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Lionel Cosnard

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Lionel Cosnard. Modeling the dynamics of the regional distribution of agri-food sectors in an openworld. Economics and Finance. Université de Bordeaux, 2020. English. NNT : 2020BORD0191 . tel-03414146

HAL Id: tel-03414146

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THÈSE PRÉSENTÉE
POUR OBTENIR LE GRADE DE

**DOCTEUR DE
L'UNIVERSITÉ DE BORDEAUX**

ÉCOLE DOCTORALE ENTREPRISE, ÉCONOMIE, SOCIÉTÉ (ED. 42)
SPÉCIALITÉ SCIENCES ÉCONOMIQUES

Par **Lionel COSNARD**

**Modeling the Dynamics of the Regional Distribution of
Agri-food Sectors in an Open World**

*Modéliser les Dynamiques de la Distribution Régionale des Filières Agricoles dans un
Monde Ouvert*

Sous la direction de M. Antoine BOUËT

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Titre: Modéliser les Dynamiques de la Distribution Régionale des Filières Agricoles dans un Monde Ouvert

Résumé: Cette thèse propose différentes innovations pour améliorer la représentation des dynamiques des filières agricoles au niveau régional dans les modèles appliqués de commerce international. Le premier chapitre présente un cadre théorique simple et original pour analyser la dynamique et la résilience des filières agricoles. Nous utilisons ce cadre pour discuter des conséquences des perturbations entraînées par la pandémie de COVID-19 sur les filières. Le second chapitre présente un modèle dynamique multirégional appliqué de filière agricole permettant la représentation d'économies d'agglomération. Nous calibrons ce modèle sur la filière laitière française. Nous simulons différents scénarios de chocs sur le marché du lait et sur les coûts de transport du lait. Nous montrons que la dynamique des filières en réponse à ces chocs peut être chaotique et hystérétique. Nous montrons que les secteurs laitiers sont plus résilients dans les régions où la production est la plus dense. Enfin, dans le troisième chapitre nous modifions le modèle de commerce en équilibre général calculable MIRAGRODEP pour intégrer la représentation de filières régionales avec économies d'agglomération développée dans le deuxième chapitre. Cela nous permet d'intégrer la complexité des interactions dans le temps et dans l'espace entre les filières régionales connectées par les marchés à travers le monde. Nous montrons l'importance de l'hystérèse dans le commerce en simulant des scénarios avec différentes chronologies de libéralisation du marché des produits laitiers. Nous étudions les conséquences sur la répartition géographique des filières de différents soutiens au secteur laitier. Enfin, nous montrons qu'une taxation des sources d'énergie carbonées mène à une augmentation des coûts de transports et à une plus forte concentration de la production laitière.

Mots clés: filières, agglomération, hystérèse, lait, transport, résilience.

Title: Modeling the Dynamics of the Regional Distribution of Agri-food Sectors in an Open World

Abstract: This thesis develops several innovations to improve the representation of the regional dynamics of agri-food sectors in applied trade models. The first chapter presents an original theoretical framework to analyze the dynamics and resilience of agricultural value chains. We use this framework to discuss the consequences of the COVID-19 pandemic on food supply chains. The second chapter presents a multi-regional dynamic model of agricultural value chain with economies of agglomeration. It is calibrated on the French dairy sector. We show that the dynamic response of regional value chains to shocks on the price of dairy products and transport costs can be chaotic and hysteretic. The regions with the densest production have the most resilient dairy sectors. In the third chapter, we modify the MIRAGRODEP computable general equilibrium trade model to integrate the representation of agricultural value chains with economies of agglomeration developed in chapter 2. We show the importance of hysteresis in trade by simulating scenarios with different chronologies of dairy market liberalization. We study the consequences of different types of supports of the dairy sector on their geographic distribution. Finally, we show that an environmental taxation of coal and petroleum products leads to an increase of transport costs and the concentration of milk production.

Key words: value chains, agglomeration, hysteresis, dairy, transport, resilience.

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Acknowledgments

I would like to thank, first and foremost, my PhD supervisor, Antoine Bouët, and my co-advisor, David Laborde. Mr Bouët, I am thankful that you accepted to supervise my PhD and that I got other occasions to work alongside you since we first met at IFPRI. You were always supportive and a great mentor along the way. Mr. Laborde, I will always be thankful for the opportunity you gave me, when 6 years ago you trusted me to work with you for a year at IFPRI. This was a defining experience for me, professionally and personally. I am happy this partnership has extended over the years as you advised me during this doctoral journey.

I would like to express my sincere gratitude to the members of the jury, Zohra Boumra-Mechemache, Carl Gagné, and Richard Sexton who kindly accepted to be part of my PhD defense committee. It is an honor to submit this work for your review. I would also like to thank Jean-Marie Cardebat, Luc Doyen and Carl Gagné once again, who accepted to be part of my PhD committee to monitor my work for these three years.

I acknowledge the French Ministry of Agriculture who gave me the opportunity to do this PhD for my first position as an *Ingénieur des Ponts, Eaux et Forêts* and supported me financially for this period. All views expressed are solely my own and do not necessarily reflect the policies or opinions of the French Ministry of Agriculture.

This thesis is dedicated to my family, who was here at every step of the way, always supporting, listening and inspiring me. I am grateful I got to grow surrounded by so many kind and amazing persons.

Last but not least, I would like to thank all my friends and colleagues that have accompanied me over the years. Everywhere I went, I got to live and work with some people that made life easier, funnier and that inspired me through their own work and lives and by countless endless

discussions. A special thanks to all the members of GREThA, who welcomed me with open-arms during these three years and made my experience in Bordeaux a pleasant one. I'd like also to thank the colleagues and friends in IFPRI who always welcomed me since my first day in D.C. You helped me grow as a researcher and made these stays far from home pleasant, fun and memorable. Finally, I'd like to thank Joakim, François, Suneha, Braulio, Jeanne, and Viola who helped review my work at different steps over these three years.

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General Introduction

THE MOVING, QUESTING people were migrants now. Those families who had lived on a little piece of land, who had lived and died on forty acres, had eaten or starved on the produce of forty acres, had now the whole West to rove in. And they scampered about, looking for work; and the highways were streams of people, and the ditch banks were lines of people. Behind them more were coming. The great highways streamed with moving people. There in the Middle- and Southwest had lived a simple agrarian folk who had not changed with industry, who had not farmed with machines or known the power and danger of machines in private hands. They had not grown up in the paradoxes of industry. Their senses were still sharp to the ridiculousness of the industrial life.

John Steinbeck, *The Grapes of Wrath*, 1939

In 1939, John Steinbeck told the story of a family of tenant farmers from Oklahoma, forced out of their land by the double strike of a drought and the industrialization of agriculture. He describes the struggle of this family to adjust to a new life as it migrates to a new land, from which the many promises turn into disappointments. It's a tale of the transformation of two regions' agriculture and the difficulty for the people caught in the middle.

The world has continued its evolution since this text was written. The share of the agricultural sector in the economy of most countries has shrunk. Production has become more and more intensive and mechanized. Value chains are optimized and fragmented and agricultural markets are globalized. However, agri-food sectors keep a number of particular features that continue to anchor them on their territories. Land remains a major production factor. Agricultural labor still requires specific know-hows that differentiate it from other occupations. Agriculture remains the main source of income in many rural regions. Therefore, the lives of many

people are still intertwined with the success and struggles of their local agricultural sector.

In this context, the growing uncertainty brought by climate change, the emergence of new diseases, rapid shifts in consumer and citizens demands as well as an unstable political environment all appear as many challenges for agri-food sectors, rural regions and their population. As the food system has become globalized, these problems are increasingly complex to tackle as their consequences spread over time and space. This thesis aims at providing tools to better understand the complex interactions between regional agri-food sectors around the world as they face these shocks.

0.1 Context

0.1.1 A globalized food system facing rapid shifts and growing uncertainty

Food production has become increasingly globalized and trade of agricultural and food products have become more liberalized in the past decades. In 2015, it was estimated that 19.1% of produced calories were crossing an international border before being finally consumed, a number steadily increasing since 1975 (Bouët and Laborde, 2017). The average tariff applied on agricultural imports has decreased from 23.8% to 17.3% between 2001 and 2013 (Bureau et al., 2019). Most developed countries, including the United-States and the European Union, have shifted away from most trade-distorting support policies and have tended to reduce the size of their agricultural support programs (Bouët and Laborde, 2017). In the meantime, most developing countries have increased their support to the agricultural sector (Laborde, 2017). Some countries have taken a growing importance in global agricultural markets. Latin American and Caribbean countries, as well as Russia and Ukraine, have significantly increased their share in world exports. Africa and China have become major importers (OECD and FAO, 2019). An important trend has also been the development of agri-food global value chains. More and more often, agricultural products are processed in a different country than the one they were produced in (OECD, 2020c).

In addition to this changing global market, agri-food sectors are dealing with new consumers

and citizen demands and an increasing uncertainty. The rise of health, environmental and animal welfare concerns is leading to new regulations and incentive policies, as well as changing consumer tastes (EU, 2017; OECD and FAO, 2020). Climate change is expected to affect yields heterogeneously across the World, with a mostly negative incidence, and to increase climate variability (FAO, 2016). The number of extreme climate events has already doubled since the early 1990s (FAO et al., 2018). The combination of climate change, rising human and animal densities, the development of international travel and transport, as well as more intensive production system, is increasing the frequency and incidence of pest and diseases outbreaks (FAO, 2013). A recent upsurge of desert locusts in the Horn of Africa is threatening food security in the region as tens of thousands hectares of crops and pastures are damaged (FAO, 2020). In 2019, an outbreak of African Swine Fever led to the culling of about 20% of pig inventories in China, with significant consequences on global feed and food markets (FAO, 2019). In 2020, the ongoing COVID-19, is deeply disrupting all operations of food supply chains (OECD, 2020b). Finally, a recent trend of growing protectionism has created an increasing policy uncertainty. The current trade war between the US and China and a number of other partner countries has already led to the further taxation of tens of billions of dollars of agricultural trade flows (Bown and Kolb, 2020).

0.1.2 The anchorage of agri-food sectors on their territory

In contrast to this rapidly changing global context, most agri-food sectors remain deeply anchored on their local territory. This comes from the basic characteristics of these production systems.

First, we observe an important asset fixity, both in agricultural production (Vasavada and Chambers, 1986; Yang and Shumway, 2018) and processing (Morrison, 1997). Land is often considered as fixed or quasi-fixed in a particular use, as its conversion generally involve significant adjustment costs (Claassen and Tegene, 1999). A large share of agricultural capital is sunk as it is generally farm or sector specific. For example, a milking parlor cannot be easily transformed for another use and its resell value will collapse if the local dairy sector is in crisis. Furthermore, agricultural labor is imperfectly mobile. Farm human capital is generally of little

use outside of the agricultural sector. Finally, the reduced size of the labor market outside agriculture in rural areas may lead to migration decisions, involving an additional set of information and transaction costs (Chavas, 2001).

We also observe large economies of scale in processing sectors. Processing factories require a sufficient size to be efficient. This makes the capital lumpy and an important input supply is required for factories to be profitable. Economies of scale seem to have become more and more significant as processing factories have been consolidating into larger units over the years (Bhuyan and Lopez, 1997; MacDonald and Ollinger, 2000; Morrison Paul, 2001; Ollinger et al., 2005). Most agricultural primary products are very costly to transport, either because they are bulky, heavy or perishable (Cohen and Paul, 2005; Chevassus-Lozza and Daniel, 2006). The combination of economies of scale and transport costs leads to economies of agglomeration. The agricultural production needs to be sufficiently large and at proximity of processing factories, otherwise either transport costs become too important or the processors do not reach economies of scale (Henderson and McNamara, 2000). Such concentration of agricultural activities can be observed across the World in a variety of sectors (Roe et al., 2002; Iski, 2004; Roguet et al., 2015). In presence of economies of agglomeration, the economic geography literature shows that multiple economic equilibria can exist, associated with different patterns of agglomeration (Fujita et al., 2001). This multiplicity of equilibria leads to the possibility of hysteresis and lock-in. We observe a self-reinforcing phenomenon as investments in the agricultural production lead to new investments in processing, that subsequently spark further investments in production, until limiting factors come to play. Small initial differences of factors distribution between regions may determine in which region one sector is agglomerated in the future, even if the factor allocation is different by then. Alternatively, one shock may have irreversible consequences as it can make the system transition from one stable equilibrium to another.

Therefore, most agri-food sectors are formed by the pool of a number of agricultural producers and processors on a same territory. This ecosystem is both stabilized by asset fixity and the self-reinforcing force of economies of agglomeration. However, any shock may leave sustainable consequences on these value chains.

0.1.3 Adjustment costs, option value and coordination issues

The anchorage of agri-food sectors on their territory is at odds with the rapid changes and uncertainty that they face domestically and on world markets. As producers and processors in agricultural value chains are co-dependent, if any agent is in difficulty, the damages may spread to the whole sector. Because of asset fixity, any shock may create large adjustments born by farmers, workers, capital and land owners as their investments lose all their value. The geographic concentration of agri-food sectors makes certain regions especially dependent on some particular production and their whole economy can be at risk if the value chain collapse.

The co-existence of asset fixity and uncertainty gives rise to an option-value as there is a probability for any investment to become unprofitable in the future (Dixit, 1992; Perrings and Brock, 2009). This is not necessarily the proof of a market failure that would justify a public intervention as this option value is mostly borne by the agents (Dixit and Pindyck, 1994). However, the irreversibility created by economies of agglomeration in agri-food sectors may give rise to a collective option-value at the scale of the value chains. The reconstruction of a sector may be complicated as individual incentives to reinvest may differ from the collective interest, due to the externality of economies of agglomeration . Therefore, if a sector is in difficulty, it may be collectively desirable to preserve it in case the conditions become favorable again. This may justify the need for a coordination policy as this collective option value may differ from the private one.

Finally, the interconnectedness of local agri-food sectors by global markets makes any change in a region likely to leave lasting consequences on competing sectors across the world. Therefore, even local shocks, whether they are planned like policies, or unplanned like pandemics, pests or climate events, may have complex implications that spread over space and time (Desmet and Rossi-Hansberg, 2010). Local policies designed to support one sector may also have adverse consequences on other regions and other countries. This may lead to dynamic political economy problems with uncooperative equilibria if regions compete in the policy space.

The construction of a sustainable and resilient food system therefore requires understanding these complex interactions, to be able to limit risks and to choose policies that are collectively desirable.

0.1.4 The difficulties of representing regional dynamics of agri-food sectors in applied trade models

Despite their potential importance, the representation of these economies of agglomeration in applied trade models is until now relatively poor. This is the result of the multiple challenges their representation implies (Irwin et al., 2010; Fujita and Thisse, 2013). First, a dynamic model is needed to represent sunk cost and hysteresis. This requires further assumptions on agents' expectations and inter-temporal behavior. Second, as economies of agglomeration occur in general at the local level, models need to be detailed at least at a regional scale. Third, the presence of internal economies of scale leads to potential market power as firms concentrate. This is in contradiction with the pure and perfect competition framework which is usually adopted in applied trade models. Finally, the multiplicity of equilibria makes the resolution of the model more complicated. More specifications are needed to rank the equilibria and determine toward which one the system may converge (Fujita et al., 2001).

Many of these challenges have been answered in some parts of the literature. Following Krugman (1991b), a number of trade models have represented economies of agglomeration using a monopolistic competition framework. However, the consequences of economies of agglomeration on the dynamic of such models have not been extensively studied. More importantly, monopolistic competition relies on hypotheses of product differentiation and taste for diversity in the procurement of inputs that are not suitable in the context of many agri-food sectors, where primary products can mostly be considered homogeneous. More and more Computable General Equilibrium (CGE) models are developed with a finer representation of value chains to better account for the role of vertical interactions (Athukorala et al., 2018; Antimiani et al., 2018; Walmsley and Minor, 2017; Bellora and Fontagne, 2019). There also exists a number of models with at least a level of regional disaggregation (Giesecke and Madden, 2013). However, the data requirement for such models is very large which can make their calibration complicated. Their level of details is therefore either reduced or they are built as top-down models which limits the representation of interactions between regional markets.

