for signal transmission from consumers to producers in these supply chains (Reis et al., 2020; E. K. H. J. zu Ermgassen et al., 2020). However, what remains unclear is the underlying factors and determinants of the stickiness found in these trade relationships that go beyond purely economic factors such as stable patterns of transport costs.

Building on this prior work, our main objective here is to understand the agency and structural factors that determine the stickiness (i.e., the persistence of trading relationships over time, corresponding to the first dimension of stickiness defined by Reis et al (2020)) of fine-scale geographic trade relations in the Brazilian soy supply chain. We seek to understand which factors influence or determine this stickiness, to also inform on other global agricultural commodity supply chains. Understanding the local predictors of these supply chain relationship patterns matters as, ultimately, these relationships influence land use patterns, such as deforestation and agricultural intensification.

Our guiding research question is “what are the local influencing factors and determinants of the stickiness observed in the relationships between Brazilian soy logistics hubs (i.e., municipalities of soy production and trade) and exporting traders over 2003-2017?” We seek to respond to this question by exploring empirically our theoretical underpinning (Section 3.2.1), which leads us to a general hypothesis as follows: *“the geographic trade stickiness of Brazilian soy logistics hubs supplying to traders can be explained by a function of (i) economic incentives, i.e., determined by infrastructure, capital*

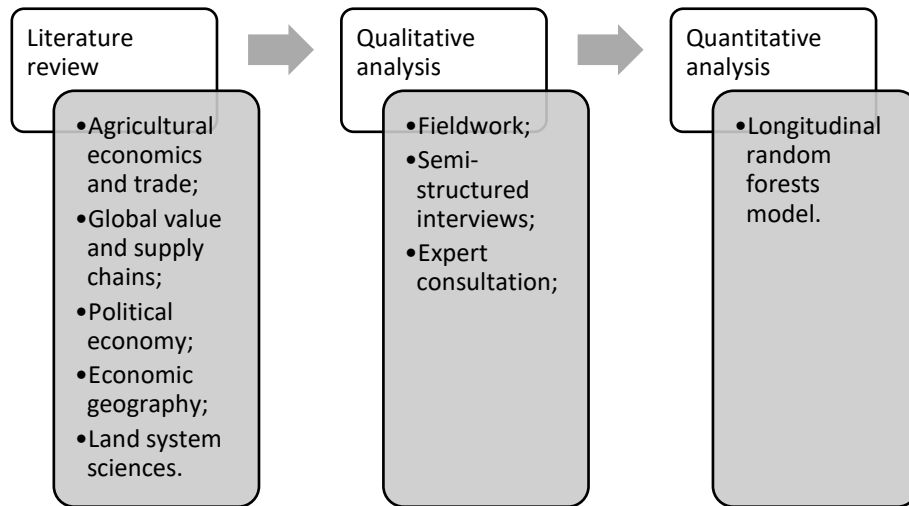
availability, costs of production, prices, market demand; (ii) institutional factors, i.e., land-tenure and environmental regulation; (iii) social and power dimensions, i.e., cohesion, power, and agency, group associations; and (iv) biophysical and technological aspects, i.e., stability of production and supply, and total factor productivity of crop production” (Section 3.2.1, Figure 3.1).

Figure 3.2 –Theoretical explanation of stickiness.



Our analytical framework consists of three steps (Figure 3.2). First, we reviewed the literature on agricultural economics and trade, global value and supply chains, political economy, and economic geography to identify factors potentially influencing stickiness (Section 3.2.1). Empirically, we then focused on Brazil's soy as a case study because soy is a relevant global commodity, and Brazil is its largest global exporter. Second, we then conducted a qualitative analysis, building on semi-structured field interviews and expert consultation, to explore the perceptions of Brazilian soy supply chain actors on how these factors shape stickiness (Section 3.2.2). Third, we gathered available quantitative data for those factors identified as relevant and used a historical (i.e., longitudinal) random forest regression model (HRF) to explore the capacity of these factors to predict stickiness levels in Brazil's soy export supply chain from 2007 to 2017 (Section 3.2.3). The qualitative analyzes focus mainly on the stickiness between farmers and local traders that act as intermediaries with traders exporting soy. The quantitative analyzes focus on the stickiness between logistic hubs, representing the aggregation of farmers and local traders in a municipality and traders that export soy.

Figure 3.3 - Research steps to build this stickiness analytical framework.



3.2. Data and Methods

3.2.1. Factors influencing geographic trade stickiness

Varied literature from agricultural economics, economic geography, sociology, and political economy, and on global commodity and value chains and production networks has examined factors influencing stickiness in trade relationships.

At the international trade level, the “Armington assumption” claims that agricultural products from one place are not fully substitutable with products from another place (Armington, 1969; Mcdaniel and Balistreri, 2003). This claim implies that geographic distance (Disdier and Head, 2008) and country-of-origin bias (Kawashima and Puspito Sari, 2010) play a significant role in trade stickiness (Villoria and Hertel, 2011). This agricultural economics literature proposes that stickiness is mostly a result of transport

infrastructure as a distance-shortening factor (Agcaoili-Sombilla and Rosegrant, 1994; Brun et al., 2005), influenced by country-of-origin bias (Kawashima and Puspito Sari, 2010), market demand and preferences (Heron et al., 2018), and biophysical conditions (Meyfroidt et al., 2013; Roux et al., 2020).

The economic geography literature has also assessed how other macroeconomic, institutional, governance, security, and socio-cultural factors influence stickiness at the international trade level. The gravity model argues that trade between countries persists due to the economies' sizes (Kepaptsoglou et al., 2010). The Melitz model suggests that trade persistence might be a function of a country's openness to trade (Demidova and Rodríguez-Clare, 2013; Melitz, 2002). Differences in institutional quality are thought to influence stickiness, *e.g.*, if the capacity to enforce contracts of two trading countries is similar, bilateral trade tends to be persistent (Hou et al., 2020; Levchenko, 2007; Nunn, 2007). Relatedly, democracies tend to trade more stably with other democracies than with non-democracies (Yu, 2010).

At local and subnational levels, economic geography and agricultural economics suggest that distance, affected by the availability of transport infrastructure, influences trade stickiness and other economic and geographic factors, typically found in agricultural frontiers. These factors include land-tenure and holding types (Browder et al., 2008), socioeconomic profile of settlers, rural development, land use, colonization patterns, the social organization of the economy, *i.e.*, cooperatives (Jepson, 2009), and institutional and

governance factors (Garrett et al., 2013a; Rasmussen and Lund, 2018). The local clustering of agricultural companies and the build-up of agglomeration economies (Garrett et al., 2013a; Iglioni, 2006; Richards, 2018) also influence stickiness, particularly agricultural trade.

Key local economic geography factors suggested to influence stickiness are: (i) availability and control of infrastructure necessary for commodity production and trading (Garrett et al., 2013b), *i.e.*, whether such infrastructure exists and whether it is public or private - if private, whether it is owned by local farmers, cooperatives, small grain warehouses or by global corporations (Jepson, 2006); (ii) availability and control of financial capital, *i.e.*, if capital is available, where it comes from: traders, private banks, subsidized public credit, or self-funded capitalized farmers (Oliveira and Hecht, 2016); (iii) land-tenure security, *i.e.*, how much is land disputed and secure in that area? (Browder et al., 2008; Jepson, 2009); (iv) level of technology employed on agricultural production (Vander Vennet et al., 2016), *i.e.*, the use of precision agriculture, resistant seeds, or technologies that improve the stability of production and increase average yields; (v) local demand and access, *i.e.*, the supply and demand interaction at the regional level and the accessibility of locations (Garrett et al., 2013c, 2013a; Garrett and Rausch, 2016; Nepstad et al., 2014); (vi) biophysical conditions (F. L. M. Freitas et al., 2018; GeoLab - USP, 2017), *i.e.*, how much available and edaphoclimatic suitable land there is; and (vii) productive arrangements (Garrett et al., 2013a, 2013b), *i.e.*, how farmers establish social and commercial relationships,

including whether they buy and sell, or lobby for change as individuals or in cooperatives and unions.

Social sciences also highlight cultural dimensions, which can all result in trade linkages to happen and persist, including (i) ethnic networks, such as Hindus in England and India (Coughlin and Wall, 2011); (ii) post-colonial linkages and common language, such as Portuguese descendants in Mozambique and Goa (Head et al., 2010; Rauch, 1999); (iii) social dependence, e.g., family ties and moral values that bind supply chain partners to long-term commitments (Narasimhan et al., 2009); and (iv) trust and the social structure of economies, resulting in local productive arrangements (Granovetter, 1985; Krippner and Alvarez, 2007; Polanyi, 1944; Uzzi, 1997).

Theories about global commodity chains (GCC), value chains (GVCs), and production networks (GPNs) offer explanations on the role of power and agency, showing how producers of raw materials, traders, processors, and retailers create, govern, and maintain trade networks (Coe et al., 2008; Gereffi, 2014, 1994). Lock-in effects appear also here, underpinned by investments and control of infrastructure - instead of social dependence as previously indicated (Fares et al., 2012). Further, input and output specificity achieved through product differentiation and technology binds suppliers to buyers who control, for example, the genetic knowledge of seeds or the combination of chemicals needed to blossom certain crops (Barrot and Sauvagnat, 2016; Van Assche and Schwartz, 2010). The company's relative position in the supply chain and whether it faces the consumer (Antràs

and Chor, 2013; Heron et al., 2018) and relative preferences such as niche market demands also influence stickiness (Akkermans, 2001).

From this review, we devise our general hypothesis outlined above and hypothesize that four overarching elements, i.e., (i) economic incentives, (ii) institutional factors, (iii) social and power dimensions, and (iv) biophysical and technological aspects (Figure 3.1), can explain the occurrence of stickiness in commodity supply chains. These factors have complex influences, possibly increasing or decreasing stickiness depending on context and local circumstances. We first explore the mechanisms through which these factors operate using qualitative analyzes of actors' perceptions from fieldwork. Then we evaluate the effect of some of these variables (Table 3.1) on stickiness statistically.

3.2.2. Investigating the perceptions of stickiness with fieldwork and qualitative analyzes

The first author conducted fieldwork between July and October 2019 in Brazil to inquire about the perceptions of stickiness causes, particularly concerning the agency and structural influencing factors of the geographic trade stickiness in the Brazilian soy supply chain. Our guiding questions were “what are the potential causes or influencing factors determining or affecting the trade stickiness in the Brazilian soy export supply chain?”, “how actors perceive the existence and effects of these factors?” and “what is their role in creating more or less stickiness?” (See the Interview Guide, Appendix 11).

We constructed a geographic stratification identifying various regions where soy arrived at different times and in different socioeconomic, technological, logistics, and biophysical contexts (Appendixes 3 and 4). Within these regions, we selected two or three municipalities ranging from low to high stickiness in their relationships with traders. Then, with a snowballing approach building on local connections between actors (Patton, 2002), the first author visited additional municipalities (Appendixes 2, 3, and 4).

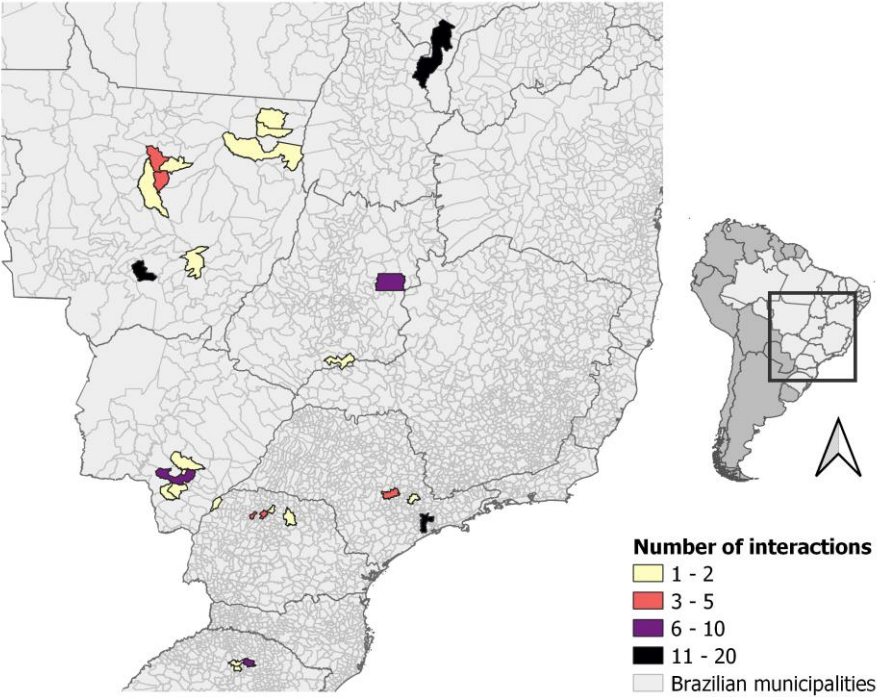
The first author visited each of these places for one or two weeks and conducted semi-structured interviews with various actors in the soy supply chain, consultations with key experts, and participant observation in agribusiness and land use meetings and conferences (Patton, 2002; Silverman, 2010, for details on interviewed actors see the Appendix 11).

These actors were identified through a combination of personal acquaintances, contacts with local rural unions and associations, the establishment of a network of gatekeepers and key informants, and snowball sampling (Silverman, 2010). In total, the first author conducted 83 interviews, 21 key-expert consultations and participated at six events in 28 municipalities (see Appendix 2, Figure 3.3). These semi-structured interviews, allowing flexibility for spontaneous topics and subjects (Patton, 2002; Silverman, 2010), ranged from 40 to 150 minutes. Seventy interviewees allowed audio recording, and the others allowed notetaking. The recorded interviews were transcribed using advanced transcription standards, *i.e.*, literal transcription with grammatical correction and clarification notes. We analyzed and

interpreted the audio and transcripts to identify and group key influencing factors of stickiness.

Acknowledging the central role of situated knowledge in qualitative and geographic research (Nielsen and D'haen, 2014; Simandan, 2019), the first author is Brazilian, originally from the countryside, and has family members and friends associated with the soy supply chain as, *e.g.*, farmers, input suppliers, employees of traders and food processors. These acquaintances contributed to this research as gatekeepers and key informants to connect the first author with interviewees in several regions. We used no field assistant, only a professional transcription service for the recorded audio, and the first author conducted all the qualitative analysis in Brazilian Portuguese as his first language.

Figure 3.3 - Map of Brazil showing the municipalities visited at fieldwork and number of interactions (in total: 83 semi-structured interviews, 21 consultations with key experts, and six participation at meetings, seminars, and conferences).



3.2.3. *Quantitative analyzes of the factors influencing stickiness*

We use the empirical measurement of the geographic trade stickiness by (Reis et al., 2020), defined as the stability of supply chain networks between regions and actors and measured by a combination of temporal network metrics such as topological overlap and temporal correlation coefficient (Büttner et al., 2016a; Nicosia et al., 2013), as our metric of stickiness for quantitative analyzes.

Reis et al. (2020) measured 468 municipalities' stickiness as logistics hubs (LHs) supplying soy to 1,709 export traders. LHs aggregate soy farmers' behavior within the logistic range of these logistics and commercial hubs for soy processing and export. They are regional market-places for defining farm-gate soy prices, storage, and freight fees, acting figuratively as soy "drains". Here, we visited 28 LHs for qualitative analysis (Section 3.2.2) and sampled 68 LHs for the quantitative analysis based on data availability to produce a complete dataset of stickiness and explanatory variables for 2007-2017. This sample represents 56% of total soy production and trade in Brazil (Trase, 2020a) over the analyzed period (2007-2017) (Table 3.1).

We combined a literature review (Section 3.2.1) with insights from our qualitative analysis (Section 3.2.2) to identify the main factors that could influence stickiness. We then collected available quantitative data that may represent or may function as a proxy of these identified factors (Table 3.1). We then trained a historical (or longitudinal) random forests regression model (HRF) to evaluate the relevance of each variable on predicting stickiness. Constrained by data availability,

we could not test quantitatively all aspects that we qualitatively found relevant for explaining the levels of stickiness. Our HRF allows us to see what are the most relevant variables, amongst those we could collect quantitatively, in terms of the predictive capacity of stickiness, and to observe their mean marginal influence (Sexton, 2018).

Random forests models suit very well the situation where the number of predictors is much larger than the number of observations (i.e., high-dimensional data) (Capitaine et al., 2020). They typically prove more powerful than logistic regressions (Couronné et al., 2018). Our predicted variable is the time average stickiness (TCi), as measured by (Reis et al., 2020) using a combination of topological overlap and temporal correlation coefficient metrics on the soy supplying relationships from logistics hubs (LHs) to traders (Büttner et al., 2016a; Nicosia et al., 2013). This dataset was updated from this previous study with new data from trase.earth version 2.4 (Trase, 2020a). This index varies between 0 and 1 and shows how stably each LH supplied soy to a set of traders in pairs of subsequent years, *i.e.*, the stickiness of 2008 compares the network configuration of 2007 with that of 2008, and so on. This calculation generates an index that, when closer to 0, indicates a high volatility in the configuration of traders sourcing from this LH, and when closer to 1 indicates that the traders sourcing from a given LH were about the same over this period.

Table 3.1 - Spatial-temporal predictors of stickiness in the historical random forests regression model (HRF). See full table and specifications at App. 5.

Variable	Data source	Relevant theoretical dimension (Figure 1)
Storage capacity (storcap_prod)	(IBGE, 2020)	(i) Economic incentives, mainly infrastructure and capital availability and; (iii) Social and power dimensions, <i>i.e.</i> , cohesion, power and agency, and group associations.
Crushing capacity (crushcap_prod)	(Trase, 2020a)	
% Soy exported (Perc_exp)	(Trase, 2020a)	(i) Economic incentives, mainly market demand and prices.
Instability of production or supply (SoyProd_dif)	(IBGE, 2020)	(iv) Biophysical and technological aspects, mainly stability of production and supply.
Average productivity (adj_pdt)	(IBGE, 2020)	(iv) Biophysical and technological aspects, mainly total factor productivity of crop production.
Yearly variation of farm-gate soy prices (SPintervar)	(Agrolink, 2019).	(i) Economic incentives, mainly market demand and prices, capital availability and costs of production; (iv) Biophysical and technological aspects, mainly stability of production and supply.
Intra-annual stability of farm-gate prices (SPintravar)	(Agrolink, 2019).	
Yearly variation in land prices (LPinteryear_var)	(IEG-FNP et al., 2018; Project MapBiomass, 2020)	(ii) Institutional factors, mainly land-tenure; (iii) Social and power dimensions, mainly cohesion, power and agency.

Weighted land prices (WeightedLP)	(IEG-FNP et al., 2018; Project MapBiomass, 2020)	(i) Economic incentives, mainly capital availability and costs of production; (ii) Institutional factors, mainly land-tenure;
Percentage of annual agricultural land of total available and suitable land (perc_AGarea)	(FUNAI, 2020; GeoLab - USP, 2017; ICMBio, 2020; INCRA, 2020; Project MapBiomass, 2020)	(ii) Institutional factors, <i>i.e.</i> , land-tenure and environmental regulation; (iv) Biophysical and technological aspects, <i>i.e.</i> , stability of production and supply, and total factor productivity of crop production.
Percentage of unprotected suitable native vegetation (perc_unpsuitNV)	(FUNAI, 2020; GeoLab - USP, 2017; ICMBio, 2020; INCRA, 2020; Project MapBiomass, 2020).	(ii) Institutional factors, <i>i.e.</i> , land-tenure and environmental regulation; (iv) Biophysical and technological aspects, <i>i.e.</i> , stability of production and supply, and total factor productivity of crop production.
Percentage of unprotected suitable lands occupied by non-annual agriculture and pasturelands (perc_unpsuitother_agr)	(FUNAI, 2020; GeoLab - USP, 2017; ICMBio, 2020; INCRA, 2020; Project MapBiomass, 2020).	(ii) Institutional factors, <i>i.e.</i> , land-tenure and environmental regulation; (iv) Biophysical and technological aspects, <i>i.e.</i> , stability of production and supply, and total factor productivity of crop production.
Count of the number of traders (Coun_Traders)	(Trase, 2020a)	(i) Economic incentives, mainly market demand and prices; (iii) Social and power dimensions, <i>i.e.</i> , cohesion, power and agency, and group associations.

**First year of colonization
(FirstYearColon) – number
of years of soy plantation** (IBGE, 2020)

- (ii) Institutional factors, mainly land-tenure;
- (iii) Social and power dimensions, *i.e.*, cohesion, power and agency, and group associations.

We ran a historical random forests regression model (HRF), where stickiness, the predicted variable, was in its original format ranging between 0 and 1 and varying over time between 2007 and 2017. HRF is a recently developed model that uses the state-of-the-art machine learning method known as random forests to be applied to temporal and high-dimension data (Couronné et al., 2018). This method is a general adaptation of random forests to analyze temporal data (Capitaine et al., 2020). For robustness checks, we compared the predictive capacity of this model to two differently specified models (Appendixes 6, 9, and 10). We focus here on the primary model using temporal, continuous data because it is more consistent with the temporal nature of the original data.

We estimate the variable importance (z-scores) by comparing the model prediction errors with and without the variable. The value represents the increase of the prediction error due to the removal of a specific variable; consequently, large z-scores are associated with the variables with the greatest contribution to the model prediction (Breiman, 2001). **NError! Bookmark not defined.**egative values are associated with variables negatively contributing to the model accuracy. The model performed better when the variable is marginalized. We also checked for multicollinearity between the variables using a correlation matrix and the variance inflation factor (VIF) and found no significant collinearity between any variable (Appendixes 7 and 8). All the analysis were carried out using the package *htree* (R Core Team, 2020; Sexton, 2018).

3.3. Results

We detail our qualitative and quantitative results across broad categories of economic incentives, institutional factors, social and power dimensions, and biophysical and technological aspects. We show the predictive capacity of the quantitative variables on stickiness (Table 3.2, positive Z-Values) and their marginal influence (mean in Table 3.2 and partial dependence plots in Figure 3.4).

3.3.1. *Economic incentives*

We found that actors perceive economic incentives affecting stickiness in several forms, including the availability and control of soy processing infrastructure, capital, farm-gate prices, and market demand.

Soy-processing infrastructure and its capacities, such as storage and crushing, the capacity of port terminals to export grains, and the capacity and frequency of ships serving these ports, are perceived as key factors influencing the level of stickiness between logistics hubs (LHs) and traders. Some regions with a crushing capacity that meets their total production tend to exhibit stickier relationships with the few traders owning these facilities because crushers tend to top the prices paid by raw bean exporters. They have too high fixed costs to risk running out of supply for their crushing facilities.

This logic appears in our quantitative analysis (Table 3.2), where “Crushing capacity” and “Storage Capacity” both appear with a Z_value (variable importance) of 3.7 and 1.9, indicating significant

predictors of stickiness. The mean marginal influence (Table 3.2) of 0.05 and 0.01, respectively, indicates that soy crushing and storage capacity surpluses tend to increase stickiness up to certain level where they stabilize (Figure 3.4), showing that excess of capacity does not increase stickiness further.

Actors perceive that *the level and control (who controls) of financial capital* can influence stickiness. On one side, financial capital enables the employment of machinery, production technology, precision agriculture, more use of inputs, fertilizers, rural insurance, which means more control over production stability leading to increased stickiness, but also more freedom to negotiate harvests, including the control of infrastructure (*e.g.*, silos), thus lowering stickiness. On the other side, the level of indebtedness of farmers may also determine their stickiness because debt locks farmers with banks and traders, reducing their negotiation levers. Critical here is to whom farmers are indebted. If they owe to banks (private or public), they retain much freedom over their production and negotiation processes. However, if they owe to traders or input suppliers, they lose control over how soy is produced and negotiated. Input suppliers and traders offer credit to farmers in exchange for future harvests and closely accompany all stages of production, harvesting, and negotiation to ensure they are repaid, thus increasing the stickiness of these relationships.

In terms of *market demand and its volatility*, the perception is that when demand for soy increases as reflected in prices, farmers are encouraged to open new cropland areas, thus promoting soy

expansion and attracting new entrants to both new and consolidated cropland regions. If demand decreases, marginal lands become unprofitable and may even experience the abandonment of soy fields. Demand and price volatility thus induce reconfigurations in business relations and thus lower stickiness.

The primary proxy or mediator of market demand is farm-gate prices because they reflect market demand and accessibility, transportation costs, and availability of trucks, storage, crushing, and processing facilities in the region. Quantitatively, “Intra-annual variation of farm-gate prices” showed a Z-value of 0.7 and a mean marginal influence of -0.001, implying that it predicts stickiness. However, the influence is negative, *i.e.*, the greater the variation, the lower the stickiness. Nevertheless, looking at Figure 3.4, the pattern is not clear. The “Yearly variation of farm-gate soy prices” do not appear with relevant (positive) predictive capacity, despite the evidence from the qualitative analysis. Although the demand is the primary determinant of price, farm-gate price variation also reflects a series of other factors that determine the feasibility of growing soy or not in each region.

The percentage of exported soy production is perceived as relevant as most exports are traded as raw beans, a more fungible commodity, while processed soy as cake, oil, or meal is somewhat less substitutable and thus constitutes less volatile markets. Places that supply mainly for exports are thus perceived to be less sticky than those supplying domestic consumption. Nevertheless, quantitatively our HRF model shows a different result. “Percentage of soy exported”

from total soy traded in each logistics hub (LH) shows high importance in predicting stickiness ($Z\_value = 6.9$), and a mean marginal influence of 0.14 (Table 3.2, Figure 3.4), indicating that the more a LH exports instead of directing the product to domestic markets, the stickier this LH is to its traders up to the level of about 20 % (Figure 3.4). Municipalities that export 20% or more of their product exhibit a consistently high stickiness in their supplying relationships with traders (Figure 3.4).

Market preferences reflected in demand for specific products, *e.g.*, certified (*e.g.*, RTRS soy) and non-genetically modified soy (non-GM), are perceived as a stickiness influencing factor by interviewed actors, as also reported by (Garrett et al., 2013c; Meijer, 2014). The production and supply of certified and non-GM crops to meet this specific market demand entails, in some cases, grains segregation with individualized infrastructure for processing and transport, which therefore requires additional prices paid as premiums. This demand stems from niche markets that are sticky from the onset. The certified and non-GM soy demand long-term investments in production and facilities to segregate grains from conventional production and favor sourcing stability because it facilitates their monitoring and trust building.

3.3.2. *Institutional enablers and constraints*

Actors perceive *land-tenure insecurity*, currently associated with agricultural frontiers, as affecting the stability of commercial relationships. Land conflicts and tenure insecurity tend to reduce

stickiness because they open space for opportunistic commercial relationships and reduce incentives for long-term investments.

Land-renting also tends to affect stickiness because farmers who rent land are likely to behave commercially differently from landowners. Land-renters tend to engage in more short-term and opportunistic commercial relationships. In addition, *environmental and land use regulation*, such as areas embargoed by the Brazilian Environmental Enforcement Agency (IBAMA), and the protection of areas as conservation parks or indigenous territories, are perceived as affecting stickiness. This influence occurs because embargoed areas cannot produce and sell. Therefore commercial links are disrupted when this happens. Protected areas are barriers for expansion; therefore, in municipalities where the availability of unprotected lands with edaphoclimatic and topographic suitability is depleted, the perception is that companies and farmers tend to consolidate and stabilize the commercial relationships with fewer new entrants in these local markets due to the impossibility of horizontal expansion (area expansion).

In the statistical analysis, land prices and their variation over the years (Yearly variation in land prices), which may reflect land-tenure insecurity or the stability of the institutional setting, we find no predictive performance (Table 3.2). Nonetheless, the actual land prices have a small predictive capacity (Weighted land prices Z_value = 0.32, Table 3.2). The mean marginal influence (-0.009, Table 3.3) shows that the higher the land prices, the lower the stickiness of the LH to traders.

3.3.3. *Social and power dimensions*

Productive arrangements and cohesion of group associations, power, trust, and agency determined by the control of infrastructure, technology, and capital are perceived as crucial factors influencing stickiness.

Power and productive arrangements are perceived to determine stickiness in different ways - first, *association with cooperatives*. Cooperatives usually function as mediators between small and medium farmers and large traders, thus affecting the power relations between farmers and traders. Cooperatives are institutions, but we analyze them here through their primary purpose, altering power dynamics between producers and traders. Cooperated farmers tend to be highly sticky to their cooperatives, which have non-sticky relationships with export traders. Indeed, cooperatives can sell their stocks to multiple traders depending on the circumstances, but they may also venture directly into exports.

The predominance of large farms (>2500ha) is also an essential aspect of power. Large farms are pointed out to trade more directly with exporters, also because they are more capitalized, have their silos, and access other credit lines not necessarily from traders. Therefore, they are more independent in the supply chain and thus less sticky with traders. Cooperatives pooling many small farmers behave similarly to large farms, increasing the benefits for cooperated farmers.

Trust between soy supply chain actors, such as input suppliers, farmers, traders, processors, and the social *embeddedness* of economies (Granovetter, 1985; Krippner, 2001), defined as how behavior, institutions and, in this case, commercial relationships within commodity supply chains, are shaped by social and personal relations, are also key factors perceived to influence stickiness. Farmer-trader relations are sticky due to trust and social relations embedded in economic decisions. Likewise, we also found non-sticky relations due to distrust and precaution against a history of frauds, business failures, and bankruptcies. Long-term investments and business relations create entire communities and their social fabric, influencing future business relations (Boekema and Rutten, 2004; Polanyi, 1944).

Ownership or control of soy infrastructure: whether soy farmers own in-farm silos or not. The ownership or control of port and railway facilities are also perceived as crucial determinants of stickiness. Farmers who own silos can keep the grains after the harvest and wait, typically, up to six months to negotiate better deals and conditions, thus non-sticky commercial relations. They will break their harvests into several quotes and deal with as many traders as possible to increase their marginal gains from price and exchange rate volatility and mitigate business risks. In contrast, farmers without silos tend to be stickier to one or a few traders because they already need to deliver the grains somewhere when they start harvesting. Although they can deliver at one warehouse and sell the grains later to another company, this implies paying storage fees that they try to avoid. Additionally,

these farmers without silos tend to make barter arrangements, *i.e.*, exchange early inputs and credit for later grains, another factor that locks them in with these traders.

We could not find and gather sufficient data to test any of these findings related to social and power dimensions through our HRF.

3.3.4. *Biophysical and technological aspects*

Actors perceive that biophysical conditions, and the control of biophysical factors through technology, determine the stability of production and supply. As a result, traders pursue *stability of supply* as a market advantage. Therefore, places where the *biophysical conditions* - such as climate, soil, and topography - and the *level of technology* employed lead to *stability of production and supply* are perceived as offering the conditions for stickier supply chain relationships. Actors perceive and believe that soy companies prefer to settle and develop stickier relationships in regions of more climate predictability because they need the stability of supply.

The use of technological tools such as efficient machinery, irrigation systems, and precision agriculture ensures smoothness in production and higher resistance to pests and climatic shocks, leading to production stability. Stability of supply is a crucial business principle to ensure the efficiency, predictability, and profitability of business operations (Vroegindewey and Hodbod, 2018). Beyond, *technology* also influences stickiness by creating lock-in relationships; for example, companies providing specific technological seeds require that crops are exclusively negotiated with them. Quantitatively, we

found no stickiness predictive capacity from our variable “Instability of production or supply”. We used “average productivity” in tons/ha as a proxy of the use of technology. We found it as a predictor of stickiness ($Z\_value = 0.58$, Table 3.2), influencing it negatively (mean marginal influence = -0.001 , Table 3.2), *i.e.*, the higher the average productivity, the lower the stickiness after peaking at around 0.75 stickiness and 3 tons/ha in average yield (Figure 3.4). Essentially, stickiness increases with increases in productivity up to 3 tons/ha. Beyond that threshold, it decreases (Figure 3.4).

Biophysical conditions also play other roles: actors perceive active agricultural frontiers - or regions with more lands with edaphoclimatic suitability for cropland expansion and where rapid agricultural growth is taking place (Graesser et al., 2015) - as experiencing lower stickiness with continuously new entrants as expansion unfolds.