In the agricultural economics literature, many models have been developed to study the consequences of asset fixity on the dynamic of agricultural markets since the seminal Cob-

web model (Ezekiel, 1938; Gouel, 2012). They highlight the role of agents' expectations in the determination of these dynamics. However, most of these models do not account for the vertical linkages between production and processing, at the recent exception of Chaudhry and Miranda (2018). Economies of agglomerations are not modeled and the representation of trade is minimal.

In conclusion, despite these efforts, there seems to be lacking a framework that simultaneously integrates all these issues and allows an appropriate representation of agri-food sectors with economies of agglomeration in a dynamic global trade model.

0.2 Research question and aim of the thesis

The objective of this thesis is to develop a theoretical framework for the better representation of regional dynamics of agri-food sectors in trade models. The end goal is to provide with a dynamic applied trade model, with a regional disaggregation, that features asset fixity and economies of agglomeration in agricultural value chains.

We want to use this framework to understand how the specific characteristics of agri-food sectors affect their dynamic at the regional level. In particular, we want to evaluate the size of the eventual adjustment costs and option-value that may have been overlooked as these features were not represented in traditional applied trade models. We hope that this tool can be used to better understand the complex interactions in space and time between regional agri-food sectors as they face a variety of shocks. We want to identify potential conflicting interests between types of agents, regions and countries in response to trade and agricultural support policies. Ultimately, we hope that by accounting for these specific features, we can better understand the conditions necessary for the construction of a profitable, sustainable and resilient global food system, in today's uncertain context.

0.3 Presentation of the chapters

This thesis is composed of three main chapters. These chapters are complementary and represent the progression from a simple analytical dynamic model of a single agricultural value

chains to a fully calibrated, dynamic Computable General Equilibrium (CGE) trade model, with regional agri-food sectors featuring economies of agglomeration.

0.3.1 Chapter 1

The first Chapter is entitled "A theoretical framework to analyze the resilience of agricultural value chains to the COVID-19 crisis". At the beginning of this PhD, first attempts of representation of asset fixity and economies of agglomeration in numerical dynamic models of agri-food sectors quickly revealed to be leading to complex and even chaotic dynamics. It appeared essential to be able to isolate the determinants of these dynamics. This chapter answers this question as it provides a simple and original framework to understand the dynamic behavior of agricultural value chains. The COVID-19 pandemic brought an unprecedented amount of disruptions to food supply chains, simultaneously affecting input and labor supply, production and demand. The model developed in this chapter is used to highlight the short-run and long-run consequences of these disruptions on agri-food sectors. We use this framework to discuss the characteristics of agricultural value chains that determine their resilience to these shocks. We developed a web application which accompanies this chapter. It allows users to use this model and run simulations with a set of parameters of their choice, so they can explore the dynamic behavior of this model by themselves.

The base model is a partial equilibrium model with a discrete dynamic solved by recursion. It represents a primary agricultural production function and a number of processing factories. In the short run, the agricultural capital and the number of factories are fixed. Prices of factors, agricultural input and final products are exogenous. We solve this short-run equilibrium to find the responses of the price of agricultural products, production levels and profits to the disruptions from COVID-19. Between each period, the representative agent in charge of the agricultural production chooses the capital level for the next period according to its expectation of the price. Factories are set up for a given fixed cost which creates economies of scale. They enter or exit the value chain before each period following a zero-profit condition. This leads to the dynamic reaction of the agricultural value chain.

We show that under certain conditions, this system can display a multiplicity of steady-state

equilibria, with different number of processing factories and associated commodity prices and levels of production. In that context, shocks to either the number of active factories, input and factors costs and final demand can be transmitted to all the agents of food supply chains and lead to an irreversible switch from one steady-state equilibrium to another. We then modify the model to allow the farmers to sell their production outside of the supply chain. We demonstrate that this access to alternative markets can make value chains more resilient as it limits bottlenecks if one stage fails. We also look at the consequences of different levels of capital durability in the agricultural production and processing. We show that the flexibility of capital allows the agents to cut losses during crises. However, it limits the resistance of value chains to shocks as they can more easily collapse to a non-productive equilibrium. Finally, we discuss the importance of coordination issues in the dynamic behavior of agri-food sectors. In particular, we show how the market structure and the level of integration affect the ability of the agents to coordinate at more desirable equilibria. In this context, we highlight the potential need for conservation or recovery policies during and after crises.

0.3.2 Chapter 2

The second chapter is entitled "A Multi-Regional Dynamic Model of the French Dairy Sector with Economies of Agglomeration". It represents the next step of the model developed in Chapter 1.

We keep the same modeling structure with a partial equilibrium and a discrete dynamic, but we make the model multi-regional. Each region has an individual agricultural production and its own processing factories. We represent intra- and inter-regional transport costs for the collection of the primary commodity and its trade between regions. These costs depend on the number of factories and the geography of regions. These give rise to economies of agglomeration as more production leads to more factories and limits the distance traveled by unprocessed products. We also represent a flexible domestic demand for the processed product as well as its trade with the rest of the World.

We calibrate this model on the French dairy sector as it provides a good example with significant transport costs of milk and economies of scale in processing factories. We show that

both shocks on the world price of dairy products as well as the rise of transport costs can lead to an irreversible collapse of the dairy sector in some regions. Milk production density appears like a main determinant of one region's resilience. Finally, we show that an import tariff can limit the vulnerability of dairy sectors. However, it corresponds to an important redistribution from the consumers to the producers. Another solution may be to let the sectors adapt during crises but to support investment to help the recovery when the conditions are favorable again.

0.3.3 Chapter 3

The last chapter is entitled "Agglomeration Patterns in an Open World: Introducing Localized Value Chains in a CGE model". In this chapter, we plug the multi-regional model of agri-food sectors developed in Chapter 2 into the existing MIRAGRODEP CGE trade model. This allows us to develop a first dynamic global trade model that allows the representation of regional value chains with economies of agglomeration. We focus once again on the representation of the dairy sector and detail its representation with a regional disaggregation in a diverse set of countries. We study three types of scenarios to demonstrate the diversity of subjects this model can tackle and how it allows to better apprehend the complexity of the interactions in time and space between regional sectors.

First, we run scenarios of full opening of the European trade of dairy products with the rest of the World. In one scenario the European dairy market opens up to imports from other countries before foreign economies open their market to European dairy exports, while in the other scenario it is the foreign markets that open first. These simulations prove how such model can highlight the potential importance of chronology in trade policy. Indeed, we show that the liberalization of domestic and foreign markets has heterogeneous and often conflicting consequences on the regional dairy sectors inside the European Union and in partner countries. As economies of agglomeration and imperfect mobility of capital create hysteresis in the system, we show that the two policy scenarios do not lead to the same steady-state regional distribution of the dairy production, even though the policies become identical after 15 years. This demonstrates how such models can be used to complement the literature on trade hysteresis.

In the second set of scenarios, we test two schemes of support of the dairy sector in the

European Union. We apply a production subsidy either to the price of raw milk or to the price of processed dairy products. We show that the support of the production of raw milk leads to the further concentration of the production in the regions where it is already the densest. We explain this by the relative share of transport costs in comparison to the input share of raw milk in dairy processing. Indeed, in the densest region, transport costs are smaller so the share of raw milk in processing costs is more important. Therefore, these regions benefit the most from a reduction of milk price. On the other side, we show that a support of the price of processed product seems to be much more neutral. It even seems to favor a deconcentration of the milk production across regions. Indeed, by supporting production in all regions, it allows to reduce transport costs. As these costs are initially higher in regions with a less dense production, they benefit the most from this support. Moreover, economies of agglomeration seem to make these consequences last over time, even when these policies are suspended. This shows how this model can help bring a new light on the long-run regional consequences of agricultural support policies.

Finally, we study the consequences of an environmental policy by simulating a scenario where the European Union taxes the production and imports of petroleum and coal products. We show that such a policy would increase transport costs, leading to the further concentration of the dairy sector in the regions where it is already the densest. The regions with a less dense milk production would see their dairy sector collapse irreversibly, even if the policy is suspended. This would create substantial adjustment costs in these regions. As the concentration of the production may lead to other negative ecological externalities, this highlights a potential environmental trade-off to this policy.

0.4 Contribution and limitations of the approach

The approach developed in this thesis allows to reduce one of the blind spot of previous applied trade models by representing dynamic agglomeration effects in agri-food sectors. We highlight new dynamic behaviors and in particular the significance of hysteresis in these systems. This allows to use simulated comparative dynamics to evaluate the short-run and long-run consequences of a variety of scenarios of policies and disruptions, such as agricultural support and

trade policies or climate change and disease outbreaks. It enables to better integrate the complexity of the interactions over time between agents, sectors, regions and countries in the world economy.

However, this approach only represents one step forward and will invite further work to overcome a number of limitations and challenges it presents. We only compare different resulting dynamic geographic distribution of agricultural activities and discuss their consequences for different types of agents. There remains the question of finding the optimal dynamic distribution of these activities and the set of policies that would allow to reach it. We also have not represented risks explicitly and only compared the consequences of variety of shocks in different scenarios. Finally, our representation of market structures, agents' expectation, heterogeneity of products and production and our measure of economies of agglomeration are still basic and further work would be necessary to make them fully accurate. Most of these limitations come from choices to keep models clear and tractable. The resolution of these issues often requires further assumptions, new data and to significantly increase the complexity of models. We further develop these limitations and discuss potential avenues for their resolution in the general conclusion of this thesis.

Chapter 1

A theoretical framework to analyze the resilience of agricultural value chains to the COVID-19 crisis

1.1 Introduction

The COVID-19 pandemic is imposing unprecedented stresses on agricultural value chains around the World (Torero, 2020b). Indeed, the outbreak and the regulations implemented to prevent its spread imposed disruptions both on the supply and the demand of food products. A number of processing factories closed to prevent further spread of the disease among workers or because too many were already infected (Reiley, 2020). Travel limitations created labor shortage due to the dependence on migrant workers. Social distancing and other worker protection measures imposed new costs to producers (Beatty et al., 2020). Lockdown policies and fears of disease transmission created significant shifts in consumption (OECD, 2020b; Tesfaye et al., 2020; Malone et al., 2020). Finally, trade and transport restriction disrupted trade (OECD, 2020a; Bouët and Laborde, 2020).

These disruptions created a number of bottlenecks, from which damages spread along value chains (Malone et al., 2020), as their agent are vertically interdependent (Bellù, 2013). The consequences were dramatic in some cases. Tens of thousands animals have been slaughtered

without being processed into food due to lack of outlets (Corkery and Yaffe-Bellany, 2020). Simultaneously, fears of food shortages and increased prices rose, leading some state to impose further trade restrictions on a number of products (Laborde and Parent, 2020). This crisis has therefore revealed a number of significant vulnerabilities in food supply chains (Evans, 2020). Despite this gloom picture, many value chains kept functioning and the food system as a whole seems to have mostly proved resilient during the ongoing pandemic (OECD, 2020b). Alternative outlets and innovative solutions were found to hold surpluses and shortages brief and contain price spikes (Reardon and Swinnen, 2020; Hawkes, 2020). However, some interrogations remain as the pandemic stretches with seemingly no foreseeable date to its end. The crisis may leave lasting consequences on food supply chains and consumer behaviors (Torero, 2020a). This raises some important questions on how to limit the further damages of the COVID-19 pandemic on agri-food value chains, how to help them recover and what transformations are needed to improve their resilience to future crises.

Agricultural value chains share a number of particular features that affect their dynamic reaction to shocks. We observe a significant asset fixity, both in the primary production (Chavas, 2001; Yang and Shumway, 2018) and at the processor's level (Morrison, 1997). This generates important sunk costs. The differentiation of long-run and short-run consequences of shocks is therefore critical as the choices made by the agents during a crisis may have lasting effects. In addition to asset fixity, we often observe significant economies of scale in food processing factories (MacDonald and Ollinger, 2000; Ollinger et al., 2005) and most agricultural products are costly to transport as they are perishable or bulky item (Cohen and Paul, 2005; Chevassus-Lozza and Daniel, 2006). This makes agricultural value chains subject to economies of agglomeration. The economic-geography literature shows how such externality can lead to a multiplicity of equilibria, with different levels of agglomeration, leading to a potentially hysteretic behavior of the system (Fujita et al., 2001). The dynamic behavior of agricultural value chains is therefore likely to be complex and a shock like the COVID-19 outbreak may make the system transition irreversibly from one equilibrium to another. A significant theoretical literature beginning by the Cobweb model (Ezekiel, 1938) has studied the dynamic behavior of agricultural markets, under a variety of rationality assumptions and production configurations (Femenia and

Gohin, 2011; Gouel, 2012). However, the consequences of vertical linkages have mostly been overlooked at the exception of a recent paper by Chaudhry and Miranda (2018). More generally, the theoretical literature on the dynamic issues specific to value chains remains scarce (Antràs and Rossi-Hansberg, 2009).

This paper fills this gap and provides a unified and simple theoretical framework to understand how the different disruptions observed during the COVID-19 crisis have affected agri-food value chains in the short run and what lasting consequences they may leave in the long run. We develop an analytical model of a two-stage value chain, with recursive dynamic in discrete time. We represent an aggregate agricultural production that uses fixed factors, capital and variable inputs and factors to supply a primary commodity. This commodity is processed into a final food product, sold at an exogenous price, by processing factories that are set up for a given fixed cost. This partial equilibrium is solved each period to provide the short-run state of the system. Between each period, the agricultural capital and the number of factories react to the previous state of the system, leading to the long-run dynamic of the system. We make this model available as a web application that allows to reproduce the scenarios presented in this paper and to create new ones ¹. The user can choose its own value chain parameters and simulate a variety of shocks.

We use this framework to explain how agricultural value chains react to the disruptions of the COVID-19 crisis depending on their characteristics and what determines their resilience. We demonstrate how the economies of scale brought by the fixed cost in processing can create multiple steady-state equilibria. In this context, we show that the different disruptions brought by the pandemic can lead to an irreversible collapse of food supply chains. We then expand this model to allow the agricultural product to be sold outside of the value chain. We show that this access to alternative markets strengthen the resilience of value chains by limiting the risk of bottleneck if one stage fails. We then study the consequences of different profiles of capital durability in farms and processing factories. We highlight how the ability to adjust capital freely can allow the agents to cut their losses during crises but threaten the recovery of value chains as it eases their deconstruction. Finally, we emphasize how the imperfect vertical

¹It is available at: <https://lcosnard.shinyapps.io/shinydynvc/>. Accessed August 21, 2020

coordination of investments is a main driver of hysteresis in our model and make the recovery of agricultural value chains difficult. We discuss the role that agents' expectations, information and market structure can have to limit coordination issues and help value chain reach an optimal equilibrium at all time. If a more integrated organization of food supply chains could appear as a solution to help the coordination of the agents, it may also hinder their resilience if it leads to their further specialization and isolation from other markets. These coordination issues could therefore justify a policy intervention, either to preserve agricultural value chains during crises or to help their recovery. This choice would depend on the expected length of the shock and the respective costs of these policies.

In the remainder of this paper, we first present the structure of the model. We then solve the short-run equilibrium and discuss the immediate impact of the disruptions from the COVID-19 crisis. We then analyze the dynamic behavior of agricultural value chains and how the COVID-19 can affect them in the long run. We highlight the roles of access to alternative markets and capital flexibility on the resilience of supply chains. Finally, we discuss coordination issues in the face of the crisis and how they can be solved.