Quantitatively and using the land use and cover areas as proxies of biophysical conditions and actual use of lands in each municipality, we found that the “Percentage of annual agricultural land of total available and suitable land” and the “Percentage of unprotected suitable lands occupied by non-annual agriculture and pasturelands” both have predictive capacity on stickiness (Z -values = 0.58 and 0.11, respectively, Table 3.2). While LHs with more lands already occupied by annual agriculture (*e.g.*, soy, maize, or cotton) tend to exhibit higher stickiness (mean marginal influence of “perc_AGarea” = 0.006, Table 3.2), but clearly up to a threshold of 80%, when stickiness decreases sharply potentially as a result of consolidation and agglomeration economies (Figure 3.4), LHs with more lands occupied by non-annual

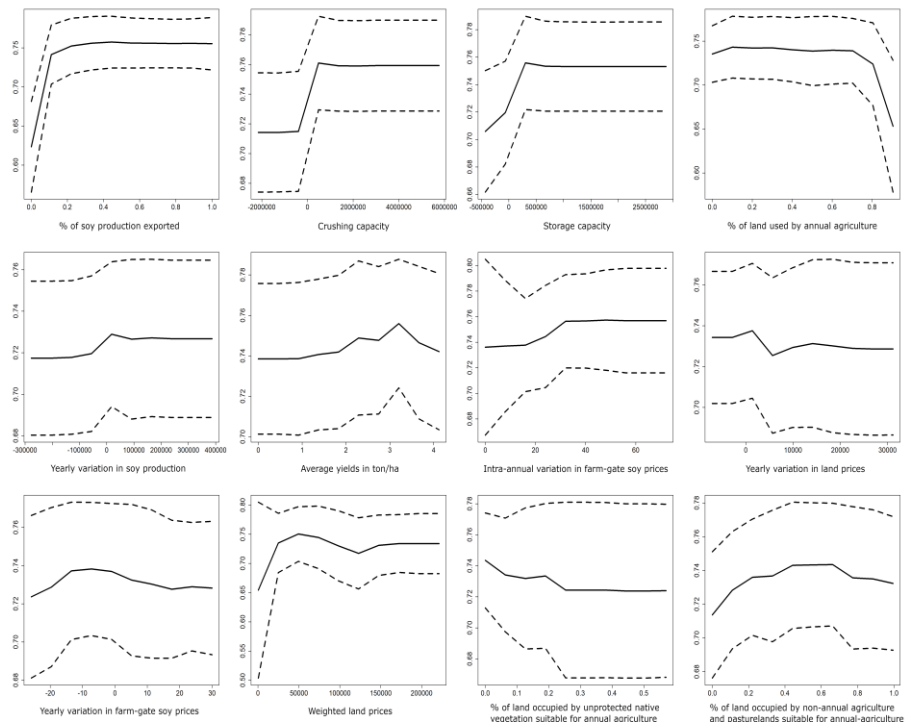
agriculture, including pasturelands, as a percentage from the total unprotected and suitable lands, tend to exhibit lower stickiness (mean marginal influence of “perc_unpsuitother_agr” = -0.009, Table 3.2), but only after the threshold of about 60%, for up to 60% stickiness grows along with % of lands occupied by non-annual agriculture (Figure 3.4).

Table 3.2 – Results of the historical random forests continuous model (HRF).

Predictor	Marginalized error	Model error	Mean marginal influence	Z-value
% Soy exported (Perc_exp)	0.0918	0.0806	0.139	6.939
Crushing capacity (crushcap_prod)	0.0847	0.0806	0.051	3.707
Storage capacity (storcap_prod)	0.0814	0.0806	0.01	1.889
Intra-annual variation of farm-gate soy prices (SPintravar)	0.0805	0.0806	-0.001	0.718
Percentage of annual agricultural land of total available and suitable land (perc_AGarea)	0.0811	0.0806	0.006	0.584
Average productivity (adj_pdt)	0.0805	0.0806	-0.001	0.581
Weighted land prices (WeightedLP)	0.0799	0.0806	-0.009	0.321
Percentage of unprotected suitable lands occupied by non-annual agriculture and pasturelands (perc_unpsuitother_agr)	0.0799	0.0806	-0.009	0.113

Instability of production or supply (SoyProd_dif)	0.0807	0.0806	0.001	-
				0.241
Yearly variation of land prices (LPinteryear_var)	0.0804	0.0806	-0.002	-
				0.667
Yearly variation of farm-gate soy prices (SPintervar)	0.0802	0.0806	-0.005	-
				1.042
Count of the number of traders (Coun_Traders)	0.0806	0.0806	0	-
				1.298
First year of colonization (FirstYearColon) – number of years of soy plantation	0.0806	0.0806	0	-
				1.298
Percentage of unprotected suitable native vegetation (perc_unpsuitNV)	0.0799	0.0806	-0.008	-
				1.452

Figure 3.4 – Partial dependence plots, showing the mean marginal influence of the stickiness predictors. Each plot represents the isolated effect of each variable on predicting stickiness.

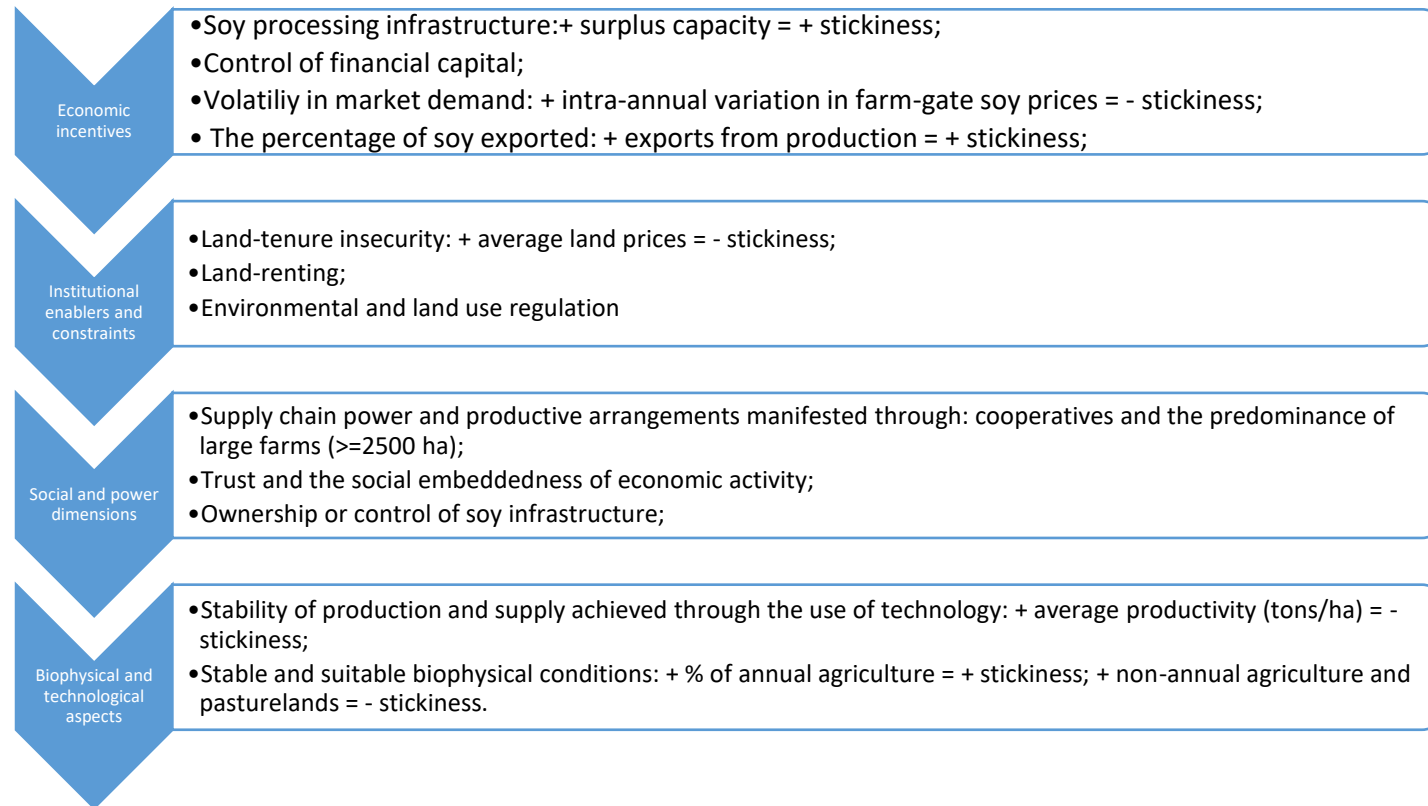


The sustainability of global agricultural trade: understanding stickiness in Brazil's soy supply chain

Table 3.3 – Tabular summary of qualitative and quantitative findings.

Overarching elements	Qualitative findings: factors perceived to affect stickiness at local level (LH)	Quantitative findings: factors predicting, and tending to increase/ decrease stickiness at local level (LH)
Economic incentives	• Soy processing infrastructure; • Control of financial capital; • Volatility in market demand; • The percentage of soy exported; • Market preferences (e.g., certified, non-GM).	• Surplus of soy processing infrastructure tends to increase stickiness; • More intra-annual variation in farm-gate soy prices tends to decrease stickiness. • More export-oriented regions tend to have higher stickiness;
Institutional enablers and constraints	• Land-tenure insecurity; • Land-renting; • Environmental and land use regulation.	• Higher average land prices tend to lower stickiness.
Social and power dimensions	• Supply chain power and productive arrangements manifested through: (i) association with cooperatives, (ii) predominance of large farms (≥ 2500 ha); • Trust and the social embeddedness of economic activity; • Ownership or control of soy infrastructure.	
Biophysical and technological aspects	• Stability of production and supply achieved through: ○ Use of technology: GM seeds, fertilisers, pesticides, irrigation systems; ○ Stable and suitable biophysical conditions: soil, climate, topography.	• LHs with higher average productivity tend to exhibit lower stickiness; • LHs with higher percentage of annual agricultural land of total available and suitable tend to exhibit higher stickiness to traders; • LHs with higher percentage of unprotected suitable lands occupied by non-annual agriculture and pasturelands tend to exhibit lower stickiness.

Figure 3.5 - Graphical summary of qualitative and quantitative findings.



3.4. Discussion

3.4.1. Main factors influencing stickiness

Our results show that multiple factors and processes underpin and may explain the stickiness of the Brazilian soy supply chain. Some of these predictors of stickiness are also crucial characteristics of economies of scale and agglomeration economies in agriculture (Garrett et al., 2013a; Iglioni, 2006; Porter, 1996; Richards, 2018). Other factors are also associated with typical productive and social network characteristics found in agricultural frontiers (Garrett et al., 2013b; Jepson, 2009, 2006; Sousa and Busch, 1998).

Factors and processes related to agglomeration economies in agriculture:

Several factors that have key influence on stickiness have also been shown to be important initiators of agglomeration economies in agriculture, such as soy processing and transport infrastructure (Garrett et al., 2013a), amounts and control of financial capital, integration with international markets via large shares of production destined to exports (Garrett et al., 2013c; Garrett and Rausch, 2016; Richards et al., 2012), and the use of technology and attractive biophysical conditions ensuring high yields. These factors strongly influence land use and socioeconomic trajectories (Garrett et al., 2013a; Richards, 2018). We here show that the stability or volatility of supply chain relationships may also be an aspect of agglomeration economies. Some of the factors that explain the emergence of agglomeration economies in agricultural regions are also predictors of

stickiness, showing that these processes are related. Nevertheless, stickiness does not equate to agglomeration economies nor the other way around but is a distinct characteristic that may be present or not in agglomeration economies.

Certain regions with a vast diversity of traders, input suppliers, and credit providers, thus characterizing agglomeration economies, may exhibit non-sticky trade relationship patterns if farmers are capitalized, own in-farm silos, and can easily choose and change suppliers and buyers. In contrast, other regions with a similar diversity of supply chain actors, but where small farmers, non-capitalized and lacking in-farm silos predominate, they may be subject to infrastructural and financial lock-ins created by traders who provide inputs, credit, and purchases almost all production, thus resulting in a sticky supply chain pattern. Therefore, even though the factors that describe both supply chain stickiness and agricultural agglomeration economies are similar and associated, their interaction results in different stickiness levels, land use patterns, and local economies.

Factors and processes related to agricultural frontiers:

Factors such as short-term volatility in market demand, reflected in farm-gate soy prices, land-tenure insecurity, weak environmental and land use enforcement, supply chain power and productive arrangements shown by the absence of cooperatives, unions, or even the inequality in land distribution as shown by the predominance of large farms in the region (≥ 2500 ha), and finally the presence of suitable lands for annual agriculture expansion, are all characteristics typically associated with agricultural frontiers (Garrett et al., 2013b; Ioris, 2020; Jepson, 2009, 2006; Richards et al., 2015, 2014; VanWey et al., 2013).

Nonetheless, not all stickiness predictors are necessarily present in agricultural frontiers. While some agricultural frontiers characterized by rapidly expanding agricultural fields and the large availability of unprotected and suitable lands for agriculture (Garrett et al., 2013b; Jepson, 2009) may exhibit non-sticky trade relationship patterns in a case where small and spot market traders operate in this region, other frontiers exhibiting the same factors and processes, but within a logistic corridor controlled by a monopolistic trader, may exhibit a sticky trade relationships pattern. We also encountered a “deep relational interaction between old and new areas” in the state of Mato Grosso, characterized as center and frontier and, therefore, with this hybrid perspective that allows stickiness to be only partially associated with frontiers or post-frontiers (Ioris, 2020, 2018). All in all, stickiness is a distinct dimension or aspect to be considered in studies of

agricultural frontiers, stabilized regions, and agglomeration economies.

3.4.2. Dynamic processes that influence stickiness beyond economic conditions: Lock-ins, trust, and power

Our statistical and qualitative analyzes identify a series of economic incentives, institutional enablers and constraints, social and power factors, and biophysical and technological aspects that underpin stickiness.

Many trading relations persist over time simply because the economic conditions are stable from one year to another – this is what is captured in the “persistence” dimension of stickiness in Reis et al. (2020) – and from that, actors make the same decisions over time. However, our results suggest that even when some economic conditions might change, trade patterns do not necessarily adjust readily because of many factors, particularly a set of dynamics that we can broadly group in three dimensions, i.e., lock-ins, trust, and power.

First, lock-in effects (Wilson, 2014), which can be infrastructural, financial, technological, institutional, or related to consumer preferences, stem from supply chain actors' agency and are thus partly related to economic capital and infrastructure but also to social and power dynamics (Bicudo Da Silva et al., 2020; Fares et al., 2012; Heron et al., 2018; Narasimhan et al., 2009; Payo et al., 2016; Schmitz et al., 2016; Vanloqueren and Baret, 2009). Such lock-ins may exert a dynamic influence on stickiness, depending on which part of the supply chain relationships they concern.

Second, trust and the social embeddedness in economic and trade relations (Granovetter, 1985; Polanyi, 1944) are dynamic processes that stem from both social and institutional factors. Studies on embeddedness in economic activities (Bair, 2008; Craviotti, 2016; Henderson et al., 2002; Uzzi, 1997), together with trust (Ghosh and Fedorowicz, 2008; Skandrani et al., 2011), can lead to the formation of social networks that may manifest through supply chain stickiness. This social structure of agrarian economies that manifest on stickiness can also explain part of the peasantry frontier dynamics. Nonetheless, we must acknowledge that the social relations embedded in peasantry and settlers' relations are different from those found in the capitalized and mechanized soy supply chain, acting more as a land concurrent use disputing land from an economically unbalanced stand-point (Caldas et al., 2007).

Finally, power and agency dynamics that result from various companies' business models, geographic sourcing strategies, asymmetries in information and knowledge (Gereffi, 2014; Gereffi et al., 2005; Ponte, 2020; Rueda et al., 2017) may dynamically influence stickiness as well in different parts of the supply chain.

We propose further research to investigate the role of lock-ins, trust, and power as dynamic processes influencing stickiness patterns.

3.4.3. Remaining research gaps

Our analysis points to some knowledge gaps. First, our statistical model shows that, amongst the variables with significant predictive capacity ($Z\text{-value} > 0$), the mean marginal influence of some variables

on stickiness contradicts our qualitative findings. For example, the HRF shows that the higher the “average productivity” (yields) in a municipality, the less sticky it tends to be with traders. The perceptions we collected would indicate otherwise since higher average yields may mean more technology, more agricultural consolidation, and more production stability, thus potentially leading to more stickiness (Garrett et al., 2013a). Yet, municipalities with high consolidation and very stable supply may also attract volatile traders that operate on the margins of spot markets.

These observations suggest that some variables may have different effects on stickiness depending on other contextual factors. Therefore, a further investigation could decompose the sample into distinct contexts, such as frontiers and stabilized regions, and see how the model would behave. Here, as an exploratory analysis, we focused on identifying stickiness predictors but did not investigate in depth the shape of their influence. Other research designs could focus on describing and explaining the shape of these influences or predictive capacity more in-depth.

Second, other study designs can build on our exploratory analysis to improve our understanding of the causal links between these factors and processes and stickiness, drawing potentially from historical land use, agricultural census, and market prices data. Approaches based on assessing mental models (Guerrero et al., 2021), the social embeddedness of supply chain relationships (Bair, 2008), and how cultural norms and values influence, predict, and underpin these supply chain relationship patterns can also improve our

knowledge of the processes through which supply chain relationship gain or lose stability. Finally, stickiness is both an outcome as well as a driving force in itself, so that further studies could explore the implications of stickiness for land use and rural development trajectories, and how stickiness can play a role in governance interventions for land use sustainability, such as zero-deforestation commitments (ZDCs) and other corporate sustainability initiatives (Thorlakson et al., 2018).

Third, in this study, we assessed the persistence dimension of stickiness, a raw quantification of changes in supply chain relationship patterns. It does not explicitly consider how economic, climatic, political, or other shocks influence supply chains relationships. Further works might develop other methods to identify shocks impacting trade relationships and investigate more in-depth the factors that influence resistance to and recovery from shocks, as Reis et al. (2020) defined.

3.4.4. Broader implications

On a higher level, we identify two primary implications from our analysis of the factors influencing supply chain stickiness. First, the *agency of supply chain actors* in establishing more stable or volatile commercial relationships with sourcing regions is vital for shaping the sustainability trajectories of these regions. The incentives provided, both economic and institutional, the power dimensions, including infrastructural and capital control, availability and constraints, and the technological capacity to manage biophysical conditions, are crucial to shaping supply chain relationships and, therefore, the fates of

landscapes. The level of stickiness in a company's geographic sourcing strategy can constitute an additional assessment criterion to gauge the company's capacity to implement and deliver sustainability commitments, adding to the work by (Garrett et al., 2019; Grabs and Carodenuto, 2021; Lambin et al., 2018; Thorlakson et al., 2018). Furthermore, knowing the factors that influence the stability or volatility of sourcing strategies, patterns and behaviors can help to understand and possibly foresee the potential restructuring of material flows, supply chains, and productive landscapes under shocks, adding to the work by (Gephart and Pace, 2015; Heron et al., 2018; Pendrill et al., 2019b; Roux et al., 2020; Waroux et al., 2017). This potential foreseeing of restructuring flows adds knowledge to theories of land-use spillovers and transitions (Meyfroidt et al., 2018).

Second, knowing the predictors of supply chain stickiness is crucial for *sustainability governance*, both public and private. The stickier the relation, the more supply chain companies, and producers, might tend to rely on the success of implementing sustainability initiatives, such as zero-deforestation commitments (ZDCs), in their sourcing regions to remain in business without future market or financial restrictions. The less sticky the relation, the easier it might be for supply chain companies to implement their ZDC by moving away from existing areas and producers and buying from elsewhere (where the deforestation cut-off dates are met) (Carodenuto and Buluran, 2021; Grabs and Carodenuto, 2021; E. K. H. J. zu Ermgassen et al., 2020). An unintended consequence might be opening more room for supply chain companies without such commitments to increase their businesses in

these areas. From an ecosystem protection standpoint, the latter is the worst the case scenario. By knowing the agency and structural factors influencing stickiness, we can think of strategies and policies to increase stickiness and influence companies' sustainability strategies. For example, governmental subsidies could be directed to construct soy processing facilities to settle companies in specific regions and divert them from others where more interest lies in conservation.

The sustainability governance implications of stickiness play out differently for distinct actors. From a trader or a downstream company perspective, the stickier the relationship, the higher the dependence on a given area or supplier. This dependence can help to prioritize efforts to ensure best practices are adopted to meet the ZDC. Investors concerned with deforestation might find more liable those companies with stickier relationships and operating in expansion areas and having no or poorly implemented ZDC since these companies will have less flexibility to move away from the deforestation issue.

From a land use planning and public policy perspective, knowing the predictors of stickiness can orient infrastructural planning, concessions, tax breaks, and subsidies to incentivize companies to settle in some frontier regions under certain conditions while allowing spot market operations in consolidated regions mostly taken by annual agriculture, for example.

From a campaigning NGO standpoint, understanding stickier relationships between companies without sustainability commitment or destination countries lagging in the zero-deforestation agenda and active deforestation regions can help target campaigns to where they

are needed to prevent further soy, cattle, or other commodity expansion over native vegetation. To protect areas with less sticky relationships, interventions need to target spot-market traders to ensure they remain in consolidated regions. A stickiness measurement of traders, mills, or slaughterhouses may identify which companies to prioritize in the design process of such initiatives and increase its impact and effectiveness more cost-efficiently.

Supply chain transparency is an important component of environmental governance (Gardner et al., 2019; Godar et al., 2016); however, transparency assessments often focus on sourcing patterns in commodity supply chains but largely miss the consideration of the (in)stability over time of these relationships between actors and places. Similar stickiness investigations could be expanded to other commodity supply chains, not only agricultural and geographies. The different features of supply chains such as infrastructural needs, power relations, agency, and biophysical and technological conditions underpinning each supply chain are likely to create distinct stickiness patterns. For instance, the iron ore supply chain tends to be much stickier due to infrastructural, capital, and technological lock-ins that, once deployed, bind regions and companies to long-term relationships (Narasimhan et al., 2009). Therefore, understanding the *a priori* stickiness relations is crucial to design sustainability strategies before these infrastructures are constructed.

3.5. Conclusions

Here we aimed at learning more about the potential causes and influencing factors of the stability in the supply chain relationships between regions and actors. We investigated supply chain actors' and experts' perceptions and the explanatory capacity of some quantifiable structural conditions determining trade stickiness. We found that surpluses in soy processing infrastructure, volatility in market demand, integration to international markets via large shares of exports from production, average land prices and yields, together with the availability of unprotected and suitable lands for agricultural expansion, are all predictors of stickiness pertaining to those theoretical categories. The influence of these predictors on stickiness, though measured, is heterogeneous and context-dependent; therefore, more econometric analyzes need to be conducted to respond to whether they increase or decrease stickiness and under what conditions. Further research might investigate the role of lock-ins, trust, and power as dynamic processes influencing supply chain relationships. Understanding what leads to supply chain stickiness is crucial for designing and implementing sustainability interventions.

After finding underlying factors and processes that influence, determine and predict the stickiness between farmers and municipalities of production and trade with export traders, and that they can be theoretically grouped as economic incentives, institutional enablers and constraints, social and power dimensions, biophysical and technological aspects, it is now time to inquiry how stickiness sourcing patterns from the traders' side may affect the adoption and implementation of sustainability initiatives. Chapter IV investigates how much the traders' sourcing patterns and behavior in terms of stickiness affects their likelihood to sign zero-deforestation commitments and to be effective in reducing overall deforestation and natural habitat conversion in Brazil.

IV. The influence of company sourcing patterns on the adoption and effectiveness of zero-deforestation commitments in Brazil's soy supply chain

Abstract: Many companies sourcing agricultural commodities with high deforestation risk have committed to zero deforestation, meaning they intend to eliminate deforestation from their supply chains. While previous research has attempted to assess progress against such initiatives, little is known about how the characteristics of sourcing patterns may influence the adoption and potential effectiveness of zero-deforestation commitments. Supply chain stickiness – here defined as the geographic persistence in trade relationships between traders and sourcing regions over time – may reflect infrastructure and other lock-in effects, market power dynamics, specific product requirements and the level of trust between the parties involved. Here, we use a metric of supply chain stickiness, calculated from temporal network analyses on the Brazilian soy export supply chain, as a proxy for these underlying dynamics to explore their effect on the adoption and effectiveness of zero deforestation commitments (ZDCs). Using data for 2004 – 2017, we find that although stickier traders are more likely to adopt ZDCs, they also appear to have less effective ZDCs than other traders (as indicated by the level of soy and territorial deforestation in their sourcing regions). This finding suggests that additional strategies are needed to increase the effectiveness of ZDCs and eliminate deforestation.

Keywords: Stickiness, commodity supply chains, zero-deforestation commitments, Amazon soy moratorium, agricultural trade, Brazilian soy production, tropical deforestation.

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Author Contributions

Conceptualization, T.N.P.R., F.L., P.M.; Methodology, T.N.P.R., F.L.; Software, F.L., T.N.P.R.; Validation, P.M., P.H.V., S.S., H.K.; Investigation, T.N.P.R., F.L.; Resources, T.N.P.R., F.L.; Data Curation, T.N.P.R., F.L.; Writing, T.N.P.R., F.L., P.M., P.H.V., S.S.; Supervision, P.M., P.H.V., S.S., H.K.; Funding Acquisition, P.M., P.H.V., S.S., H.K.

4.1. Introduction

The international trade and consumption of agricultural commodities are estimated to drive around 26% of forest loss in the tropics and sub-tropics (Pendrill et al., 2019a). As a result, multiple agricultural supply chain actors have committed to eliminate or reduce deforestation from their supply chains, either through multi-stakeholder coalitions, such as the Amazon Soy Moratorium (ASM) or through unilateral zero-deforestation commitments (ZDCs) (Garrett et al., 2019; Lambin et al., 2018).

Recent advances in remote sensing (Curtis et al., 2018) and supply chain mapping (Godar *et al* 2015, Trase 2020a) have facilitated empirical research on such initiatives' effectiveness. For example, zu Ermgassen *et al* (2020) used spatial data on individual supply chains to monitor progress against ZDCs in the Brazilian soy export sector. While these studies inform on the overall effectiveness of ZDCs, they provide scant evidence on how different sourcing strategies and patterns influence this effectiveness. Sourcing strategies are the main lever through which traders of deforestation-risk commodities influence activities further upstream in the supply chain (Lyons-White and Knight, 2018). Therefore, a better understanding of how different sourcing strategies, as reflected in spatiotemporal sourcing patterns, could influence actions on the ground is needed to enhance the effectiveness of ZDCs.

A critical characteristic of supply chain sourcing patterns is the degree of geographic persistence in bilateral trade flows (Villoria and Hertel, 2011). Such persistence may have a considerable influence on

traders' capacity to source deforestation-risk commodities compliant with their ZDCs (Garrett et al., 2019; Reis et al., 2020).

Patterns of trade persistence may result from traders' strategies but also other factors beyond their direct control. For example, at the country-to-country trade level, geographic distance between trading countries affects the persistence of bilateral trade flows as more distant countries tend to have less persistent bilateral flows (Disdier and Head, 2008). Additionally, larger economies tend to have more persistent linkages (Kepaptsoglou et al., 2010), as do those with greater openness or exposure to trade (Melitz, 2002), ethnic and post-colonial linkages and those with similar governance regimes (Yu 2010).

The above referenced studies have provided insights into why trade relationships persist at the country-to-country level. However, the factors determining the persistence of subnational trade relationships, *i.e.*, between companies, producers and subnational jurisdictions, are less well known. Persistent subnational trade relationships are driven by both economic (e.g., transportation costs) and non-economic factors (e.g., levels of trust) that are hard to quantify and disentangle from each other. Key gaps remain in our understanding of how such unobserved drivers of persistent subnational trade relationships may influence sustainability outcomes.

We apprehend this persistence in trade patterns through the notion of "stickiness", which is defined as *"the maintenance and recovery, over time and through shocks, of supply chains' geographic network configurations, i.e., the network of trade linkages and flows between specific places of production and consumption, and specific*

actors including producers, traders, retailers, and consumers” (Reis et al., 2020).

At the subnational trade level, at least three non-economic factors may influence supply chain relationships' stickiness at the supply-side (between production places and traders), namely lock-in effects, trust and the social structure of supply chains, and power dynamics. First, lock-in effects encompass a range of factors, some stemming from the actors' past decisions that constrain their supply chain relationships. Lock-in effects can be (i) infrastructural (Payo et al., 2016; Vanloqueren and Baret, 2009), when physical facilities bind together different supply chain actors; (ii) financial, *e.g.*, through the existence of credit mechanisms; (iii) technological, *e.g.*, when one actor dominates and patents key technologies upon which other actors are dependent (Fares et al., 2012), (iv) institutional when governance systems and norms exist (*e.g.* the ASM); or (v) related to consumer preferences for a brand, product or ingredient transparency, origin or quality (Akkermans, 2001; Narasimhan et al., 2009). Lock-in effects may be a result or a materialization of power dynamics, leading to power imbalances in supply chains. However, here we consider lock-ins separately from power dynamics as a specific, concrete manifestation of power which can be observed and analyzed separately from other manifestations of power, such as entry barriers or market dumping, which are further detailed below.

Second, trust and the social structure of supply chains – *i.e.*, the networks of social relations embedded in economies that determine the market structure – may influence the stickiness of subnational

supply chain relationships (Granovetter, 1985; Krippner et al., 2004; Polanyi, 1944). The levels of trust and social relations between actors can make trade relationships more persistent over time (Bair, 2008; Granovetter, 1985; Henderson et al., 2002; Krippner and Alvarez, 2007; Polanyi, 1944; Uzzi, 1997).

Third, supply chain power and agency dynamics, resulting from different sourcing strategies and asymmetries in information and knowledge, have been shown to influence trade persistence and stickiness (Coe et al., 2008; Gereffi, 2014, 1994). Downstream actors in supply chains have incentives to procure unique commodities that require specialization from their suppliers. If there is the demand for such specialized commodities, the brand or company controlling these supply chains gains market power. It may prevent competitors from entering the market, thus resulting in supply chain stickiness (Heron et al., 2018).

The literature suggests that these three groups of factors are likely to influence the adoption (Dauvergne and Lister, 2013; Gardner et al., 2019; Thorlakson et al., 2018) and effectiveness of sustainability commitments by companies (Garrett et al., 2019; Lambin et al., 2018).

First, lock-in effects due to social dependence, technology and investments, bind farmers and companies together in long and stable relationships, potentially leading to imbalances in market power relations (Narasimhan et al., 2009). In some markets, especially in buyer-driven supply chains (Gereffi 1994), traders strive for more power imbalances in their supply chains to exert more control over their suppliers (Dauvergne and Lister, 2013). Committing to

sustainability criteria that condition suppliers' practices can further increase buyer companies' supply chain power and lock-ins while increasing power and market dominance (Bastos Lima and Persson, 2020; Heron et al., 2018). There may, however, also be reverse causality: companies that are more powerful and tend to be more dominant may also be more likely to commit to sustainability criteria because they have the means to do so or the agency to influence actors upstream in the supply chain. Finally, different levels of trust or distrust may promote or hinder more effective engagement between companies and producers to implement sustainability criteria (Ghosh and Fedorowicz, 2008; Heron et al., 2018; Skandrani et al., 2011).

Given the above, it is plausible that these three groups of factors are likely to influence both the observed patterns of stickiness in supply chain relationships and the adoption and effectiveness of sustainability commitments. Nevertheless, no datasets exist that measure these factors comprehensively over large supply chains in a way that would enable quantitative evaluation of their influence on the adoption and effectiveness of ZDCs. Therefore, here we use observed patterns of trade stickiness. We measure these stickiness patterns through temporal network analyses of traders' relationships with production locations, as a proxy of these different factors, to explore their combined effects on both ZDC adoption and effectiveness by traders in the Brazilian soy export supply chain.

We focus on the soy export sector in Brazil, given its importance in deforestation and the momentum of ZDCs in this sector. We use spatiotemporal data on supply chain stickiness from Reis *et al* (2020)

covering the years 2003 – 2017. We employ two distinct econometric models to assess (i) whether and to what extent supply chain stickiness tends to increase the probability of adopting a ZDC, and (ii) how supply chain stickiness may influence the overall effectiveness of ZDCs, measured through observed reductions of native vegetation loss in sourcing regions for companies with or without commitments. Here we highlight that our objective is not to assess the effectiveness of the ASMs or individual company's ZDCs according to their own definitions of forest and deforestation. As these definitions are heterogeneous, sometimes unclear or ambiguous, and temporally changing (zu Ermgassen et al. 2020, Leijten et al. 2020), this would essentially preclude any meaningful and statistically robust analysis. We rather build on a standardized and well-accepted definition of deforestation and native vegetation conversion in Brazil (Soterroni et al., 2018). By doing so, our assessment of ZDC effectiveness encompasses not only the aspects of implementation but also the design of these policies.

Through our empirical analysis, we seek to test two hypotheses:

1. Supply chain stickiness tends to increase the probability of adopting a ZDC, as stickier companies are more likely to have lock-ins, trust and power over a market, suggesting they also have the capacity to commit to sustainability.
2. The stickiness of different traders influences their effectiveness in implementing their ZDCs, through their capacity to influence their upstream supply chain, thus potentially reducing overall supply chain deforestation.

4.2. Methodology

To explore how the level of stickiness may influence the adoption and effectiveness of ZDCs within the Brazilian soy export sector, we used a panel data set with observations for all 1,599 traders involved in the export of Brazilian soy during the years 2004 – 2017. These data control for mergers and acquisitions during the period 2004 – 2017. Below, we first describe how we compiled and processed these data (section 4.2.1). After that, we describe the methods used to estimate the effect of stickiness on the adoption (section 4.2.2) and effectiveness (4.2.3) of ZDCs.

4.2.1. Data

We obtained time-varying data on the level of stickiness for each of the 1,599 traders from Reis et al (2020). These data are based on the topological overlap metric used in network analysis. This metric captures the supply network configuration changes over time around a specific trader (given the municipalities they source from in a certain year) and ranges from 0 to 100%. Stickiness levels of 0% would indicate a complete change in a specific trader's supply chain configuration in two consecutive years. In contrast, stickiness levels of 100% would indicate complete persistence in the supply chain configuration. We use two consecutive years to measure the stickiness of the soy supply network because this is the minimal time granularity allowed by our dataset. Stickiness is the calculation of the persistence of a trade network over any two points in time. In our case, the dataset was constructed aggregating all soy transactions occurred over one year.

Therefore, we estimate the persistence of these trade networks over two consecutive years. Figure S1 in *Appendix 15* plots the general trend in stickiness between 2004 – 2017 in the Brazilian soy supply chain.

To examine how different levels of stickiness may influence the effectiveness of ZDCs, we focus on two outcome variables believed to be directly related to the effectiveness of ZDCs: the level of soy deforestation risk and territorial deforestation allocated to individual traders (Trase, 2020b). Soy deforestation risk refers to the annual area of soy expansion (in hectares) within areas that have been deforested or converted in the previous five years. Risk refers to the way this deforestation is allocated to the actors (here traders) along the supply chain, which is in proportion to the volume of soy that they export from a given municipality, relative to the total production of soy (by all producers) in the same municipality (Trase 2020c, note that supply chain data at the submunicipal level are not available). Territorial deforestation differs from soy-deforestation in that it captures all deforestation from a municipality in the soy supply chain, regardless of whether it is linked to the direct expansion of soy or not (Trase, 2020c). Although this could mean that some territorial deforestation cannot be directly linked to the expansion of soy, it arguably provides a more accurate indication of the overall effectiveness of ZDCs, as it also partially accounts for indirect deforestation (Gollnow et al., 2018).. We sourced data on both types of deforestation risks from Trase (2020b; 2020c) and zu Ermgassen *et al* (2020). Deforestation includes any conversion of native vegetation within the Amazon,

Cerrado and Pantanal biomes. We provide a sensitivity analysis towards forest definition choice in *Appendix 15*. Figure 4.1 plots the aggregated annual level of both soy deforestation and territorial deforestation between 2004 – 2017.

As the empirical relationships between stickiness and the adoption and effectiveness of ZDCs may be confounded by other variables, we sought to control for these variables in our multivariate regression analysis (see sections 4.2.2 and 4.2.3). Table 4.1 lists all variables (i.e., both the variables of interest and control variables) used in the analysis, including their types and sources.

Figure 4.5 – Time series plot showing the total level of soy deforestation and territorial deforestation in Brazil's soy sourcing regions, after aggregating the data for all 1,599 traders. Soy deforestation levels are not available for the years 2004 and 2005.

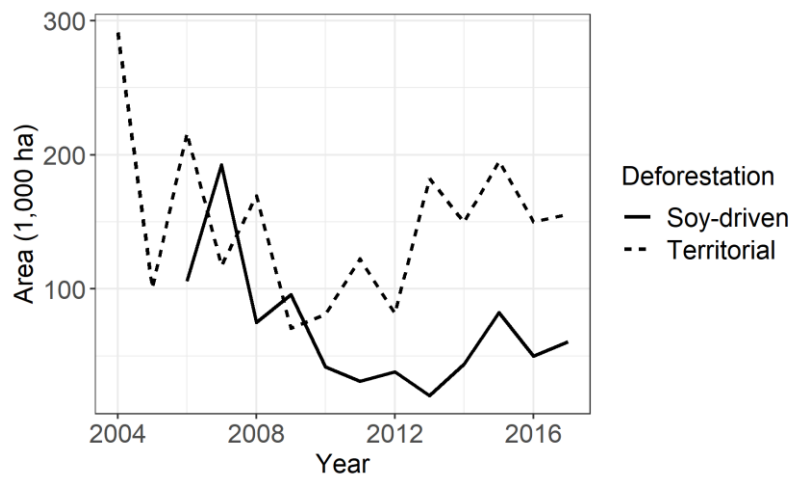


Table 4.1 – Variables used in the multivariate regression analysis. All variables are attributed to companies.

Variable	Type	Source
<i>Variables of interest:</i>		
Adoption of zero-deforestation commitment	Binary (0/1)	zu Ermgassen et al (2020)
Soy deforestation risk (Kha)	Continuous	Trase (2020) and zu Ermgassen et al (2020)
Supply chain stickiness (unitless)	Continuous	Reis <i>et al</i> (2020)
Territorial deforestation risk (Kha)	Continuous	Trase (2020) and zu Ermgassen et al (2020)
<i>Control variables:</i>		
Export share (company's export relative to total exports) (percentage)	Continuous	Trase (2020c)
Exports to Asian markets (company's export to Asian markets relative to company's total exports) (percentage)	Continuous	Trase (2020c)
Exports to European markets (company's export to European markets relative to company's total exports) (percentage)	Continuous	Trase (2020c)
Total unprotected area suitable for soy in sourcing region (ha)	Continuous	FUNAI (2020), ICMBio (2020), INCRA (2020), GeoLab - USP (2017)

4.2.2. *The influence of stickiness on the adoption of ZDC*

To explore how the probability of adopting a ZDC may depend on the company-specific level of stickiness, we estimated several logistic regression models using the variables listed in Table 1, with the adoption of a ZDC in a particular year as the dependent binary variable. As traders can only once commit to zero deforestation, we set traders' observations after the first year of the announcement to missing, as recommended by McGrath (2015). In all models, we controlled for each trader's export share within a given year and the share of exports going to the two most important export markets (Asia and Europe). As companies may be triggered to adopt ZDCs in response to increases in overall deforestation risk (Rueda et al., 2017), we also controlled for the level of territorial deforestation risk in the previous year.

To account for time-invariant heterogeneity across traders (e.g. stemming from different attitudes toward environmental management practices; see Ho and Lin, 2012), we used a weighted demeaning approach that enabled us to explicitly estimate trader-specific fixed effects, implemented in the 'alpaca' package in R version 4.02 (R Core Team 2020, Stammann 2017). Although this approach could lead to biased estimates if the number of traders with commitments is large relative to the number of years – a statistical phenomenon known as the incidental parameters problem (Neyman and Scott 1948, Lancaster 2000) – this was not a concern in our case given that only 22 traders in our dataset have adopted ZDCs (which, when taken in aggregate, account for 78% of all soy exports between 2004 – 2017). Formally, we estimated the following model:

$$\ln\left(\frac{P_{i,t}}{1-P_{i,t}}\right) = \alpha_i + \beta_1 stickiness_{i,t} + \sum_{k=1}^K \omega_k x_{k,i,t}, \quad (1)$$

where $P_{i,t}$ denotes the probability that trader i adopts a ZDC in year t (where ZDC can either refer to an individual ZDC or a ZDC adopted as part of the ASM), $stickiness_{i,t}$ denotes the level of stickiness, $x_{k,i,t}$ is a control variable (see Table 1), and α_i , β_1 and $\omega_1, \dots, \omega_K$ are parameters to be estimated. This equation resulted in 3 different regression models: one for all ZDCs, one for just the ASM and one for unilateral commitments.

Given the low number of traders with ZDCs, we did not account for year-specific fixed effects and the unprotected area suitable for soy as this would overfit the model (Hawkins, 2004). As the number of traders with unilateral commitments (i.e., commitments that are not part of the ASM) is even lower ($n = 5$), we set the third model's positive convergence tolerance to 0.2, thus ensuring convergence (see McCullough 2009 for further details). To assess the overall effect of stickiness on the probability of adopting a ZDC, we used all three models' parameter estimates to compute the Average Marginal Effect (AME; Hilbe 2009) of stickiness. Although it is plausible that the adoption of a ZDC also affects levels of stickiness in consecutive years (i.e., reverse causality), we circumvented the issue by setting all consecutive observations to missing.

4.2.3. *The moderating effect of stickiness on the effectiveness of ZDCs*

Having assessed the effect of stickiness on the adoption of ZDCs, we examined how stickiness could moderate the effectiveness of soy ZDCs in reducing deforestation in Brazil. We estimated several regression models specifying how stickiness may amplify or repress the effect of ZDCs on soy deforestation and territorial deforestation, holding other things constant. As both dependent variables follow a heavily skewed distribution with many observations equal to 0, we used a negative binomial regression model. As opposed to the linear regression model, the negative binomial regression model's underlying probability density function is more suited for modelling non-negative distributions clustered around 0 (Hilbe, 2011). Although the Poisson regression model may also be used for modelling such zero-inflated variables, it imposes the restrictive assumption that the mean and variance of the dependent variable are equal, which does not hold for our data. In the absence of publicly available information on the intended time schedules of all individual zero-deforestation commitments (Garrett et al., 2019), we arbitrarily assumed an implementation deadline of 2 years for all traders after the commitment was announced (after which a ZDC is expected to become effective). As a sensitivity test, we also consider an alternative implementation deadline of 5 years.

To explicitly estimate the trader-specific fixed effects in a computationally efficient way, we used the *fixest* package in R version 4.0.2 (Bergé, 2020; R Core Team, 2020). The underlying algorithm

replicates the results of an unconditional negative binomial fixed effects model with no downward bias in the standard errors (Bergé 2018; Allison and Waterman 2002). This measure enabled us to estimate the following equation:

$$Def_{i,t} = \exp(\alpha_i + \beta ZDC_{i,t} + \phi stickiness_{i,t} + \delta ZDC_{i,t-2} * stickiness_{i,t} + \sum_{k=1}^K \omega_k x_{k,i,t} + \gamma_t), \quad (2)$$

where $Def_{i,t}$ refers to either the annual level of soy risk or territorial deforestation for trader i in year t , $ZDC_{i,t-2}$ is a dummy (binary) variable denoting whether trader i has adopted a commitment in the 2 years preceding year t , $stickiness_{i,t}$ refers to the level of stickiness (rescaled to the unit interval to address overdispersion), $x_{k,i,t}$ is a control variable (see Table 1), and α_i , ϕ , β , δ , γ_t and $\omega_1, \dots, \omega_K$ are parameters to be estimated. To explore the sensitivity of our results to the choice of forest definition, we re-estimated equation (1) after excluding sourcing areas outside the Amazon biome, as these may not be considered forest according to some definitions (Leijten et al., 2020).

To gauge the moderating effect of stickiness on the effectiveness of ZDCs, we used the results of our regression estimates to predict, for each company that has adopted a commitment, what the effect of ZDCs would have been in the absence of an interaction effect. In other words, we compared the outcomes of a scenario that assumes no interaction between stickiness (i.e., $\delta = 0$) and the effectiveness of ZDCs with a scenario that does account for interaction (i.e., $\delta \neq 0$). To explore our estimates' uncertainty, we drew on the variance-

covariance matrix of the parameter estimates and ran 1,000 Monte Carlo simulations, thereby following (Heilmayr et al., 2020a).

4.3. Results

4.3.1. *The influence of stickiness on the adoption of ZDCs*

Table 4.2 reports the regression estimates of equation (1). The first column shows the results for all ZDCs, while the second and third columns show separate regression estimates for the ASM (column 2) and unilateral commitments (column 3). Due to the small number of companies with ZDCs ($n = 22$, which nevertheless account for 78 % of all soy exports), the sample size reduces to 104 observations in model 1. The results in column 1 indicate that stickiness has a positive and significant effect on the adoption of ZDCs ($P < 0.05$) in the consecutive year, other things being equal. More specifically, the results from column 1 suggest that a one percentage point increase in stickiness increases the odds of adopting a ZDC by 5% ($\exp(0.05) \approx 1.05$). We obtained the same result when focussing only on the Amazon Soy Moratorium (second column, first row; $P < 0.1$). However, stickiness appears to have a stronger effect on the adoption of unilateral commitments ($P < 0.001$): a one-percentage-point increase in stickiness increases the odds of adopting a unilateral ZDC by 14% ($\exp(0.13) \approx 1.14$).

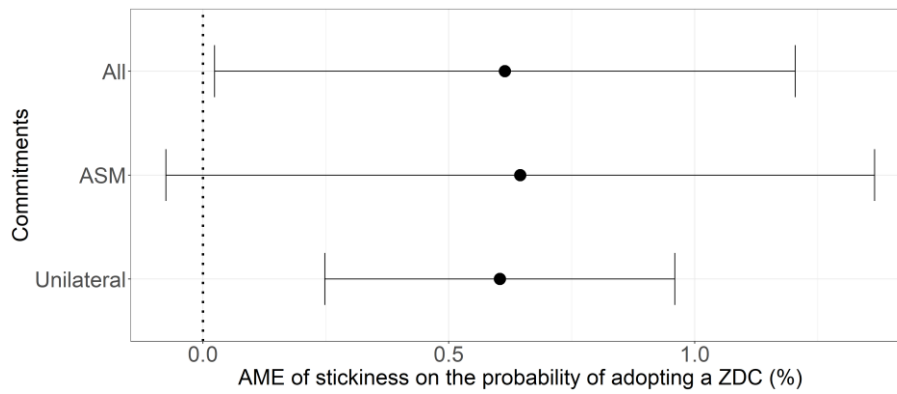
Figure 4.2 plots the Average Marginal Effect (AME) of stickiness on the probability of adopting a ZDC. The top row of Figure 4.2 indicates that on average, the probability of adopting a ZDC increases by 0.6% if stickiness increases by one percentage-point. Similar results are

obtained when focussing only on the ASM (second row) or on unilateral commitments (third row).

*Table 4.2 – Logistic regression estimates of the probability of adopting a ZDC. Heteroskedasticity robust (White-Huber) standard errors in parentheses. Asterisks indicate the level of statistical significance (· $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$). AIC denotes Akaike information criterion and BIC denotes Bayesian information criterion.*

	All commitments	Amazon Soy Moratorium	Unilateral Commitments
Stickiness (%)	0.05 * (0.03)	0.05 . (0.03)	0.13 *** (0.03)
Territorial deforestation (1-year lag)	0.02 (0.02)	0.01 (0.02)	0.09 *** (0.02)
Soy volumes (%)	0.04 (0.26)	0.05 (0.26)	-0.73 ** (0.26)
Destination - Europe (%)	0.58 * (0.29)	0.56 * (0.28)	-0.04 (0.03)
Destination - Asia (%)	0.60 * (0.29)	0.58 * (0.27)	0.04 ** (0.01)
McFadden's Pseudo R ²	0.34	0.28	0.61
Observations	104	92	61
Trader fixed effects	Yes	Yes	Yes
Year fixed effects	No	No	No
AIC	125.35	123.15	33.55
BIC	196.75	188.71	124.54
Log Likelihood	-35.67	-35.57	-6.77

Figure 4.2 – Average Marginal Effect (AME) of stickiness on the probability of adopting a ZDC, thereby distinguishing between commitments made as part of the Amazon Soy Moratorium (ASM; second row) and unilateral commitments (third row). Error bars denote 95% confidence intervals. Confidence intervals that do not contain the number 0 (here indicated by the dotted vertical line) are statistically different from 0.



4.3.2. *The moderating effect of stickiness on the effectiveness of ZDCs*

We report the regression estimates of equation (2) in Table 4.3. The first two columns show a positive and statistically significant relationship between stickiness and soy deforestation (first row, $P < 0.01$). Conversely, there is no statistically significant relationship between stickiness and territorial deforestation, as shown in columns (3) and (4). In addition, there is no relationship between the adoption of ZDCs and soy deforestation or territorial deforestation, regardless of whether a 2-year (third row) or 5-year lag (fourth row) is assumed. However, the third and fourth columns indicate a positive interaction effect between stickiness and the adoption of ZDCs on territorial deforestation ($P < 0.05$, regardless of the choice of implementation deadline), suggesting that stickiness may hamper the effectiveness of ZDCs. These results remain robust when focussing only on deforestation in the Amazon biome (see Table S1 of *Appendix 15*).

To examine the magnitude of this interaction effect (in kha) as well as the underlying uncertainty, Figure 4.3 shows the results of the Monte-Carlo simulation. Each of the four notched boxplots compares the results of 1,000 simulations with and without an interaction effect on the total level of soy deforestation (top row) and territorial deforestation (bottom row). Given the uncertainty regarding the implementation deadline of ZDCs, boxplots in the left column account for an implementation period of 2 years, and boxplots on the right account for an implementation period of 5 years. The boxes display the interquartile range (25 to 75th percentile) of all 1,000 simulations'

outcomes. The notches show the 95% confidence interval around the median (see McGill *et al* 1978 for a more detailed explanation of notched box plots). Most simulations confirm that the interaction effect of stickiness and ZDCs tends to result in more soy deforestation and territorial deforestation, with none of the notches overlapping. By way of example, the top-left plot shows that the median estimate of the effect of ZDCs on soy deforestation increases from 28 (6 – 49) to 738 (697 – 778) kha if there is an interaction effect between stickiness and ZDCs. These findings suggest that traders with higher stickiness are less likely to effectively implement their ZDCs than traders with lower stickiness. However, even in the absence of an interaction effect, most simulations still show a positive effect of ZDCs on soy deforestation and territorial deforestation, suggesting that notwithstanding the level of stickiness, additional efforts are needed to implement ZDCs.

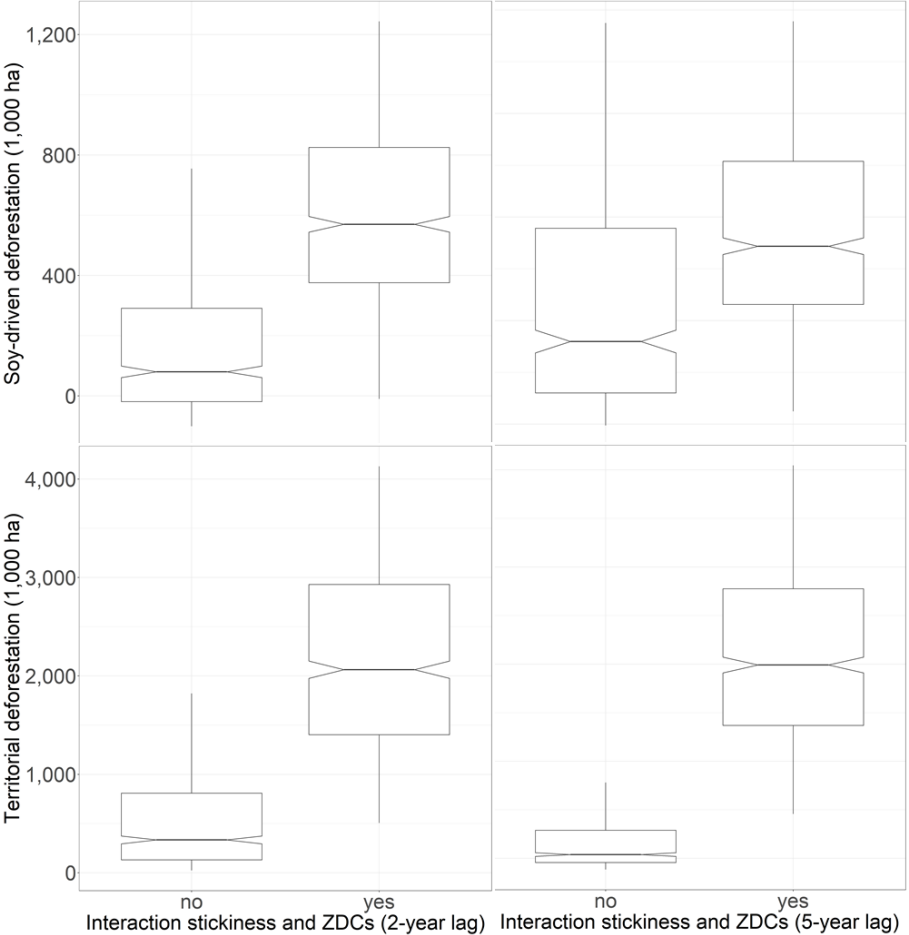
Table 4.3 – Negative binomial regression estimates of the annual amount of soy deforestation risk and territorial deforestation. Columns (1) and (3) assume a ZDC implementation deadline of 2 years, while columns (2) and (4) assume an implementation deadline of 5 years. Heteroskedasticity robust (White-Huber) standard errors in parentheses. Asterisks indicate the level of statistical significance ($\cdot p < 0.10$, $*p < 0.05$, $**p < 0.01$, $***p < 0.001$). Soy and territorial deforestation are represented in kha.

	Soy deforestation risk	Soy deforestation risk	Territorial deforestation	Territorial deforestation
Stickiness (0 –1)	0.60 ** (0.22)	0.63 ** (0.23)	0.13 (0.20)	0.11 (0.20)
Commitment (2-year lag)	0.06 (1.18)		0.69 (0.51)	
Stickiness x Commitment (2-year lag)	0.30 (1.32)		1.23 * (0.61)	
Commitment (5-year lag)		0.79 (1.00)		-0.34 (0.79)
Stickiness x Commitment (5-year lag)		-1.57 (1.22)		1.98 * (0.89)
Export share (%)	0.29 *** (0.09)	0.24 * (0.10)	0.16 * (0.06)	0.20 ** (0.07)
Destination - Europe (%)	0.05 *** (0.01)	0.05 *** (0.01)	0.06 *** (0.00)	0.06 *** (0.00)
Destination - Asia (%)	0.05 *** (0.00)	0.05 *** (0.00)	0.06 *** (0.00)	0.06 *** (0.00)
Unprotected suitable forest area	0.48 * (0.22)	0.52 * (0.24)	0.42 * (0.21)	0.53 * (0.23)
Theta (overdispersion)	1.17 ***	1.20 ***	0.99 ***	0.96 ***

Chapter 4: The influence of company sourcing patterns on the adoption and effectiveness of zero-deforestation commitments in Brazil's soy supply chain

	(0.18)	(0.19)	(0.11)	(0.11)
McFadden's Pseudo R ²	0.61	0.61	0.60	0.60
Observations	4692	4692	7168	7168
Trader fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
AIC	1980.98	1978.99	2994.98	3003.94
BIC	4626.96	4624.97	6660.63	6669.59
Log Likelihood	-580.49	-579.49	-964.49	-968.97

Figure 4.3 – Notched box plots showing the results of 1,000 Monte Carlo simulations of the effects of ZDCs – with and without an interaction effect with stickiness – on soy deforestation and territorial deforestation. Median estimates – including their confidence intervals - are indicated by the notches in each plot. Upper hinges represent 75% quantiles, and lower hinges represent 25% quantile. Upper (lower) whiskers represent the largest outcomes that are less than or equal to upper (lower) hinge * the interquartile range.



4.4. Discussion

Our study contributes to a burgeoning empirical literature on the effectiveness of zero-deforestation commitments (Garrett et al., 2019; Moffette and Gibbs, 2019; E. K. H. J. zu Ermgassen et al., 2020). The usefulness of ZDCs to halt deforestation in Brazil and elsewhere depends on solving issues like clarity of definitions, risk of leakage, supply chain opacity, regionalizing traceability systems, scope of ecosystems and commodities covered (Garrett et al., 2019; Lambin et al., 2018; Lathuillière et al., 2021; Leijten et al., 2020). Although ZDCs like moratoria may be effective in reducing specific commodities' directly-driven deforestation, *e.g.*, beef (Holly K. Gibbs et al., 2015) and soy (H.K. Gibbs et al., 2015; Heilmayr et al., 2020b), spillover effects like deforestation leakage still needs to be better assessed (Alix-Garcia and Gibbs, 2017; Gollnow et al., 2018; Leijten et al., 2021b; Meyfroidt et al., 2020; Moffette and Gibbs, 2021). Here we expand on these studies by looking at deforestation and native vegetation loss associated with soy expansion not only on forests or in the Amazon biome as most studies do, and we add the relational aspect of stickiness as an influencing factor. We consider the conversion of native ecosystems within the Brazilian Amazon, Cerrado and Pantanal biomes, thus accounting for leakage effects within Brazil.

Additionally, our study builds on these previous works by highlighting the concept of stickiness as a potential proxy for unobserved value chain dynamics that may influence the adoption and effectiveness of ZDCs and other corporate sustainability initiatives. Whilst our findings suggest that stickiness incentivizes traders

operating in the Brazilian soy export sector to adopt ZDCs, they also show that, up until 2017, stickiness may have counteracted their overall effectiveness.

We find that stickiness tends to increase the probability of adopting a ZDC in the consecutive year, supporting our first hypothesis that stickier companies are more likely to have lock-ins, trust, and market power. A potential explanation for this is that stickier traders deliberately aim for stable trade relations with certain geographical regions and committing to zero-deforestation can be a strategy to reduce the risk of supply disruptions (Rueda et al., 2017). Additionally, sticky traders may also be more vulnerable than volatile traders to reputational damage if their suppliers are brought into disrepute, which may incentivize sticky traders to adopt ZDCs to manage reputational and systemic risks (Guerrero et al., 2021; Tamayo-Torres et al., 2019; Virah-Sawmy et al., 2019). This explanation is consistent with the green club theory, which describes how reputational risk aversion may trigger firms to participate in 'green clubs' (Barnett and Hoffman, 2008; Potoski and Prakash, 2013).

Despite the presumed positive influence of stickiness on the adoption of ZDCs, we also found strong evidence that stickiness tends to increase the risk of soy-deforestation, supporting our second hypothesis on the *link* between stickiness and effectiveness of commitments. Moreover, traders committed to zero-deforestation with higher levels of stickiness also show higher risks of territorial deforestation. Both findings suggest that stickiness may undermine the implementation and overall effectiveness of ZDCs at the level of

companies. This explanation could be because sticky traders drive continued demand for soy from certain regions, which may send encouraging signals to actors on the ground to expand production (Richards et al., 2012). Moreover, stickiness may also give rise to lock-in effects where traders become dependent on certain suppliers, thus hindering traders from switching to producers complying with ZDC-criteria (Schmitz et al., 2016). Hence, stickiness combined with ZDCs may incentivize soy-laundering, frauds and the emergence of black markets that purchase soy contaminated by deforestation and mixes with “clean” soy before reselling to committed export traders (Bicudo Da Silva et al., 2020; Nepstad et al., 2019).

Conversely, low-stickiness traders may more easily achieve a ZDC, but if only by switching to low-deforestation sourcing regions, this may not necessarily contribute to more effective deforestation reduction on the ground. We highlight that we did not find any evidence that the ZDCs reduce native vegetation loss, regardless of the level of stickiness. This finding is consistent with recent literature for individual ZDCs (E. K. H. J. zu Ermgassen et al., 2020). In contrast, for the ASM as a collective ZDC, the literature shows it effectively reduces deforestation (Heilmayr et al., 2020b). These two studies nuance the interpretation that stickiness is indeed thwarting the effectiveness of ZDCs, as it could also be that at the end of our study period (*i.e.*, the year 2017), no action had been taken yet to implement the commitments. These findings suggest that to effectively interrupt the commodity-driven deforestation cycle, combining multiple strategies, such as public-private partnerships (Furumo and Lambin, 2020),

moratoria (Soterroni et al., 2019), certification schemes (van der Ven et al., 2018), and mandatory zero-deforestation criteria in international trade, implemented by consumer-countries and blocs (Bager et al., 2021; Kehoe et al., 2020) may be needed to support the implementation of ZDCs and to eliminate deforestation.

Furthermore, our study shows that the relational dimension of stickiness in commodity supply chains alters the dynamics of ZDCs, influencing both their likelihood of adoption and overall effectiveness. Therefore, beyond private, individual or collective, disaggregated and un-coordinated ZDCs that are subject to the influence of various sourcing and relational patterns, we might need higher-level, concerted and mandatory public policies to address the issue of commodity-driven deforestation. Our findings may suggest that only by the creation of a level playing field by public authorities, we may reduce the stickiness bias in supply chains and achieve overall deforestation reductions.

One limitation of our study, as explained in the introduction, is that our stickiness metric captures and reflects several underlying dynamics, including lock-in effects, trust, and power. Thus, the data do not allow us to identify which of these factors are more influential in the adoption and effectiveness of ZDCs. Whilst there are reasons to believe that stickiness is a useful proxy for these value chain dynamics, additional data are required to attribute the overall effect of stickiness to these underlying factors. These factors may influence ZDC adoption and effectiveness in different, contradictory ways. Furthermore, due to the small number of traders with zero-deforestation commitments

in our sample, our analysis may suffer from a lack of statistical power, potentially resulting in type II errors, *i.e.*, failing to identify certain statistical significance effects that are occurring. Moreover, given that the supply chain data are aggregated at the municipality level, it is conceivable that our conclusions do not hold at the property level (an example of the ecological inference problem; Freedman *et al* 1998). Yet, assessing ZDC at municipality level allows to account for local spillovers and thus measures ZDC's effectiveness at jurisdictional level beyond the specific sourcing farms (Godar et al., 2016). Further research could explore the extent to which our qualitative conclusions hold in other supply chains or at more disaggregated levels, assuming future data availability.

After showing that traders with higher stickiness in their sourcing patterns and behaviors exhibit higher likelihood to adopt zero-deforestation commitments in the forms of either the Amazon Soy Moratorium or unilaterally, and that higher stickiness also tends to increase deforestation and native vegetation conversion risks, it is time to inquiry how different stickiness levels from the municipality side supplying to traders may lead to different rural development outcomes. Chapter V compares four soy Brazilian municipalities, being one with high temporal average stickiness located in an agricultural consolidated region and one high-stickiness municipality in a frontier. Then another low-stickiness and consolidated and a fourth low-stickiness in a frontier.

V. How supply chain relations influence development outcomes: The case of soy in Brazil

Abstract: Global agricultural commodity trade is a key driver of landscape (and social) transformations in rural areas. Such trade may create revenue opportunities and wealth as much as land concentration and local community displacement. Yet we still have a limited understanding of how supply chain actors and their embedded networks (including traders, farmers, and input suppliers) develop, maintain, or shift relationship patterns – and what implications these supply chain relations have on development outcomes. One measure of those relations is stickiness, understood as the persistence of trade relationships over time, as opposed to volatile or shifting supply chain relationships. Comparing the cases of four different soy-growing municipalities in Brazil, we use stickiness to analyze how their persistent or non-persistent trade relationships affect rural development outcomes. Our analysis draws from extensive fieldwork and qualitative exploratory data from interviews as well as quantified measures of supply-chain stickiness. The cases include quite contrasting Brazilian municipalities: (1) one with relatively persistent relationships between grain suppliers and export traders located in a consolidated agricultural region, (2) another with low persistence in a similar region, (3) one with persistent supply-chain relationships in a frontier region, and finally (4) a frontier municipality showing low persistence in those relations. We explore how stickiness processes, such as lock-in effects, trust, and power dynamics, may lead to different rural development outcomes with these four case studies. We find that cooperatives are mediating institutions that may interact and alter these three supply chain relationship processes, thus leading to more inclusive or more excluding rural development outcomes.

Keywords: Stickiness, commodity supply chains, social networks agricultural trade, Brazilian soy production, rural development outcomes, agricultural cooperatives.

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Author Contributions

Conceptualization, T.N.P.R., P.M., G.R.L., M.G.B.L.; Methodology, T.N.P.R., P.M.; Software, T.N.P.R.; Validation, P.M., G.R.L, M.G.B.L.; Investigation, T.N.P.R.; Resources, T.N.P.R; Data Curation, T.N.P.R.; Writing, T.N.P.R., P.M.,G.R.L., M.G.B.L.; Supervision, P.M.; Funding Acquisition, P.M.

5.1. Introduction

Recent growth in agricultural commodity production and international trade has radically shifted landscapes worldwide towards an increasingly global agri-food system (Canfield et al., 2021; McMichael, 2009). That has triggered important environmental and socio-economic changes across the globe (da Silva et al., 2017; Escobar et al., 2020; Green et al., 2019; World Bank, 2019b). On the one hand, the increasing production of agricultural commodities – including to supply distant markets (da Silva et al., 2017) – has offered crucial opportunities for rural development, certain livelihoods, and income generation in rural areas (Martinelli et al., 2017; Oliveira and Hecht, 2016; Weinhold et al., 2013). However, on the other hand, those have also been critical drivers of land-use change and deforestation, biodiversity loss (Curtis et al., 2018; Green et al., 2019), increased greenhouse gas emissions (Meyfroidt et al., 2014; Pendrill et al., 2019a), and often the displacement of local populations and erosion of rural livelihoods not involved with the few select agricultural commodities demanded by the global market (Lopes et al., 2021).

One notable feature of the consolidating global agri-food system is its market volatility (Clapp, 2009; IPES-Food & ETC Group, 2021). That includes not only commodity price fluctuations, but also shifting supply-chain relations such as sourcing regions, and corporate reallocation of resources (Bastos Lima et al., 2019; le Polain de Waroux et al., 2016). However, not all supply chain relations are equally (un)stable – their “stickiness” varies, and due to reasons not yet fully understood (Reis et al. 2020). It is important to understand not only

what underpins those firmer or looser connections between trade partners and supply chain actors, which determine the stability or volatility of such commercial relationships, but – critically – also how that affects rural development trajectories.