1.2 A dynamic model of agricultural value chain

We build a dynamic partial equilibrium model of a 2-stage value chain to study the resilience of agricultural value chains to shocks similar to the ones observed during the COVID-19 crisis.

In the upstream stage, a representative agent produces the primary agricultural commodity with a Cobb-Douglas production function using one unit of fixed factors, quasi-fixed factors or capital (K) and variable inputs and factors (V). We have the commodity production function, $Q = K^\alpha \cdot V^\beta$, with $\alpha > 0$ and $\beta > 0$ the capital and variable inputs share coefficients such that $\alpha + \beta < 1$. This formulation allows us to represent different levels of asset fixity as observed in most agricultural productions (Yang and Shumway, 2018) and to differentiate short-run and long-run reactions. We assume that the prices of capital P_K and the price of variable inputs P_V are fixed exogenously, while the price P_Q of the primary commodity is endogenous to the value chain.

In the downstream stage, we assume that a number n of identical processing factories use the

primary commodity as an input to process into a final product following an isoelastic production function. We have the production per factory, $y = d^\sigma$, with d the commodity demand per factory and $\sigma \in]0; 1[$ the production elasticity to input demand. The total processing demand for agricultural commodity is $D = n \cdot d$ and the total final product supply is $Y = n \cdot y$. The agricultural primary product is bought at the price P_Q and the processed product is sold at the price P_Y . We assume that individual value chains sell their final product on greater markets and therefore consider that the price P_Y is exogenous. Factories are set up for a given fixed cost F which create economies of scale in the processing stage, as observed in many food supply chain (MacDonald and Ollinger, 2000; Morrison Paul, 2001; Ollinger et al., 2005).

We assume that the quantity of capital in the agricultural production (K) and the number of processing factories (n) are fixed in the short run. However, before each period the level of agricultural capital can evolve following the previous state of the system. Factories can then enter or exit the value chain following this evolution. This creates a system with a recursive dynamic.

1.3 Short-run equilibrium and immediate consequences of the COVID-19 disruptions

We assume that all value chain agents are price takers. This strong assumption in the context of agricultural value chains (Sexton, 2013) allows to keep the model simple and analytically tractable. However, we show in Appendix A.3 that an oligopsonistic structure does not affect significantly the behavior of the system. Under this hypothesis, the representative agent in the agricultural stage maximizes its short-run production program:

$$\max_V \pi_Q = K^\alpha \cdot V^\beta \cdot P_Q - V \cdot P_V. \quad (1.1)$$

This leads to the variable input demand:

$$V = \left(\frac{P_V}{\beta \cdot K^\alpha \cdot P_Q} \right)^{\frac{1}{\beta-1}}, \quad (1.2)$$

And to the agricultural commodity supply function:

$$Q = K^{\frac{\alpha}{1-\beta}} \cdot \left(\frac{P_V}{\beta \cdot P_Q} \right)^{\frac{\beta}{\beta-1}}. \quad (1.3)$$

Each processing factory optimizes the production program:

$$\max_d \pi_y = d^\sigma \cdot P_Y - d \cdot P_Q. \quad (1.4)$$

As all factories are identical, this leads to the total agricultural commodity demand:

$$D = n \cdot \left(\frac{P_Q}{\sigma \cdot P_Y} \right)^{\frac{1}{\sigma-1}}, \quad (1.5)$$

And the total final product supply:

$$Y = n \cdot \left(\frac{P_Q}{\sigma \cdot P_Y} \right)^{\frac{\sigma}{\sigma-1}}. \quad (1.6)$$

The market-clearing condition for the agricultural commodity, $Q = D$, then allows to find the short-run equilibrium of its price:

$$P_Q = n^{\frac{(1-\sigma)(\beta-1)}{\beta \cdot \sigma-1}} \cdot K^{\frac{\alpha \cdot (1-\sigma)}{\beta \cdot \sigma-1}} \cdot \left(\frac{P_V}{\beta} \right)^{\frac{\beta \cdot (\sigma-1)}{\beta \cdot \sigma-1}} \cdot (\sigma \cdot P_Y)^{\frac{\beta-1}{\beta \cdot \sigma-1}}. \quad (1.7)$$

On equation 1.7, we notice that the short-run equilibrium price of the agricultural commodity is an increasing function of the number of processing factory (n), of the price of agricultural variable inputs (P_V) and of the price of final processed products (P_Y).

We have the agricultural profit:

$$\pi_Q = P_Q^{\frac{1}{1-\beta}} \cdot K^{\frac{\alpha}{1-\beta}} \cdot (P_V)^{\frac{\beta}{\beta-1}} \cdot \beta^{\frac{\beta}{1-\beta}} \cdot (1-\beta), \quad (1.8)$$

And he profit per factory:

$$\pi_y = n^{\frac{\sigma \cdot (\beta - 1)}{1 - \beta \cdot \sigma}} \cdot K^{\frac{\alpha \cdot \sigma}{1 - \beta \cdot \sigma}} \cdot \left(\frac{P_V}{\beta}\right)^{\frac{\beta \cdot \sigma}{\beta \cdot \sigma - 1}} \cdot (\sigma \cdot P_Y)^{\frac{1}{1 - \beta \cdot \sigma}} \cdot \left(\frac{1 - \sigma}{\sigma}\right), \quad (1.9)$$

And the total profit of processing factories:

$$\pi_Y = n^{\frac{1 - \sigma}{1 - \beta \cdot \sigma}} \cdot K^{\frac{\alpha \cdot \sigma}{1 - \beta \cdot \sigma}} \cdot \left(\frac{P_V}{\beta}\right)^{\frac{\beta \cdot \sigma}{\beta \cdot \sigma - 1}} \cdot (\sigma \cdot P_Y)^{\frac{1}{1 - \beta \cdot \sigma}} \cdot \left(\frac{1 - \sigma}{\sigma}\right). \quad (1.10)$$

In the context of the COVID-19 crisis, we can see how disruptions to trade likely to raise the price of imported agricultural variable inputs (P_V in the model) would not only affect agricultural profit but also the processing sector and ultimately the supply of processed products. We can also consider labor shortages due to lockdown policies and travel restrictions equivalent to a rise in the price of variable costs P_V with similar consequences. We can interpret factory closures due to the COVID-19 outbreaks as a decrease of n . We see that farmers' profits are then affected as they lack outlet for their product. The remaining factories would benefit of it as they would have less competition for the agricultural commodity. However, the processing sector as a whole would lose, as it would miss the profit from these lacking factories. The supply of processed products would decrease, possibly leading to shortages. Finally, drops in the price of the processed product due to consumption shifts during the lockdown are likely to transmit along value chains and affect the profit of the processors and farmers alike.

1.4 Long-run dynamic, multiplicity of equilibria and resilience

We now look at the dynamic of agricultural value chains to understand their determinants and study the long-run consequences of the COVID-19 crisis.

First, we assume that between each period, the representative agent for the agricultural production can decide freely of its capital level for the next period t , by maximizing its expected profit, based on its expected future price of the agricultural commodity, $\hat{P}_{Q,t}$. This free capital adjustment is a strong assumption as sunk assets and imperfect access to capital may create adjustment limitations. However, this enables us to find analytically the possible dynamic equi-

libria of the value chains and we discuss the implications of limited capital flexibility on value chains dynamic in a following section. The representative agent optimizes the following long-run production program:

$$\max_{K_t, V_t} \Pi_t^Q = K_t^\alpha \cdot V_t^\beta \cdot \hat{P}_{Q,t} - V_t \cdot P_{V,t} - K_t \cdot P_{K,t}. \quad (1.11)$$

This leads to the reaction function of the agricultural capital:

$$K_t = \left[\frac{1}{\hat{P}_{Q,t}} \cdot \left(\frac{P_{K,t}}{\alpha} \right)^{1-\beta} \cdot \left(\frac{P_{V,t}}{\beta} \right)^\beta \right]^{\frac{1}{\alpha+\beta-1}} \quad (1.12)$$

We assume that processing factories enter or exit the value chain in reaction to the investment in agricultural production (K_t) before each period t following a zero-profit condition. Therefore, the number of factories n_t is such that the short-run profit per factory $\pi_y(n_t)$ allows them to just cover the fixed cost per factory per period F , but the profit with an additional factory would not be enough, $\pi_y(n_t + 1) < F$. If we write the condition $\pi_y(n_t) = F$ following equation 1.9 and rearrange, we find:

$$n = \left[\left(\frac{F}{1-\sigma} \right)^{\beta \cdot \sigma - 1} \cdot \frac{P_{Y,t} \cdot K^{\alpha \cdot \sigma} \cdot \beta^{\beta \cdot \sigma}}{\sigma^{\beta \sigma} \cdot (P_{V,t})^{\beta \cdot \sigma}} \right]^{\frac{1}{\sigma \cdot (1-\beta)}} \quad (1.13)$$

As the number of factories n_t must be an integer with $\pi_y(n_t) \geq F$, $\pi_y(n_t + 1) < F$ and as $\pi_y(n_t)$ is a decreasing function of n_t , we verify this condition by inserting a floor function in equation 1.13. We have each period the number of factories as a function of the agricultural capital K_t :

$$n = \lfloor \left[\left(\frac{F}{1-\sigma} \right)^{\beta \cdot \sigma - 1} \cdot \frac{P_Y \cdot K^{\alpha \cdot \sigma} \cdot \beta^{\beta \cdot \sigma}}{\sigma^{\beta \sigma} \cdot (P_V)^{\beta \cdot \sigma}} \right]^{\frac{1}{\sigma \cdot (1-\beta)}} \rfloor \quad (1.14)$$

We now assume that the representative farmer uses a myopic expectation of the future price of the agricultural commodity to decide of its capital level for the next period: $\hat{P}_{Q,t} = P_{Q,t-1}$. This is a strong assumption, however econometric analyses show that perfect foresight does not seem to hold in the context of farm decisions (Nerlove and Bessler, 2001; Femenia and

Gohin, 2011). We show in Appendix A.4 that an adaptive expectation assumption lead to similar equilibria. Under these hypotheses, the dynamic of the value chain can be fully described by its initial agricultural capital K_0 , its exogenous variables $(P_{K,t}, P_{V,t}, P_{Y,t})_{t \geq 0}$ and the system of reaction equations 1.12, 1.7 and 1.14 of the agricultural capital, the price of the agricultural commodity and the number of factories:

$$\begin{cases} K_{t+1} = \left[\frac{1}{P_{Q,t}} \cdot \left(\frac{P_{K,t+1}}{\alpha} \right)^{1-\beta} \cdot \left(\frac{P_{V,t+1}}{\beta} \right)^\beta \right]^{\frac{1}{\alpha+\beta-1}}, \\ P_{Q,t} = n^{\frac{(1-\sigma)(\beta-1)}{\beta \cdot \sigma-1}} \cdot K_t^{\frac{\alpha \cdot (1-\sigma)}{\beta \cdot \sigma-1}} \cdot \left(\frac{P_{V,t}}{\beta} \right)^{\frac{\beta \cdot (\sigma-1)}{\beta \cdot \sigma-1}} \cdot (\sigma \cdot P_{Y,t})^{\frac{\beta-1}{\beta \cdot \sigma-1}}, \\ n = \lfloor \left[\left(\frac{F}{1-\sigma} \right)^{\beta \cdot \sigma-1} \cdot \frac{P_{Y,t} \cdot K^{\alpha \cdot \sigma} \cdot \beta \beta \cdot \sigma}{\sigma^{\beta \cdot \sigma} \cdot (P_V)^{\beta \cdot \sigma}} \right]^{\frac{1}{\sigma \cdot (1-\beta)}} \rfloor. \end{cases} \quad (1.15)$$

We simplify this system with the following notations:

$$\begin{cases} K_{t+1} = A_{t+1} \cdot (P_{Q,t})^{\frac{1}{1-\alpha-\beta}}, \\ P_{Q,t} = B_t \cdot n_t^{\frac{(1-\sigma)(\beta-1)}{\beta \cdot \sigma-1}} \cdot K_t^{\frac{\alpha \cdot (1-\sigma)}{\beta \cdot \sigma-1}}, \\ n_t = \lfloor C_t \cdot K_t^{\frac{\alpha}{1-\beta}} \rfloor, \end{cases} \quad (1.16)$$

With:

$$A_t = \left[\left(\frac{P_{K,t}}{\alpha} \right)^{1-\beta} \cdot \left(\frac{P_{V,t}}{\beta} \right)^\beta \right]^{\frac{1}{\alpha+\beta-1}}, \quad (1.17)$$

$$B_t = \left(\frac{P_{V,t}}{\beta} \right)^{\frac{\beta \cdot (\sigma-1)}{\beta \cdot \sigma-1}} \cdot (\sigma \cdot P_{Y,t})^{\frac{\beta-1}{\beta \cdot \sigma-1}}, \quad (1.18)$$

$$C_t = \left[\left(\frac{F_t}{1-\sigma} \right)^{\beta \cdot \sigma-1} \cdot \frac{P_{Y,t} \cdot \beta \beta \cdot \sigma}{\sigma^{\beta \cdot \sigma} \cdot P_{V,t}^{\beta \cdot \sigma}} \right]^{\frac{1}{\sigma \cdot (1-\beta)}}. \quad (1.19)$$

We notice that the number of processing factories is an increasing function of the agricultural capital, as it guarantees a greater supply. Therefore, if there is not enough agricultural capital K_t at a given time to supply at least one processing factory at a reasonable price so it covers fixed cost, all factories will leave the value chain. Without outlet, the agricultural commodity will be worthless. This will lead to even less investment in the production the next period, which

implies ultimately the definitive collapse of the value chain without further action.

Rearranging the three equations of the system, we find the reaction function of the agricultural capital to its level in the previous period:

$$K_{t+1} = A_t \cdot \left[B_t \cdot \left[C_t \cdot K_t^{\frac{\alpha}{1-\beta}} \right]^{\frac{(1-\sigma)(\beta-1)}{\beta \cdot \sigma - 1}} \cdot K_t^{\frac{\alpha \cdot (1-\sigma)}{\beta \cdot \sigma - 1}} \right]^{\frac{1}{1-\alpha-\beta}}. \quad (1.20)$$

Figure 1.1 shows an example of this function with a set of parameter and two prices of the processed product. We observe discontinuities that correspond to the entry of factories in the previous period when the capital is higher. This function is not monotonous, it is therefore difficult to analyze the convergence of the sequence $(K_t)_{t \geq 0}$. However, the floor function implies that $\left[C_t \cdot K_t^{\frac{\alpha}{1-\beta}} \right] < C_t \cdot K_t^{\frac{\alpha}{1-\beta}}$. Therefore, we notice that regardless of its previous level, the agricultural capital level for the next period K_{t+1} is bounded by:

$$K_{t+1} < A_t \cdot \left[B_t \cdot C_t^{\frac{(1-\sigma)(\beta-1)}{\beta \cdot \sigma - 1}} \right]^{\frac{1}{1-\alpha-\beta}}. \quad (1.21)$$

This can be explained by the fact that processing factories will stop entering past a certain price of the primary commodity, following equation 1.9 and the zero-profit condition. Therefore, the price is bounded which in return limits investments in agricultural capital.