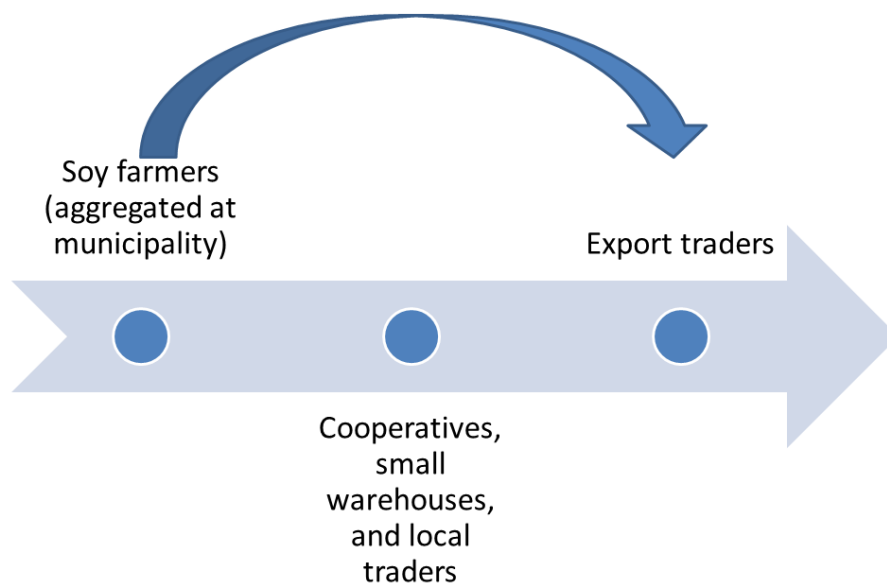
Reis et al. (2020, p. 102) define stickiness as “the maintenance and recovery, over time and through shocks, of supply chains’ geographic network configurations.” Its analysis helps not only to characterize the linkages between specific places of production or consumption and certain actors (e.g., producers, traders, retailers, consumers), but also to identify and assess the geographical embeddedness of given production networks and trade flows, as much as its social impacts. Knowing which actors are more or less persistent in their supply-chain relations allows us to possibly predict the restructuring of trade flows, *i.e.*, who will source from where and which regions will supply to whom (Waroux et al., 2017). Eliciting these patterns is also key to design sustainability policy interventions, because they indicate who tends to reconfigure and displace social-environmental impacts to other regions or to be more effective in transmitting sustainability demand signals upstream in the chain. In short, assessing stickiness can help understand the impact of policy measures on commodity supply networks.

Here we focus particularly on the relationships between soy farmers and commodity traders, a link sometimes – but not always – mediated by cooperatives, warehouses and other local intermediaries (see Figure 5.1). Soy is one of the world’s fastest-expanding crops, widely used by the food industry, in animal feed, and increasingly for

the bioeconomy (Bastos Lima, 2021; Lopes et al., 2021; Oliveira and Hecht, 2016). To analyze how stickiness affects broader rural development trajectories, we analyze four Brazilian municipalities that are key soy supplying regions. As Reis et al. (2020) explain and define, the stickiness of commodity supply chains can be analyzed at various levels or steps and different types of relationships. Here, we qualitatively assess the farmers' supplying relationships with cooperatives, small warehouses, and commodity traders (see Figure 5.1).

Figure 5.6 – Supply chain types of relationships analyzed here.

The sequence in the main arrow refers to supplying relationships. The above arrow refers to the supply chain relationship type where farmers trade directly with export traders without the intermediation of cooperatives, brokers, small warehouses, local traders or cerealists.



We focus our analysis on three underlying processes that steer and shape stickiness levels. First, lock-in effects can be infrastructural, technological, financial, institutional, or consumer preferences. Second, trust and the social embeddedness of economies, which account for the networks of social relations embedded in economies that determine the market structure. Third, power and agency dynamics, which relate to power imbalances and information asymmetries in supply chains. By taking a closer look at these three underpinning processes, we aim to investigate how stickiness influences rural development trajectories.

To assess development outcomes, here we define development in a very simplified way as either inclusive or excluding. The latter is also conceptualized as “maldevelopment” (Lopes et al., 2021). Inclusive development occurs when the benefits of an economic driver are equitably distributed across society, implicitly recognizing development as the freedom to gain the capabilities to overcome deprivation (Hickey et al., 2014; Sen, 2000). For example, in agricultural landscapes, the expansion of commodity production comes with the equitable distribution of land, income, and wealth. The social-environmental burdens are not left exclusively with the most marginalized societal groups (Gupta and Lebel, 2010). Excluding or “maldevelopment”, in contrast, is “an inequitable process of change that excludes and impoverishes local actors, undermining their economic or political capabilities and thus their social freedoms” (Lopes et al., 2021, p. 3). In agricultural landscapes, this process occurs when the expansion of commodity production leads to wealth, land,

and income concentration in the hands of a few groups, blocking marginalized communities' access to environmental resources and imposing burdens on them (Pouw and Gupta, 2017).

We conducted fieldwork and semi-structured interviews to provide a qualitative exploratory analysis of the four cases. We analyzed their different rural development patterns and sought associations with the observed stickiness levels in the relations between farmers supplying to cooperatives, local traders, small warehouses, and export traders, and between farmers and cooperatives collectively grouped as producer municipalities and export traders. We hypothesize that cooperatives might be a key institution that mediates the influence of the three abovementioned processes on supply chain relationships' stickiness at the supply-side (between production places and traders).

5.2. Conceptual Framework

From land system science, we know that the pattern of colonization of agricultural frontiers, the level of land-tenure security, the availability of capital and accessible credit, the presence of private colonization firms or public-driven colonization enterprises (Jepson, 2006), the existence of farmers' associations or cooperatives all have impacts on determining the clustering (Garrett et al., 2013b; Jepson, 2009), the agglomeration of economies, innovation, intensification, socio-economic development and the industrialization of agricultural frontiers (Garrett et al., 2013a; Richards, 2018). Despite showing that cooperatives are crucial determinants and drivers of rural

development and that these associations are manifestations of trust and social embeddedness in economies (Garrett et al., 2013b; Jepson, 2006; Sousa and Busch, 1998), this set of studies says little about the role of trust and social embeddedness in supply chain relationships patterns (Ghosh and Fedorowicz, 2008; Granovetter, 1985; Skandrani et al., 2011). This literature lacks what underpins the connections between trade partners and supply chain actors that determine the very stability or volatility of commercial relationships and how this stability or instability influences different rural development trajectories.

A previous study has assessed the potential causes of the stickiness between soy producer municipalities and traders in Brazil, identifying several categories of influencing factors, including: “(i) economic incentives, i.e., as determined by infrastructure, capital availability, costs of production, prices, market demand; (ii) institutional factors, i.e., land-tenure and environmental regulation; (iii) social and power dimensions, i.e., cohesion, trust, power and agency, group associations; and (iv) biophysical and technological aspects, i.e., stability of production and supply, and total factor productivity of crop production (Reis et al., 2021a). This study also suggested that these predicting factors influence stickiness in supply chains through three main groups of processes, namely lock-in effects, trust, social relations, and power dynamics.

We treat lock-in effects as a separate process from trust, social relations and power dynamics because we consider that lock-ins are concrete manifestations of power dynamics that materially bind

supply chain actors, i.e., lock-ins manifest in credit systems, soy processing and logistic infrastructure, for example. Trust, social relations and power dynamics have more ambiguous manifestations and fuzzier effects on supply chains. For example, while one can observe the construction of a storage facility that binds farmers in a proximal radius, trust and social relations are more fluid. Similarly, power dynamics and agency manifest through information and knowledge asymmetries, and relational imbalances, for example. Nonetheless, we acknowledge that social relations, trust and power are intertwined with lock-ins (Schmitz et al., 2016; Wilson, 2014), and our decision to decompose these processes is to observe how they separately affect on stickiness patterns.

The literature on agricultural frontiers and agglomeration economies (Garrett et al., 2013a; Jepson, 2006, 2009; Richards, 2018) suggests that cooperatives may have a determinant role in stabilizing or de-stabilizing certain supply chain relationships, depending on which factors and processes interact with the supply chain social landscape where cooperatives operate. From this knowledge, combined with (Reis et al., 2021b) and (Leijten et al., 2021a) studies, we hypothesize that cooperatives might be a key institution that mediates the influence of the three processes identified above on supply chain relationships' stickiness at the supply-side (between production places and traders). Figure 5.2 summarizes the conceptual framework.

5.2.1. *Lock-In Effects*

Lock-in effects encompass various factors, some stemming from the actors' past decisions that constrain their supply chain relationships. Lock-in effects can be (i) infrastructural (Payo et al., 2016; Vanloqueren and Baret, 2009), when physical facilities bind together different supply chain actors; (ii) financial, e.g., through biased or preferential credit mechanisms (Bicudo Da Silva et al., 2020); (iii) technological, e.g., when one actor dominates and patents key technologies upon which others are dependent (Fares et al., 2012), (iv) institutional, from existing norms or governance mechanisms in place (e.g., the Amazon Soy Moratorium); or (v) related to consumer preferences, such as for products of a certain origin or quality (Akkermans, 2001; Narasimhan et al., 2009).

Cooperatives can have a mediating role in these lock-in effects because in the soy supply chain, for example, they also build their physical facilities, provide credit to associated farmers at lower interest rates than traditional traders, and in some cases even lower than traditional banks, conduct and invest in research to develop their seed qualities, but also organize farmers' buying pools that decrease the cost of technological access, create their own governance rules that are applied to associated farmers, and produce customized soybeans to supply directly to niche markets such as organic or conventional (Bicudo Da Silva et al., 2020; Garrett et al., 2013b; Oliveira, 2016; Turzi, 2017).

5.2.2. Trust and Social Embeddedness

Trust and the social structure – i.e., the networks of social relations embedded in economies that determine the market structure – may influence the stickiness of subnational supply chain relationships (Granovetter, 1985; Krippner et al., 2004; Polanyi, 1944). The levels of trust and social relations between actors can make trade relationships more persistent over time (Bair, 2008; Granovetter, 1985; Henderson et al., 2002; Krippner and Alvarez, 2007; Polanyi, 1944; Uzzi, 1997). Cooperatives may also increase trust and strengthen the social structure and trade dynamics in regions where they are prevalent. As these studies show, cooperatives influence agricultural towns' social and economic dynamics, especially the smaller ones (Adams, 2011; Bacaltchuk et al., 2015; Craviotti, 2016; Empinotti, 2015; Garrett et al., 2013b; Ofstehage, 2016; Sauer, 2018).

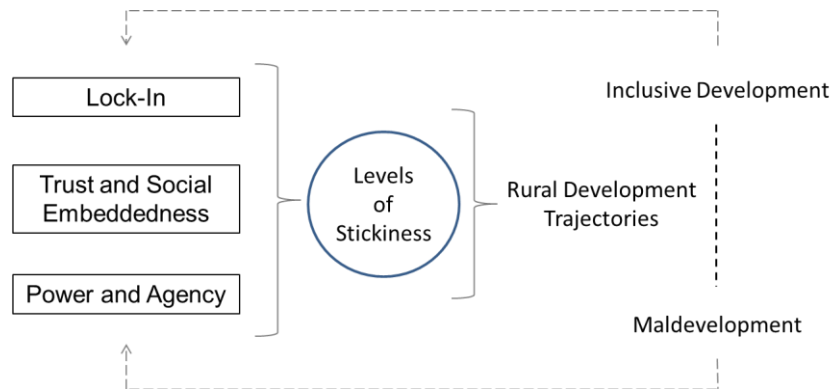
5.2.3. Supply Chain Power and Agency

Supply chain power and agency dynamics, resulting from different sourcing strategies and asymmetries in information and knowledge, have been shown to influence trade persistence and stickiness (Clapp, 2021; Coe et al., 2008; Gereffi, 2014, 1994). Downstream actors in supply chains have incentives to procure unique commodities that require specialization from their suppliers. If there is a demand for such specialized commodities, the brand or company controlling these supply chains gains market power. It may prevent competitors from entering the market, thus resulting in supply chain stickiness. Cooperatives are also found as a relevant mediating institution in

supply chain power dynamics, mainly altering the power imbalances typically found in buyer-driven supply chains. In other words, cooperatives may result from farmers' intention to break through traders' power (Gereffi et al., 2005; Gereffi, 1994; Oliveira and Hecht, 2016; Turzi, 2017). Cooperatives are also found as a relevant mediating institution in supply chain power dynamics, mostly altering the power imbalances typically found in buyer-driven supply chains. These three stickiness processes, mediated by cooperatives, may result in different development outcomes because they determine how supply chains evolve and interact with land use and rural development trajectories.

Figure 5.2 – Conceptual framework showing the interactions between the underpinning processes (lock-ins, trust, and power), levels of stickiness, and rural development trajectories.

A feedback loop explains these interactions. The solid arrows represent direct influence, and the dashed arrows represent the reverse influence, or feedback loop, between the mediators and the outcomes.



5.3. Data and methods

The first author conducted fieldwork between July and October 2019 in Brazil to inquire about the perceptions of stickiness causes and implications. The semi-structured interview guide oriented the conversation towards understanding how these underpinning stickiness factors of lock-ins, trust and social structure, and supply chain power and agency dynamics may affect local development trajectories. The questions asked about the soy supply chain actors' factors, reasons, and motives to engage in more stable or volatile relationships (Patton, 2002; Silverman, 2010). The notion of stickiness was explained to interviewees as having stable, consistent, or loyal relationships with buyers, suppliers, or commercial partners.

We constructed a geographic stratification identifying regions where soy arrived at different times and in different socio-economic, technological, and biophysical contexts. These regions exhibit different production arrangements, profiles, technology levels, productivity, and logistic access (Tables S1 and S2, Appendix 16). With a snowballing approach building on local connections between actors (Patton, 2002), the first author identified the actors to interview in the four selected municipalities studied here. These municipalities were chosen as low and high stickiness cases in frontier and consolidated regions to explore and elicit similarities and differences.

The first author conducted 32 interviews, one key-expert consultation and attended two events in two municipalities (Table S3, Appendix 16). The fieldwork data's qualitative analysis involved a semi-structured guide for the interviews, allowing flexibility for

spontaneous topics and subjects (Patton, 2002; Silverman, 2010). These interviews ranged from 40 to 150 minutes, and only twenty-eight interviewees (out of 32) allowed audio recording. These 32 interviewed actors belong to the following stakeholders: soy and corn farmers, farmer union or association leaders, agricultural input suppliers, local procurement managers or procurers of exporting traders, grains, local warehouses and storage companies, transportation companies, technical assistants, academic researchers, NGO representatives, consultants and certification companies.

For data analysis, the first author first selected literal narratives or parts of oral accounts that referred to the themes of lock-ins, trust, and social structures embedded in economic or commercial relationships, and supply chain power and agency dynamics. The first author coded these accounts into the three overarching themes, identifying the links between stickiness factors and development trajectories.

Acknowledging the central role of situated knowledge in qualitative and geographic research (Nielsen and D'haen, 2014; Simandan, 2019), the first author is Brazilian, originally from the countryside. Gatekeepers and key informants contributed to this research to connect the first author with interviewees in several regions. In places where we had no connections, the first author contacted the presidents or leaders of local farmers' unions, rural associations, or academic researchers. The first author conducted all the qualitative analysis in Brazilian Portuguese as his first language.

For the comparative analysis, we defined a two-dimensional space delineating a 2 x 2 quadrant to select relevant municipalities that the first author visited during fieldwork in 2019. A 2 x 2 quadrant means comparing four municipalities with two similarities and two differences, being similar and different stickiness levels and landscape profile: agriculturally consolidated or a frontier region. Thus, we selected two municipalities with relatively high stickiness in the municipalities' supplying relations with export traders as measured by Reis et al. (2020), one located in an agricultural frontier and the other in a consolidated agricultural region. The other two municipalities exhibit relatively low stickiness, one in an agricultural frontier and the other in a consolidated agricultural region.

To measure stickiness, we used an index of time average stickiness over 2003-2017, at the municipality level, measuring the stickiness between producer municipalities that aggregate farmers, including cooperatives, small warehouses, and local traders supplying to export traders. This index is the arithmetic mean between the successive stickiness indices over successive years, e.g., with the stickiness index of 2004 comparing the trading relations of a municipality in 2003 with those of 2004. The annual indices, and thus the time average, range between 0 and 1. Zero means a complete reconfiguration of the supply network around the node (i.e., the producer municipality supplying to traders), while 1 means complete maintenance of the supply network. In other words, one means absolute stability or stickiness, and zero means absolute volatility or total non-stickiness. High stickiness means that the supply network has been more stable over time, and low

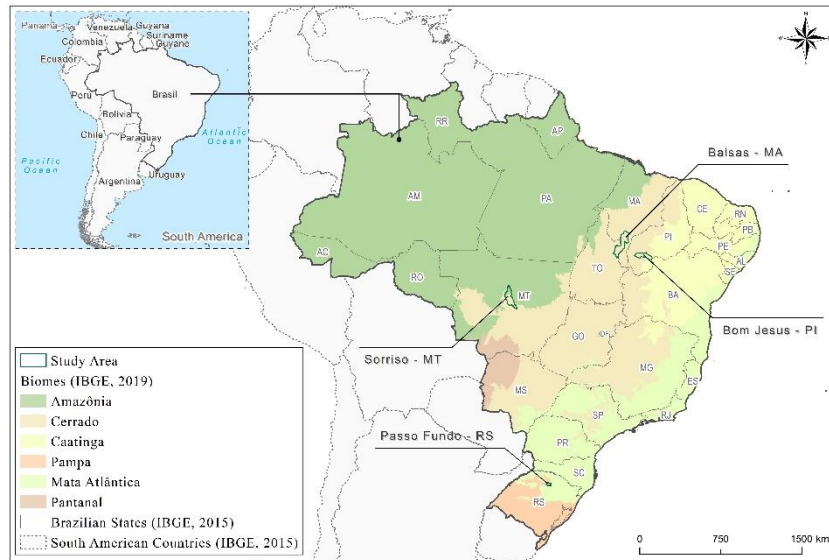
stickiness means it has been more volatile over time in terms of the traders that sourced soy from that municipality. We can consequently compare this stickiness index across municipalities, characterizing each as high or low compared to the group. We also used here the stickiness index comparing the earliest and latest years available in our data, which is the stickiness calculated by comparing the supply network configuration in 2003 directly with 2017 (Reis et al., 2020).

5.3.1. Contextualizing Consolidated and Frontier Regions

Frontier regions and consolidated agricultural areas exhibit different socio-economic profiles in Brazil. Consolidated areas – mostly in the country's south and southeast regions – generally are more industrialized, economically developed, and have older, more established colonization patterns. Wealth and land are, on average, also more evenly distributed (Imaflora, 2021).

Farmers in consolidated regions are more capitalized and add more value to production, while frontier farmers are less capitalized and more reliant on credit from banks or commodity traders (Garrett et al., 2013b). In the consolidated locations, export traders barely engage directly with farmers. They source primarily from small warehouses and cooperatives. Therefore, in the consolidated southern regions, small farms predominate, primarily associated with cooperatives. Cooperatives are a solid social, economic, and industrial power, not necessarily in the consolidated regions, but culturally in the southern states of Brazil (Rio Grande do Sul, Santa Catarina and Paraná, See Figure 5.3).

Figure 5.3 - Map of Brazil showing its biomes, states and the four municipalities studied here.



In the northern frontier regions (especially Mato Grosso, Maranhão, and Piauí), farmers are predominantly larger and negotiate more directly with export traders. They trade larger volumes and commit larger shares of their expected harvests with traders in exchange for credit and input supplies in barter deals. In the consolidated southern regions, the commitment in future contracts is relatively minor, and farmers leave more grains for spot deals. However, cooperatives supply almost everything to cooperated farmers, including credit, technical assistance, agricultural supplies, fuel, clothing, groceries, and other items. This relationship pattern makes farmers and cooperatives much closer than farmers do with traders.

The land is more valuable in the consolidated southern regions than in the north due to more infrastructure, capital, and proximity to larger consumer markets. Therefore, many farmers have been selling their southern lands to buy larger farms in the northern frontiers and expand production onto native vegetation. The current level of soybean prices at international markets makes this movement viable. Some farmers remain in the south and invest in northern lands. Therefore, we could argue that the south is a producer of soy farmers, sending them to the entire country and south America. In short, Brazil's southern agriculturally consolidated regions are more social, cooperative, equal, and the northern frontiers are economically and socially wilder, concentrated, and unequal.

In this study, we found various factors subjectively and objectively permeating farmers' relations with traders, stability, or volatility, resulting in different development outcomes. Here we focus on the subjective factors leading to supply chain actions and outcomes. Acknowledging the differences across consolidated southern and northern frontier regions and the fact that the selected municipalities exhibit low or high stickiness profiles, different levels of socio-economic development, and different land use and rural development trajectories, we present the factors below as the interviewed actors' perceptions. They explain how these trade relations arise, unfold, stick or break, and may lead to different development trajectories across these municipalities.

5.3.2. *Passo Fundo – Rio Grande do Sul (RS)*

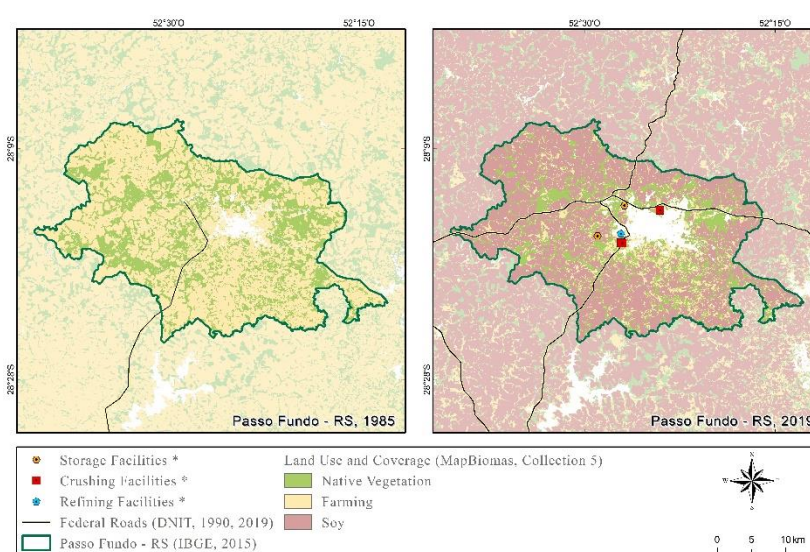
Passo Fundo is a soy producer and logistics hub located in the center of the southernmost Brazilian state of Rio Grande do Sul. It is a region of old colonization, where the 1960s first introduced soy. The stickiness profile of Passo Fundo has been relatively high in supplying relationships to export traders, as seen in Figure 5.3. Passo Fundo was selected as a case study because it is located in a consolidated agricultural region and has high stickiness profile. It is a hub of innovation, a cluster of agro-industry companies resulting in an agrarian agglomeration economy (Bacaltchuk et al., 2015).

Passo Fundo can be considered a relatively high stickiness profile in its supplying relationships with traders. Its temporal average stickiness annually calculated over 2003-2017 (TCi) is 0.79, and the longest 2003-2017 stickiness is 0 (Table 1, Figure 5.8) (Reis et al., 2020). These figures indicate something contradictory, but it is not. They mean that Passo Fundo has been reconfiguring its supply chain network slowly over time. These small yearly changes resulted in a complete supply network reconfiguration between 2003 and 2017. This fact implies relative supply chain stability in annual terms compared to the other municipalities in this study. However, it means that the Passo Fundo supply chain was totally different in 2017 than in 2003. Amongst the Brazilian 468 municipalities with stickiness measured, Passo Fundo has the 75th highest TCi (Reis et al., 2020).

Passo Fundo had 62,4% of its area in 1985 occupied by farming (crop and pasturelands), and 34% covered by native vegetation. In 2019, farming covered 71.7%, and native vegetation, 21,3%

(Mapbiomas, 2021) (Table 5.1, Figure 5.4). This figure shows that although Passo Fundo was already a consolidated agricultural region in 1985, it has subtly increased its agricultural area.

Figure 5.4 – Map of Passo Fundo - RS in 1985 and 2019 showing soy and transport infrastructure, land use and cover change.



Data show that Passo Fundo has an agro-industrial, developed, and innovative socio-economic and rural development profile. In 2010, the agricultural sector employed only 3.3% of the town's working population, a low figure compared to the 13.5% of Brazil as a whole (Atlas Brasil, 2021). The gross agricultural added value of Passo Fundo into the local economy was 2.2% against 7.7% of Brazil in 2016. Its *per capita* GDP was around 28 thousand Brazilian reais (BRL) in 2016, higher than Brazil's average of 20 thousand in the same year. The *per capita* income was at BRL 1.068,69 monthly in 2010, higher than Brazil's average of BRL 793.87. The Gini index, showing inequality,

where closer to one indicates that all wealth belongs to fewer people and 0 indicates complete distribution, was 0.53 in 2010, slightly less unequal than Brazil at 0.55 (Atlas Brasil, 2021).

5.3.3. *Balsas – Maranhão (MA)*

Balsas is a recent soy frontier, with production commencing in the 1990s and rapidly expanding after the 2000s. It is a soy logistics hub located in the south of Maranhão state, in the region known by the acronym Matopiba, purportedly the last Brazilian agricultural frontier including the Cerrado biome parts of the states of Maranhão, Tocantins, Piauí and Bahia.

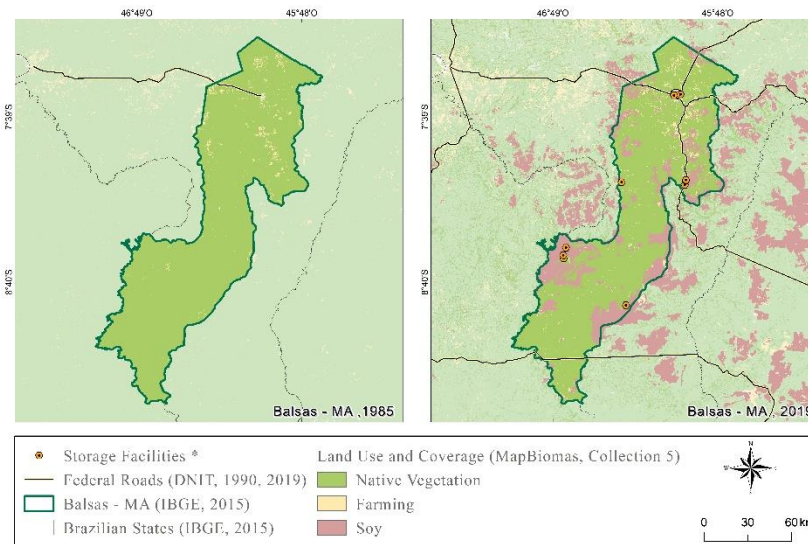
The stickiness profile of Balsas has been relatively high in its supplying relationships to export traders, as seen in Figure 5.8. Balsas was selected as a case study because it is located in an agricultural frontier region where soy has been rapidly expanding, particularly after the 2000s, and has a high stickiness profile. It contrasts with Passo Fundo, which also has high stickiness but is more developed and in a consolidated region. In contrast to Passo Fundo, Balsas is a town where poverty, inequality, and under-development persists. A few large traders dominate the market for export purposes, adding little value to the local economy (Lopes et al., 2021).

Balsas' temporal average stickiness annually calculated over 2003-2017 (TCi) is also 0.79, as Passo Fundo, but it is 0.41 in the 2003-2017 measurement (Reis et al., 2020) (Table 5.1, Figure 5.8). These figures indicate that Balsas has been reconfiguring its supply chain network slowly over time, maintaining relative stability, a similar pattern as

found in Passo Fundo, also implying a relative supply chain stability compared to other municipalities in this study. Considering the 2003-2017 entire reconfiguration, it has changed, but not entirely as Passo Fundo did. This fact means that Balsas' supply network in 2017 was about 40% the same as 2017. Amongst the Brazilian 468 municipalities with stickiness measured, Passo Fundo has the 72nd highest TCi (Reis et al., 2020).

Considering land use aspects, Balsas had only 2% of its area in 1985 occupied by farming (crop and pasturelands), and 97.8% covered by native vegetation. In contrast with Passo Fundo, this figure shows that Balsas was mainly preserved and covered by native vegetation in 1985. In 2019, however, farming covered 22.5%, and native vegetation, 76.9% (Mapbiomas, 2021) (Table 5.1, Figure 5.5). This fact clearly shows the speed of agricultural expansion. Nevertheless, it is still a frontier because there are about one million hectares of native vegetation (76.9%) to be converted, acknowledging here the notion of the agricultural frontier, which implies that there are unexplored lands open for agricultural expansion (Jepson, 2009).

Figure 5.5 – Map of Balsas - MA in 1985 and 2019 showing soy and transport infrastructure, land use and cover change.



Data show that Balsas has a cash-crop, export-oriented, land and wealth unequally distributed, poor and under-developed profile in socio-economic and rural development aspects. In 2010, the agricultural sector employed 17.5% of its working population. It is a high figure compared to 13.5% of Brazil as a whole. The gross agricultural added value of Balsas into the local economy was 18.5% against 7.7% of Brazil in 2016. Its *per capita* GDP was around 17 thousand Brazilian reais (BRL) in 2016, lower than Brazil's average of 20 thousand in the same year. The *per capita* income was at BRL 531.60 monthly in 2010, lower than Brazil's average of BRL 793.87 and much lower than Passo Fundo. The Gini index, showing inequality, was 0.55 in 2010, the same as Brazil at 0.55 (Atlas Brasil, 2021).

5.3.4. *Sorriso – Mato Grosso (MT)*

Sorriso is a 1980s soy frontier, with production beginning in the 1970s and rapidly expanding after the 1980s. It is a soy logistics hub located in the center of Mato Grosso state. It is known as a model town, with large and planned streets and avenues and relatively good urban planning compared to Brazil's regular towns. It hosts high education, sanitation, and development indices. Sorriso can be considered a post-frontier and recent agricultural consolidated region. The soy industry depicts it as a development model (Garrett et al., 2013a; Lima et al., 2011).

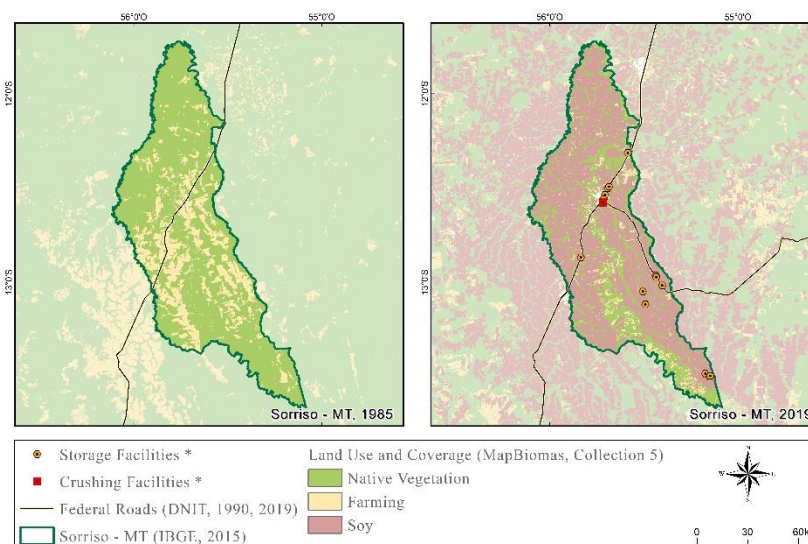
The stickiness profile of Sorriso has been relatively low in its supplying relationships to export traders, as seen in Figure 5.8, even though the last years of the series show relatively high stability. Sorriso was selected as a case study because it is located in an agricultural post-frontier region where soy has been rapidly expanding, particularly after the 1990s, and has a low stickiness profile. It contrasts with Passo Fundo that has high stickiness and high development but is located in an old agricultural consolidated region. Sorriso has low stickiness but high development. It is located in a recent agricultural region, slightly older than Balsas, but has recently developed. Nonetheless, in contrast with Balsas and like Passo Fundo, Sorriso is also considered a pole of innovation, a cluster of agri-companies, and an agglomeration economy (Garrett et al., 2013a).

Sorriso's temporal average stickiness annually calculated over 2003-2017 (TCi) is 0.68, and 2003-2017 directly calculated is 0.26 (Reis et al., 2020) (Figure 5.8, Table 5.1). These figures indicate that Sorriso

has been substantially reconfiguring its supply chain network annually over time, more than Passo Fundo and Balsas, implying relative supply chain volatility compared to the other municipalities in this study. The longest stickiness measurement shows even more reconfiguration, indicating that Sorriso's supply network in 2017 was only about 26% the same as in 2003. Among the Brazilian 468 municipalities with stickiness measured, Sorriso has the 110th highest TCI (Reis et al., 2020), which is still high compared to the overall sample but lower in our group.

Considering land use aspects, Sorriso had 22.1% of its area in 1985 occupied by farming (crop and pasturelands), and 77.1% covered by native vegetation. In contrast with Passo Fundo, this figure shows that Sorriso was mainly preserved and covered by native vegetation in 1985. In 2019, however, this figure shifted dramatically, having 68.6% covered by farming and 30% by native vegetation (Mapbiomas, 2021) (Table 5.1, Figure 5.6). This fact clearly shows the speed of agricultural expansion. Nevertheless, it is still somewhat a frontier because about 280 thousand hectares of native vegetation (30%) probably fall under protected areas such as legal reserves, permanent protection areas, conservation units, or indigenous lands (F. L. M. M. Freitas et al., 2018). Nonetheless, other neighboring municipalities with large native vegetation areas are suitable for crop and pasture expansion, and these expansions stem from or are related to Sorriso as an economic pole.

Figure 5.6 – Map of Sorriso - MT in 1985 and 2019 showing soy and transport infrastructure, land use and cover change.



Data show that Sorriso has a cash-crop, export-oriented model, but with crushers, biofuel factories, cotton processors, and some agri-food facilities that end up aggregating value to the local economy and promoting local development and innovation. In 2010, 15.7% of its working population was employed by the agricultural sector. Yet, a high figure compared to the 13.5% of Brazil as a whole, but lower than Balsas, for example. The gross agricultural added value of Sorriso into the local economy was 26.6% against 7.7% of Brazil in 2016, also higher than Balsas, indicating that indeed the agrarian sector is crucial for Sorriso's local economy. Its *per capita* GDP was around 45 thousand Brazilian reais (BRL) in 2016, more than double Brazil's average of 20 thousand in the same year. The *per capita* income was at BRL 988.74 monthly in 2010, higher than Brazil's average of BRL 793.87 and

slightly lower than Passo Fundo. The Gini index, showing inequality, was 0.55 in 2010, the same as Brazil at 0.55 (Atlas Brasil, 2021).

5.3.5. Bom Jesus – Piauí (PI)

Bom Jesus is a very recent soy frontier, with production starting in the 1990s and rapidly expanding from the 2000s. It is a minor soy logistics hub located in the south of Piauí state. It is a typical north-eastern, poor and under-developed town, with many social issues related to food, water scarcity, and inequality (Lopes et al., 2021).

The stickiness profile of Bom Jesus has been relatively low in its supplying relationships to export traders, as seen in Figure 5.8, even though the last years of the series show relatively high stability. The explanation for this very low stickiness profile of Bom Jesus is that, although the municipality has started a significant soy production in the 2000s, for example, 60-thousand tons in 2004 (Trase, 2020a), only in 2012 with the arrival of a Cargill soy storage and processing facility that Bom Jesus became an export logistics hub. Before Cargill's arrival, Bom Jesus supplied soy mainly to the domestic market through small and shifting local grain warehouses, which provide soy feed to regional poultry or pork production, or exported through other logistics hubs, like Uruçuí-PI or Balsas-MA.

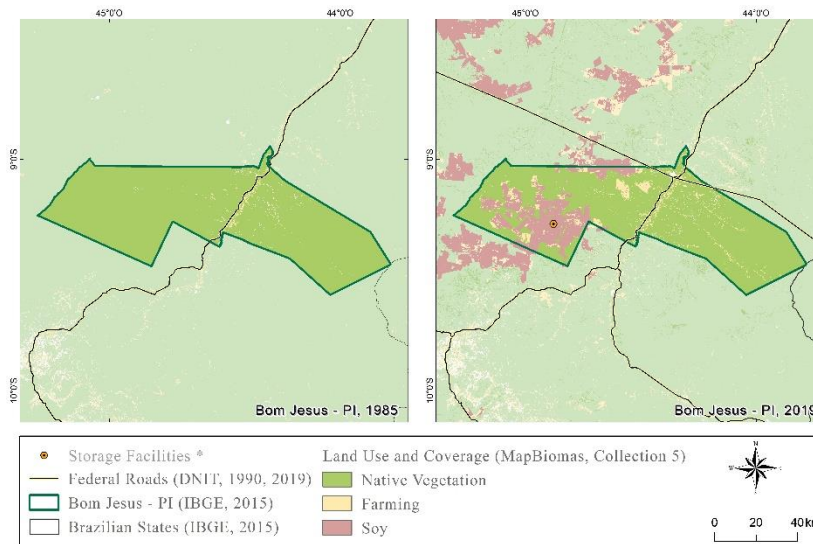
Those trading patterns appear as low stickiness or as a volatile supply network in the stickiness measurement. Bom Jesus was selected as a case study because it is located in an active agricultural frontier region where soy has been rapidly expanding, particularly after the 2000s, and has a low stickiness profile. It contrasts with

Sorriso-MT with a low stickiness profile but high development and clustering and agglomeration economies characteristics (Garrett et al., 2013a). Bom Jesus contrasts with Balsas-MA because it has a low stickiness profile, despite its location within the same agricultural frontier region.

Bom Jesus' temporal average stickiness annually calculated over 2003-2017 (TCi) is 0.28, and the 2003-2017 direct calculation is 0 (Reis et al., 2020) (Figure 5.8, Table 5.1). These figures indicate that Bom Jesus has been substantially reconfiguring its supply chain network over time and even more drastically over the entire period of 2003-2017. This fact implies a significant supply chain volatility in comparison with the other municipalities in this study. Amongst the Brazilian 468 municipalities with stickiness measured, Bom Jesus has the 222nd highest TCi (Reis et al., 2020).

Considering land use aspects, Bom Jesus had only 0.8% of its area in 1985 occupied by farming (crop and pasturelands), and 98.6% covered by native vegetation. In contrast with Passo Fundo, this figure shows that Bom Jesus was mainly preserved and covered by native vegetation in 1985. In 2019, however, this figure shifted radically but not entirely as Sorriso-MT, then having 21.4% covered by farming and 77.9% by native vegetation (Mapbiomas, 2021) (Table 5.1, Figure 5.7). This fact clearly shows the speed of agricultural expansion. Nevertheless, it is still quite a frontier in the sense that there are about 426-thousand hectares of native vegetation (77.9%) to be cleared and transformed into croplands.

Figure 5.7 – Map of Bom Jesus - PI in 1985 and 2019 showing soy and transport infrastructure, land use and cover change.



In contrast with Sorriso, these areas are mostly uncovered by environmental protection, as private properties in the Piauí's Cerrado are mandated to preserve only 30% as legal reserves. The municipality has only one protected area, the ecological station Uruçuí-Una, covering 1.6-thousand hectares within the Bom Jesus territory (ISA, 2021). These areas in Bom Jesus are likely to be converted for croplands, primarily soy, maize, and cotton, shortly given its edaphoclimatic suitability for annual agriculture (GeoLab - USP, 2017). Besides, other neighboring municipalities with large native vegetation areas suitable for crop and pasture expansion are likely to consolidate Bom Jesus as a relevant soy logistics hub in the future.

Data show that Bom Jesus has a cash-crop, export-oriented model, without adding value through processed output but rather exporting unprocessed raw beans, resulting in different food and water scarcity,

pressure for land-grabbing, and speculation, which in turn results in violent conflicts, inequality, disruption of traditional farming and livelihood systems, and other issues reported by Lopes et al., (2021).

In 2010, 24.7% of Bom Jesus' working population was employed by the agricultural sector. Yet, a high figure compared to the 13.5% of Brazil as a whole, but lower than Balsas, for example. The gross agricultural added value of Bom Jesus into the local economy was 11.8% against 7.7% of Brazil in 2016, also lower than Balsas. This number indicates that the agricultural sector is not crucial for Bom Jesus local economy, but likely the public sector and public programs for cash transfer like the *Bolsa Família*. Its *per capita* GDP was around 13.9-thousand Brazilian reais (BRL) in 2016, well below Brazil's average of 20-thousand in the same year, showing that Bom Jesus is an impoverished town.

The *per capita* income was at BRL 501.14 monthly in 2010, well below Brazil's average of BRL 793.87 and much lower than Passo Fundo, showing the substantial geographic inequality between Brazil's south and north-eastern regions. The Gini index, showing inequality, was 0.63 in 2010, above Brazil at 0.55 (Atlas Brasil, 2021), indicating wealth inequality in the municipality.

Table 5.2 – Summary of supply chain stickiness, local rural and socio-economic contexts, municipalities' profile description, and fieldwork.

Case study	Passo Fundo-RS	Balsas-MA	Sorriso-MT	Bom Jesus-PI
Temporal average stickiness (TCi)	0.79	0.79	0.68	0.28
Stickiness position in the 468 soy municipalities in Reis et al (2020)	75 th	72 nd	110 th	222 nd
2003-2017 stickiness	0	0.41	0.26	0
1985 farming area (%)	62.38	2.03	22.12	0.79
1985 native vegetation (%)	34.02	97.81	77.06	98.56
2019 farming area (%)	71.68	22.53	68.6	21.41
2019 native vegetation (%)	21.28	76.9	30	77.92
% working population employed at agriculture (2010)	3.32	17.51	15.75	24.67

(%) Gross agricultural added value into local GDP (2016)	2.23	18.49	26.65	11.82
<i>Per capita</i> GDP (2016) (BRL)	28.000,00	17.000,00	45.000,00	13.900,00
Monthly <i>Per capita</i> income (2010) (BRL)	1.068,69	531,60	988,74	501,14
Gini index (2010)	0.53	0.55	0.55	0.63
Number of interviewed actors	10	13	9	13
Participant observation events	1	1	0	1
Fieldwork days	5	7	5	7
Neighbouring municipalities visited	2	1	3	1

Figure 5.8 - Temporal stickiness profiles of the four studied municipalities.

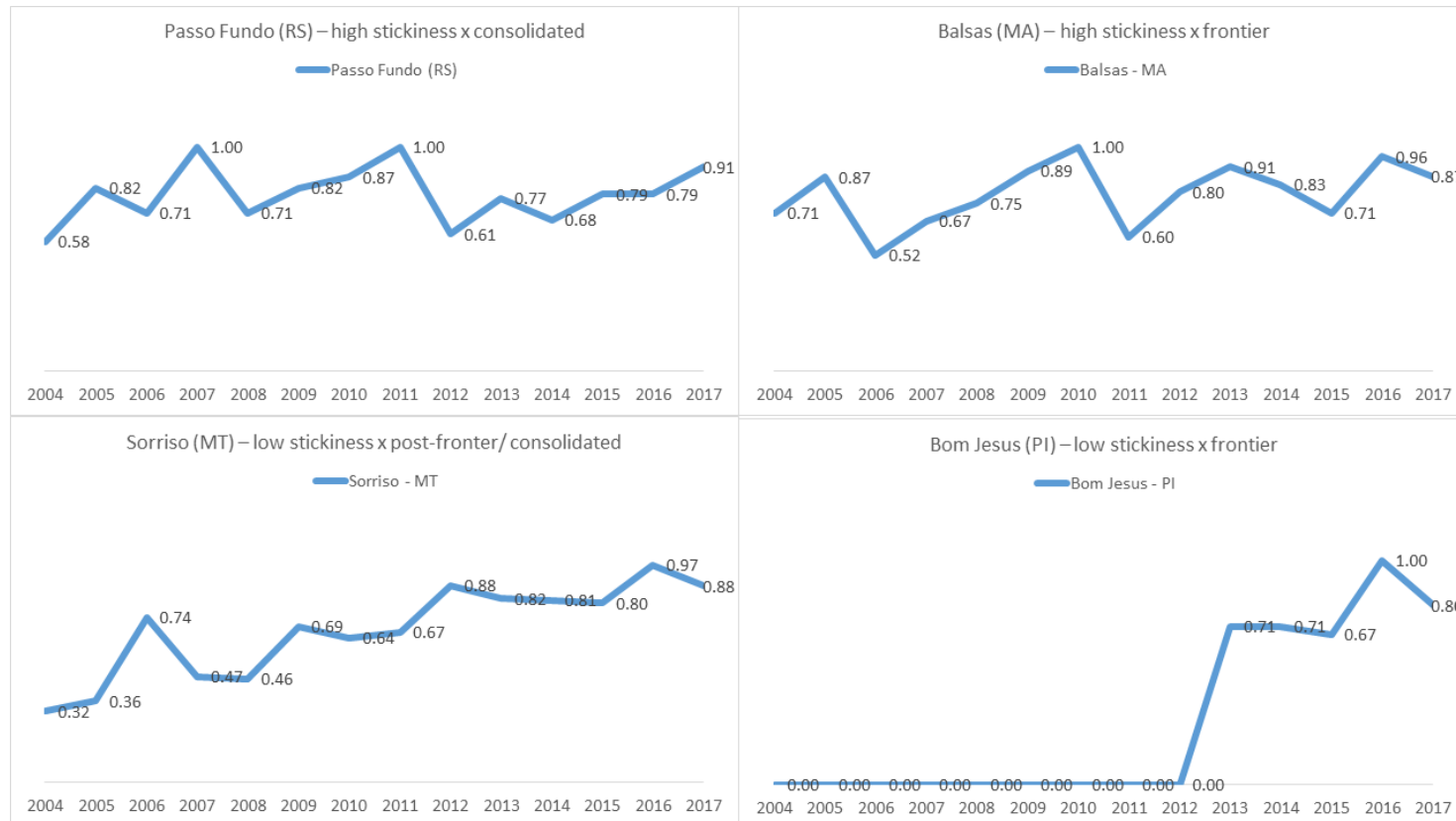
Passo Fundo (RS) shows a relatively high stickiness or soy supply chain stability over time in a consolidated agricultural region.

Balsas (MA) shows a relatively high stickiness or soy supply chain stability over time in an agricultural frontier region.

Sorriso (MT) shows a relatively low stickiness or soy supply chain volatility over time in a post-frontier, consolidated agricultural region but neighboring frontiers.

Bom Jesus (PI) shows a relatively low stickiness or soy supply chain volatility over time in an agricultural frontier region, except for the very last year when a few exporting traders have settled and dominated the market.

The sustainability of global agricultural trade: understanding stickiness in Brazil's soy supply chain



5.4. Results

5.4.1. Lock-in effects:

Lock-in effects or situations in supply chains are when firms bind certain upstream suppliers or downstream customers, either other firms or end-consumers, excluding others from access to certain benefits or enabling economic advantages (Gereffi et al., 2005). These lock-ins are similar to creating path dependencies, and they imply creating infrastructural (Wilson, 2014), financial (Bicudo Da Silva et al., 2020), technological (Vanloqueren and Baret, 2009), or institutional (Narasimhan et al., 2009; Schmitz et al., 2016) conditions that attach these actors.

In the four municipalities studied here, we found accounts and perceptions that explain the manifestation of these lock-in effects in the soy supply chain and may be associated with different development trajectories.

The silo trade-off (infrastructural lock-in)

Owning a silo on the farm is crucial in determining the stickiness of trade relations and development outcomes. The actors perceive farmers with silos to have more bargaining power. By having a silo, farmers can divide their crops into smaller shares and negotiate with as many traders as possible, breaking many deals at different times and prices to achieve higher average prices. In contrast, traders who control reception and processing facilities retain more power, especially in frontier regions.

Soybean is a perishable crop after harvest. Farmers who do not own a facility to receive, clean, process, dry, and store the grains safely after harvest, especially in regions where the harvest time may coincide with wet and rainy seasons, lose negotiating power. They need to harvest and deliver quickly somewhere. Traders know that fact and use it as bargaining power. They monitor crop growth, climate conditions and use market intelligence instruments to gauge how much of the expected harvest each farmer has already committed with other traders and themselves. As the harvest approaches, they know the farmers without access to silos and those who left specific amounts to deal in spot markets, and they reap the benefits of having ready facilities to receive those grains.

The increase of capitalized farmers owning large plots and managing their silos has been challenging the traders' infrastructural lock-in, particularly in frontiers where entrepreneurial farmers or farming companies are already arriving with access to large volumes of capital. This access to capital was not a pattern in the Brazilian

frontiers during the 1990s and 2000s. Therefore, the power traders used to have based on easy access to capital and infrastructure was not so prevalent during the 2010s frontier expansion.

More recently and from this 2010s market structure, traders have perceived silos and storage facilities as costly assets that need to be sold and outsourced, in contrast to their earlier perceptions of storage facilities as power instruments. Consequently, most traders are already trying to get rid of these facilities in the frontiers. They already have almost no facilities in the consolidated regions. In the currently active frontiers, such as the Matopiba, a few farmers consolidate large areas and gather in pool clubs or build their facilities to undermine large traders' infrastructural lock-in. This movement allows many small entrant traders to source directly from farmers and ship grains to the ports. As one frontier farmer said:

"I don't have a silo, but I wish I had because then I would have more time to think and trade my grains. I would gain up to six months after harvest to find better prices, and I would be able to sell to those opportunistic traders who appear out of nothing paying great sums because they have an empty ship waiting at the port. You know, sometimes it is costlier for a trader to keep a ship waiting at the port than paying whatever price here"¹.

¹ The first author as native speaker of Brazilian Portuguese translated literally all the direct quotes shown in this study.

A quote from another farmer reveals how determinant for a trader is its reception capacity:

“after price, the first thing I consider when dealing with a trader is its reception capacity, whether the trucks’ queue is long, how fair they use to be in classifying and qualifying my grain. If the queue is too lengthy, I may consider selling for a lower price to a nearby small warehouse that will mix my bad grains with good grains to classify as good quality, pay a fair price and receive my trucks speedily”.

This silo trade-off may be associated with different development trajectories because it relates to capital and land concentration. Regions with lower stickiness in supplying relationships with traders tend to have larger and capitalized farmers with their silos, thus closer to maldevelopment as farmers need to concentrate land and capital, acquire economies of scale, and thus break through this traders’ lock-in. The sticky farmers in frontiers are relatively smaller, without access to silos, and therefore more vulnerable to large export traders. In contrast, despite being numerous, farmers of consolidated regions gather more frequently in cooperatives, storage clubs, or even around small warehouses, thus characterizing a more inclusive development as land is more distributed. In frontiers, the farmer has either his silo or needs to rely on traders. Therefore, cooperatives are a crucial factor to break infrastructural lock-ins and lead to more land, wealth, and income distribution in the regions where they operate.

Financial and technological lock-in

In frontiers, risks are higher. Farmers usually do not have a good credit assessment. They find credit access more challenging than in stabilized regions, either from public or private banks. Because of this necessity and market gap, traders have started financing production, charging much higher interest rates that are embedded in barter deals, where they supply inputs, technical assistance and anticipate some cash in exchange for future harvests. In the end, farmers pay with bags of soybeans that must be delivered straight upon harvest. If traders perceive a farmer as too risky, few will be willing to finance him, and the interest will be higher. However, if the farmer ventures into production, he binds himself to the trader who gave him inputs and credit. Therefore, this mechanism creates stickiness. It is also described by (Bicudo Da Silva et al., 2020) as the “soybean trap”, which entails a mechanism where traders finance farmers in exchange for their future harvests and embed relatively high and binding interest rates in these transactions, thus creating farmers’ dependence.

The interviewed actors call these inputs and assistance, together with finance, “technological package”. It is a package including genetically modified seeds, technological pesticides and fertilizers, credit, assistance to use these inputs. They are supplied all together in “take-it or “leave-it” deals. This financial-technological lock-in mechanism appeared explicitly in interviews, especially in the frontier regions. This financial lock-in also tends to accentuate land and income concentration in the frontiers. It divides farmers with capital or access to regular banks and the riskier ones who rely only on traders’ finance.

Therefore, they are trapped without much capacity to negotiate better prices and deals. As a local procurement manager of a large trader explains:

“We have a financing system that we call 70-30. This 70-30 means that a farmer to obtain credit from us has to use 70% of this credit to buy our agrochemicals and fertilizers, and only 30% we advance to him in cash. Whatever the total amount of credit we give to him is quantified and put in the contract in bags of soy. So when he harvests, let's say, six months later, he pays us by giving the amount of soybean bags that was agreed, regardless of the current soy price”.

Actors also perceive cooperatives to break financial lock-ins, primarily as they can provide flexible and cheap credit lines to associated farmers based on collective funding systems. Technologically speaking, they do not control patents or specific techniques but manage to make larger purchases of technological products and therefore reduce costs for associated farmers. Also important to acknowledge is the fact that soy cooperatives are primarily found in consolidated regions. In frontiers, soy cooperatives are scarce, frequently minor, and irrelevant from a market perspective, or they appear as informal buying pools or voluntary associations. These buying pools or voluntary associations diminish information asymmetry for farmers and affect somewhat power imbalances in supply chains, acting similarly to cooperatives. However, they do not exert the same institutional roles of the cooperatives

mostly found in consolidated regions, which also bear social, cultural, and increased economic relevance.

Institutional lock-ins

The actors perceived some institutional conditions from public policies like the Brazilian Forest Code, the embargoed areas from IBAMA, and supply chain social-environmental governance initiatives, such as the Amazon Soy Moratorium (ASM), as excluding lock-ins. Traders cannot source from lands that IBAMA embargoed. The enforcement of this measure is perceived as stringent. On the other hand, the ASM is perceived as a market control initiative because it does not prevent soy from entering the market but decreases the soy prices of blacklisted farmers. As one farmer puts it:

“This soy moratorium is a thing created by European companies to lower our prices. It only benefits some. It is effective only to make my soy costlier because I have to issue an invoice with my brother’s name or sell the beans at a lower price to a non-signatory company. Then this smaller company will mix all soy and sell to any of these large signatory traders when they need. So I say this is a hypocritical law. But the embargo from IBAMA, if you have one, you don’t sell, you don’t finance, you don’t do anything. The good thing is that you can make a deal with IBAMA, restore the area and clear your name. In the moratorium, one can never be clear”.

Overall, the actors perceive these environmental governance mechanisms as factors that may hinder development because they reduce profits and expansion opportunities. They create a kind of reverse lock-in by encouraging farmers to trade with smaller companies that are non-ASM signatories, for example.

These lock-in effects ultimately increase the power of traders, thus promoting more land, income, and wealth concentration. The consolidated regions also exhibit some lock-in effects, including infrastructural, financial, and technological, as farmers mainly source all inputs and credit and trade primarily with cooperatives. Nonetheless, this lock-in is mainly based on trust and embeddedness, in opposition to the pattern found in agricultural frontiers. In the frontiers, the lock-ins are instruments of power.

5.4.2. Trust and the social embeddedness of the economy

Trust and the social structure of economies refer to the concept of embeddedness (Granovetter, 1985). These notions have been mobilized to explain supply chain or inter-firm relationships that go beyond the idea that economic action only occurs on a rational-actor basis (Beckert, 1996; Uzzi, 1997). The embeddedness of social relations in economic activity means that commercial decisions may also be taken, disregarding the profit motive. These decisions may be due to trust, family, ethnic or simply subjective preferences based on social values and norms (Bair, 2008). Here we explain some perceived factors related to trust and social embeddedness influencing the

manifestation of stickiness and potentially related to different development outcomes.

Cultural and ethnic origins related to trust and business patterns

The actors reported a cultural binding factor. For example, a farmer in a frontier region tends to trust a trader's manager or broker more and favor business deals if they emigrated from the same southern region. As a southern farmer who owns lands in the Tocantins state (Matopiba frontier) illustrated:

"In Tocantins, if I find a "gaúcho" (southern ethnic group), I try to find out from where in "Rio Grande" he came. Those people from Missões, for example, are indigenous mixed with Portuguese and Africans. They have a way to deal. Those from here (Passo Fundo), a mixture of indigenous, Germans, and Italians, deal differently. It is very different the way one or another pay you. For some of these, you can only accept upfront payment. With the others, they are more opportunistic. They will deal with you this year if it is good for them. The next year they drop you for cents and deal with someone else. If they sign a contract with you today considering soy at a given price and in six months when he needs to deliver the contract prices are much higher, they disappear from here with all the soy to sell somewhere else. There is no loyalty with some kind of guys, but others do".

In addition, here, cooperatives are perceived as a key factor because farmers tend to gather, especially in the consolidated southern regions, based on ethnic and cultural values. Actors perceive cooperatives that have sense of belonging and shared values as stronger. Furthermore, associated farmers do not tend to default on cooperatives because they know that if they trade downstream with increased prices, these profits will be equally distributed later. All in all, we found that cooperatives increase trust and social embeddedness. Consequently, they increase the stickiness between farmers and cooperatives to decrease the stickiness between cooperatives and traders as cooperatives are in a better position to negotiate. Therefore, cooperatives tend to lead to inclusive development.

Farmer profiles: urban entrepreneur and identity farmer.

Differences in farmers' cultural profiles influence relationship patterns as entrepreneurial farmers tend to be less sticky due to their opportunistic stance. In contrast, identity farmers tend to be stickier since they consider values such as trust, loyalty, and identity to guide their commercial relationships. Some farmers are identified as urban businesspersons who buy or rent land and manage it efficiently. They have complete knowledge and control of costs, technology, the inputs needed. They know the average yield of each plot in each year precisely. They measure all aspects related to production and harvest. This profile favors volatility in trade relationships as he or she is always

seeking the best price and benefit. They have no attachment to land or farming. They only rely on spreadsheets to make decisions and may quit or resume production as soon as they identify any trend. They see the value of making double or triple cropping to cover the costs and invest in the soil profile or enriching the soil's organic matter to increase soy productivity.

In contrast, there is the identity farmer. Not formally educated, this profile lives on the farm or in a small town nearby. He does not know all the costs, average yields, or productive aspects relevant to the business. He farms because that is the only thing he claims to be able to do. He mixes his life and personal costs with the farm's costs; therefore, it is impossible to disentangle his or the farm's expenditure. He tends to fail or get highly indebted because of this financial confusion. They feel attached to the land, and farming soy is part of their identity and cultural value. When asked why he continued farming even after realizing he had huge losses and that he could sell his valuable lands in the south and retire comfortably in a town, an identity farmer replied:

"I am stubborn, I love the land and farming. I can't see myself living in the town far from my fields".

In contrast, an urban entrepreneur farmer said:

"In the north of Mato Grosso where I have five thousand hectares of soy and maize rotating, if the price of soy goes below 90 reais (BRL), I stop production and rent my land to a cattle rancher who

will be happy to use my highly fertilized lands, or to a reckless soy farmer who demonstrates the capacity to pay my rent and have faith that the prices will go up”.

Trust in commercial relationships

Fear of bankruptcy: Farmers tend to dilute their deals with as many traders as possible, except when associated with a cooperative. Actors reported cases of small traders, warehouses, or cerealists that failed. Farmers only commit a large share of their expected harvests with their cooperatives. One broker said:

“It is a real risk. There is a mechanism in the Brazilian legal system called judicial recuperation, which regulates bankruptcy and allows legally declared failing companies to postpone the payment of their suppliers. Therefore farmers are becoming scarier to commit future contracts or even deposit harvested soybeans in these small warehouses or traders, fearing default”.

These cultural and ethnic factors, and trust, underpinning stickiness relates to different development trajectories because it grounds commercial relations. Commercial partnerships based on these values are long-lasting, fairer, based on mutual respect, and driven by the principle of sharing the profits and benefits reaped from the supply chain. These values indeed are found more explicitly in

consolidated regions. In contrast, in frontiers, the perception is that no one can trust anyone. Most economic actors are adventurous entrepreneurs who want to reap all benefits for themselves. There is no sense of sharing, and the intention usually is to get as wealthy and as quickly as possible, regardless of any constraint. Therefore, the perception is that commercial relationships in frontiers are always dodgier and riskier than in consolidated regions. Also, cooperatives significantly alter the trust dynamics. In addition to the fact that farmers are owners and shareholders of the cooperatives, typically, they represent the very social fabric of southern and consolidated agricultural towns. The cooperatives are part of the social and cultural life of these places. The relationships are quite personal, beyond purely economic and business ties.

5.4.3. Supply chain power and agency

In terms of supply chain power and agency, we found perceptions pointing to various sourcing strategies to increase supply chain power and control. We also found a clear perception that there is a struggle between farmers and traders to increase their share of power. Farmers gather in cooperatives, buying pools or clubs to challenge traders' power and break, for example, infrastructural and financial lock-ins created by traders to exert power. On the other hand, traders consolidate logistics corridors; invest in exclusive railways, port terminals, and other logistics facilities that can grant them control of logistics corridors. Traders race to dominate these corridors because they are crucial.

Nonetheless, farmers also have strategies to defend their positions. They use associations and lobbying groups to influence public policies, to keep logistics facilities as open, accessible, and public as possible. Supply chain power and agency is an underpinning factor of stickiness and may be associated with different development outcomes because it tends to determine, for example, how many companies and farmers will produce and trade in one or another region.

Different sourcing strategies: traders' business and geographic strategies.

Traders seek to diversify as much as possible their geographic sourcing patterns because they mitigate climate risk. For crushers and export traders, stability of supply, logistics planning, including the external demand, the program of ships, trucks availability, are perceived by the interviewed actors as the key factors to determine the business success. Therefore, if a trader concentrates its sourcing excessively in one geographic region, it is exposed to climate shocks. The more geographically widespread the trader operations are, the less climate risk it bears. Therefore, all traders seek to be in as many locations as possible, favoring those with climate stability and predictability history. That is why Sorriso and Sinop are crucial hubs for traders.

Rainfall patterns are clear and stable in comparison with other Brazilian soy production regions. The region has a long rainfall window that allows for two or sometimes even three crops a year. Riskier

frontiers tend to attract only the largest traders that can bear the risks. In years of high yields, smaller and spot market traders may come to reap the benefits of sound production, but they will only source directly from large farmers with storage facilities. In lousy crop years, only the large traders will source and potentially absorb losses with the elevated costs of maintaining idle storage facilities if the production break is too severe. As one broker said:

“Some companies need to invest in physical facilities because there are no others, and farmers don’t have facilities. These regions are normally the riskier. It is harder to get credit, inputs, everything. But some traders may have seen an advantage of pioneering and controlling the region, while others now are changing their minds and trying to get rid of their facilities because they already have good relationships in regions of good and stable supply”.

We need to acknowledge the perception of actors about cooperatives sourcing strategies. As actors reported, the cooperatives’ sourcing advantages come from their capillarity, i.e., their capacity to reach many small farmers in various regions. There are many small farmers in the southern consolidated regions, ranging between 20-100 hectares, in contrast with the northern frontiers where farmers have on average 1000-2000 hectares. The large traders have high transaction costs to engage in relationships with all those farmers. The cooperatives, in contrast, are already settled and have widespread

means of access, trust, information, knowledge, and communications with all those small farmers. Therefore, the economic relationships are social, as the cooperatives promote celebrations, gatherings, distribute profits, provide everything from farming input supplies to fuel, clothing, and groceries. In small southern consolidated towns, the cooperatives are well-respected and admired institutions determining the life and fate of the population. Everyone in these towns wants to work for or with the cooperatives. This perception is not prominent in the northern frontiers. Consequently, the power dynamics at play by large traders in the northern frontiers are different in the southern consolidated locations. The large export traders, instead of sourcing directly from farmers, source mostly from cooperatives in the south, having less power because some grown-up cooperatives are venturing even for export markets.

Knowledge and information asymmetries

Large traders monitor crop growth, climate conditions and use market intelligence instruments to gauge how much of the expected harvest each farmer has already committed with other traders and themselves. As the harvest approaches, they know the farmers without access to silos and those who left certain amounts to deal in spot markets, and they reap the benefits of having ready facilities to receive those grains. In addition, they also know the consumer markets more than farmers do. They know soy usages that the farmers still do not know. Therefore, there is a general perception that these knowledge and information asymmetries influence the stickiness of

trade relations and, thus, development outcomes. As farmers manage to group, share knowledge and information, they increase their power. As one farmer said:

“We have a WhatsApp group only amongst friends, reliable and trustworthy people where we share our trade deals and information, so that at least within the group we know when someone is making a bad or good deal. The traders share their prices with each other, why shouldn’t we do the same? We also have regular meetings, we gather to buy inputs as well, so that we can negotiate better prices”.

Cooperatives are also perceived as instruments to break through traders’ knowledge and information asymmetries once they share market information collectively.

Entry barriers from market power

The interviewed actors perceive traders as willing to create entry barriers. They control prices, practice dumping when needed, and seek to crowd out other traders from logistics corridors or regions. They may use infrastructural lock-ins to exert market power and strengthen entry barriers. The cooperatives, however, are a crucial factor challenging traders’ market power, unbalancing these power dynamics and potentially leading to different development trajectories.

Traders' business model: heavy facilities x light start-ups

Recent managerial and operation innovations have shaken the soy market in Brazil. New traders entering the market rely on very light operations and structures, deploying business strategies that have much lower costs than the traditional competitors such as the ABCD group (Oliveira, 2016; Turzi, 2017), and focusing on sourcing soy from larger, established farmers or cooperatives, or local warehouses. The interviewed actors perceive the business model of these small traders to rely primarily on finding soy and shipping it to the destination markets. This new business model has been creating volatility in trade relations as they fragment the market. Also, they operate primarily in spot markets. So while large traders bear high costs with physical facilities, providing inputs and credit to farmers, including technical assistance and monitoring teams to ensure that farmers are producing correctly and will deliver their future contracts, these new traders only come at certain market opportunities, pay higher prices than the large traders, and grab significant market shares from farmers that have their sources of input, credit and technical assistance and are free from traders' lock-ins. As a broker said:

"The big trading companies, overall, are trying to reduce their costs with physical facilities. These new start-up traders are threatening them. Take this X trader, for example, they come here paying 0.5 or 1 real (BRL) over the big traders' prices, and they buy everything that is left, without a binding contract, in our region's silos. They take everything to the port

and without all those costs that the big traders have. They are opportunistic, and they are shaking the market. I don't know how long these big traders will continue ruling things here".

Presence of cooperatives or buying pools:

Farmers use the cooperatives to break through traders' market power. In the southern and consolidated regions of Brazil, cooperatives are highly organized and significantly powerful. They rule the markets, and traders need to source from them for exports. Some cooperatives are even challenging the traders' export markets as they start to venture into exports. Farmers associated with cooperatives tend to trade most of their harvests with their cooperatives, mainly because they do barter agreements exchanging input supplies, credit, technical assistance, clothing, fuel, groceries, and whatever they may need for future harvests. Minor portions are left untraded to negotiate at spot markets and potentially benefit from market fluctuations. This pattern is mainly observed in southern consolidated municipalities.