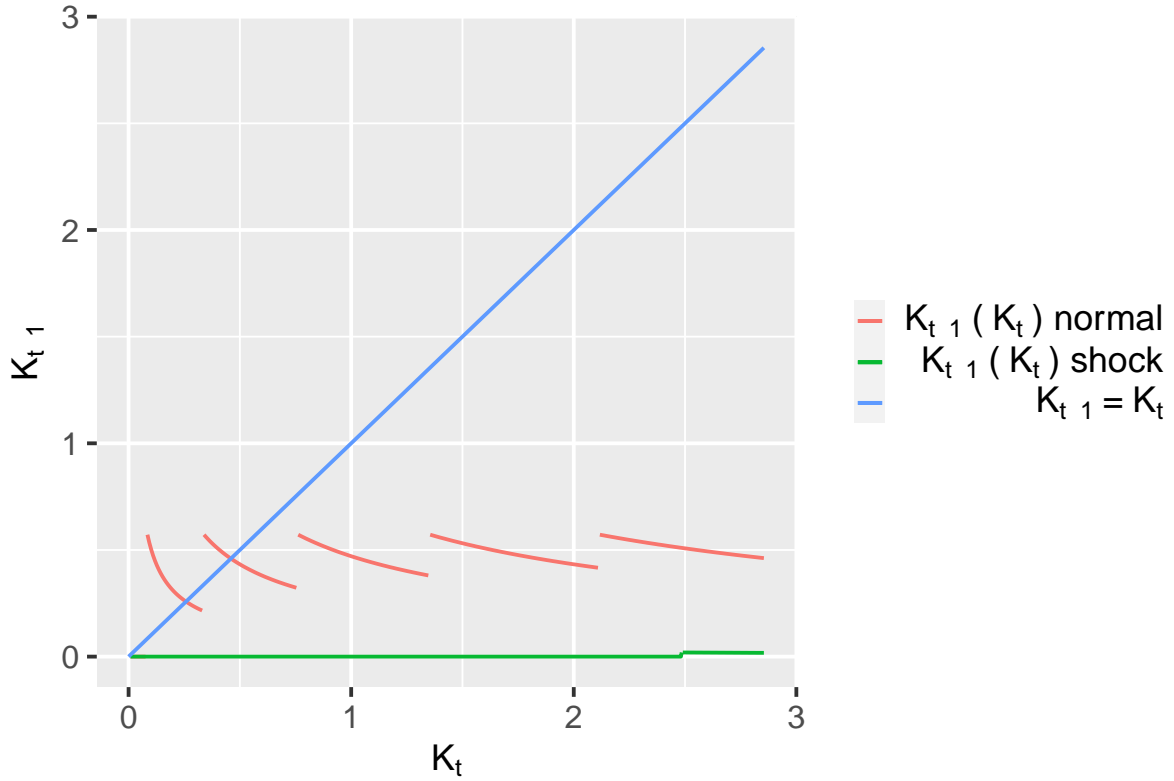
In order to look for steady-state equilibria of this sequence, we first analyze the dynamic of the agricultural capital, assuming the number of factories n_t remains stable at n_E . Combining the first two equations of the system 1.16, we have the dynamic of the agricultural capital:

$$K_{t+1} = A_t \cdot B_t^{\frac{1}{1-\alpha-\beta}} \cdot n_t^{\frac{(1-\sigma)(\beta-1)}{(\beta \cdot \sigma - 1) \cdot (1-\alpha-\beta)}} \cdot K_t^{\frac{\alpha \cdot (1-\sigma)}{(\beta \cdot \sigma - 1) \cdot (1-\alpha-\beta)}} \quad (1.22)$$

If $n_t = n_E$ is fixed, this function is decreasing for all $K_t > 0$, therefore the sequences (K_{2t}) and (K_{2t+1}) are monotonous. We then prove in Appendix A.1 that the sequence (K_t) converges under the condition:

$$2 \cdot \alpha + \beta - \sigma \cdot \alpha \beta \cdot \sigma - \alpha \cdot \beta \cdot \sigma - \beta^2 \cdot \sigma < 1 \quad (1.23)$$

Figure 1.1: Reaction function of the agricultural capital K_{t+1} to its previous period level K_t during a normal period ($P_Y = 3$) and a shock period ($P_Y = 2$)



Parameters: $\alpha = 0.3$, $\beta = 0.4$, $\sigma = 0.4$, $F = 1.1$, $P_V = P_K = 1$.

As α , β and σ are positive, this condition is verified if $2 \cdot \alpha + \beta < 1$. Therefore, it is valid if the share of variable and quasi-fixed factors are limited in the agricultural production, which seem a reasonable assumption regarding empirical estimates (Yang and Shumway, 2018). If K_t converges, we prove in Appendix A.1 that it is toward the fixed point K_E , given by the following equilibrium function f :

$$f : n_E \mapsto K_E = \left[A_t^{1-\alpha-\beta} \cdot B_t \right]^{\frac{\beta \cdot \sigma - 1}{(\beta-1) \cdot (1-\alpha \cdot \sigma - \beta \cdot \sigma)}} \cdot n_E^{\frac{1-\sigma}{1-\alpha \cdot \sigma - \beta \cdot \sigma}} \quad (1.24)$$

This result is similar to what can be observed in a Cobweb model (Ezekiel, 1938; Gouel, 2012). Indeed, when the number of processing factories is fixed, we are in a similar configuration. The imperfect expectations of farmers lead to cycles of over- and under-investment, which can finally converge if the elasticity of demand is sufficiently high in comparison to the supply elasticity.

The value chain admits a steady-state equilibrium if both the number of factories and the

level of agricultural capital are stable. Therefore, there must be a number of factories n_E , such that its corresponding steady-state agricultural capital K_E given by f , leads to a stable reaction of the number of factories. We note $g : K_t \mapsto n_t = \lfloor C_t \cdot K_t^{\frac{\alpha}{1-\beta}} \rfloor$, the reaction function of the number of factories from system 1.16. The set of steady-state equilibria of the value chain is then $\{(K_E, n_E) \in \mathbb{R}^+ \times \mathbb{N} | K_E = f(n_E), \text{ and } n_E = g(K_E)\}$.

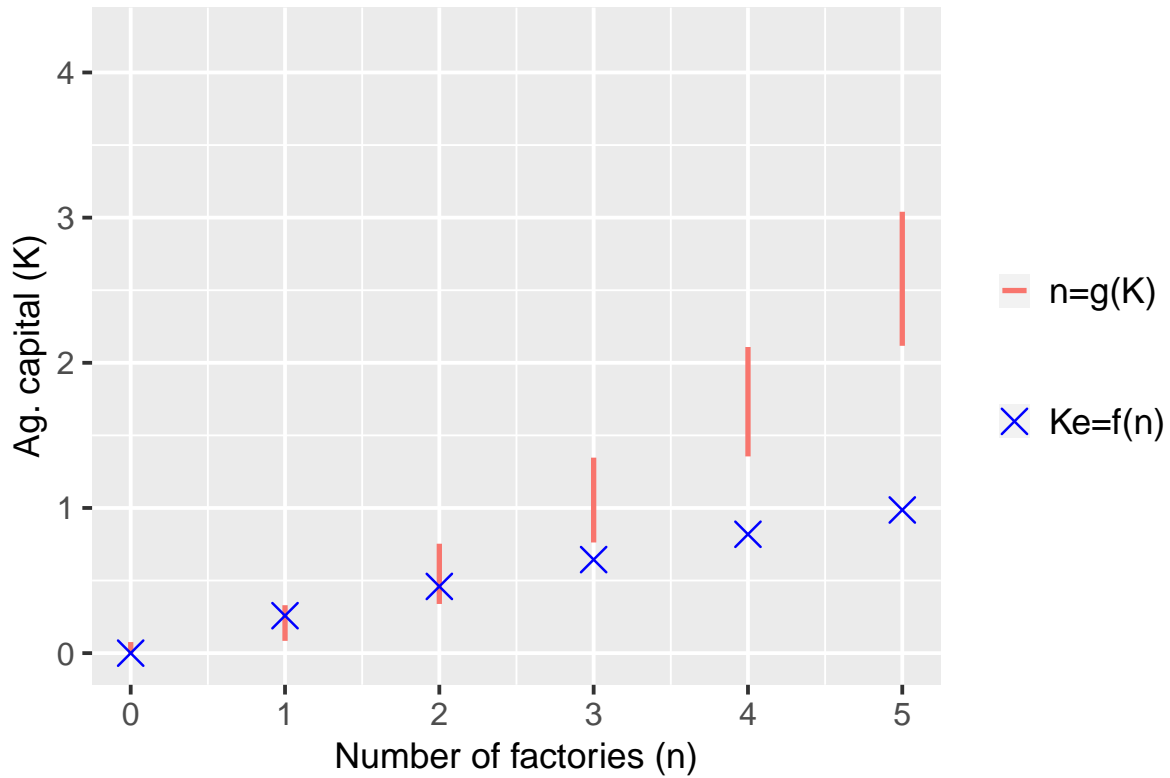
We saw that $(K_E = 0, n_E = 0)$ is always an equilibrium as the value chain cannot take off without a first investment. If other equilibria exist, they can be found graphically by plotting the capital equilibrium function $f(n)$ and the factory reaction function $g(K)$ on the same plot and looking for the intersection of f and g . Figure 1.2 presents an example on which we can observe three possible steady-state equilibria, for $n = 0$, $n = 1$ and $n = 2$. These equilibria can also be observed with the same set of parameters on figure 1.1 during normal periods, when the reaction function intersects the identity line $K_{t+1} = K_t$. Therefore, this value chain can sustain up to two processing factories. The setting-up of more factories requires levels of agricultural capital that are not profitable for the commodity price these factories could offer. This existence of a multiplicity of equilibria is a classical result of systems that admit non-convexities, such as the economies of scale due to the fixed set-up cost of factories. Therefore, this system can display hysteresis. Depending on its initial conditions, it may not reach the same dynamic equilibrium and a shock may make the system transition irreversibly from one equilibrium to another

Figure 1.3a presents an example of scenario where we apply a one period shock on the price of processed products at time $t = 10$. We observe that the shock leads to the closure of processing factories, leading to a collapse of the price of the agricultural commodity and a total disinvestment in the agricultural production the next period. Therefore, the value chain reaches this new unproductive steady-state equilibrium and never recovers when the exogenous conditions come back to their initial level.

Steady-state equilibria can also be found by solving this system analytically, as the equilibrium condition can be written as: $n_E = g \circ f(n_E)$. Therefore, we need to find n_E such that:

$$n_E = \lfloor C_t \cdot \left(\left[A_t^{1-\alpha-\beta} \cdot B_t \right]^{\frac{\beta \cdot \sigma - 1}{(\beta-1) \cdot (1-\alpha \cdot \sigma - \beta \cdot \sigma)}} \cdot n_E^{\frac{1-\sigma}{1-\alpha \cdot \sigma - \beta \cdot \sigma}} \right)^{\frac{\alpha}{1-\beta}} \rfloor \quad (1.25)$$

Figure 1.2: Example of equilibrium diagram with the equilibrium function of agricultural capital (f) and the reaction function of the number of factories (g)



Parameters: $\alpha = 0.3$, $\beta = 0.4$, $\sigma = 0.4$, $P_Y = 3$, $F = 1.1$, $P_V = P_K = 1$.

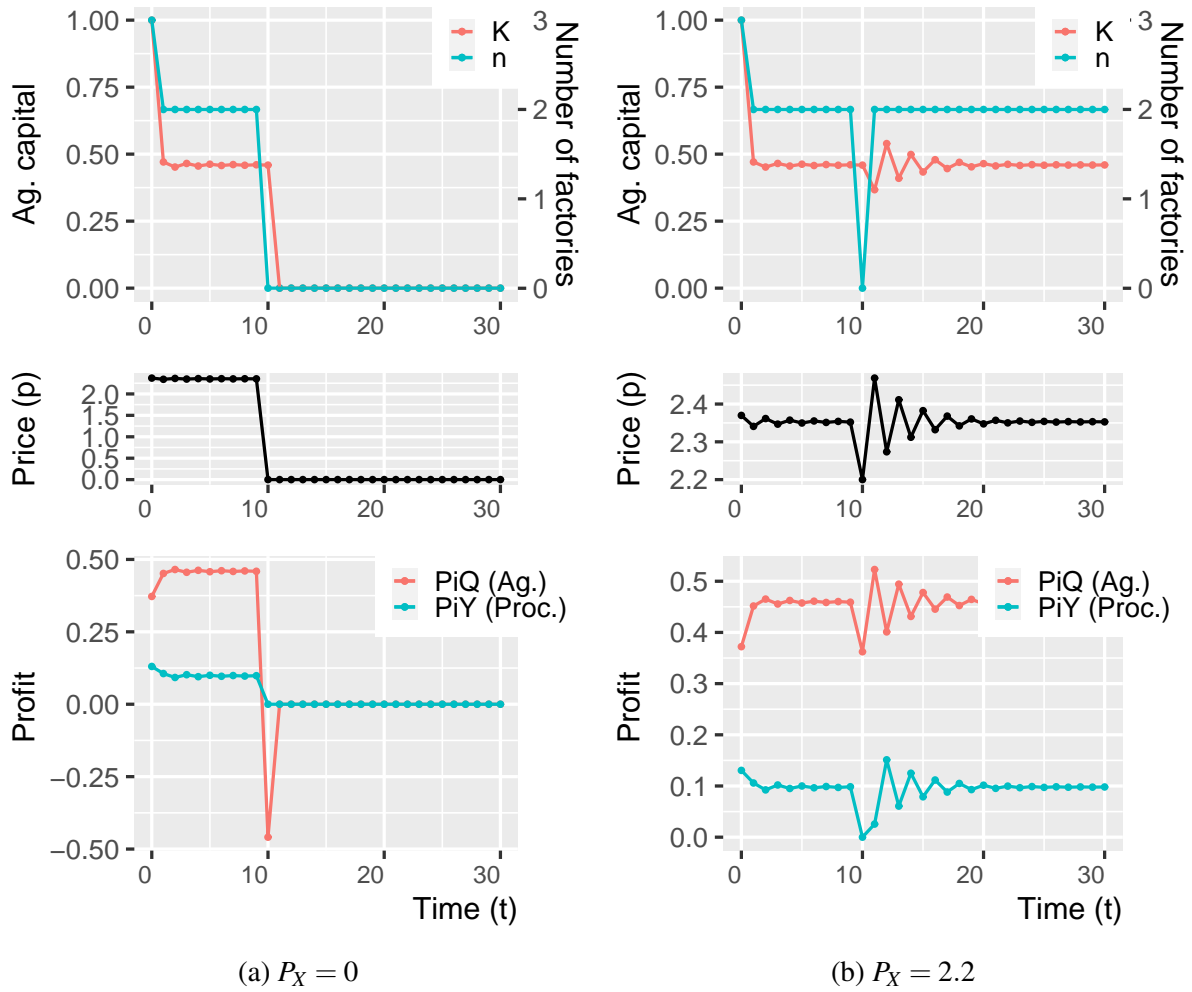
We prove in Appendix A.2 that following this condition, the highest number of factories that a value chain can sustain is given by the solution:

$$\bar{n} = \left\lfloor \left(\frac{F_t}{1-\sigma} \right)^{\frac{\alpha \cdot \sigma + \beta \cdot \sigma - 1}{\sigma \cdot (1-\alpha-\beta)}} \cdot \left[\left(\frac{P_{V,t}}{\beta} \right)^{\beta \cdot (\beta \cdot \sigma - 1)} \cdot \left(\frac{P_{K,t}}{\alpha} \right)^{\alpha \cdot (\beta \cdot \sigma - 1)} \cdot \sigma^{\alpha - \beta + \alpha \cdot \beta \cdot \sigma + \beta^2 \cdot \sigma} \cdot P_{Y,t}^{\frac{1-\beta \cdot \sigma}{\sigma}} \right]^{\frac{1}{(1-\alpha-\beta) \cdot (1-\beta \cdot \sigma)}} \right\rfloor \quad (1.26)$$

Therefore, the maximum number of processing factories a value chain can sustain is a decreasing function of the fixed cost of factory set-up, a decreasing function of the price of agricultural variable inputs and capital, and an increasing function of the price of the final processed product. $n_E = 0$ is always solution of equation 1.25. Therefore, if $\bar{n} < 1$, we have only one possible steady-state equilibrium, $n_E = 0$. The value chain cannot sustain any processing factory. However, if $\bar{n} \geq 1$, we have at least two steady-state equilibria: one unproductive, $n_E = 0$, and one productive, $n_E = \bar{n}$.