Control of ports and logistics corridor, including access to port terminals.

The control of logistics corridors is part of the infrastructural lock-in notion. It is also a determining factor of market control because it determines which companies operate within a logistics corridor. A small warehouse or brokers can operate in the region, but the export trader will control the ports terminal. The perception by the

interviewees points to the fact that if only one trader controls a logistics corridor, the development is more concentrated. For example, the trader Amaggi owns a terminal in the port of Itacoatiara (AM). Therefore, most soy produced in the west of Mato Grosso and Rondônia is traded by Amaggi, because Amaggi controls the best logistics facility. Either Amaggi buys directly from farmers in this region or buys from brokers, local warehouses, or pools of farmers. As one broker said:

“Who has the investment in the port becomes fixed in the region, who does not have this investment is obliged to subcontract terminal’s idleness from those who have terminals in order to export”.

Also, as a local manager of trader said:

“All this production from the west of Mato Grosso and from Rondônia is dominated by Amaggi. If Amaggi does not buy this soy, it has to go through the Port of Santos, much further away and costlier than Itacoatiara”.

5.5. Discussion

5.5.1. The role of cooperatives in shaping stickiness and rural development outcomes

We found that cooperatives mediate both stickiness and development outcomes, particularly in consolidated southern regions. Frontier regions, where cooperatives are mostly absent and stickiness patterns are different, face different outcomes. Cooperatives shape stickiness because they bind upstream farmers – not by lock-ins and power dynamics as traders do, but by increasing trust and socially embedding trade and commercial relationships (see also (Ghosh and Fedorowicz, 2008; Skandrani et al., 2011; Sousa and Busch, 1998). Cooperatives increase trust and the social embeddedness of trade relations between farmers and cooperatives, who act as forms of “social” or “socially embedded” traders, thus distributing the profits and benefits of growing and trading soy.

The pattern is less sticky on the following supply chain relationship between cooperatives and large export traders than on the farmers-cooperatives links. This lower stickiness occurs because the cooperatives function as large and capitalized farmers, capable of negotiating better with the export traders. We found cases where the cooperatives themselves did the exports, where traders did not offer advantageous prices or payment conditions. Therefore, cooperatives are mediators of stickiness because, on one side, they increase stickiness by binding farmers together through trust and embeddedness. The way cooperatives bind farmers together through trust and embeddedness is extensively described by (Craviotti, 2016).

To this description by Craviotti (2016), we add the argument that this process of trust and embeddedness created by agricultural cooperatives also creates stickiness in supply chains, making trade relations more persistent over time. Cooperatives are also mediators of inclusive development by offering farmers fair access to credit, inputs, and resources (Bacaltchuk et al., 2015; Sousa and Busch, 1998).

We add to the knowledge produced by (Garrett et al., 2013b), who find that cooperatives are associated with higher soy planted areas and yields by indicating that cooperatives also substantially affect rural development outcomes. We add that cooperatives lead to higher soy yields and increased trust, stickiness, and social embeddedness of supply chains, which all lead to more inclusive development (Gupta and Pouw, 2017; Gupta and Vegelin, 2016).

5.5.2. Cooperatives, stickiness, lock-ins and supply chain power

The cooperatives as a social fabric may be characterized as a farmers' creation precisely to break through the lock-ins created by large export traders. As (Bicudo Da Silva et al., 2020) shows the financial trap, we add that cooperatives can unlock this financial trap, similarly breaking infrastructural and technological lock-ins as shown by (De Maria et al., 2020; Oliveira and Schneider, 2016; Turzi, 2017). Cooperatives may also be described as a farmers' solution to decrease traders' power and agency in the supply chain, increasing the leverage for the action of farmers, even altering the governance structure of supply chains as suggested by (Gereffi et al., 2005; Neilson et al., 2014).

Stickiness can be a relevant analytical framework because it captures the intrinsically sticky nature of the relations between farmers and cooperatives and the non-sticky intrinsic nature of the relations between cooperatives and export traders, which can be similar to large farmers' relations with traders in frontiers. Therefore, cooperatives may be a determinant factor that alters the rural development dynamic and outcomes, being a mediator of stickiness and a manifestation, i.e., cooperatives increase and induce stickiness. However, at the same time, cooperatives cannot emerge without the underpinning stickiness processes that provide the very conditions for them to emerge, namely lock-ins (or the intention to break traders' lock-ins), social trust, and supply chain power (or the intention of shifting power from traders to farmers through cooperatives). Cooperatives challenge and destabilize processes that manifest through stickiness, such as lock-ins, trust and supply chain power, altering the development outcomes that could be expectedly found for sticky or non-sticky supply chain relations.

Finally, cooperatives mediate stickiness and inclusive development. Their absence may result in *maldevelopment* as formulated and shown by (Lopes et al., 2021) in agricultural frontiers where cooperatives are absent, trust levels are perceived as low, and power is perceived as unbalanced towards export traders, who also implement lock-ins with local farmers. If stickiness can manifest these three processes, the interaction between stickiness and cooperatives may determine the rural development trajectory towards inclusive development or *maldevelopment*.

5.6. Conclusion

Here we found that cooperatives are a key mediator of stickiness processes, namely lock-ins, trust, and supply chain power. We elicited the perceptions of soy supply chain actors interviewed during fieldwork about the processes that underpin stickiness and how they may lead to different rural development outcomes through various factors such as the silo trade-offs, financial traps, fear of bankruptcy, and others. We found that the way farmers assess their options and make decisions, such as whether to build their silo, join a cooperative, trade with a risky small warehouse or take credit from a large trader, is decisive for stickiness and rural development outcomes. We found that in regions where cooperatives exist, they challenge infrastructural, financial, and technological lock-ins created by soy traders. This existence of cooperatives leads to more intensified soy production, higher yields, better socio-economic, inclusiveness, and rural development conditions.

Cooperatives also increase trust in the supply chain and alter the power dynamics, resulting in more land, wealth, and income distribution compared to regions where they are not prevalent. In that sense, cooperatives are a key mediator of the three identified stickiness processes and a key determinant of two contrasting rural development outcomes: inclusive development or *maldevelopment*. Stickiness can be used as the manifestation of these three processes to assess the potential of different rural development outcomes.

VI. Thesis conclusions

6.1. Summary and main results

This thesis aimed to increase our collective understanding of the relationship patterns in global commodity supply chains. I aimed at developing approaches for assessing how sticky, *i.e.*, stable or volatile, supply chain relationships can be, seeking to understand why and how these relationship patterns may affect sustainability governance. At a higher level, I sought to find pathways to transform global commodity supply chains into drivers of positive change. Now it is time to reflect upon this thesis' research findings and results, interpret the research outputs, and extract meaning from them to provide answers to the questions asked in the introduction.

Chapter 1 sets the context for this objective, describing the thesis outline and research approach, the theoretical and methodological foundations, and the land system and economic geography context of Brazil's soy supply chain.

Chapter 2 responded to the Introduction's questions (i) How can we analyze supply chain relationship patterns? (ii) What is the relevance of these supply chain relationship patterns for sustainability governance? And (iii) how sticky, meaning stable or volatile, can these supply chain relationship patterns be?

To respond to these questions, I conceptualized stickiness in commodity supply chains using various theoretical foundations. I formulated a method to observe and measure these supply chain relationship patterns using temporal network analyses. I empirically analyzed the stickiness concept and method on Brazil's soy supply chain between soy production and trade municipalities, export

traders, and consuming countries. This empirical operationalization was successful. It showed relevant patterns that required more investigation. For example, it demonstrated that soy traders with the largest market share are geographically stickier. Stickier traders in their sourcing relations also show higher soy-deforestation risk and are signatories of zero-deforestation commitments (ZDCs).

Nevertheless, I did not assess causal mechanisms in this chapter. A deeper assessment of potential causes of stickiness and a more robust appraisal of the interactions between stickiness patterns, ZDCs, and deforestation were still required.

In Chapter 3, I responded to the question (iv) What are the underpinning factors or predictors of this supply chain stickiness or non-stickiness? To find these answers, I moved to address part of the causality gaps indicated in Chapter 2. I investigated the potential causes, predictors, or influencing factors of stickiness. For this, I conducted fieldwork in Brazil across six soy producing regions, interviewed and consulted 127 soy supply chain actors, including farmers, local managers and national-level directors of export traders, small warehouses and cerealists, input suppliers, leaders of soy associations and unions, soy and infrastructure lobbyists, managers of logistics companies, state-level policymakers, agronomic consultants, specialists, academics and researchers. From this field experience, I collected the perceptions of these actors on factors determining and predicting stickiness. Together with some quantifiable variables, I ran a historical random forests model (HRF) to evaluate the predictive

capacity and the mean marginal influence of these variables on stickiness.

The direct answer to question (iv) is: several factors, perceived by actors and some of them also tested by the HRF, theoretically grouped as economic incentives, institutional enablers and constraints, social and power dynamics, biophysical and technological aspects influence, predict and determine the stickiness between soy municipalities and export traders.

Nevertheless, in this Chapter, I analyzed these factors as static structural determinants underpinning stickiness. I did not inquire about some crucial processes that dynamically influence stickiness and potentially affect the interactions between stickiness patterns and sustainability governance. They were mainly lock-in effects, trust, and supply chain power. Thence, the investigation needed to continue.

In Chapter 4, I responded to the question (v) what are the interactions between these supply chain relationship patterns and environmental governance? For finding these answers, first, I deepened the theoretical review, seeking elements allowing the framing of stickiness as a proxy for these three dynamic processes elicited in Chapter 3. They are lock-in effects, such as infrastructural, financial, technological, and related to consumer-preferences; trust and the social embeddedness in trade relations; and, finally, supply chain power and agency dynamics. In other words, we found evidence suggesting that these three processes may manifest through stickiness, which thus is a quantifiable pattern as measured in Chapter 2. Second, I analyzed the relationships between stickiness patterns

from traders' sourcing operations and (i) their likelihood to adopt zero-deforestation commitments (ZDCs), and (ii) the effectiveness of these commitments. Assessing this interaction addresses the question of stickiness relevance for sustainability governance.

From this conceptual understanding of stickiness processes and using panel regression analysis, I found that although stickier traders are more likely to adopt ZDCs, they also appear to have a higher deforestation risk than other traders (as indicated by the level of soy and territorial deforestation in their sourcing regions). Therefore, some links were more deeply established between stickiness and sustainability governance using the soy ZDCs case. Yet, exploring the implications of stickiness and its relationships with rural development outcomes were missing. Therefore, the direct answer to question (v) is that stickiness tends to increase the traders' likelihood of adopting a ZDC and increases their deforestation risk, thus potentially jeopardizing companies' sustainability initiatives.

In Chapter 5, I responded to the question (vi) What are the implications of these supply chain relationship patterns for local development? To do this, I selected four municipalities that I visited during fieldwork in Brazil in 2019, characterized by a 2x2 quadrant. One municipality had a relative (compared to the others) high stickiness in its supplying relations with traders and was located in a consolidated agricultural region. One municipality had low stickiness and was located in a region also characterized as consolidated. Then one high stickiness municipality in a frontier and one low stickiness also in a frontier. From this investigation, I learned that agricultural

cooperatives are key mediators of the interactions between the three stickiness processes of lock-ins, trust and supply chain power and agency, and whether these interactions in the form of feedback loops lead to inclusive or not *mal-* (excluding) development. I found that cooperatives are farmers' creations to undermine export traders' lock-ins, to increase trust and social embeddedness in supply chains, and alter unbalanced power dynamics. Therefore, cooperatives increase the stickiness in one part of the supply chain, *i.e.*, between farmers and cooperatives, and decrease the stickiness in the next part, which is the relations with export traders. Thus cooperatives and stickiness result in different rural development outcomes, as cooperatives interacting with stickiness processes may lead to inclusive development. In contrast, the absence of cooperatives and the incapacity of farmers to influence stickiness processes may lead to *maldevelopment*. Thus, the direct answer to question (vi) is that cooperatives and stickiness combined have relevant implications for landscapes, determining further development and land use trajectories and outcomes.

Finally, this thesis has increased our knowledge of the dynamics, processes, and factors underpinning and determining relationship patterns in global commodity supply chains. Therefore, it has identified policy opportunities and levers for designing and implementing sustainability governance initiatives, either public or private, mainly related to land use and land use change. This knowledge contributes to answering my primary question raised in the Introduction, 'how can we understand and interpret global commodity supply chains to change them into drivers of positive social and

environmental transformations?’ The direct answer is that we need to consider and study the relationships embedded in global commodity supply chains, including systematically observing and measuring their patterns. Moreover, we need to increase the transparency of our supply and value chains, particularly our food and natural resources chains. The opacity of global value and supply chains does not interest the well-being of humankind. By studying the relationships embedded in supply chains, their causes, determinants, interactions with sustainability governance initiatives, and implications for land use and development, we learn about relevant levers for systemic transformation.

For example, by knowing that infrastructure is a crucial determinant of sourcing patterns, governments may plan infrastructural development, including social network considerations. In addition, by knowing that trust or distrust in trade relations and networks may be crucial for defining business expansion and investment decisions, companies may include measures to increase confidence in sourcing relations for sustainability initiatives. Finally, this knowledge can be transferred to analyze any commodity supply or value chain.

6.2. Limitations and ways forward

This thesis has several limitations. They can be grouped in terms of methods, data, scale, situated-knowledge biases, stickiness dimensions, causality, and endogeneity. Here I reflect upon these limitations and potential direct ways forward that can be implemented in the future to address them. I did not implement these potential “ways forward” in this thesis because they are out of scope or because I did not have the time, energy, or capacity.

6.2.1. Methods

As exposed in the Introduction, subsection 1.5, the methods involved in this thesis are pretty novel, particularly their application for supply chain and trade relationships. Here I used a mix of qualitative and quantitative methods. I aimed to uncover and explore relationship patterns, causal mechanisms, perceptions, factors, and predictors using methods ranging from longitudinal or temporal network analyses, including graph theories, passing through random forest regressions, to semi-structured interviews and fieldwork. If these methods did not allow me to make causal assertions, they provided me with opportunities to conduct exploratory analysis opening new paths for future research. They also led me to elicit potential causal mechanisms that, although not firmly proven, at least were observed and identified.

Spatial-temporal data are dynamic, requiring methods to capture the lagged effects of factors and the influence of processes over time. Yet, these lagged effects are not fixed. For example, I knew from the

field that some variables analyzed in Chapter 3 could be lagged in one, two, three, or even five years because of different aspects. In the Matopiba frontier, where Balsas and Bom Jesus are located, farmers reported getting at least one crop break every three to five years due to rainfall shortages. Therefore, I could have sampled the Matopiba frontier municipalities and lagged the biophysical variables differently than in other regions. However, I would be diving into deep regional details that would prevent me from seeing the bigger national soy supply chain picture.

This type of trade-off happened with other variables that would also manifest differently across regions. I decided to keep the national-level consistency and assess the overarching effects of the variables on national-level stickiness. One potential solution for these trade-offs is breaking the universe of Brazil's soy supply chain into regional samples and implement many random forests models with varying configurations of variables and time lags. Doing this was not my expertise nor interest.

In principle, these mixed qualitative and quantitative methods applied to the land system and social sciences allow exploring phenomena through various angles, showing and underlining multiple nuances and aspects that generally would pass disregarded by more traditional methods. Therefore, if the choice for a combination of multiple methods seems weak in terms of finding and asserting causality, it is strong in the sense that it allows a more unrestrained exploration of the real world. It permits grasping a broader spectrum of factors and dynamic processes. Most importantly, this mix of

methods allowed me to elicit the interactions, feedback loops, and relationships between these multiple factors, processes, and dimensions. Thus, it gave me the capacity to interpret, explain, and make some sense of them. I would suggest other researchers conduct more profound stickiness assessments with more robust causal methods as potential ways forward.

For example, Tom Snijders, a Professor of the Universities of Groningen and Oxford, designed a model called *Siena Model* to assess actors' behaviors and causality in longitudinal social networks data using graph theories. Structural equation modelling (SEM) approaches also seemed quite promising as a multivariate technique to analyze causal relationships. Bayesian networks could also be explored to assess supply chain network relationships. I studied all these approaches but did not implement them in the end. I understood that going deep in computational learning and probabilistic models was not my focus nor interest. There are, however, large open fields for researchers willing to use these methods.

Data.

The fundamental data used in this thesis are relatively novel. The spatially explicit supply chain data provided by Trase enabled me to construct a network of supply chain relationships where the municipalities of soy production and trade, the export traders and consumer countries were all nodes interconnected by linkages. As explained in the Introduction (Subsection 1.4), there were no subnational level trade data linked to environmental impacts before Trase.

In addition, the availability of this subnational trade dataset, with this level of granularity and the temporal dimension, *i.e.*, trade transactions recorded almost daily by trucks entering traders silos or crushers and then being exported, allowed me to analyze the configuration and reconfigurations of these trade relations and to understand their geographic relations.

This novel dataset is robust for allowing this network reconstruction and appraisal. In contrast, the absence of other supply chain data with the same spatial granularity and temporal length makes it difficult for stickiness analysis to be conducted and compared with other supply chains. The novelty also implies an absence of other studies, approaches, and methods from which this thesis could benefit and learn. Therefore, given the novelty of the data, this thesis navigated into new and unexplored waters, using various methods and adaptations to explore, inquire, understand and explain relationship patterns emerging from this subnational trade dataset.

As ways forward, these data are evolving rapidly with new mobile phone Apps designed to assist consumers in acting both as users and collectors of supply chain information. With these Apps, researchers will deepen the granularity of supply information, knowing, for example, where and when a product was bought and consumed. In addition, subnational governments like Brazilian states are slowly increasing transparency of data such as deforestation permits, land registries, and cattle movement. These emerging datasets will allow for deeper and more accurate network reconstructions, enabling us to

understand relationship patterns, the causality of behaviors, and changes over time.

6.2.2. *Scale*

Scale is a limitation of this thesis by both being too large and too narrow at the same time. The scale is narrow because I could only assess Brazil and the soy supply chain in this thesis. Other soy producers like Argentina, Paraguay, the United States, Russia or China could and should have been assessed. For example, other supply chains, such as beef, cocoa, maize, cotton, or coffee, also could and should be assessed for stickiness. However, spatial-temporal data at the subnational level and prolonged periods are unavailable for these countries and supply chains. This data availability justifies the choice for Brazil's soy supply chain.

Nevertheless, Brazil is today the largest soy producer and exporter in the world. Much of what happens in the soy supply chain stems from Brazil or is influenced by it. This limitation of the scale at the country level allows for a deeper understanding of the social network relations embedded in the soy supply chain. Nevertheless, I also see the scale as limited because I identified and described at least six soy production regions that exhibit different social, economic and environmental profiles, making soy relationships significantly different across them. If on one side, the soy supply chain assessed only in Brazil seems too narrow because other countries were not, it is also potentially too large. Brazil is the largest soy producer and exporter and a continental country comprising six soy regions with various characteristics. Each

region would require in-depth analyzes and samples to appropriately comprehend its angles, processes, and nuances. Therefore I suggest as ways forward assessing the stickiness of other supply chains, countries, and smaller supply networks, for example, those between beef farmers and slaughterhouses in a particular region or subnational jurisdiction.

6.2.3. Situated-knowledge

It is relevant to underline the role my biases as a Brazilian, original from a soy-producing town where this crop is quite relevant for the local economy, may have played in this thesis. In addition to growing up in agricultural countryside towns in Brazil, I also worked for almost four years at a Brazilian NGO dedicated to environmental research and policy in the Brazilian Amazon and Cerrado biomes. For those two reasons, I had access to supply chain actors using my personal, family, and professional networks that otherwise I would not have. Additionally, I was educated in Brazil until my bachelor's degree, speaking Brazilian Portuguese as the primary language, including the accents, oralities, and subtleties of the countrymen's spoken language. These factors granted me the opportunity to engage more deeply with fellow citizens, traditional farmers and uneducated people that otherwise would be reluctant to speak to someone identified as an "outside and urban" researcher.

Naturally, these advantages also carry disadvantages. For example, a foreign investigator would probably see the same things differently, stress other points imperceptible for me, or even choose other

geographic directions and locations to explore, considering he or she would have an open book to explore. Nevertheless, as far as possible, I sought to mitigate these biases by going to locations that I had never been to and talking to entirely different people from my cultural background and social networks. I also used snowballing techniques to connect with supply chain actors that were referred by other supply chain actors and not only by my networks.

6.2.4. Stickiness dimensions

In Chapter 2, I defined conceptually and analytically three dimensions characterizing stickiness, namely persistence, resistance to shocks and recovery from shocks. However, in Chapter 2 I observed and measured only the first and most elementary dimension: persistence. I did this because despite being able to conceptually propose and describe these multi-scalar and non-exclusive dimensions, I could only devise methods to measure the persistence of supply chain relationships, which is the observation and quantification of these patterns using temporal network adapted metrics, as explained in Chapter 2. I did not have the time, energy, and capacity to develop methods further to identify shocks affecting supply chain relationships over time, isolate and evaluate their effects, and estimate the resistance and recovery levels of supply chain networks and trade relationships.

Consequently, this thesis misses a critical development: a methodological design and empirical analysis of these other dimensions of resistance and recovery. Therefore, I recommend that

further stickiness research target these two other dimensions since the first dimension of persistence is relatively more established than the other dimensions. Again, methods like the *Siena Model*, Bayesian networks, or structural equation modelling could be used for this purpose. I already identified their potential capacity but was unable to implement assessments with these methods fully. Yet, other more traditional methods for shock identification and measurement of effects are possible, such as longitudinal regressions and other econometric models.

Currently, I have an index capable of showing the persistence levels of trade networks. Suppose I had indices capable of showing the resistance and recovery levels from shocks of supply chain networks. In that case, I could expand this thesis to inquire predictors and influencing factors of resistance and recovery (as I did in Chapter 3 for the persistence dimension of stickiness), to investigate the relationships and interactions between resistance and recovery of supply networks with policy interventions (as I did in Chapter 4 using persistence and zero-deforestation commitments), and to analyze the rural development outcomes from varying levels of supply network resistance and recovery (as I did in Chapter 5 with persistence).

Furthermore and freely reflecting, since I identified these primary processes that underpin and may manifest dynamically through stickiness, or at least through the persistence dimension of stickiness that was measured in this thesis, namely lock effects, trust, and supply chain power and agency dynamics, potential ways forward could be related to the design of “sub-stickiness” components or indices. If

future stickiness researchers can devise methods to quantify the levels of stickiness due to lock-ins, trust, power, and agency, we would have components of stickiness resulting in overall stickiness. This methodological development also appears relevant.

6.2.5. Causality

One fundamental aspect of this thesis was its exploratory nature. I sought by various means and at different times along this thesis' journey to elicit causal mechanisms and attribute causality after learning and describing basic processes and dynamics. However, I was unsuccessful to go beyond local predictors, influencing factors, structural determinants, dynamic underpinning processes, and interactions with policy interventions and rural development outcomes as identified and described in Chapters 3, 4 and 5. Robust and proper causal attribution was not possible or achieved yet.

The reasons for falling short of this objective so far relate to some factors. First, the novelty of the data and methods used here made it more complex to go deeper into causal investigation and attribution. I would need another set of methods and data to go beyond observing and calculating persistence in supply chain relationships. For example, I would need to have soy farm-gate prices at longer periods and for more municipalities. I would require more data on infrastructural facilities, including current and projected expansions.

Second, commodity supply chains are still largely opaque, despite Trase's data. Although Trase is a crucial breakthrough in supply chain transparency, we still have a long way to go to increase transparency

in financial flows, other supply chains, and fiscal policies affecting trade flows, to name a few. Third, I analyzed trade relationship patterns and changes, focusing on factors and processes beyond economic drivers and rational-actor theory assumptions. This thesis involved subjective, social, subtler, and often unquantifiable aspects such as trust, ethnic links, and the power exerted by large exporting traders or banks on supply chains and how they implement lock-ins. It is a real-world analysis where I could not easily identify and isolate factors to estimate their individual impacts without too significant uncertainties that would reduce explanatory power. These aspects make causal attribution more complex and impossible to be achieved at this moment.

6.2.6. Endogeneity

The issue of endogeneity is common in research involving data analyses. Endogeneity happens when unobserved and unaccounted factors influence a variable in the analysis. In this stickiness analysis, endogeneity manifests through more or less persistent trade relationship patterns measured by the stickiness index. This non-persistence may be a result of an issue internal to the data. For example, some municipalities did not produce and trade soy in some years. If a supply network disappears from one year to the next simply because the trade partners ceased to trade, be it due to a crop failure for drought or a business decision by any export trader, the stickiness index measured over these two years goes to zero, indicating a complete volatility or non-persistence of the supply network.

However, if a supply network between one municipality and a set of export traders changes to a completely different set of traders, the stickiness index also goes to zero, likewise indicating complete volatility or non-persistence of the supply network.

In this example and this thesis, it is clear the presence of endogeneity in the data. However, two things must be considered for reflection. First, the stickiness index conceived and implemented in this thesis does not aim to explain and measure the cause of persistence or non-persistence. It aims to show and expose these patterns of persistence or non-persistence in quantitative terms. The mere disappearance of trade links over two consecutive years leads the stickiness index to the same value of a complete reconfiguration because it reflects a reconfiguration.

Nevertheless, the index fulfills its objective as it indicates complete volatility or non-persistence of a given supply network, be it for changing to an entirely new set of export traders or for the complete interruption of the supply network. In both cases, there is volatility or non-persistence, and the stickiness index is practical to point this volatility out. Causal investigations seeking to explain why there was volatility or persistence in a given supply network must be conducted to find the reasons for change or permanence. An initial assessment is looking at the supply network and observing whether it has changed to a new network of traders or ceased to exist. Then, a second step is inquiring more in-depth infrastructural, economic, social, power, and agency motives for change or permanence, as conducted in chapter 3 on the observations made by chapter 2.

Moreover, chapter 3 filtered out the municipalities with stickiness values of 0 due to the interruption of trade links. Consequently, while chapter 2 shows the stickiness patterns of 468 Brazilian soy municipalities or logistics hubs, chapter 3 analyzes the potential causes and predictors of stickiness on a sample of 68 municipalities. This sample was constructed because we were not interested in learning the causes of trade interruption, but rather the causes of the reconfiguration of trade networks that continued to exist over time but congregating different actors over years.

6.3. Implications for sustainability governance and policy

This thesis increased our knowledge of supply chain functioning, particularly relationship patterns. By knowing more about how supply chain networks may reconfigure by the influence of the factors and processes described here, such as economic incentives, institutional enablers and constraints, social and power dimensions, biophysical and technological aspects, including lock-in effects, trust, power and agency dynamics, researchers and policymakers can better predict how volume may restructure and adjust in the face of interventions. Supply chain actors have business models and sourcing strategies that may be opaque. However, using stickiness analysis, we can elicit these patterns and behaviors by looking at historical patterns and project the supply chain reconfiguration or consequences in the face of similar changes or interventions.

This knowledge, thus, may contribute to the design of public policies for territorial planning, for example, that generally do not

consider companies' geographic sourcing patterns. In other words, territorial planning may consider why companies prefer to locate and source consistently from specific regions while others prefer to source volatily.

For private zero-deforestation commitments (ZDCs), as another example, one can know that it is elementary for non-sticky companies to commit since they already have a volatile sourcing pattern, meaning that they can move away from deforestation-risk areas. On the other hand, sticky companies tend to be more reluctant because, historically, it has been more difficult for them to move territorially. Therefore, stickiness knowledge may contribute to designing targeted interventions that consider the company's geographic relationship patterns and propose different approaches to each. I also found that the power and agency disputes within supply chains affect and are affected by stickiness.

This feedback loop between agency and stickiness affects the capacity of companies, especially soy export traders, to implement their ZDCs. For instance, interventions designed to increase the agency of farmers and cooperatives, if potentially positive from social and economic justice points-of-view, may hinder the capacity of traders to influence their suppliers towards zero deforestation. In contrast, we must acknowledge that the capacity of traders to deliver zero-deforestation lies more on their infrastructural decisions, *i.e.*, where they decide to set up a silo, refinery, or crushing facility and, therefore, the signals they issue to actors on the ground, than what they demand from their suppliers (farmers). Once farmers are occupying and

producing on land, and supplying to value chains, they tend to clear whatever they have a legal right to do and expand production. Therefore, traders have more agency and impact on land use decisions when they locate facilities. This decision tends to encourage or discourage actors seeking new frontiers to expand beyond their actual farms.

Despite these potential implications, some questions remain. For example, what is the role and impact of shocks? Shocks like unpredicted climatic events, changes in transportation infrastructure, demand shocks reflecting either on prices or changes in consumer preferences, and policy interventions can all affect stickiness patterns. In this thesis, I conceptualized and characterized three dimensions of stickiness. Chapter 2 laid out persistence, resistance, and recoverability from shocks as multi-scalar and non-exclusive characteristics of supply chain stickiness. Nevertheless, I could not profoundly assess the occurrence and impacts of shocks on stickiness patterns. The remaining questions related to shocks are the roles and implications of different shocks on stickiness and supply chain reconfiguration.

Furthermore, what levers do policy interventions have to steer sustainability in supply chains? In this thesis, I identified several of them: economic incentives, institutional enablers and constraints, social and power dimensions, and biophysical and technological aspects. However, we researchers still do not know which levers would be more effective and efficient to deliver sustainability outcomes. Therefore, we need more policy analyzes linking supply chain

interventions and land use outcomes. More specifically, we need policy analyzes that consider causal mechanisms and the role of relationship patterns in supply chains in generating social-environmental outcomes. More broadly, I re-emphasize the same question I asked at the beginning of this thesis: how can global commodity supply chains promote sustainability?

VII. References

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VIII. Appendixes

List of appendixes:

Appendix 1: Supplemental Information of "Understanding the Stickiness of Commodity Supply Chains Is Key to Improving Their Sustainability".

Appendix 2: List of places visited at fieldwork and the number and type of interactions.

Appendix 3: Contextual characteristics of logistics hubs scanned for fieldwork.

Appendix 4: Additional characteristics of logistics hubs scanned for fieldwork.

Appendix 5: Spatial-temporal potentially predictive variables of stickiness at the municipality (logistics hubs) level in each year (complete version of Table 3.1 in the main text).

Appendix 6: Robustness analysis comparing the predictive capacity of stickiness using four random forests methods.

Appendix 7: Checking for multicollinearity amongst Historical Random Forests Model – Correlation matrix.

Appendix 8: Checking for multicollinearity amongst Historical Random Forests Model – Variance Inflation Factor (VIF).

Appendix 9: Results from the pooled (non-historical) continuous random forest model (Z_hrf_nI).

Appendix 10: Results from the historical boolean random forests model (Z_hIb).

Appendix 11: Interview guide.

Appendix 12: Correlation matrix between all variables.

Appendix 13: P-values for the correlation matrix in table Appendix 11.

Appendix 14: Selected photographs from the field.

Appendix 15: Supplementary material – The influence of company sourcing patterns on the adoption and effectiveness of zero-deforestation commitments in Brazil's soy supply chain.

Appendix 16: Supplementary material – How supply chain relations influence development outcomes: The case of soy in Brazil.

8.1. Appendix 1 - Supplemental Information of Understanding the Stickiness of Commodity Supply Chains Is Key to Improving Their Sustainability.

Adapted from: “Reis, T.N.P. dos, Meyfroidt, P., zu Ermgassen, E.K.H.J., West, C., Gardner, T., Bager, S., Croft, S., Lathuillière, M.J., Godar, J., 2020. Understanding the Stickiness of Commodity Supply Chains Is Key to Improving Their Sustainability. *One Earth* 3, 100–115. <https://doi.org/10.1016/j.oneear.2020.06.012>”.

Supplemental Data Items

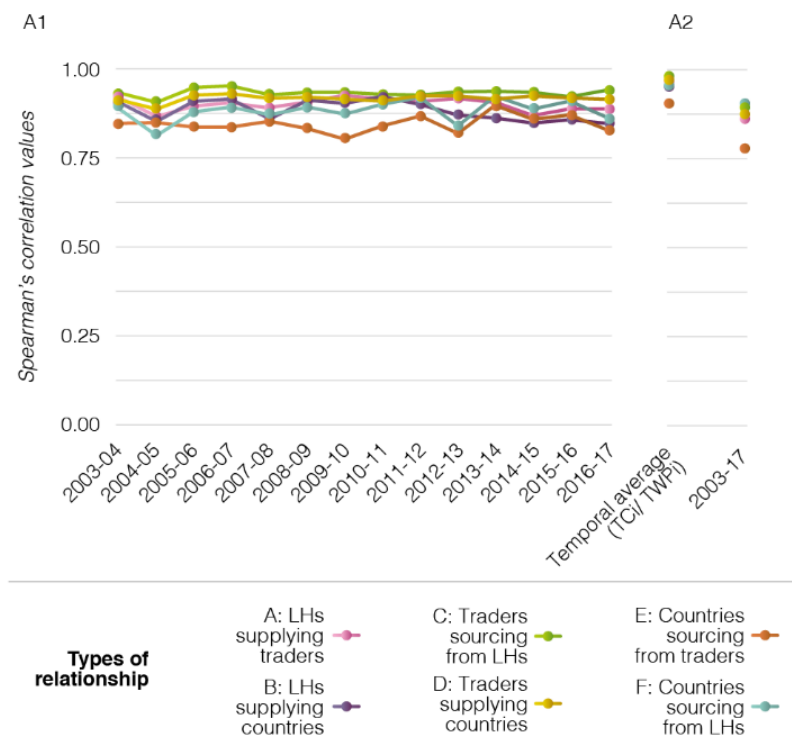


Figure S1. All measurements of stickiness on trade linkages (C_i) and flows (WPI) are strongly and positively correlated, but also provide independent

and complementary information. This complementarity justifies the choice we made of decomposing trade into linkages and flows. The panel A2 shows the correlations between TC_i and TWP_i and the correlations between 2003-2017 C_i and 2003-2017 TWP_i .

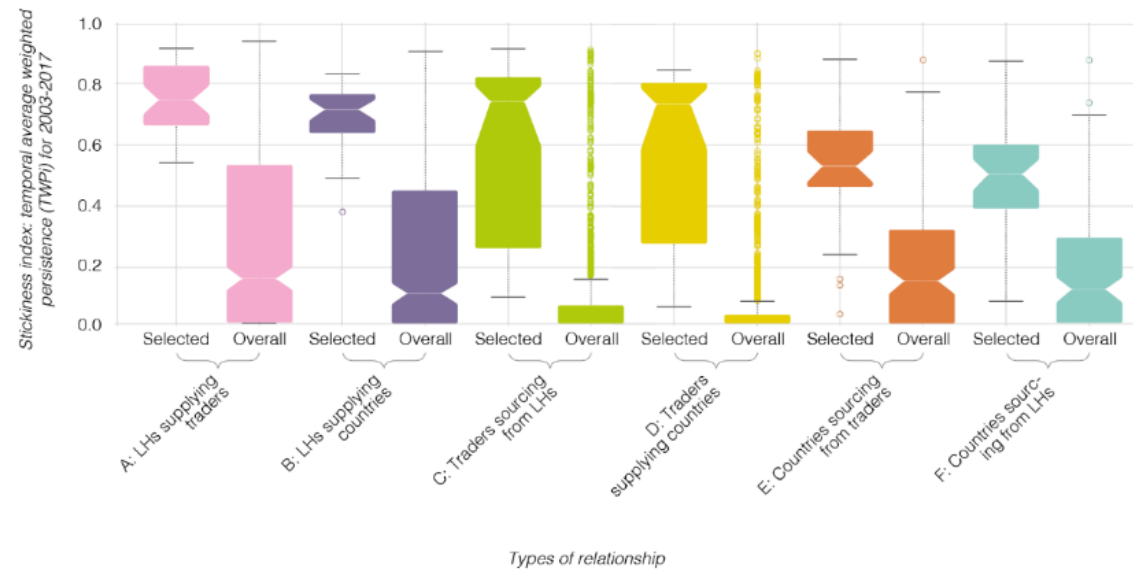


Figure S2. The overall distribution of stickiness measured on the weighted network (soy flows) (TWPi, Eq.6 in *Experimental Procedures*, main text). In the boxes identified as “Overall”, we see that traders are the least sticky group in the Brazilian soy supply chain. However, if we look at the traders identified as “Selected”, they are stickier. In the boxes identified as “Selected”, we subset logistics hubs and traders that commercialized at least 1% of the total soy volume in any year after 2008, and countries that imported at least 0.5% of the total soy volume in the same period.

We see that the “selected” traders, logistics hubs, and countries are stickier overall. This figure complements Figure 3 on the main text by providing the same type of information but measured on soy flows configuration instead of linkages. The bars in the boxplots represent quartiles. The horizontal bar inside the colored range indicates the median. The upper and lower ranges indicate the 25% and 75% quartiles, respectively. The upper and lower black lines indicate the max and min values.

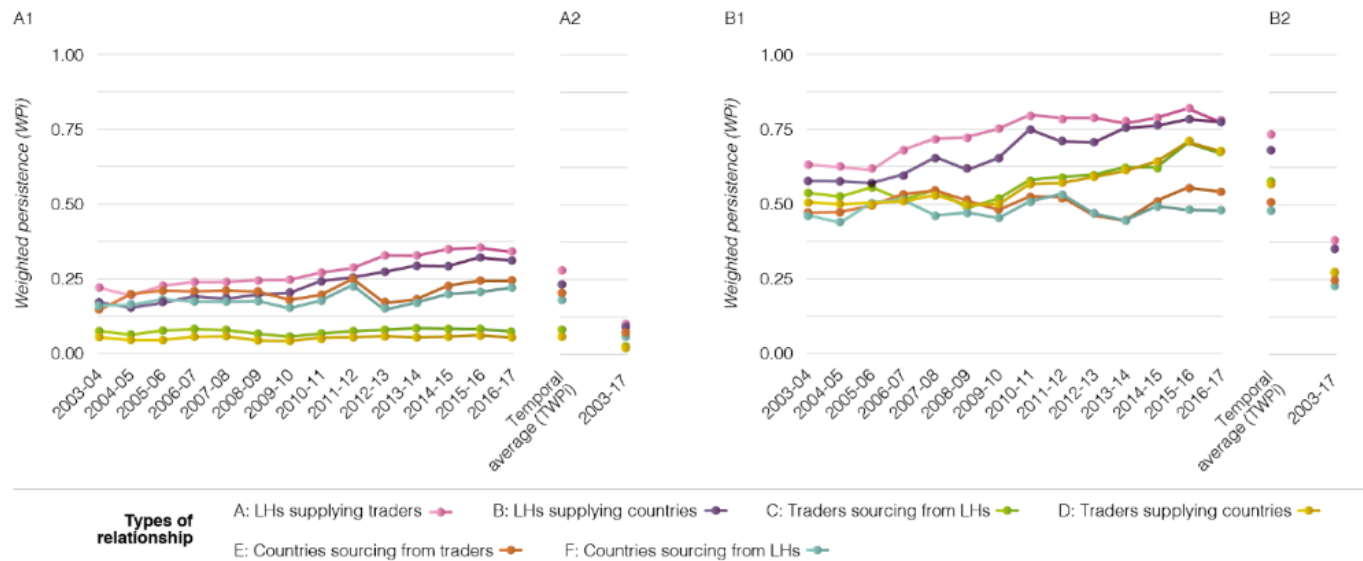


Figure S3. Temporal profile of stickiness measured on the weighted network (soy flows) (WPI and TWPI, Eq.5-6 in *Experimental Procedures*, main text). In A1-2, LHs are stickier than others in both types of relationships. Nonetheless, in B1-2 the selected traders sourcing from LHs show higher stickiness than the overall group in A1-2. The figures A2 and B2 complement the temporal profiles by showing the temporal average (TWPI, Eq.6 in *Experimental Procedures*, main text) and the WPI calculated for the comparison between the 2003 snapshot with the 2017, instead of for each subsequent biannual snapshots. The same type of figure measured on linkages is presented in Figure 2.4, main text.

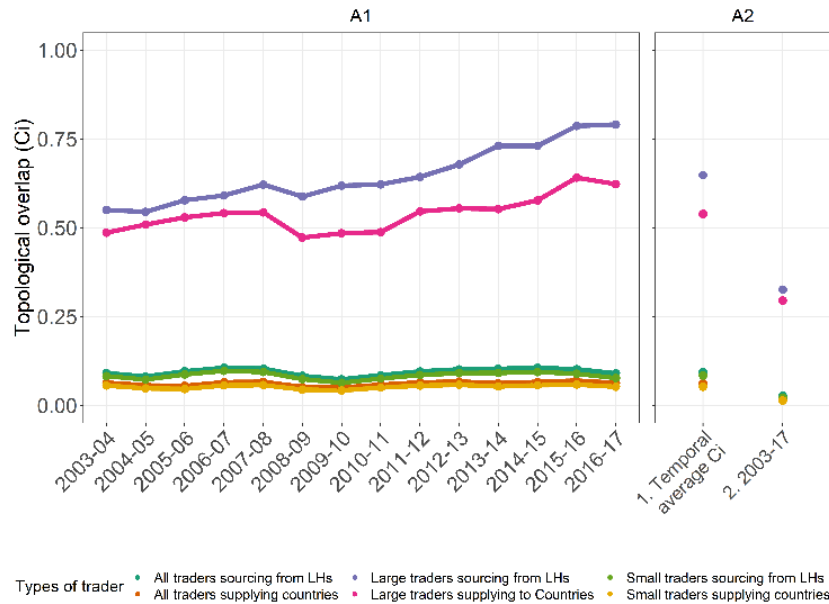


Figure S4. Temporal stickiness profile of traders. Measured on the configuration of commercial linkages of traders (C_i and C_m ; Eq.1 and 3 in Experimental Procedures). The large traders (largest market-share, $n = 31$) sourcing from LHs show higher stickiness than the overall group of traders ($n = 1,709$). The group of all traders ($n = 1,709$) shows a similar temporal stickiness pattern of small traders ($n = 1,678$). This figure represents a specific cut to focus on different categories of traders, complementing Figure 2.4 in the main text. The Panel A2 shows the temporal average (TC_i ; Eq.2, *Experimental Procedures*) stickiness, and the C_i calculated for the comparison directly between 2003 and 2017, instead of for each consecutive biannual snapshots compared as in Panel A1.

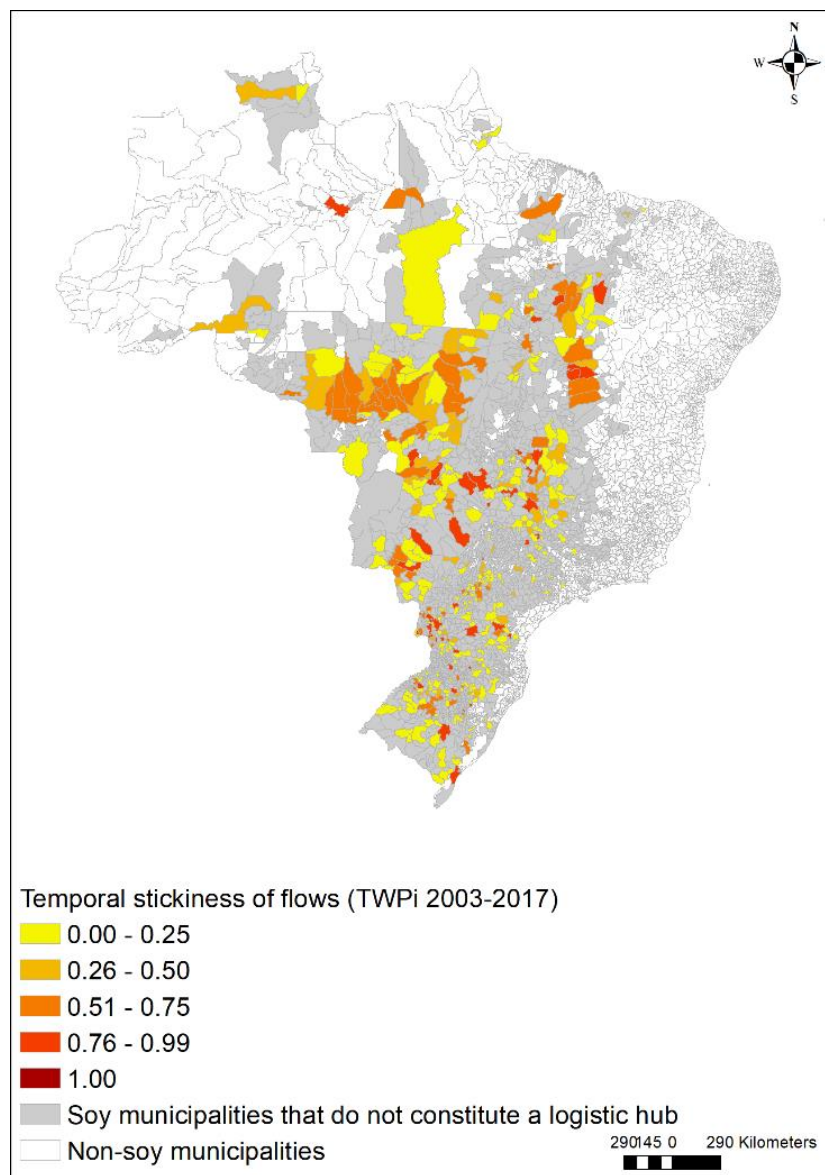


Figure S5. Spatial distribution of stickiness measured on the weighted network (soy flows) between Brazilian soy logistics hubs and traders. A map with stickiness measured on linkages configuration displays similar patterns on the main text (Figure 2.6). Municipalities in green produce soy, but this soy is bought by traders through one of the logistic hubs municipalities.

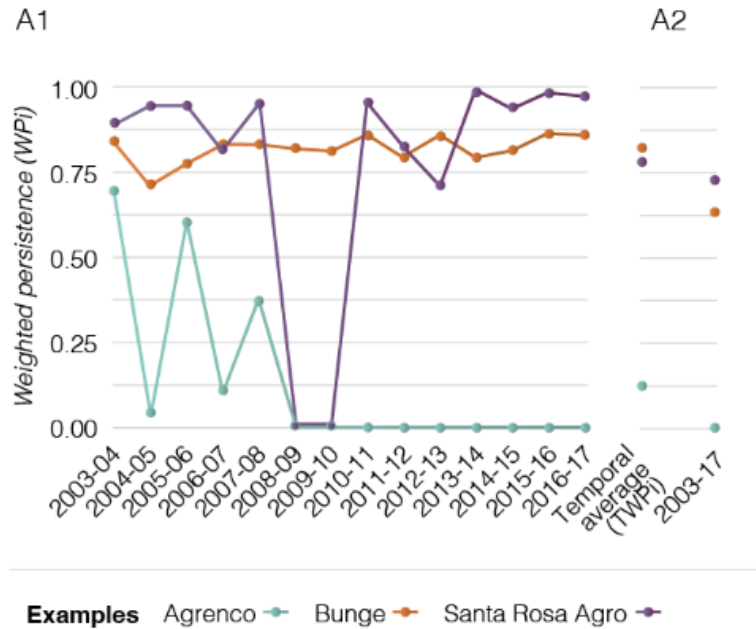


Figure S6. Temporal stickiness measured on selected traders' flows from logistics hubs. The same type of graph showing measurements on trade linkages is in Figure 2.7 (main text). The panel A2 complement the temporal profiles by showing the temporal average weighted persistence (TWPI, Eq.5-6 in *Experimental Procedures*) and the WPI calculated for the comparison between the 2003 snapshot with 2017, instead of for each subsequent biannual snapshots.

Supplemental Experimental Procedures

The soy supply chain in Brazil

Soy was the most traded agricultural commodity in the world in 2018. Total soy exports in the world accounted for roughly more than 18 billion tons¹. Soy monocultures are associated with the rapid impoverishment of ecosystems, as cultivation requires vast land expanses to achieve economies of scale and profit margins in global markets^{2,3}. In the 2017/2018 crop season, the world produced almost 340 million tons (Mt) of soy. The USA accounted for about 36% and Brazil for 35% of this global output⁴. Brazil was the second-largest producer but the largest exporter in 2017. Brazil supplied about 68 Mt of soy at a trade value of 21.5 billion USD to the world¹.

The revealed comparative advantage (RCA) index of the Brazilian soy oil products in 2017 was at 14.7, much higher than the US at 1.35, Russia at 8.7, and China at 0.01 (4, own calculation). This significant comparative advantage against the main competitors indicates an important growth potential for soy production in Brazil⁵. The soy industry is a key economic driver in the Brazilian economy. In 2017, soy exports added roughly 1% to the country's GDP^{1,6}. It is responsible for improving the country's trade surplus and driving the economic development of the countryside^{7,8}. The commercial dynamics and trading relationships developed between soy traders, production and distribution centers in Brazil and consuming countries are currently only available for the Brazilian soy supply chain, thanks to the data collection effort of the Trase (trase.earth) initiative. These commercial dynamics are the object of this empirical application of the stickiness concept.

In summary, the Brazilian soy supply chain is relevant for the empirical application of this concept for both socio and macroeconomic, global food security^{7–10}, geopolitical², and social-ecological reasons^{11–14}.

Data

Trase (trase.earth)¹⁵ is an initiative undertaken to increase the transparency of global commodity supply chains. The objective is

informing consumers, companies, investors, and policymakers on the social and ecological impacts that the production of commodities such as soy causes. The fundamental principles of the Trase approach are to balance both detail (about the production location and actors involved) and scale (covering the entirety of a commodity sector in the target country)¹⁶. The links between agricultural production, social and ecological risks and the products consumed worldwide are shown in great detail, connecting jurisdictions of production, distribution hubs, intermediary exporters, importers, and country destinations.

For this empirical analysis of the Brazilian soy supply chain, Trase provides historical trade data from municipalities of production, logistics hubs of distribution, exporters, importers, and country destinations between 2003 and 2017. All the soy produced in Brazil and exported in this period is mapped across these supply stages. Although Trase offers soy trade data down to the municipal level of production, we conducted the assessment at the LH level, because this is the smallest production unit over which the Trase database directly relies on actual transaction records¹⁷. The allocation of flows from LHs to municipalities relies on modeling, which is very robust regarding the overall patterns of soy flows but may create artifacts in our stickiness metrics that compare network configurations over successive years.

Methods

For measuring stickiness and observing the three dimensions defined, we assembled the Brazilian soy trade data from Trase version 2.3^{15,17} as a network, in the format of edges lists, and transformed them into adjacency matrices. The nodes in this network are (i) the logistics hubs (LHs), which are essential distribution centers in Brazil, (ii) the soy exporters or traders, and (iii) the countries of destination. The edges are the links connecting these nodes. The edges are observed as either linkages (presence or absence of a trade connection between two nodes over a given year) or flows (volumes of soy traded across a given linkage over a given year).

For this study, we prepared two separate edges. The first connected LHs to traders and traders to countries. With the first list of edges, we

measured the following types of relationships: (a) logistics hubs (LHs) supplying traders, as outgoing linkages and flows, (b) traders sourcing from LHs, as incoming linkages and flows, (c) traders supplying countries, as outgoing linkages and flows, and (d) countries sourcing from traders, as incoming linkages and flows. In the second edges list, we removed the intermediary traders from the network, and we measured: (e) LHs supplying countries, as outgoing linkages and flows, and (f) countries sourcing from LHs, as incoming linkages and flows.

To apply the calculation steps, we transformed these two edges lists into adjacency matrices. On the matrices used to measure stickiness on linkages, we replaced entries larger than 27 tons by 1, representing the existence of a linkage between two adjacent nodes, and 0 when no link existed or the volume was smaller than 27 tons (considered as an error), thus creating an unweighted adjacency matrix. On the matrices used to measure stickiness on flows, we maintained the original values representing the volume of soy that flowed through each trade link in each year. However, we adjusted any entry smaller than 27 tons to 0. 27 tons is the total load of a regular grains truck, considered as the minimum reasonable amount of soy traded in any year.

To organize and prepare the data, we used the software R¹⁸, plus the packages igraph¹⁹ and tidyverse²⁰.

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8.2. Appendix 2 - List of places visited

List of places visited at fieldwork and the number and type of interactions.

Places	Interviews	Consultations with experts	Participation in events
Astorga - PR	1		
Balsas - MA	9	1	1
Brasília - DF	1	5	1
Campinas - SP		2	
Caarapó	1		
Carazinho - RS	2		
Confresa - MT	1		
Cuiabá - MT	8	3	
Douradina - MS	1		
Dourados - MS	8	1	
Espigão do Leste/ São Félix do Araguaia - MT	4		
Itumbiara - GO	2		
Laguna Caarapã - MS	1		
Londrina - PR	1		
Maringá - PR	5		
Não-me-Toque - RS	1		1
Passo Fundo - RS	7		1
Piracicaba - SP		4	
Porto Alegre do Norte - MT	1		
Primavera do Leste - MT	1		
Querência do Norte - PR	1		
Rio Brilhante - MS	1		
Santa Carmem - MT	1		
São Jorge do Ivaí - PR	4		
São Paulo - SP	13	5	2
Sinop - MT	4		

Appendixes

Sorriso - MT	1		
Vera - MT	3		
Total	83	21	6

8.3. Appendix 3 - Contextual characteristics of municipalities

Contextual characteristics of logistics hubs scanned for fieldwork.

Selected LH	State	Main characteristics	TCi	TWPI	Soy production in 2017 in tons (Trase)	Area of annual agriculture in 2017 in ha (Mapbiomas)	ETD avrg productivity (tons/ha)	Total soy traded in tons 2003-2017 (Trase)*
Passo Fundo	RS	Soy introduction in the 1940s and 1950s; Subtropical climate with enough rain for first seed types in the country; Predominance of small farms (<500 ha); Large employment of technology and precision agriculture; High productivity and no deforestation risk	0.79	0.77	156,000	52,410	2.98	14,611,714

Maringá	PR	Soy introduction in the 1940s and 1950s; Subtropical climate with enough rain for first seed types in the country; Predominance of small farms (<500 ha); Large employment of technology and precision agriculture; High productivity and no deforestation risk	0.85	0.72	86,400	27,224	3.17	33,741,005
Não-me-Toque	RS	Soy introduction in the 1940s and 1950s; Subtropical climate with enough rain for first seed types in the country; Predominance of small farms (<500 ha); Large employment of technology and precision agriculture; High productivity and no deforestation risk	0.19	0.14	92,000	29,390	3.13	112,227

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Dourados	MS	Soy introduction in the 1960s and 1970s; Subtropical climate with enough rain, but seeds had some adaptations; Predominance of medium farms (>500<2500 ha); Medium employment of technology and precision agriculture; High productivity and no deforestation risk	0.8	0.81	575,700	156,408	3.68	7,127,929
Rio Brilhante	MS	Soy introduction in the 1960s and 1970s; Subtropical climate with enough rain, but seeds had some adaptations; Predominance of medium farms (>500<2500 ha); Medium employment of technology and precision agriculture; High productivity and no deforestation risk	0.21	0.16	396,000	110,669	3.58	122,776

São Félix do Araguaia/Baianos	MT	Soy introduction in the 2010s; Tropical climate with marked rainy and dry seasons; Seeds are highly adapted; Predominance of large farms (>2500 ha); Low employment of technology; Low productivity and high deforestation risk.	0.87	0.73	725,800	186,989	3.88	1,700,120
Sinop	MT	Soy introduction in the 1980s and 1990s; Tropical climate with rainy and dry seasons, but rainfalls all around the year; Seeds are highly adapted; Predominance of large farms (>2500 ha); Medium-high employment of technology and precision	0.58	0.56	495,855	167,883	2.95	4,856,489

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		agriculture; High productivity and high deforestation risk.						
Sorriso	MT	Soy introduction in the 1980s and 1990s; Tropical climate with rainy and dry seasons, but rainfalls all around the year; Seeds are highly adapted; Predominance of large farms (>2500 ha); High employment of technology and precision agriculture; High productivity and high deforestation risk.	0.38	0.65	2,157,600	607,269	3.55	3,210,752

Vera	MT	Soy introduction in the 1980s and 1990s; Tropical climate with rainy and dry seasons, but rainfalls all around the year; Seeds are highly adapted; Predominance of large farms (>2500 ha); Medium employment of technology and precision agriculture; High productivity and high deforestation risk.	0.22	0.17	445,400	151,256	2.94	36,855
Balsas	MA	Soy introduction in the 2000s and 2010s; Tropical climate with marked rainy and dry seasons; Seeds are highly adapted; Predominance of large farms (>2500 ha); Medium-low employment of	0.79	0.7	505,289	243,178	2.08	9,140,812

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		technology and precision agriculture; Medium productivity and high deforestation risk.						
Bom Jesus	PI	Soy introduction in the 2000s and 2010s; Tropical climate with marked rainy and dry seasons; Seeds are highly adapted; Predominance of large farms (>2500 ha); Low employment of technology; Medium productivity and high deforestation risk.	0.26	0.16	176,019	87,527	2.01	1,156,146

8.4. Appendix 4 - Additional contextual characteristics of municipalities

Additional characteristics of logistics hubs scanned for fieldwork.

Selected LH	State	Main traders 2003-2017 (Trase)**	Number of traders 2003-2017 (Trase)	Forestland in ha (Mapbiomas)	Cerrado (savanic formations and natural fields) in ha (Mapbiomas)	Natural fields in ha (Mapbiomas)	Pasturelands in ha (Mapbiomas)
Passo Fundo	RS	BSBIOS, Amaggi, Noble, Cofco, Multigrain, Bertol, Bunge, Companhia Zaffari, Master Alimentos.	17	11,104	899	899	1,196
Maringá	PR	ADM, Amaggi, Bunge, Cocamar, Glencore, Cargill, Nidera, Noble, Seara.	27	2,736	-	-	2,762
Não-me-Toque	RS	Cotrijal, E. Orlando	2	3,602	-	-	588

		Comércio de Cerais					
Dourados	MS	Louis Dreyfus, Bunge, Lar Cooperativa Agroindustrial, Cargill, Eleva Alimentos, Cooperativa Agropecuária Industrial em Liquidação, São Fernando Açúcar e Alcool	12	38,646	9,357	7,468	68,018
Rio Brilhante	MS	Usina Eldorado, C. Vale Cooperativa Agroindustrial, Lar Cooperativa Agroindustrial	3	60,620	17,020	10,251	43,823

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São Félix do Araguaia/Baianos	MT	Amaggi, Bunge, Glencore, Sinagro	4	809,704	368,735	140,787	194,346
Sinop	MT	Bunge, Cargill, Amaggi, Aliança Agrícola do Cerrado, ADM, Cofco	29	161,105	-	-	44,827
Sorriso	MT	Bunge, Multigrain, Cofco, Caramuru, Fiagril, Engelhart, ADM, Cargill, Nidera (Cofco), CHS, Noble (Cofco), Amaggi, Gavilon, Sipal.	60+	238,703	47,959	655	16,228
Vera	MT	Amaggi, Agrinvest Brasil, Arnildo Zocolotto,	4	130,321	-	-	6,188

Appendixes

		Pedro Misturini					
Balsas	MA	Cargill, Bunge, Agrex, Amaggi & Louis Dreyfus Joint- Venture, Multigrain, CHS, Glencore, Ceagro, ABC Industrial, ADM.	15	222,305	820,606	358,735	11,677
Bom Jesus	PI	Cargill, CHS, Amaggi & Louis Dreyfus Joint-Venture, Glencore, Multigrain, Bunge, Gavilon, Agrex	10	112,516	344,678	82,120	-

8.5. Appendix 5 - Spatial-temporal stickiness variables and data sources

Spatial-temporal potentially predictive variables of stickiness at the municipality (logistics hubs) level in each year (complete version of Table 1 in the main text).

Variable	Specification	Data source	Relevant theoretical dimension
Storage capacity (storcap_prod)	Storage capacity (tons) - total production (tons) in a given year, lagged one year to predict stickiness.	(IBGE, n.d.) tables 278, and 5457 (corrected by Imaflora).	(i) Economic incentives, mainly infrastructure and capital availability and; (iii) Social and power dimensions, <i>i.e.</i> , cohesion, power and agency, and group associations.
Crushing capacity (crushcap_prod)	Annual crushing capacity (tons) - total production (tons) in a given year, lagged one year to predict stickiness.	(Trase, 2020) (logistics maps), (IBGE, n.d.) Table 5457.	
Soy exported (Perc_exp)	Percentage export (PE) soy for total traded (TT) (tons), <i>i.e.</i> , not consumed domestically (exports/ total traded in LH) in a given year, lagged one year to predict stickiness.	(Trase, 2020)	(i) Economic incentives, mainly market demand and prices.

$PE = \frac{\text{volumeexported}}{\text{volumetraded}}$			
Instability of production or supply (SoyProd_dif)	Variation in production (VP) (tons) from y2 to y1, <i>i.e.</i> soy production in y2 – soy production in y1 (tons), lagged one year to predict stickiness in y3.	(IBGE, n.d.) table 5457 (corrected by Imaflora).	(iv) Biophysical and technological aspects, mainly stability of production and supply.
Average productivity (adj_pdt).	Average productivity (AP) (tons/ha) = total production (tons) / total area of cropland (ha) in a given year, not lagged one year, <i>i.e.</i> , to predict stickiness in the same year.	(IBGE, n.d.) table 5457 (corrected by Imaflora).	(iv) Biophysical and technological aspects, mainly total factor productivity of crop production.
Inter-annual stability of farm-gate prices (SPintervar).	Variation of farm-gate prices (FGP) from y1 to y2, <i>i.e.</i> , average of farm-gate soy prices paid in a given LH in year 2 - year 1, lagged one year to predict stickiness in y3.	(Agrolink, 2019).	(i) Economic incentives, mainly market demand and prices, capital availability and costs of production;
Intra-annual stability of farm-gate prices (SPintravar).	Variation of farm-gate prices within the same year, <i>i.e.</i> , max price in year 1 – min price in year 1, not lagged one year to predict stickiness in the same year.	(Agrolink, 2019).	(iv) Biophysical and technological aspects, mainly stability of production and supply.
Stability of land prices. (LPinteryear_var)	Variation of land prices (LP) from y2 to y1. We calculate a proportional land price	(IEG-FNP et al., 2018; Project	(ii) Institutional factors, mainly land-tenure;

	according to land cover in each LH and year, accounting for price differences in forestlands (and native vegetation), pasturelands and croplands, lagged one year to predict stickiness in y3.	MapBiomas, 2020)	(iii) Social and power dimensions, mainly cohesion, power and agency.
Weighted land prices (WeightedLP)	Average land prices per municipality (LH) per year (y1) considering prices and relative size of the three main categories of land use categories: agriculture, pasture and native vegetation lands. Lagged one year to predict stickiness in y2.	(IEG-FNP et al., 2018; Project MapBiomas, 2020)	(i) Economic incentives, mainly capital availability and costs of production; (ii) Institutional factors, mainly land-tenure;
Percentage of annual agricultural land of total available and suitable land (perc_AGarea).	Percentage of total area used by annual agriculture of total unprotected area with edaphoclimatic suitability for croplands (y1), <i>i.e.</i> , non-available for soy expansion because it is already occupied by soy or other annual agriculture. Lagged one year to predict stickiness in y2.	(FUNAI, 2020; GeoLab - USP, 2017; ICMBio, 2020; INCRA, 2020; Project MapBiomas, 2020)	(ii) Institutional factors, <i>i.e.</i> , land-tenure and environmental regulation; (iv) Biophysical and technological aspects, <i>i.e.</i> , stability of production and supply, and total factor productivity of crop production.
Percentage of unprotected suitable native vegetation (perc_unpsuitNV).	Percentage of unprotected native vegetation with crop suitability for the total unprotected area with edaphoclimatic suitability for croplands in	(FUNAI, 2020; GeoLab - USP, 2017; ICMBio, 2020; INCRA,	(ii) Institutional factors, <i>i.e.</i> , land-tenure and environmental regulation;

	each LH and year (y1), <i>i.e.</i> , potentially available for soy expansion. Lagged in one year to predict stickiness in y2.	2020; Project MapBiomass, 2020).	(iv) Biophysical and technological aspects, <i>i.e.</i> , stability of production and supply, and total factor productivity of crop production.
Percentage of unprotected suitable lands occupied by non-annual agriculture and pasturelands (perc_unpsuitother_agr)	Percentage of non-annual agriculture and pasturelands with edaphoclimatic suitability for annual croplands of the total area (y1), <i>i.e.</i> , potentially available for soy expansion. Lagged in one year to predict stickiness in y2.	(FUNAI, 2020; GeoLab - USP, 2017; ICMBio, 2020; INCRA, 2020; Project MapBiomass, 2020).	(ii) Institutional factors, <i>i.e.</i> , land-tenure and environmental regulation; (iv) Biophysical and technological aspects, <i>i.e.</i> , stability of production and supply, and total factor productivity of crop production.
Count of the number of traders (Coun_Traders)	A variable to test the effect of having multiple numbers of traders operating in each LH and each year, thus reducing the model bias of having, for example, only 3 traders operating in a LH in a given year versus having 20. Not lagged one year to predict stickiness in the same year.	(Trase, 2020)	(i) Economic incentives, mainly market demand and prices; (iii) Social and power dimensions, <i>i.e.</i> , cohesion, power and agency, and group associations.

**First year of colonization
(FirstYearColon) – number
of years of soy plantation.**

A variable to test the effect of having very recent versus very old soy colonization in a given LH. Some LHs are very recent agricultural frontiers while others have started planting soy in the 1940s. Therefore, this variable is aimed at reducing this bias. Not lagged one year to predict stickiness in the same year.

(IBGE, n.d.) –
Table 5457.

(ii) Institutional factors, mainly land-tenure;
(iii) Social and power dimensions, *i.e.*, cohesion, power and agency, and group associations.