The risk of a crisis like the COVID-19 is therefore that even a temporary disruption desta-

Figure 1.3: Dynamic of the agricultural capital, the number of factories, commodity price and profits of an agricultural value chain facing a shock, without and with an alternative market



Parameters: $\alpha = 0.3$, $\beta = 0.4$, $\sigma = 0.4$, $P_Y = 3$ (normal) and $P_Y = 2$ (shock), $F = 1.1$, $P_V = P_K = 1$. One period shock at $t = 10$.

bilizes the value chains, as farmers and processors disinvest during the crisis. If it is brought to a full collapse, it may never recover even when market conditions improve, as the agents in the value chain have no incentives to re-invest after, as they now lack a processing demand for their product upstream and supply of input downstream. We see that both a rise in factors and input costs can lead to this collapse as well as a fall of final product prices. The closure of processing factories can also bring food supply chains down, as it brings the price of commodities down and may lead the farmers to exit the value chain the next period. Finally, we notice that fixed costs play an important role in this phenomenon. The more fixed costs per factory there are, the more agricultural product is needed to reach economies of scale, therefore the more agricultural capital is needed and the harder it is for an agricultural value chain to take off. If the increase

of scale operation in the food processing sector may have helped productivity in regular times (Morrison Paul, 2001; Ollinger et al., 2005), it may hinder food supply chain resilience as the producers are increasingly reliant on a single factory and its closure can bring the whole value chain down indefinitely.

1.5 Value chain isolation and resilience

We now allow the agricultural commodity to be sold outside of the value chain, at an exogenously fixed price $P_{X,t}$, either to be processed in another region or to be used in a different production. Therefore, $P_{X,t}$ is now a lower bound of the equilibrium price of the agricultural commodity as the farmers can sell their production out of the value chain if the price offered by the processors is too low. Therefore, the price reaction equation of the dynamic system 1.16 is now:

$$P_t = \max \left[P_{X,t}, B_t \cdot n_t^{\frac{(1-\sigma)(\beta-1)}{\beta \cdot \sigma - 1}} \cdot K_t^{\frac{\alpha \cdot (1-\sigma)}{\beta \cdot \sigma - 1}} \right]. \quad (1.27)$$

If the price $P_{X,t}$ is too high, the processors profit becomes too low to cover their fixed cost, $\pi_y < F$. Therefore, to have active factories, $n_t > 0$, we need:

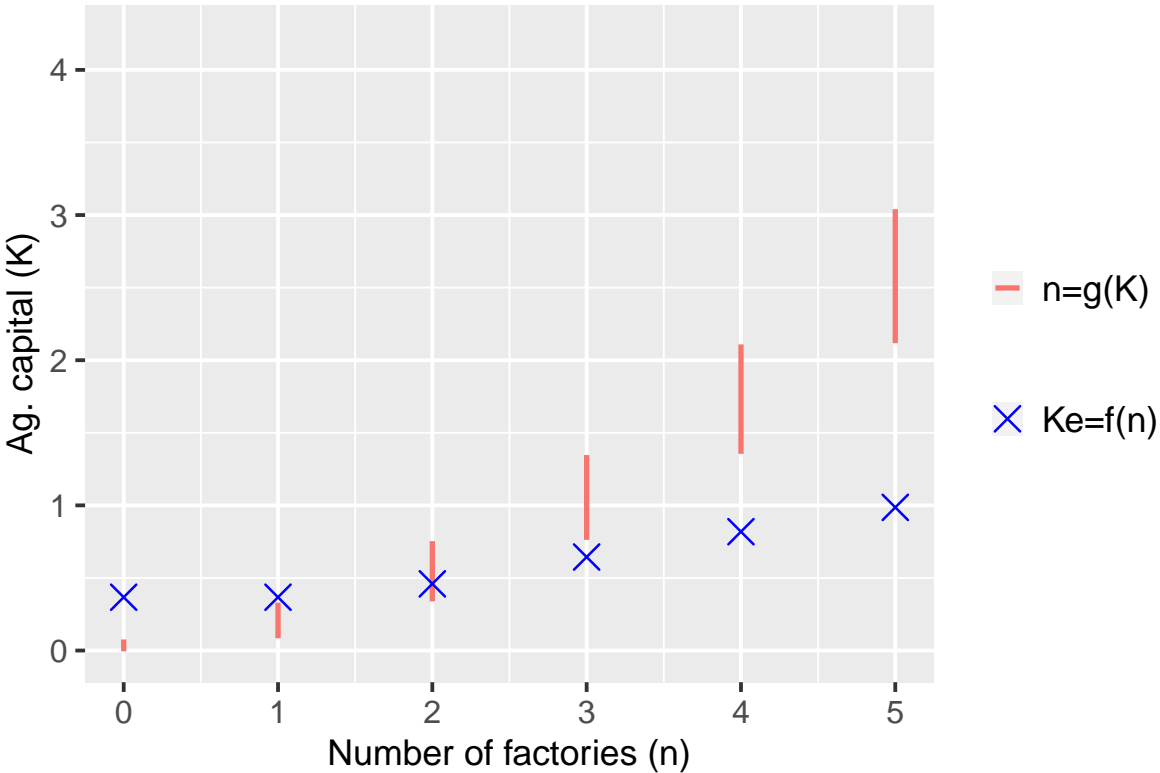
$$\pi_y(P_{X,t}) = P_{X,t}^{\frac{\sigma}{\sigma-1}} \cdot (\sigma \cdot P_Y)^{\frac{1}{1-\sigma}} \cdot \left(\frac{1-\sigma}{\sigma} \right) > F \quad (1.28)$$

Therefore, we need:

$$P_{X,t} > \left(F \cdot \frac{\sigma}{1-\sigma} \right)^{\frac{\sigma-1}{\sigma}} \cdot (\sigma \cdot P_Y)^{\frac{1}{\sigma}} \quad (1.29)$$

Figure 1.4 presents the new dynamic equilibrium diagram for such a system, with the equilibrium agricultural capital level for each number of factories $K_E = f(n)$ and the reaction of the number of factories to the capital installed $n_t = g(K_t)$. We notice now that even when there are no factories, some agricultural capital remains as farmers can still sell their production outside the value chain at the price $P_{X,t}$. Moreover, the equilibrium level of capital is higher when there is only one factory. This is because the equilibrium price offered by a single factory would be lower than $P_{X,t}$. Therefore, we notice that now, only one dynamic steady-state equilibrium is

Figure 1.4: Example of equilibrium diagram with the equilibrium function of agricultural capital (f) and the reaction function of the number of factories (g) with an alternative market ($PX = 2.2$)



Parameters: $\alpha = 0.3, \beta = 0.4, \sigma = 0.4, P_Y = 3, F = 1.1, P_V = P_K = 1.$

possible for a number of factory $n_E = 2$. With a single equilibrium, the hysteretic behavior of the supply chain is limited as it would always converge back to this equilibrium after a shock. We can relate this result to the economic geography literature. Indeed, if we consider that the access to the alternative market is made possible by a decrease of transport costs, we find back that the decrease of economies of agglomeration leads to a unique equilibrium.

Figure 1.3b presents the evolution of capital, factories, price and profits for such a scenario, where we apply the same shock on the final product price $P_{Y,t}$ as in figure 1.3a, but now the farmers can sell their product at the price $P_{X,t} = 2.2$ even during the shock. We notice that the possibility for the farmers to sell their product outside of the value chain allow them to save part of their profit during the shock. More importantly, even if factories don't operate and lose their profit during the shock, there remains enough agricultural capital at the end of the shock to allow them to settle back when the condition are better. Therefore, the whole value chain can bounce back to its initial equilibrium, when it would have collapsed without this alternative

market.

In the case of COVID-19, the agricultural surpluses and the disposal of animals and animal products without processing that appeared where a symptom of the isolation of value chains. These products are costly to transport and economies of scale have led to concentration and the reduction of the number of processing factories (Morrison Paul, 2001). Therefore, when some factories closed, the farmers had no access to alternative markets which made their production worthless. The isolation of food supply chains in the product space also leads to similar problems. Many productions have become more and more specific, with more bonding contracts. The farmers supply more tailored products, for processors to optimize their factories and differentiate their product to cater to a specific demand (Sexton, 2013). This created bottlenecks during the crisis as it made it harder for producers to find alternative markets (Gibbens, 2020; Malone et al., 2020). However, facing these limitations, value chain agents developed a number of innovative solutions during the COVID-19 to develop alternative market and link available suppliers and customers, especially at the local level (Hawkes, 2020).

1.6 Capital flexibility, adjustment costs and resilience of value chains

We now consider the possibility that the agricultural capital is not fully adjustable between periods. We take a putty-clay formulation and we consider that the capital is sunk once installed. Therefore, the stock of capital can only decrease through depreciation at a rate δ . This assumption makes sense in the context of agricultural value chains as a large part of the agricultural capital is often farm-specific, therefore it has a very low resell value (Mundlak, 2001).

The representative producer now chooses its capital level with the following long-run program:

$$\begin{aligned} \max_{K_{t'}} \sum_{t' \geq t} \pi^Q(K_{t'}) - (K_{t'} - (1 - \delta) \cdot K_{t'-1}) \cdot P_{K,t} \\ = \max_{K_{t'}} \sum_{t' \geq t} \hat{P}_{Q,t}^{\frac{1}{1-\beta}} \cdot K_{t'}^{\frac{\alpha}{1-\beta}} \cdot P_{V,t}^{\frac{\beta}{\beta-1}} \cdot \beta^{\frac{\beta}{1-\beta}} \cdot (1 - \beta) - (K_{t'} - (1 - \delta) \cdot K_{t'-1}) \cdot P_{K,t}, \end{aligned} \quad (1.30)$$

With the constraint $K_t' \geq (1 - \delta) \cdot K_t'$. The first-order condition gives:

$$K_t = \left[\frac{1}{\hat{P}_{Q,t}} \cdot \left(\frac{\delta \cdot P_{K,t}}{\alpha} \right)^{1-\beta} \cdot \left(\frac{P_V}{\beta} \right)^\beta \right]^{\frac{1}{\alpha+\beta-1}} \quad (1.31)$$

If we note the unit cost of capital in that configuration $P'_{K,t} = \delta \cdot P_{K,t}$, we find back the reaction equation 1.12. As we have the constraint $K_t \geq (1 - \delta) \cdot K_{t-1}$, we have:

$$K_t = \max \left((1 - \delta) \cdot K_{t-1}, \left[\frac{1}{\hat{P}_{Q,t}} \cdot \left(\frac{P'_{K,t}}{\alpha} \right)^{1-\beta} \cdot \left(\frac{P_{V,t}}{\beta} \right)^\beta \right]^{\frac{1}{\alpha+\beta-1}} \right) \quad (1.32)$$

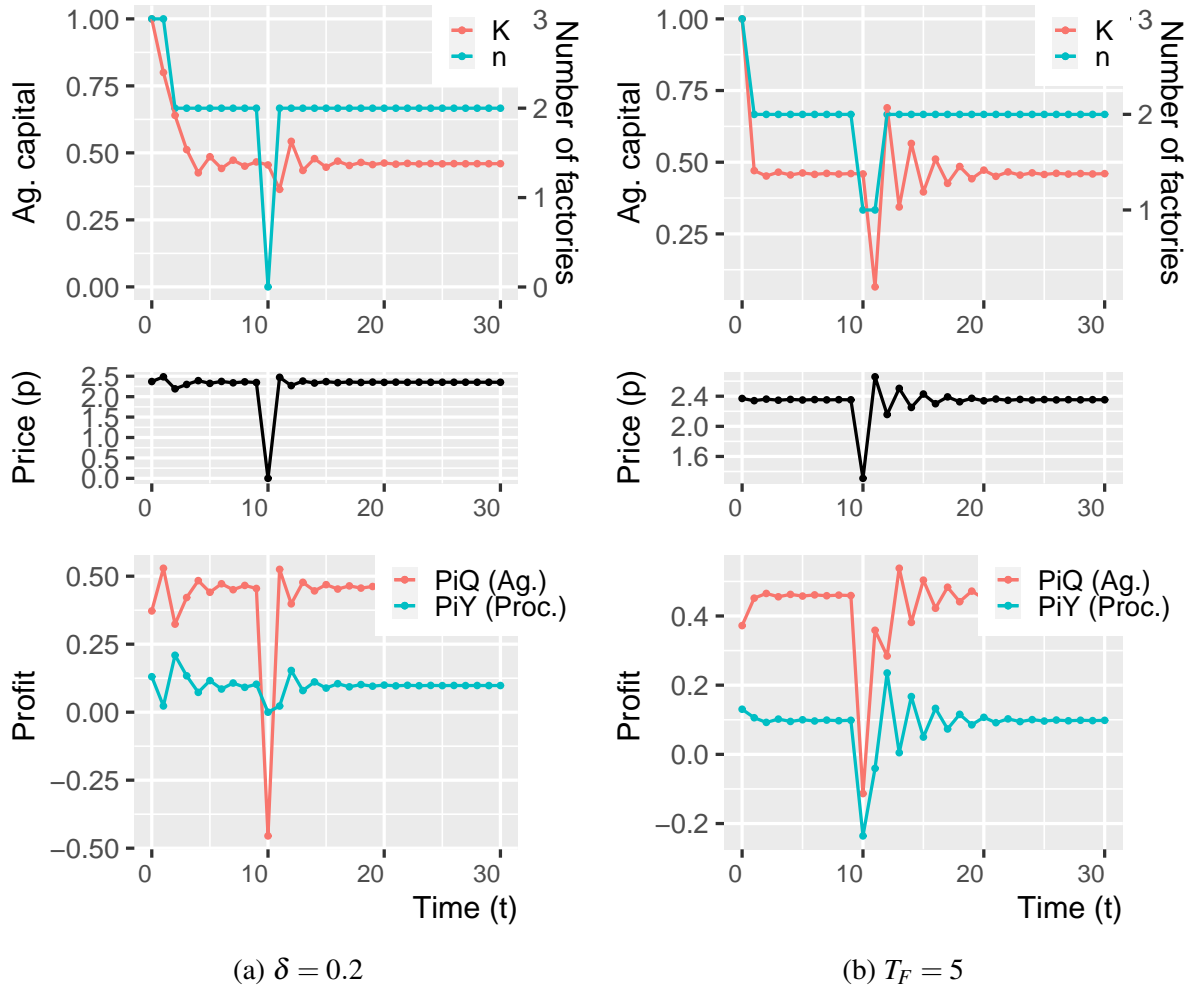
We can see an example of dynamic with a depreciation rate of $\delta = 0.2$ in figure 1.5a, where we apply a similar shock on the price of processed product as in figure 1.3a. We notice that the sunk capital create large losses for the agricultural sector during the shock as the farmers cannot cut these spending even though they don't produce. However, as there remains enough capital at the end of the shock for processing factories to settle back when the economic conditions are favorable again, this rigidity allows the supply chain to fully recover to its original production level, contrary to what is observed when the capital is fully flexible.