8.6. Appendix 6 - Robustness analysis of the Historical

Random Forests model

Robustness analysis comparing the predictive capacity of stickiness using four random forests methods. The numbers indicate the predictive capacity of each variable on stickiness under the four methods: Z_lm - linear model; Z_hrf - longitudinal continuous; Z_hrf_nl – non-longitudinal continuous (pooled); Z_hrb - longitudinal boolean (0.5). The larger the number (positive or negative), the higher the predictive capacity.

var	Z_hrf (chosen method, historical continuous model)	Z_hrf_nl (non-historical continuous)	Z_hrb (historical boolean)
Perc_exp (% of soy production exported)	6.939	8.619	6.973
crushcap_prod (Crushing capacity)	3.707	8.111	3.008
storcap_prod (Storage capacity)	1.889	5.395	2.164
SPintravar (Intra-annual variation in farm-gate soy prices)	0.718	1.566	-1.39
perc_AGarea (% of land used by annual agriculture)	0.584	3.705	1.739
adj_pdt (Average yields in ton/ha)	0.581	2.293	2.809
weightedLP (Weighted land prices)	0.321	5.305	-1.19
perc_unpsuitother_agr (% of land occupied by non-annual agriculture and pasturelands suitable for annual-agriculture)	0.113	4.798	1.118
SoyProd_dif (Yearly variation in soy production)	-0.24	1.123	1.208

LPinteryear_var (Yearly variation in land prices)	-0.67	-0.321	-0.16
SPintervar (Yearly variation in farm-gate soy prices)	-1.04	1.333	0.37
Coun_Traders (Number of traders operating)	-1.3	9.244	0.729
FirstYearColon (First year of colonization – number of years of soy plantation)	-1.3	4.759	0.729
perc_unpsuitNV (% of land occupied by unprotected native vegetation suitable for annual agriculture)	-1.45	4.345	0.129

8.7. Appendix 7 - Checking for multicollinearity - Correlation matrix

The highest correlation observed was between LPinteryear_var and weightedLP, with a correlation coefficient (r) of 0.56. Nothing relevant.

	storcap_prod	crushcap_prod	Perc_exp	SoyProd_dif	adj_pdt	SPintervar	SPintravar	weightedLP	LPinteryear_var	Coun_Traders	FirstYearColon	perc_AGarea	perc_unpsuitNV	perc_unpsuittother_agr
storcap_prod	1	0.33	-0.06	-0.1	-0.06	0	0.08	0.05	0.02	0.56	0.09	0.17	0.02	-0.24
crushcap_prod	0.33	1	-0.33	-0.16	-0.14	0.06	0.06	0.06	0.1	0.14	-0.25	0.13	-0.06	0.13
Perc_exp	-0.06	-0.33	1	0.07	0.03	0.05	0.06	-0.24	-0.15	0.17	0.31	-0.24	-0.01	0
SoyProd_dif	-0.1	-0.16	0.07	1	0.28	-0.19	-0.11	-0.03	-0.13	0.08	0.07	-0.1	0.01	-0.01
adj_pdt	-0.06	-0.14	0.03	0.28	1	-0.17	-0.06	0.23	0.02	0.01	-0.1	-0.05	0.03	-0.05
SPintervar	0	0.06	0.05	-0.19	-0.17	1	0.41	-0.16	0.21	-0.04	0.01	-0.04	0	0.04
SPintravar	0.08	0.06	0.06	-0.11	-0.06	0.41	1	-0.06	0.18	0.1	0.05	-0.07	-0.07	0.02

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weightedLP	0.05	0.06	-0.24	-0.03	0.23	-0.16	-0.06	1	0.56	-0.15	-0.39	0.43	0.09	-0.41
LPinteryear_ var	0.02	0.1	-0.15	-0.13	0.02	0.21	0.18	0.56	1	-0.14	-0.29	0.33	0.07	-0.32
Coun_Trade rs	0.56	0.14	0.17	0.08	0.01	-0.04	0.1	-0.15	-0.14	1	0.35	-0.15	-0.03	-0.08
FirstYearCol on	0.09	-0.25	0.31	0.07	-0.1	0.01	0.05	-0.39	-0.29	0.35	1	-0.33	-0.01	0.02
perc_AGare a	0.17	0.13	-0.24	-0.1	-0.05	-0.04	-0.07	0.43	0.33	-0.15	-0.33	1	0.45	-0.68
perc_unpsui tNV	0.02	-0.06	-0.01	0.01	0.03	0	-0.07	0.09	0.07	-0.03	-0.01	0.45	1	-0.46
perc_unpsui tother_agr	-0.24	0.13	0	-0.01	-0.05	0.04	0.02	-0.41	-0.32	-0.08	0.02	-0.68	-0.46	1

8.8. Appendix 8 - Checking for multicollinearity – Variance

Inflation Factor (VIF)

Using VIF = 5 as the threshold, VIF also corroborates the correlation matrix, showing no relevant collinearity.

Variables	VIF
storcap_prod	1.830866
crushcap_prod	1.534093
Perc_exp	1.291017
SoyProd_dif	1.171595
adj_pdt	1.236919
SPintervar	1.39438
SPintravar	1.263096
weightedLP	2.167008
LPinteryear_var	1.80676
Coun_Traders	1.873493
FirstYearColon	1.604542
perc_AGarea	2.825087
perc_unpsuitNV	1.416521
perc_unpsuitothers_agr	2.806635

8.9. Appendix 9 - Results from the pooled (non-historical) continuous random forest model (Z_hrf_nl)

This is the model with the better proportion of the variance explained.

Predictor	Marginalized error	Model error	Mean marginal influence	Z-value
Count of the number of traders (Coun_Traders)	0.0668	0.0498	0.343	9.244
% Soy exported (Perc_exp)	0.0568	0.0498	0.142	8.619
Crushing capacity (crushcap_prod)	0.0532	0.0498	0.068	8.111
Storage capacity (storcap_prod)	0.0508	0.0498	0.021	5.395
Weighted land prices (WeightedLP)	0.0511	0.0498	0.027	5.305
Percentage of unprotected suitable lands occupied by non-annual agriculture and pasturelands (perc_unpsuiother_agr)	0.0501	0.0498	0.007	4.798
First year of colonization (FirstYearColon) – number of years of soy plantation	0.0504	0.0498	0.012	4.759
Percentage of unprotected suitable native vegetation (perc_unpsuitNV)	0.0504	0.0498	0.013	4.345
Percentage of annual agricultural land of total available and suitable land (perc_AGarea)	0.0512	0.0498	0.029	3.705
Average productivity (adj_pdt)	0.0498	0.0498	0.002	2.293
Intra-annual stability of farm-gate prices (SPintravar)	0.0498	0.0498	0.001	1.566
Yearly variation of farm-gate soy prices (SPintervar)	0.0501	0.0498	0.006	1.333
Instability of production or supply (SoyProd_dif)	0.0498	0.0498	0	1.123
Yearly variation in land prices (LPinteryear_var)	0.0496	0.0498	-0.003	-0.321

**8.10. Appendix 10 - Results from the historical boolean
random forests model (Z_htb)**

Predictor	Marginalized error	Model error	Mean marginal influence	Z-value
% Soy exported (Perc_exp)	0.4047	0.3188	0.269	6.973
Crushing capacity (crushcap_prod)	0.3491	0.3188	0.095	3.008
Average productivity (adj_pdt)	0.3208	0.3188	0.006	2.809
Storage capacity (storcap_prod)	0.3196	0.3188	0.003	2.164
Percentage of annual agricultural land of total available and suitable land (perc_AGarea)	0.3251	0.3188	0.02	1.739
Instability of production or supply (SoyProd_dif)	0.3191	0.3188	0.001	1.208
Percentage of unprotected suitable lands occupied by non-annual agriculture and pasturelands (perc_unpsuitother_agr)	0.3196	0.3188	0.002	1.118
Count of the number of traders (Coun_Traders)	0.3188	0.3188	0	0.729
First year of colonization (FirstYearColon) – number of years of soy plantation	0.3188	0.3188	0	0.729
Yearly variation of farm-gate soy prices (SPintervar)	0.3181	0.3188	-0.002	0.37
Percentage of unprotected suitable native vegetation (perc_unpsuitNV)	0.3188	0.3188	0	0.129
Yearly variation in land prices (LPinteryear_var)	0.3232	0.3188	0.014	-0.157

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Weighted land prices (WeightedLP)	0.318	0.3188	-0.003	-1.194
Intra-annual stability of farm- gate prices (SPintravar)	0.3161	0.3188	-0.009	-1.385

8.11. Appendix 11 - Interview guide

What are the conditions and influencing factors of stickiness in Brazil's soy export supply chain?

Goal: identify and understand the conditions and influencing factors of stickiness in the soy supply chain of Brazil, and the potential consequences.

Justification:

After conduction of the preliminary measurement of stickiness on the Brazilian soy export supply chain, both on linkages and flows, I want to identify and understand the conditions, influencing factors and implications of stickiness. At this first stage, I will conduct an initial qualitative research using semi-structured interviews with farmers, traders (employees at local and strategic levels), brokers, input suppliers, and Brazilian agronomical, logistics and land use researchers, lobbyists and specialists, to raise influencing factors, conditions and implications of stickiness. After that, I will conduct quantitative analysis using GIS and panel data methods. This analysis is performed iteratively with stakeholders.

The notion of stickiness was explained to interviewees as having stable, consistent, resistant and trade relationships capable to recover from shocks. To facilitate the understanding, the first author framed this pattern as having loyal relationships with their buyers, suppliers, or commercial partners for input suppliers, transportation companies or other stakeholders.

Acknowledgements:

This interview guide was first elaborated in English but then adapted to Brazilian Portuguese. It was not strictly applied because some questions or topics were *a priori* deemed irrelevant or unnecessary to some actors and interviewees according to certain circumstances that I (interviewer already knew). It functioned rather as a guide. In addition, this guide was frequently changed and adapted, reflecting my evolution in terms of acquiring knowledge of soy supply chain characteristics, factors and circumstances. The interviews also were free to evolve and deepen into certain topics or aspects that seemed more relevant in each case. It was quite a deep-learning procedure about the Brazilian soy supply chain.

Interviewed actors:

The interviewed actors include soy producers, i.e., small (<500ha), medium (500-2500ha), and large soy farmers (>2500ha), leaders of soy farmers' associations, and local unions., At the local level, interviewees include input suppliers, local procurement managers of traders and processing companies, transportation companies, technical assistants and agronomical researchers, cooperatives, small grain warehouses, grain and land brokers, and agronomical consultants. Further, at the national level, various actors within companies were interviewed, such as directors and managers of procurement, operations, sustainability, and logistics at the Brazilian or Latin American headquarters of the largest grain traders operating in Brazil. The experts consulted are academic researchers on land use, agronomics and agricultural economics, state policymakers, socio-environmental NGOs, supply chain and infrastructure lobbyists and specialists.

I. Objectives:

1. Identify preliminary conditions of stickiness in Brazil's soy supply chain, guided by the measurement we already conducted.
2. Identify key maps, datasets and information that we can use as relevant explanatory variables in a quantitative analysis of the causes of stickiness (for later panel data analysis).

II. Questions/ topics for semi-structured interviews:

1. Farmers:

1.1. Fundamental questions:

- Do you have a sticky (stable) relationship with any trader historically? With only one or with more than one?
- What made you have this sticky relationship with any trader(s) over time?
- Have you ever or would you ever sign a long-term contract (> 1 year or crop season) with any trader?
- If yes, what is necessary for you to sign a long-term contract with any trader? What does the trader need to offer to convince you for that?
- Once you have a sticky relationship with any trader, or more than one, what are the consequences of that for you? What happens to you if you have a long-term contract?
- What are the benefits, advantages and disadvantages in your opinion of having a long term contract?

- And how about of not having long term contracts at all?

1.2. Production history and infrastructure:

- Since when have you been producing soy here?
- Do you have other farms? Why and how have you developed?
- Have you produced elsewhere, and if yes, have you previously produced/specialised in other crops?
- To which trader have you been selling your harvest all these years?
- What were the options when you started producing?
- What are the options to sell your harvest now?
- Have you been selling your harvest always to the same trader? If not, to whom have you been selling?
- What shocks have ever affected your production and your capacity to deliver on your contracts?
- Then, what happened? Did you find other trader to negotiate, if the trader decided not to buy from you? Or did you have a rural insurance if you had a crop failure due to drought? Or did you have any subsidy from the government if you faced financial problems? (such as interest rates ended up being too high in face of low market prices, or exchange rate, or costs?)
- If you had a stable relationship with a trader, then you have suffered a loss of contract without an explanation from the trader, why do you believe the trader made this decision?
- Do you have your own silo? What is its capacity?
- If you don't have your own silo, where do your trucks deliver straightly after the harvest?
- Why? Why this place/ company and not others that are closer to your farm?
- Do you intend to build a silo? Is it advantageous for you? Why yes or why not?
- Are you member of any cooperative or association?

1.3. Relationship with trader:

- Do you export your soy? If yes, do you know where it goes after you sell to the trader?
- What do you expect a trader to offer you to sign with them?
- How do you negotiate your harvest every year?
- What is the length of contracts typically offered to you by traders?

- How much of your expected harvest do you commit with traders in general? Or with any specific trader? Why? Why do you commit this much of your projected harvest and not more or not less?
- Have you ever failed to deliver a contract? Why? What happened?
- Which factors are more important to choose one or other trader? (e.g. price, length of contracts, input or technological package supply, financing and interest rates, other conditions, speed of reception, personal relationships?).
- Has the trader any day come to you and stopped buying without clear reasons?
- How do you protect yourself from market volatility? And from exchange volatility? And from input supply volatility? And from transport volatility?
- Has the strike of truck drivers affect you? How?

1.4. Sustainability considerations:

- What do you believe to be the key potential future 'shocks' to you and your producing capacity?
- Are there environmental problems that impact your production?
- Are you concerned about environmental degradation? In your farm? In the region? In the world?
- Do you think it may affect you?
- How do you see environmental legislation? Is it limiting or a barrier in your view?
- Do you think environmental legislation could make you or other farmers to move from one region to others?

2. Traders' local employees/ middlemen/ brokers/ independent buyers:

2.1. Fundamental questions:

- Do you have a sticky (stable) commercial relationship with any farmer(s)? If yes, how many and for over which period?
- What do you prefer: to negotiate every year with every farmer or to have long-term contracts with as many farmers as possible?
- What do you offer farmers to get them engaged for long periods?
- What makes (causes) you have sticky relationships with farmers?

2.2. Trader's history:

- Since when is your company operating here in this region?
- When have you started working for them?
- Do you know why or what made the company to set up an office/silo or crusher here?

2.3. Relationship with farmers:

- How do you negotiate contracts with farmers?
- What do you offer them to sign up with you?
- What is the length of contracts typically offered by you to farmers?
- What is your flexibility in dealing? Do you have a price and interest rate range?
- What can you offer to the farmer to get a contract signed? Or how far can you go?
- What are your procurement targets?)
- How do you seek information?
- Do you monitor farmers and production sites? If yes, how? Financially or only productively?
- How do you choose which farmers to target? (Do you have a plan, a priority, a preference, specific targets? If yes, how do you define them?)
- Have you ever suffered any cut or sudden shock that made you reduce drastically the amount of soy you bought in any given year? If yes, what was that?
- How far do you go to buy soy? What is your geographic scope in this office?

2.4. Sustainability considerations:

- What do you believe to be the key potential future 'shocks'? Things that may happen here in the region that might affect your work of buying soy, for example?

3. Traders' senior managers and directors in headquarters:

3.1. Fundamental questions:

- Is it important for you to have a sticky relationship with any region(s)? Why?
- What do you prefer as a strategy for your company: to buy soy every year from exactly the same places or to move around and buy from different places every year?
- What would make you to buy soy always from the same regions?

- What would make you buy soy always from different regions?
- In your opinion, who comes first: the trader or the farmer?
- I mean, who drives production and expansion into a new region?
- How would you describe your company's procurement policy?
- What makes your company stickier to certain regions over time than to others?
- Why are you located in these places and not in others?
- How do you choose the places where you will put an office, a silo or a crusher?
- As a procurement strategy, do you think it is better to be sticky to certain regions and make investments for that or to have a dynamic procurement approach, buying from different places every year? Why?
- What do you look at when you are deciding where to open a new office/ silo/ crusher? Or how do you decide where and when to open a new office/ silo/ crusher?

3.2. Trader's history:

3.3. Trader's relationship with regions:

- How much are you dependent on decisions made in the past, in terms of facilities and logistics infrastructure? Try to understand how much the trader today is dependent on decisions made on the past.
- Do you use only your own facilities or do you hire services from other companies?
- How much are you dependent on your own or outsourced infrastructure? Try to understand how much the trader today is dependent on its own or outsourced infrastructure. In other words, how much the trader relies today on its own facilities or on contracts and partners that provide storage, crushing and logistics services.
- Has your company ever closed any facility (office/ silo/ crusher) somewhere? If yes, where?
- Why did you make this decision? What caused you to close in one place?
- Are you moving away from some regions or towards spot-markets?
- After that, did you reopen any facility in a new place?
- Why did you decide to establish in these logistics hubs (then show the main logistics hubs of this trader) and not in others? Which reasons made you go to these places and stay there?

- If there was any movement from one place to other, ask why.
- What are your relations with politicians in the localities you are placed?

3.4. Sustainability considerations:

- What do you believe to be the key potential future 'shocks'?
 - How do you see your trader in the market? What are your differentials in relation to others? What are your strengths and weaknesses to improve in relation to your competitors?
 - Do you think your company has a role or a capacity to influence the prices? Or do you only take prices from the market?
 - Which shocks have you ever suffered that made you change your company's strategies?
 - What were the outcomes of this shock you mention?
 - Which shocks do you think your company is still vulnerable to?
 - Are you concerned about environmental degradation? In the regions you source from? In the world?
 - How do you see environmental legislation? Is it limiting or a barrier in your view?
- Do you think environmental legislation could make you or other companies to move from one region to others?

4. Land use scientists and specialists in Brazil (reorganize and plan better the sequence of topics to be presented in each case and dynamically. I need to make sure this is not a strict questionnaire, but rather a conversation, for methodological reasons):
- First, I explain and show stickiness.
 - What do you think that can cause stickiness?
 - Horizon scanning: what do you believe to be the key potential future 'shocks'?
 - Which analyses do you think it would be worth doing to understand the causes of this?
 - Which data do you think is worth using for this?
 - Which applications do you think we can derive from this stickiness analysis?
 - Which shocks do you think that could affect these stickiness patterns?

1 **8.12. Appendix 12 - Correlation matrix between all variables**

	Ci_avrg S	infarmstorcap_p erc	Perc_FarmersCredTrad ers	Perc_Larg eF	Perc_Coo p	Perc_Arre nd	Perc_RT RS	case s
Ci_avrgS	1	<u>0.131</u>	0.035	<u>0.19</u>	<u>-0.142</u>	-0.047	<u>0.153</u>	0.021
infarmstorcap_perc	0.131	1	0.035	0.204	-0.117	-0.022	0.151	0.002
Perc_FarmersCredTrad ers	0.035	0.035	1	0.055	0.324	0.132	-0.038	0.037
Perc_LargeF	0.19	0.204	0.055	1	-0.216	0.228	0.29	0.008
Perc_Coop	-0.142	-0.117	0.324	-0.216	1	0.399	-0.265	0.179
Perc_Arrend	-0.047	-0.022	0.132	0.228	0.399	1	-0.083	0.192
Perc_RTRS cases	0.153 0.021	0.151 0.002	-0.038 -0.037	0.29 0.008	-0.265 -0.179	-0.083 -0.192	1 0.033	0.031

2

3 **8.13. Appendix 13 - P-values for the correlation matrix in App. 11.**

	Ci_avrg S	infarmstorcap_p erc	Perc_FarmersCredTrad ers	Perc_Larg eF	Perc_Coo p	Perc_Arre nd	Perc_RT RS	case s
Ci_avrgS	NA	<u>0.006</u>	0.468	<u>0</u>	<u>0.003</u>	0.324	<u>0.001</u>	0.658
infarmstorcap_perc	0.006	NA	0.472	0	0.014	0.642	0.002	0.965
Perc_FarmersCredTrad ers	0.468	0.472	NA	0.255	0	0.006	0.429	0.443
Perc_LargeF	0	0	0.255	NA	0	0	0	0.865
Perc_Coop	0.003	0.014	0	0	NA	0	0	0
Perc_Arrend	0.324	0.642	0.006	0	0	NA	0.082	0
Perc_RTRS	0.001	0.002	0.429	0	0	0.082	NA	0.499
cases	0.658	0.965	0.443	0.865	0	0	0.499	NA

4

8.14. Appendix 14 - Selected photographs from the field.

Figure 8.1 - My son Nicolas doing some fieldwork with me.



Figure 8.2 - Rio Grande do Sul: mosaic of land uses. Small holdings prevail.

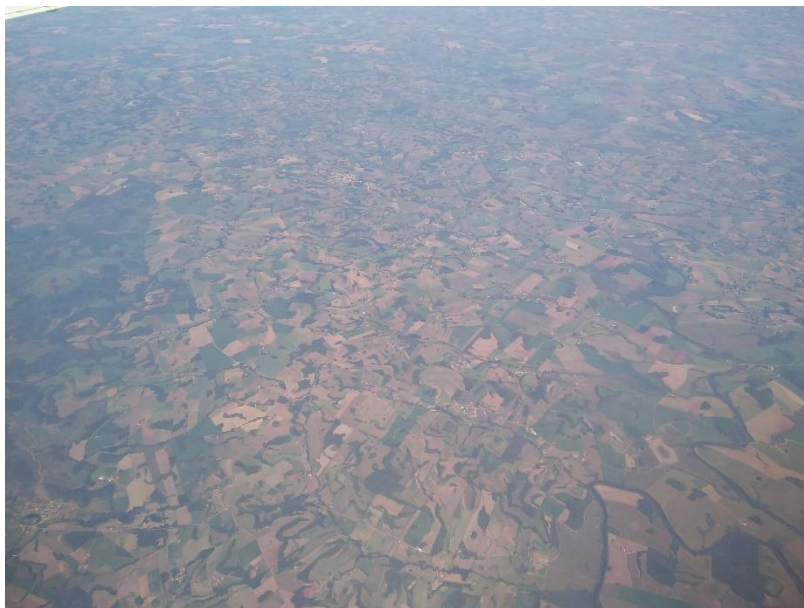


Figure 8.3 - Wheat plantations in Rio Grande do Sul.



Figure 8.4 - Não-Me-Toque - Rio Grande do Sul - self-considered the national capital of precision agriculture.



Figure 8.5 - Production landscape in Sinop - Mato Grosso.



Figure 8.6 - Production landscape in the North of Mato Grosso. Large farms prevail.



Figure 8.7 - Silos and headquarters of Cootrijal, a large cooperative in Não-Me-Toque - RS.



Figure 8.8 - Araguaia river in Mato Grosso.



Figure 8.9 - Northeastern landscape in Mato Grosso.



Figure 8.10 - Meeting of the soy moratorium working group.



Figure 8.11 - Meeting of the Soy Farmers Association in Maranhão (Aprosoja - MA).



Figure 8.12 - Seminar about agricultural development at University of Balsas - Maranhão.



8.15. Appendix 15 - Supplementary material – The influence of company sourcing patterns on the adoption and effectiveness of zero-deforestation commitments in Brazil's soy supply chain.

Figure S1 – Smoothed levels of stickiness in the Brazilian soy supply chain between 2004 – 2017, using a penalised cubic regression spline. Grey areas denote 95% confidence intervals.

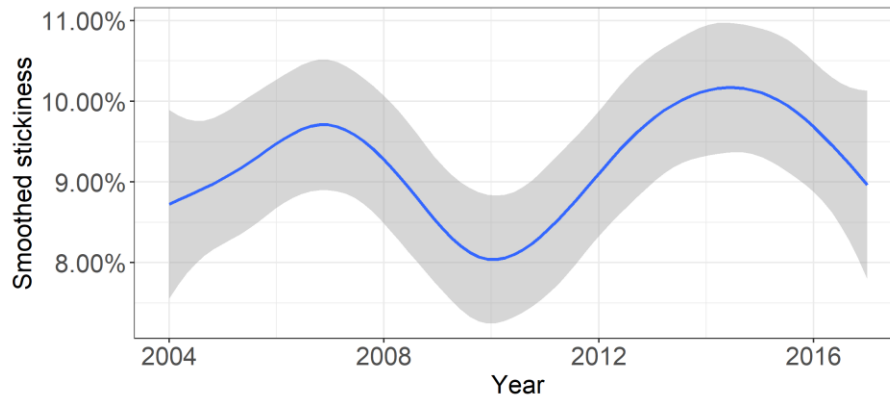


Table S1 – Negative binomial regression estimates of the annual amount of soy deforestation risk and territorial deforestation. Columns (1) and (3) assume a ZDC implementation deadline of 2 years, while columns (2) and (4) assume an implementation deadline of 5 years. Sourcing areas outside the Amazon biome are excluded. Heteroskedasticity robust (White-Huber) standard errors in parentheses. Asterisks indicate the level of statistical significance (· $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, * $p < 0.001$). Soy and territorial deforestation are represented in kha.**

	Soy deforestation risk	Soy deforestation risk	Territorial deforestation	Territorial deforestation
Stickiness (0 –1)	0.01 (0.01)	0.01 (0.01)	-0.01 (0.01)	-0.01 (0.01)
Commitment (2-year lag)	0.15 (1.81)		-0.10 (0.98)	
Stickiness x Commitment (2-year lag)	0.00 (0.02)		0.02. (0.01)	
Commitment (5-year lag)		0.62 (2.22)		-1.79 (1.40)
Stickiness x Commitment (5-year lag)		-0.02 (0.03)		0.03 * (0.02)
Soy volumes (%)	0.21 (0.13)	0.15 (0.13)	0.14 . (0.08)	0.19 * (0.08)
Destination - Europe (%)	1.88 (1.78)	1.43 (1.83)	1.69 (1.49)	1.80 (1.51)
Destination - Asia (%)	1.44	0.96	1.31	1.42

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	(1.61)	(1.62)	(1.48)	(1.50)
Unprotected suitable forest area	0.01	0.01	-0.00	0.00
	(0.01)	(0.01)	(0.01)	(0.01)
Theta (overdispersion)	0.97 ***	1.01 ***	1.31 ***	1.31 ***
	(0.25)	(0.26)	(0.32)	(0.33)
McFadden's Pseudo R ²	0.31	0.32	0.32	0.32
Observations	269	269	336	336
Trader fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
AIC	754.71	752.29	1165.60	1167.60
BIC	1121.38	1118.95	1654.19	1656.19
Log Likelihood	-275.36	-274.14	-454.80	-455.80

8.16. Appendix 16 - Supplementary material – How supply chain relations influence development outcomes: The case of soy in Brazil.

Table S1 – Contextual characteristics of logistics hubs scanned for fieldwork. These regions exhibit different productive arrangements, profiles, and levels of technological application, productivity, and logistic access.

Selected LH	State	Main characteristics	TCi	TWPi	Soy production in 2017 in tons (Trase)	Area of annual agriculture in 2017 in ha (Mapbiomas)	ETD avrg productivity (tons/ha)	Total soy traded in tons 2003-2017 (Trase)*
Passo Fundo	RS	Soy introduction in the 1940s and 1950s; Subtropical climate with enough rain for first seed types in the country; Predominance of small farms (<500 ha); Large employment of technology and precision agriculture; High productivity	0.79	0.77	156,000	52,410	2.98	14,611,714

		and no deforestation risk						
Maringá	PR	Soy introduction in the 1940s and 1950s; Subtropical climate with enough rain for first seed types in the country; Predominance of small farms (<500 ha); Large employment of technology and precision agriculture; High productivity	0.8 5	0.72	86,400	27,224	3.17	33,741,005

		and no deforestation risk						
Não-me-Toque	RS	Soy introduction in the 1940s and 1950s; Subtropical climate with enough rain for first seed types in the country; Predominance of small farms (<500 ha); Large employment of technology and precision agriculture; High productivity	0.19	0.14	92,000	29,390	3.13	112,227

		and no deforestation risk						
Dourados	MS	Soy introduction in the 1960s and 1970s; Subtropical climate with enough rain, but seeds had some adaptations; Predominance of medium farms (>500<2500 ha); Medium employment of technology and precision agriculture; High productivity	0.8	0.81	575,700	156,408	3.68	7,127,929

		and no deforestation risk						
Rio Brilhante	MS	Soy introduction in the 1960s and 1970s; Subtropical climate with enough rain, but seeds had some adaptations; Predominance of medium farms (>500<2500 ha); Medium employment of technology and precision agriculture;	0.2 1	0.16	396,000	110,669	3.58	122,776

		High productivity and no deforestation risk						
São Félix do Araguaia/Baianos	MT	Soy introduction in the 2010s; Tropical climate with marked rainy and dry seasons; Seeds are highly adapted; Predominance of large farms (>2500 ha); Low employment of technology; Low productivity and high deforestation risk.	0.8 7	0.73	725,800	186,989	3.88	1,700,120

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Sinop	MT	Soy introduction in the 1980s and 1990s; Tropical climate with rainy and dry seasons, but rainfalls all around the year; Seeds are highly adapted; Predominance of large farms (>2500 ha); Medium-high employment of technology and precision agriculture; High productivity and high deforestation risk.	0.5 8	0.56	495,855	167,883	2.95	4,856,489

Sorriso	MT	Soy introduction in the 1980s and 1990s; Tropical climate with rainy and dry seasons, but rainfalls all around the year; Seeds are highly adapted; Predominance of large farms (>2500 ha); High employment of technology and precision agriculture; High productivity and high deforestation risk.	0.3 8	0.65	2,157,600	607,269	3.55	3,210,752

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Vera	MT	Soy introduction in the 1980s and 1990s; Tropical climate with rainy and dry seasons, but rainfalls all around the year; Seeds are highly adapted; Predominance of large farms (>2500 ha); Medium employment of technology and precision agriculture; High productivity and high deforestation risk.	0.2 2	0.17	445,400	151,256	2.94	36,855

Balsas	MA	Soy introduction in the 2000s and 2010s; Tropical climate with marked rainy and dry seasons; Seeds are highly adapted; Predominance of large farms (>2500 ha); Medium-low employment of technology and precision agriculture; Medium productivity and high deforestation risk.	0.7 9	0.7	505,289	243,178	2.08	9,140,812

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Bom Jesus	PI	Soy introduction in the 2000s and 2010s; Tropical climate with marked rainy and dry seasons; Seeds are highly adapted; Predominance of large farms (>2500 ha); Low employment of technology; Medium productivity and high deforestation risk.	0.2 6	0.16	176,019	87,527	2.01	1,156,146

Table S2 - Additional characteristics of logistics hubs scanned for fieldwork.

Selected LH	State	Main traders 2003-2017 (Trase)**	Number of traders 2003-2017 (Trase)	Forestland in ha (Mapbiomas)	Cerrado (savanic formations and natural fields) in ha (Mapbiomas)	Natural fields in ha (Mapbiomas)	Pasturelands in ha (Mapbiomas)
Passo Fundo	RS	BSBIOS, Amaggi, Noble, Cofco, Multigrain, Bertol, Bunge, Companhia Zaffari, Master Alimentos.	17	11,104	899	899	1,196
Maringá	PR	ADM, Amaggi, Bunge, Cocamar, Glencore, Cargill,	27	2,736	-	-	2,762

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		Nidera, Noble, Seara.					
Não-me-Toque	RS	Cotrijal, E. Orlando Comércio de Cerais	2	3,602	-	-	588
Dourados	MS	Louis Dreyfus, Bunge, Lar Cooperativa Agroindustri al, Cargill, Eleva Alimentos, Cooperativa Agropecuária Industrial em Liquidação, São Fernando Açúcar e Álcool	12	38,646	9,357	7,468	68,018

Rio Brilhante	MS	Usina Eldorado, C. Vale Cooperativa Agroindustri al, Lar Cooperativa Agroindustri al	3	60,620	17,020	10,251	43,823
São Félix do Araguaia/ Baianos	MT	Amaggi, Bunge, Glencore, Sinagro	4	809,704	368,735	140,787	194,346
Sinop	MT	Bunge, Cargill, Amaggi, Aliança Agrícola do Cerrado, ADM, Cofco	29	161,105	-	-	44,827
Sorriso	MT	Bunge, Multigrain, Cofco,	60+	238,703	47,959	655	16,228

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		Caramuru, Fiagril, Engelhart, ADM, Cargill, Nidera (Cofco), CHS, Noble (Cofco), Amaggi, Gavilon, Sipal.					
Vera	MT	Amaggi, Agrinvest Brasil, Arnildo Zocolotto, Pedro Misturini	4	130,321	-	-	6,188
Balsas	MA	Cargill, Bunge, Agrex, Amaggi & Louis Dreyfus	15	222,305	820,606	358,735	11,677

		Joint-Venture, Multigrain, CHS, Glencore, Ceagro, ABC Industrial, ADM.					
Bom Jesus	PI	Cargill, CHS, Amaggi & Louis Dreyfus Joint-Venture, Glencore, Multigrain, Bunge, Gaviion, Agrex	10	112,516	344,678	82,120	-

Table S3 - List of places visited at fieldwork and the number and type of interactions.

Places	Inter views	Consultations with experts	Participatio n in events
Balsas – MA and Bom Jesus - PI	13	1	1
Passo Fundo - RS, Carazinho – RS, Não-Me-Toque-RS	10		1
Sorriso – MT, Sinop – MT, Santa Carmem – MT, Vera - MT	9		
Total	32	1	2