We can also look at the rigidity of capital in the processing stage. We now assume processing factories have a definite durability of T_F periods. Therefore, factories cannot exit the value chain for T_F periods until they reach obsolescence. We consider that factory owners assume their observed profit at time t remains stable in the future when they make their entry/exit condition. Therefore, their long-run program and the zero profit-condition do not change. However, the number of factories at a given time n_t is now bounded by the factories that entered in the $T_F - 1$ previous periods, as they cannot exit at time t . If we note the entry of factories at time t : $newF_t = n_t - (n_{t-1} - newF_{t-T_F})$. We have the lower bound on the evolution of the number of factory: $n_t \geq \sum_{t-T_F < t' < t} newF_t'$. Therefore, the reaction of the number of processing factories is given by:

$$n_t = \max \left(\sum_{t-T_F < t' < t} newF_t', \lfloor C_t \cdot K_t^{\frac{\alpha}{1-\beta}} \rfloor \right). \quad (1.33)$$

We can observe an example of dynamic of supply chain when the durability is set at $T_F = 5$ on figure 1.5b with the similar shock on the price of processed products applied. We notice

Figure 1.5: Dynamic of the agricultural capital, the number of factories, commodity price and profits of an agricultural value chain facing a shock, under limited disinvestment of capital and processing factories



Parameters: $\alpha = 0.3$, $\beta = 0.4$, $\sigma = 0.4$, $P_Y = 3$ (normal) and $P_Y = 2$ (shock), $F = 1.1$, $P_V = P_K = 1$. One period shock at $t = 10$.

a similar behavior to the one observed with rigid agricultural capital in figure 1.5a, but with the roles reversed. Now the processing sector registers a significant loss during the shock, however as one factory remains active as it hasn't reach obsolescence, it sustains a demand for the agricultural commodity that keeps its price high enough for the farmers to keep investing the next period. This allows the value chain to bounce back after the shock to its original equilibrium.

Therefore, we conclude that the ability to adjust capital is a big determinant of the resilience of food supply chains to consider in the analysis of the consequences of the COVID-19 crisis. Value chains in which the capital is sunk may suffer the most during the crisis, as they have to

deal with the burden of these sunk costs without being able to register any benefit. However, this rigidity may also allow them to recover best after the crisis. On the other end, value chains agents for which their capital is more flexible, either because it can be more easily sold or because it has reach obsolescence may be able to exit value chains during the crisis and avoid some of these adjustment costs. However, if all the agents exit during the crisis, it will be hard to recreate a profitable value chain as no agent will have any incentive to invest alone, without agricultural commodity supply or demand from processors. Regarding the uncertainty on the length of the COVID-19 pandemic, one should wonder if it is worth preserving the capital in the supply chains affected, assuming the crisis will be short enough. Or, if it is better avoiding these conservation costs and reinvesting now elsewhere, at the risk of losing permanently some value chains that could be profitable again when conditions come back to normal.

We have shown the role of capital rigidity limits as it limits the ability for the agents to disinvest. We could also represent imperfect access to capital as they have the opposite role on capital adjustment ability and limit investment. These would limit the ability of value chains to recover quickly after a shock and prevent the agents to profit of favorable economic conditions. However, in the context of imperfect expectations of the agents they may also avoid pro-cyclical over-investment and the risk of price collapse in the next periods.

1.7 Coordination issues, policy intervention and resilience of agri-food value chains

The multiplicity of steady-state equilibria in our model comes mainly from the impossibility between farmers and processors to perfectly coordinate their investments. The processors don't integrate the long-run supply function of the farmers and offer them a price that leads them to keep their investments low. Then without supply, no processors have any incentive to set up new factories. Therefore, the value chain may end-up stuck in an equilibrium with a lower level of production and less profitable for all. Besides the horizontal coordination problem due to the Cobweb-like imperfect expectations of the commodity price by the farmers, we observe a potential vertical coordination problem. If a single representative agent could decide both the

level of agricultural capital and variable inputs and the number of factory, there would be only one optimal equilibrium for any given exogenous set of costs and final product prices. In this context, the long-run consequences of a COVID-19 type shock would be limited as, even if supply chains shutdown during the crisis, this would not hinder their ability to bounce back.

The difficulty of coordination increases with the number of agents at each stage. Integration can then appear as a tool to bypass both vertical and horizontal coordination issues (Barkema and Drabentstott, 1995; Lierberman, 2001; Myers et al., 2010), whether by firm mergers, acquisitions, co-operatives (Sexton, 1986) or through greater contractualization (Oliveira et al., 2013). However, all this tools of coordination also bear the risks to strengthen dependencies between supply chain agents. On one side, if it leads to increased concentration and reduces the number of factories, it increases the risk of bottlenecks if some close. Furthermore, increasing contractualization may limit the ability of agents to connect to other markets in case of crisis and further sunk their capital into specific investments (Bouamra-Mechemache et al., 2015). Therefore, we come back to the absence of alternative market and rigidity that creates important adjustment costs.

Additional information could also be used to help coordination among agents in value chains with irreversible investments. For example, a futures market could help coordinate investments in upstream and downstream stages by creating an equilibrium between future productions and demand levels before investments are made (Kuwornu et al., 2006). It is key to appropriately represent these market structures and their consequences on the information available to the agents as they can significantly affect their ability to coordinate in time, as shown in the literature on dynamic cooperative games (Gale, 1995; Dasgupta, 2007; Richards et al., 2016).

These coordination failures could justify the need for policy interventions to help the conservation of value chains during crises or to help their recovery. Some state have already set up a number of policies to preserve agricultural value chains, whether by offering financial support or by supporting demand and helping the creation of alternative markets (Hawkes, 2020; Torero, 2020b). States could also help with the recovery of collapsed supply chains. The complementarity of investments along value chains and the possible vertical coordination problems that can arise could justify some temporary interventions, similar to the ones described in the

Big-Push literature (Murphy et al., 1989). The goal of such a policy would be to coordinate a number of investments along agricultural value chains to help them reach back to a productive and profitable equilibrium. This could be achieved by a variety of policies, such as direct financial support to prices and investments. As expectations play a key role in our framework by directing investment choices, changing these expectations could help steer the system toward a better equilibrium as shown in Krugman (1991a). We could therefore also imagine some policies that would strengthen the trust of the agents in the future profitability of the value chain, either by providing financial guarantees or coordination tools to the agents, by factorizing for example more contractualization. However, as the uncertainty upon the duration of the crisis and the state of the World after remains, policies need to be carefully evaluated. Indeed, conservation costs may outweigh the benefits from the preservation of certain value chains if the crisis drags on. Even worse, if the conditions are not favorable enough, such policies risk to lock-in some agents in some unprofitable supply chains.

1.8 Conclusion

The COVID-19 pandemic has created a number of unprecedented disruptions at every stage of agricultural value chains. This paper provides an original framework to represent these different shocks and analyze their short- and long-run consequences on food supply chains depending on their characteristics. We show that the specific features of agri-food chains, in particular economies of scale, sunk capital, transport costs and imperfect expectations, can make them subject to hysteresis. The main risk of the COVID-19 for the food system is therefore the irreversible loss of a number of supply chains.

In this paper, we show how the ability to find alternative markets during the crisis can have a key role in preventing bottlenecks and preserving the profits and the structure of the less affected stages. The more isolated value chains are, either because of transport costs or because their production is very specific, the more all of their participants are at risk if one stage fails. Innovation has appeared as an important tool during the COVID-19 crisis to limit these issues by creating alternatives and better link available supplies and demands. Our model only represents a two-stage value chain, however, this also implies that the longer value chains are, the more

exposed they are, as trouble at any stage may spread along.

We also highlight the role of the ability to adjust capital on the resilience of agricultural value chains. The more flexible value chains are, the more they are able to prevent losses during the crisis as they can avoid a number of adjustment costs. However, this also limits their resistance as if they disinvest too quickly, they may not be able to reach economies of scale anymore and may irreversibly collapse. Then, their reconstruction becomes very complicated as no agent has any incentive to invest alone, without existing agricultural supply or processing demand.

Finally, we discuss the importance of coordination issues in the resilience of agricultural value chains to the disruptions from the COVID-19 outbreak. Indeed, the existence of a multiplicity of equilibria and the associated hysteresis comes mainly from the inability of the agents to coordinate their investments vertically. In this context, vertical integration could be a tool to limit these irreversible consequences. However, if it isolates agricultural value chains more as it brings their agents into more binding contract and more specific productions, this may create more adjustment costs during crises. An alternative could be a policy intervention, either with supports to help the conservation of supply chains during the crisis or temporary measures to help their reconstruction after. Regarding the uncertainty around the duration of the pandemic and its consequences, this must be carefully planned as the costs of the preservation may outweigh its benefits and a coordination policy also has the risk of locking-in the agents in a sub-optimal equilibrium.

This work represents a first step toward better understanding the resilience of agricultural value chains. The key determinants of value chain resilience that we highlighted need to be properly measured and modeled when studying a supply chain. This will allow to accurately evaluate the risks and vulnerabilities in each specific type of value chain, as they differ in their market structure and production characteristics. These features can be seen as levers for the transformation of food supply chains toward more resilient system, keeping in mind the potential trade-off we highlighted between short-run adjustment costs, long-run recovery, efficiency and the distribution of these costs.

Chapter 2

A Multi-Regional Dynamic Model of the French Dairy Sector with Economies of Agglomeration

2.1 Introduction

Most agri-food sectors bear some characteristics that make them widely differ from their neo-classical representation in applied models. The productive capital is generally non-malleable, both in the primary production and at the processor's level, which generates important sunk costs (Chavas, 2001). We observe economies of scale at the factory level in processing industries (MacDonald and Ollinger, 2000; Ollinger et al., 2005). Finally, there are some important transport costs, in particular before processing, for fresh products like animal productions (Cohen and Paul, 2005). It is well known in the economic geography literature that in the presence of economies of scale and transport costs, some economies of agglomeration can arise, due to marshallian externalities (Fujita et al., 2001; Cohen and Paul, 2005). The same literature shows that with such externalities, multiple equilibria are possible, with various patterns of agglomeration, leading up to potential hysteretic behavior of the system. Such geographical concentrations of agri-food activities are well observed across the World (Cohen and Paul, 2005; Bagoulla et al., 2010). In such a framework, any shock is susceptible to generate irreversible

consequences on the production system of a region, raising issues of resilience. However, these characteristics are not represented in most applied models and the issues associated with the subsequent hysteresis are likely to be overlooked. From a policy perspective, it leads to the omission of the eventual option value associated with the irreversible consequences that a decision may have in an uncertain environment.

This paper proposes a multi-regional dynamic model of agri-food sector that allows the representation of sunk costs as well as economies of agglomeration between primary production and processing. We calibrate this model on the dairy sector of France as it provides a good example of agri-food sector with such economies of agglomeration (Barjolle and Jeanneaux, 2012). We compute simulations with a set of scenarios displaying a variety of shocks on milk transport costs and trade of dairy products. We observe in some cases the hysteretic collapse of some regional dairy value chains in response to adverse shocks. This affects not only the producers of these regions, but also consumers as the lacking supply increase prices of dairy products. It appears therefore important to understand the determinants of the resilience of these value chains.

Following Grafton et al. (2019), we discuss resilience as a property composed of three dimensions: resistance, recovery and robustness. Resistance is the ability of a system to maintain its performance during adverse shocks. Recovery is the speed to which a system recovers its previous level of performance after a shock. Robustness is the probability that a system stays functional, maintains its identity and does not cross an undesirable (and possibly irreversible) threshold following one or more adverse events. The simulation results show that agglomeration economies affect the dynamics of dairy value chains through a tipping point mechanism. Indeed, agglomeration economies play a minor role on the resistance of value chains to small adverse shocks. However, when a shock is more substantial, the exit of a number of processors increase the distance from farms to factories and the subsequent transport costs. This further affect the rest of the value chain until the whole system collapses. When transport costs are high, value chains become closer to their collapse tipping point. The milk production density explains most of the disparities in transport costs between regions and therefore appears like an important determinant of their dairy sectors' robustness.

A regional dairy sector is not able to recover of an adverse shock if at its end, the supply of milk has become too low for new processing factories to settle in again and if the local demand from processors is too low to stimulate new investments in production. The speed at which capital in milk production and processing depreciates therefore determines how long a shock a sector can sustain before it is not able to recover. Ultimately, the recovery problem comes in our model from the lack of coordination of investments between primary production and processing. We compare the effects on resilience of two types of policies in our set of scenarios. The first is a tariff on imports. It mostly increase the resistance and robustness of regional value chains as it limits the consequences of a trade shock on dairy production and the subsequent chances of a sector collapsing. However, it is a costly policy and an important redistribution from consumers to producers. The other policy we test is focused on recovery with post-shock forced investment in regions where value chains have collapsed. This policy appears efficient to revive regional dairy production and limit costs. However, it would require being able to identify the conditions when a regions dairy-sector could become profitable again. Moreover, its real implementation would require either state investment or a mechanism to persuade agents at both stages of the value chains to invest again.

Multiple modeling challenges explain why classical applied simulation models have been mostly unable to account for agglomeration economies and hysteresis (Fujita and Thisse, 2013). First, internal economies of scale are likely to generate concentration and market power to the incumbent firms, in contradiction with the pure and perfect competition hypothesis. Second, most models are solely detailed at the country level, thus making the representation of the regional effects occurring with agglomeration economies impossible. Third, multiple-equilibria systems require categorizing each equilibrium and further specifying the dynamic leading to one or another (Fujita et al., 2001). Fourth, sunk cost cannot be accounted in a static equilibrium framework. They require making further assumption about the agents' intertemporal decisions and their anticipations. The model proposed in this paper answers these different issues. It is built as recursively dynamic equilibrium model. In the short run, it corresponds to a classical convex partial equilibrium model. However, the long-run recursive dynamic allows to integrate sunk costs with the representation of a quasi-fixed input in regional milk supply func-

tion as well as fixed capital cost for the implementation of processing factories. These create internal economies of scale that combined with transport costs of milk between factories and farms generate economies of agglomeration. Multiple dynamic steady-state equilibria are then possible. However, agricultural investments and processing factories entry decisions are made under a set of adaptive expectations of the agent which drive the dynamic of the system. We also complements the literature on agricultural market dynamics and the staple Cobweb models (Ezekiel, 1938; Gouel, 2012). This paper offers a rare dynamic model of vertically linked agricultural markets, as the only other example to our knowledge in Chaudhry and Miranda (2018) does not tackle the issue of scale economies.

The following section presents the structure of the model and its short-run resolution. We then introduce the long-run agricultural investment and processors entry and exit processes. The calibration of the model on the French dairy sector and the related data are then presented. Finally, the different set of simulation scenarios is introduced and we discuss their results and their implications relative to the resilience of dairy value chains.

2.2 Description of the model and short-run resolution

We build a recursively dynamic partial equilibrium model of an agri-food sector. It represents a nation's agri-food sectors with a disaggregation in multiple regions. Each region has an aggregated primary agricultural supply and processing factories which use this product as an input in the production of a final product. The agricultural product is collected and transported with an intra-regional transport cost. It can also be traded between regions with an inter-regional transport cost. The final processed product can be consumed domestically or traded on the world market. The short-run evolution of the system, equivalent to a one year period, is given by a static partial equilibrium model. The long-run dynamic evolution of the system is based on the reactions of capital in primary and processing stages to the resulting state of the short-run partial equilibrium, for each year t . The association of indivisible capital in the processing stage and transport costs creates external economies of scale. This structure allows us to represent how an agri-food sector can agglomerate or not in a region. Associated with the imperfect expectations of the agents at both stages of the agri-food Value Chain, the model enables the representation

of hysteretic behaviors.

2.2.1 Local agricultural production

The aggregated primary agricultural production ($QM_{r,t}$) in a region r at time t is modeled as the result of a Constant Elasticity of Substitution production function, which uses three factors: a fixed factor (AL_r), a quasi-fixed factor ($KF_{r,t}$) and variable inputs ($VI_{r,t}^{opt}$). We have:

$$QM_{r,t} = \alpha_{M,r} \cdot \left(\beta_{F,r} \cdot (KF_{r,t})^{\theta^M} + \beta_{V,r} \cdot (VI_{r,t})^{\theta^M} + \beta_{A,r} \cdot (AL_r)^{\theta^M} \right)^{\frac{1}{\theta^M}}, \quad (2.1)$$

With $\beta_{F,r} \geq 0$, $\beta_{V,r} \geq 0$ and $\beta_{A,r} \geq 0$ are the share parameters, and $\theta^M < 1$ an elasticity of substitution parameter.

The fixed factor is an exogenous variable and considered inelastic over time. The quasi-fixed input is endogenous and can evolve in the long run from one period to another, however it is inelastic in the short run. This generates a sunk cost. It is purchased at an exogenous price PKF_t . The consumption of variable inputs is endogenous and flexible in the short run. The cost of the variable input (CV_t) is exogenous. This formulation of the production function allows us to represent the different types of asset fixity that can be found in agricultural production (Yang and Shumway, 2018). The agricultural production is sold at an endogenous farm price $PM_{r,t}^F$.

We consider that a regional agricultural production is the result of the maximization of the aggregate profit by a representative agent. We assume that there is a multiplicity of farmers producing locally the primary product, so the representative agent is price taker. In the short run, the aggregate quantity of quasi-fixed input in the agricultural sector ($KF_{r,t}$) is fixed. Therefore the program of the representative agent is:

$$\max_{(QM_{r,t}, VI_{r,t})} QM_{r,t} \cdot PM_{r,t}^F - VI_{r,t} \cdot CV_t, \quad (2.2)$$

Under the constraint of Equation 2.1. This leads to the aggregate agricultural production for

region (see figure 2.1):

$$QM_{r,t} = \alpha_{M,r} \cdot \left(\frac{\beta_{F,r} \cdot (KF_{r,t})^{\theta^M} + \beta_{A,r} \cdot (AL_r)^{\theta^M}}{\max \left(0, 1 - (\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r} \cdot \left(\frac{CV_t}{PM_{r,t}^F \cdot (\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r}} \right)^{\frac{\theta^M}{\theta^M - 1}} \right)} \right)^{\frac{1}{\theta^M}}, \quad (2.3)$$

And the consumption of variable input in region r is given by:

$$VI_{r,t} = QM_{r,t} \cdot \left(\frac{CV_t}{PM_{r,t}^F \cdot (\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r}} \right)^{\frac{1}{\theta^M - 1}}. \quad (2.4)$$

We note that if the price of primary product is too low, the regional agricultural supply is null. The minimum short-run production price is:

$$PM_{r,t}^{F,minSR} = \frac{CV_t}{(\beta_{V,r})^{\frac{1}{\theta^M}} \cdot \alpha_{M,r}}. \quad (2.5)$$

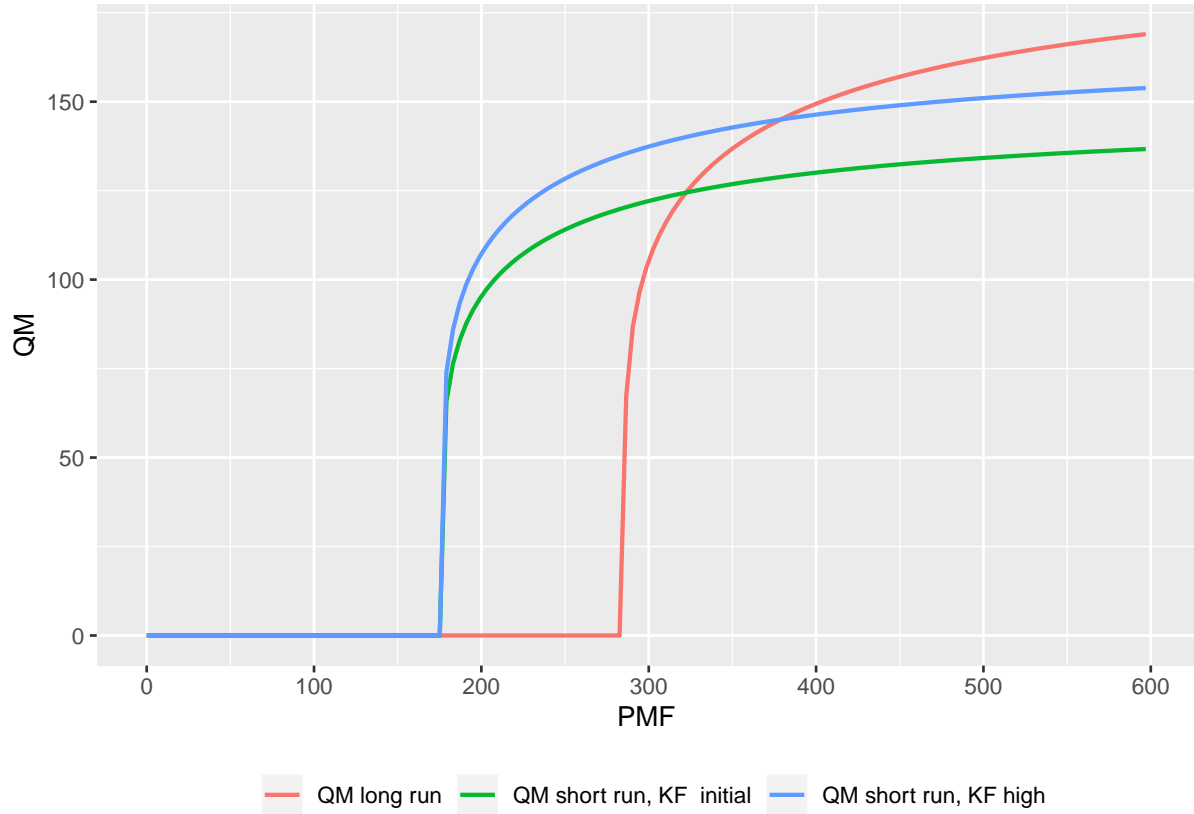
We notice that the minimum short-run production price is not dependent on the quantity of capital but only on the cost of variable inputs. Figure 2.1 presents the shape of the short-run agricultural production function with too levels of quasi-fixed input.

2.2.2 Processing industry

We model in each region an industry which processes the primary agricultural product into a final product. We assume that in each region r , the industry is composed of $n_{r,t}$ factories at time t , that are identical across regions. Each factory is composed of a fixed indivisible amount of capital K . The number of factories is inelastic in the short run but can evolve endogenously in the long run. Each factory has an identical CES production function using capital (K), primary agricultural product ($\frac{DM_{r,t}}{n_{r,t}}$) and other variable factors ($L_{r,t}$) to produce a final food product:

$$QC_{r,t} = \alpha^C \left(\beta_{K,r} \cdot K^{\theta^C} + \beta_M \cdot \left(\frac{DM_{r,t}}{n_{r,t}} \right)^{\theta^C} + \beta_L \cdot L^{\theta^C} \right)^{\frac{1}{\theta^C}}, \quad (2.6)$$

Figure 2.1: Long-run and short-run regional production functions in region NW



$\beta_K \geq 0$, $\beta_M \geq 0$ and $\beta_L \geq 0$ are the share parameters, and $\theta^C < 1$ an elasticity of substitution parameter. $DM_{r,t}$ is the quantity of primary agricultural product consumed by the whole processing industry in region r , ass all factories are identical, in each region $DM_{r,t}/n_{r,t}$ is the quantity of primary product consumed by factory. This quantity is flexible in the short run and purchased at the price of the agricultural product at the processing factory $PM_{r,t}^P$. The quantity of other variable factors consumed per factory ($L_{r,t}$) is also flexible in the short run and purchased at an exogenous price PL_t . The factory capital is valued at an exogenous price PK_t . As the amount of capital per factory is fixed, this generates a fixed sunk cost at the origin of scale economies in the processing industry. The processed product is sold at an endogenous national domestic price PC_t^D .

We assume that processing factories are price-takers on the primary product and the processed product markets. Their short-run program is therefore:

$$\max_{QC_{r,t}, DM_{r,t}, L_{r,t}} QC_{r,t} \cdot PC_{r,t}^D - \frac{DM_{r,t}}{n_{r,t}} \cdot PM_{r,t} - L_{r,t} \cdot PL_t, \quad (2.7)$$

Under the constraint of Equation 2.6.

The resulting supply of processed product per factory in region r is given by:

$$(QC_{r,t})^{\theta^C} = \frac{(\alpha^C)^{\theta^M} \cdot \beta_{K,r} \cdot (K)^{\theta^C}}{\max \left(0, 1 - (\alpha^C)^{\theta^M} \cdot \left[\beta_M \cdot \left(\frac{PM_{r,t}^P}{(\alpha^C)^{\theta^C} \cdot \beta_M \cdot PC_t^D} \right)^{\frac{\theta^C}{\theta^C-1}} + \beta_L \cdot \left(\frac{PL_t}{(\alpha_{M,r})^{\theta^M} \cdot \beta_L \cdot PC_t^D} \right)^{\frac{\theta^C}{\theta^C-1}} \right] \right)}, \quad (2.8)$$

With the demand for primary product per factory:

$$\frac{DM_{r,t}}{n_{r,t}} = QC_{r,t} \cdot \left(\frac{PM_{r,t}^P}{PC_t^D \cdot (\alpha^C)^{\theta^C} \cdot \beta_L} \right)^{\frac{1}{\theta^C-1}}, \quad (2.9)$$

And the demand for variable factor per factory:

$$L = QC_{r,t} \cdot \left(\frac{PL_t}{PC_t^D \cdot (\alpha^C)^{\theta^C} \cdot \beta_L} \right)^{\frac{1}{\theta^C-1}}. \quad (2.10)$$

We note that if the price of primary product is too high relative to the price of the processed product, the regional supply of processed product is nothing.

2.2.3 Intra-regional collection and transport costs

In order to compute the level of collection costs, we make three assumptions. First, we assume that the production inside one region is distributed uniformly on the whole territory. Second, we assume that processing factories in each region are uniformly distributed. We approximate that each region at time t is composed of $n_{r,t}$ identical squares with a factory at the center of each square. Third, we assume that factories split the territory into as many equal and exclusive supply-areas. Therefore, they collect all and only the primary production in their "square" at time t . It results that collection costs $\tau_{r,t}^C$ in each region depend only on its surface area S_r and its number of factories $n_{r,t}$ at time t . We compute this cost as the average distance between the center of a square of a surface area of $S_r / \max(1, n_{r,t})$ and a random point in this square with a uniform density and multiply it by τ_t^I , the transport cost per unit of distance at time t . The

collection cost in each region is given by the equation:

$$\tau_{r,t}^C = \tau_t^I \cdot \sqrt{\frac{S_r}{\max(1, n_{r,t})}} \cdot \left(\frac{\sqrt{2} + \log(1 + \sqrt{2})}{6} \right). \quad (2.11)$$

This transport cost is specific. Subsequently, the farm price and the processing factory price of the primary product are linked in each region by the equation:

$$PM_{r,t}^P = PM_{r,t}^F + \tau_{r,t}^C. \quad (2.12)$$

Of course this is an imperfect measure of the evolution of collection costs and the subsequent economies of agglomeration. It implies that when one factory enters or exits, it changes the location and distance between existing farms and factories. However, the question of the location of production and processing activities can become quickly complex, especially if we consider irregular geography. The decisions of location of farms and factories are co-dependent and depends on many other parameters, including market structure, pricing mechanisms and factors distribution (Parr and Kim Swales, 1999; Kilkenny and Thisse, 1999; Graubner et al., 2011). These assumptions allow us to keep the model simple, tractable and to limit the number of data necessary for its calibration.

The hypothesis that the production is uniformly distributed over the territory of each region is reasonable if we assume that the production factors are uniformly distributed. It is therefore important to use regions that are defined with this criterion in mind. Moreover, it also implies that farmers inside a region all receive the same price, independently of their location. This uniform delivered pricing assumption seems reasonable in the case of many agricultural markets, including dairy (Graubner et al., 2011). Finally, the fact that factories collect the agricultural product on the whole territory of a region may be a strong assumption if the distance to the furthest farms becomes very large. However, in some sectors including dairy, marketing cooperatives can force the processors to collect on a whole market (Graubner et al., 2011). Therefore, we believe this measure of collection costs is reasonable as a first approximation, but more work will be necessary in the future to be more accurate and better fit each particular geographic and marketing setting.

2.2.4 Inter-regional trade and transport costs

Trade of the primary product is possible between regions following a transport cost with exports from a region r to a region s at time t noted $T_{r,s,t}$. The transport cost at time t from a region r to a region s is equal to:

$$\tau_{r,s,t}^R = \tau_t^I \cdot D_{r,s}, \quad (2.13)$$

With $D_{r,s}$ the distance between the centers of region r and s .

Inter-regional transport costs apply after collection of the primary product, therefore they add up to the processing factory price in the origin region. The primary product is considered homogeneous. Therefore, it is exported from region r to region s only if the factory price $PM_{r,t}^P$ in region r is equal or lower than the factory price $PM_{s,t}^P$ in region s minus the inter-regional transport costs. In that case, the law-of-one-price will make the factory prices in both regions equalize at the difference of transport costs. Therefore, if $T_{r,s,t} > 0$, we have

$$PM_{s,t}^P = PM_{r,t}^P + \tau_{r,s,t}^R. \quad (2.14)$$

2.2.5 Demands and trade of the final processed product

We assume that the national domestic demand for the processed product follows the Armington assumption, therefore it considers domestic processed product and imports as two different varieties. The Armington aggregation follows a Constant Elasticity of Substitution between the domestic and imported variety, we have:

$$U_t = \left(a_D \cdot (DC_t)^{\theta^A} + a_M \cdot (MC_t)^{\theta^A} \right)^{\frac{1}{\theta^A}}, \quad (2.15)$$

The domestic demand for the Armington aggregate is isoelastic, we have:

$$U_t = a_U \cdot (P_t)^{\sigma^U}, \quad (2.16)$$

With a a quantity parameter, σ^U the price elasticity of demand. P_t is the price of the Armington aggregate:

$$P_t = \left(a_D \cdot (PC_t^D)^{1-\sigma^A} + a_M \cdot (PC_t^M)^{1-\sigma^A} \right)^{\frac{1}{1-\sigma^A}} \quad (2.17)$$

The imported processed product is purchased at a price PC_t^M . The resulting demands for the domestic and imported processed product are:

$$DC_t = a_D^{\sigma^A} \cdot U_t \cdot \left(\frac{P_t}{PC_t^D} \right)^{\sigma^A}, \quad (2.18)$$

and

$$MC_t = a_M^{\sigma^A} \cdot U_t \cdot \left(\frac{P_t}{PC_t^M} \right)^{\sigma^A}, \quad (2.19)$$

With $\sigma^A = 1/(\theta^A - 1)$.

We assume that the foreign demand XC_t for the processed product at time t is the result of an isoelastic demand. We have:

$$XC_t = a_X \cdot \left(\frac{PC_t^X}{(PC_t^D)} \right)^{\sigma^X}, \quad (2.20)$$

With a_X a quantity parameter, σ^X the price elasticity of export demand and PC_t^X an exogenous foreign reference price.

2.2.6 Market closure

In each region r , we have the closure on the regional market for the primary product:

$$QM_{r,t} + \sum_s T_{s,r,t} = DM_{r,t} + \sum_s T_{r,s,t} \quad (2.21)$$

We have the closure on the national market for domestic processed product:

$$\sum_r QC_{r,t} = DC_t + XC_t \quad (2.22)$$

2.3 Long-run recursive resolution of the model

The long-run model enables to represent the long-run evolution of the agricultural quasi-fixed input and the number of processing factories in each region. It is constructed as the recursive resolution of the static short-run partial equilibrium model, which describes the state of the system for each one-year period t . Between each period, the long-run model describes the reaction of the farmers and the processing industry to the previous equilibria in terms of production choices and investments for the future periods, according to their anticipations and long-run cost considerations.

2.3.1 Evolution of the quasi-fixed input in the agricultural production

The quantity of quasi-fixed input $KF_{r,t}$ in each region r agricultural production can evolve between every period t . However, we assume that it is a sunk asset that cannot be sold back. Therefore, it only decreases by its depreciation every period at a rate δ . We assume that the investment choice $I_{r,t}$ for period t is made in each region by a representative agent with a price of the quasi-fixed input PKF_t . The interest rate is r . It then chooses the regional quantity of quasi-fixed input in the agricultural production by maximizing its net present value under adaptive expectations on the product prices and input costs. The expectations of future prices of the agricultural product and variable input at time t are:

$$PM_{r,t}^{F,exp} = \lambda \cdot PM_{r,t}^F + (1 - \lambda) \cdot PM_{r,t-1}^{F,exp} \quad (2.23)$$

$$CV_t^{exp} = \lambda \cdot CV_t + (1 - \lambda) \cdot CV_{t-1}^{exp} \quad (2.24)$$

With λ the speed of adaptation of the expectations. The representative agents have myopic expectations on the future price of capital that they assume remains at PKF_t .

This leads to the following optimization program on future investments and variable input consumptions:

$$V(KF_{r,t}) = \max_{I_{r,t'}, VI_{r,t'}} \left(\sum_{t'=0}^{\infty} \frac{1}{(1+r)^{t'-t}} \cdot [\pi_{r,t}(KF_{r,t'}, VI_{r,t'}) - I_{r,t'} \cdot PKF_t] \right), \quad (2.25)$$

subject to:

$$KF_{r,t+1} = (1 - \delta) \cdot KF_{r,t} + I_{r,t}. \quad (2.26)$$

With $\pi_{r,t}(KF_{r,t'}, VI_{r,t'}) = QM(K_{t'}, VI_{r,t'}) \cdot PM_{r,t}^{F,exp} - VI_{r,t} \cdot CV_t^{exp}$.

We get the Bellman equation:

$$V(KF_{r,t}) = \max_{I_{r,t}, VI_{r,t}} \left(\pi(KF_{r,t}, VI_{r,t}^{opt}) - I_{r,t} \cdot PKF_t + \frac{1}{(1+r)} \cdot V((1-\delta) \cdot KF_{r,t} + I_{r,t}) \right). \quad (2.27)$$

The resolution of the Bellman equation leads to the optimal choice of quasi-fixed input quantity for period t ¹:

$$KF_{r,t+1}^{opt} = QM_{r,t+1}^{opt} \cdot \left((\delta + r) \cdot \frac{PKF_t}{(\alpha_{M,r})^{\theta^M} \cdot \beta_{F,r} \cdot PM_{r,t}^{F,exp}} \right)^{1/\theta^{M-1}}, \quad (2.28)$$

With the long-run expected supply (see Figure 2.1):

$$(QM_{r,t+1}^{opt})^{\theta^M} = \frac{\beta_{A,r} \cdot (AL_r)^{\theta^M}}{\left(\frac{1}{\alpha_{M,r}} \right)^{\theta^M} - \left[\beta_{F,r} \cdot \left((\delta + r) \cdot \frac{PKF_t}{(\alpha_{M,r})^{\theta^M} \cdot \beta_{F,r} \cdot PM_{r,t}^{F,exp}} \right)^{\frac{\theta^M}{\theta^{M-1}}} + \beta_{V,r} \cdot \left(\frac{CV_t^{exp}}{(\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r} \cdot PM_{r,t}^{F,exp}} \right)^{\frac{\theta^M}{\theta^{M-1}}} \right]}, \quad (2.29)$$

Quasi-fixed input is invested only if $QM_{r,t+1}^{opt} \geq 0$. The minimum long-run production price is:

$$PM_{r,t}^{F,minLR} = (\alpha_{M,r})^{\theta^M - 1} \cdot \left[\beta_{F,r} \cdot \left((\delta + r) \cdot \frac{PKF_t}{(\alpha_{M,r})^{\theta^M} \cdot \beta_{F,r}} \right)^{\frac{\theta^M}{\theta^{M-1}}} + \beta_{V,r} \cdot \left(\frac{CV_t}{(\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r}} \right)^{\frac{\theta^M}{\theta^{M-1}}} \right]^{\frac{\theta^M - 1}{\theta^M}}, \quad (2.30)$$

The related long-run agricultural supply function is visible on graph 2.1. We notice that the long-run minimum production price is higher than the short-run minimum price. If the price is between these two bounds, production would continue but the depreciated quasi-fixed input would not be replaced.

As disinvestment is not possible in this model, the investment in quasi-fixed input at period

¹Resolution of the optimization problem in Appendix B.3

t is then:

$$I_{r,t} = \max \left(0, KF_{r,t+1}^{opt} - KF_{r,t} \cdot (1 - \delta) \right), \quad (2.31)$$

2.3.2 Long run evolution of the number of processing factories

The long-run model describes the dynamic of the number of domestic processing factories $n_{r,t}$ in each region r . Every year t , this number reacts to the state of the system in the previous year equilibria, following expectations on the future state of the system and long-run cost considerations. The set-up of a new factory correspond to an investments in an indivisible amount K of capital units at price PK_t . This represents a sunk cost for the owner. Processing factories are productive for a number T_F of one year periods once they are set up. After this time, they are considered obsolete and disappear. The number of active processing units at time t is then:

$$n_{r,t} = n_{r,t-1} + newC_{r,t} - newC_{r,t-T_F}, \quad (2.32)$$

With $newC_t$ the number of new entrants in region r at time t .

We consider that each processing factory corresponds to a different company. Therefore, the set-up of new factories corresponds to the entry of new companies on the market. We assume that new companies will be set up in a region r prior to each year t until the anticipated net present value of a new factory $NPV_{r,t}$ is equal or below 0. The net present value (NPV) is computed on a horizon equal to the firm durability T . We assume that processing companies have an adaptive expectation on the future price of the processed product that is assumed to remain fixed at :

$$PC_t^{D,exp} = \lambda \cdot PC_{t-1}^D + (1 - \lambda) \cdot PC_{t-1}^{D,exp}. \quad (2.33)$$

We assume that processing companies make expectations on the price of the primary product following a reduced short-run model of the regional primary product market. The demand from factories follows Equations 2.8 and 2.9 from the short-run model under the adaptive expectation of the processed product price. The number of factories in region r is expected to remain stable at n_t on the horizon of the NPV computation. The agricultural short-run supply is assumed to remain stable following Equation 2.2 , this corresponds to a myopic expectation of the quasi-

fixed input quantity which is assumed to remain at $KF_{r,t-1}$. We assume an adaptive expectation on the transport cost per unit of distance:

$$\tau_t^{I,exp} = \lambda \cdot \tau_{t-1}^I + (1 - \lambda) \cdot \tau_{t-1}^{I,exp}. \quad (2.34)$$

No imports of the primary product are considered possible as we assume that processors consider that any existing regional excess of primary product would be absorbed by new processing factories in these regions. However, we assume that factories consider that the primary product price cannot be below a lower bound $PM_{r,t}^{P,bd}$ given by the maximum price farmers from their region would have gotten by exporting to another region at the previous period.

$$PM_{r,t}^{P,bd} = \max_s \left(PM_{s,t-1}^P - \tau_{r,s,t}^{R,exp} \right) + \tau_{r,t}^{C,exp}. \quad (2.35)$$

Finally, the Expected Net Present Value of a new factory in region r at time t is:

$$NPV_{r,t}(newC_{r,t}) = -K \cdot PK_t + \sum_{t'=t}^{t+T_{proc}-1} \left[QC_{r,t'}^{exp} \cdot PC_t^{D,exp} - \frac{DM_{r,t'}^{exp}}{n_{r,t}^{exp}} \cdot PM_{r,t'}^{P,exp} - L_{r,t'}^{exp} \cdot PL_{t-1} \right] \cdot (1+r)^{t'-t}. \quad (2.36)$$

The full model is described in Appendix B.5. Therefore, to determine the number of new factories set up or companies entering the market at time t , we increase the number of new factories $newC_t \in \mathbb{N}$ from 0 until the net present value of a new entrant, with one more factory, becomes negative ($NPV_{r,t}(newC_{r,t} + 1) < 0$). This implies that factories see how many others are entering at the moment they make their decision.

2.4 Data and calibration

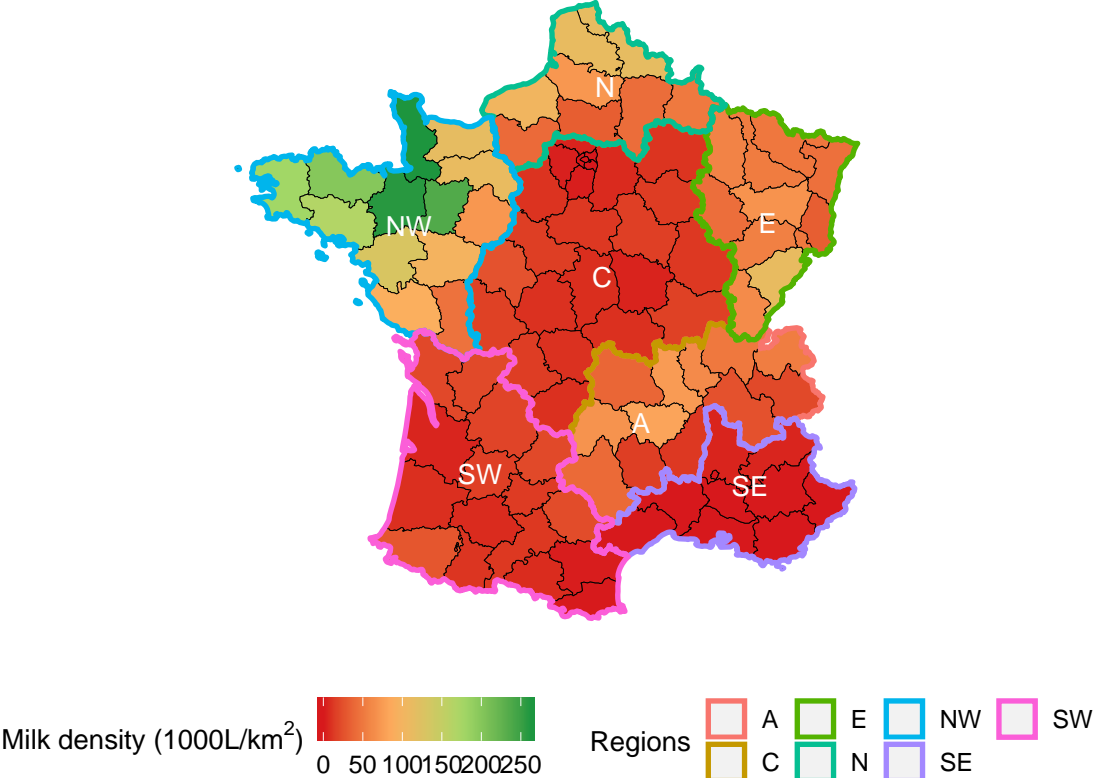
This model is programmed with the software *GAMS* to solve it numerically. We use a number of approximations in order to replace functions that are not derivable at some points. These are presented in Appendix B.5 with all the numeric model's equations.

We calibrate this model on the dairy sector from France in the year 2014. The sources come mainly from the French Ministry of Agriculture (Annual Dairy Survey), FranceAgriMer

(Monthly Dairy Survey) and the Farm Accountancy Data Network (FADN). France dairy sector is a good example for this model because it operates mainly at an industrial scale and transport costs of milk from farms to dairy factories are quite important.

We divide arbitrarily the continental territory of France into 7 model regions, based on an aggregation from the NUTS3 level "départements": North (N), North-West (NW), South-West (SW), South-East (SE), Center (C), Alpine (A) and East (E). The two main criteria for this aggregation were to create some geographically coherent regions with a homogenous dairy production density on their territory. Figure 2.2 presents the milk production density in 2014 at the NUTS3 level and the regions used in the model.

Figure 2.2: Map of the milk production density in France in 2014 and production regions of the model



Sources: National Statistics Agency (INSEE), Monthly Dairy Survey (FranceAgriMer)

One of the key choices for the calibration of this model was to choose the base size of a dairy factory at it would describe the scope of scale economies. In France in 2014, the 13 dairy factories that pack more than 100 million of litters of liquid milk annually account for 73% of the national production and 16% of the total number of factories packing liquid milk. We

find similar numbers looking at factories processing milk into cheese or butter. Therefore, we choose to calibrate a factory on a scale of processing of 100 million liters of milk per year.

In order to simplify calibration, we assume that in the base year 2014, all the milk produced in each region is processed domestically in each region. There is no inter-regional trade. Therefore, the initial number of factories per region is determined by the total milk production of each region that we round at 100 million liters digit. Table 2.1 provides the actual milk supply by region of the model in 2014 and their corresponding number of factories in the model.

Table 2.1: Surface area, milk supply and number of dairy factories per model region

Region	Surface area (km^2)	Milk supply in 2014 (10^6L)	Number of factories / Milk supply in model (base year, 10^8L)	Initial producer milk price in model (euros/1000L)
A	69743.06	2922.31	29	379
C	128085.87	1343.21	13	360
E	54239.54	3125.44	31	383
N	49352.92	3454.52	35	384
NW	82878.35	12380.77	124	388
SE	49883.5	47.59	0	NA
SW	100971.43	1233.54	12	363
France	535154.67	24507.38	244	383

Sources: National Statistics Agency (INSEE); Annual Dairy Survey (French Ministry of Agriculture, AGRESTE); Monthly Dairy Survey (FranceAgriMer).

We assume that the price of milk at the processing factory is initially the same across region. The farm price of milk only differs across regions depending on the intra-regional collection costs. We assume the collections costs represent on average 15 euros per 1000L of milk which is an estimate of transportation costs in France in plains area (Baron and Pechuzal, 2018), we compute accordingly the transport cost per kilometer. The average producer price of milk is of 383 euros per 1000L in France in 2014. We therefore add the average transport cost and set the initial price at the processing factory at 398 euros per 1000L and compute the initial producer price in each region accordingly (see table 2.1). The distance for inter-regional transport costs are computed between the centroids of each region.

The input shares of the CES milk supply function are homogeneous across regions and based on data from the FADN for 2014. The share of the variable input corresponds to the share of costs on feed, seeds, energy and other operating costs on the total productions (0.500). The

share of the quasi-fixed input corresponds to the share of the costs on rented land, building, machinery and paid labor on the total production (0.249). The depreciation rate is fixed at 12% in line with the estimate from Statistics Canada (2007) and the interest rate at 0.04%. The share of the fixed input, that we can attribute to family labor and owned land, is computed by difference to have the sum of input shares equal to one. As the year 2014 corresponds to the last year when milk production quota existed and were bounding in the region, we correct the production function to account for a quota-rent of 17% (estimate from Bouamra-Mechemache et al., 2008) and we attribute this rent to the fixed input. We compute the parameter θ_F to get a short-run price elasticity of 0.249 (see Bouamra-Mechemache et al., 2008). The shape of the resulting short-run and long-run milk supply function is displayed for region "NW" on figure 2.1. We notice that both short-runs and long-runs regional milk supply are infinitely elastic near their minimum production price. However, the supply is not very elastic around the initial price.

We assume a durability of dairy factories T_F equal to ten years and that in each regions, existing factories have been set up along the 10 previous years as uniformly as possible. The value of the total production of the dairy sector in 2014 was 21.450 billion euros. We normalize the price of the processed dairy product, therefore we divide this total production value by the initial number of factories in France to find their initial production. We assume that all the value added created by the dairy processing sector in 2014 (15% of the production value) comes from the capital and that the dairy sector is at a dynamic equilibrium. We compute accordingly the fixed amount of capital per factory. The total regional milk demand is the same as the regional supply in each region because of the initial equilibrium assumption. We normalize the prices of the input. We get the initial quantity of variable factor by difference between the production value and capital and milk demand. Finally, using the equilibrium hypothesis, we can find the corresponding parameters: $\beta_{K,r}$, β_M and β_L .

Exports of dairy products were worth 7.029 billion euros in France in 2014 and the imports were worth 3.544 billion euros. We compute the domestic demand by difference with the domestic supply and exports. The price of imports is normalized and we calibrate the export and domestic demands accordingly.

2.5 Dynamic simulations

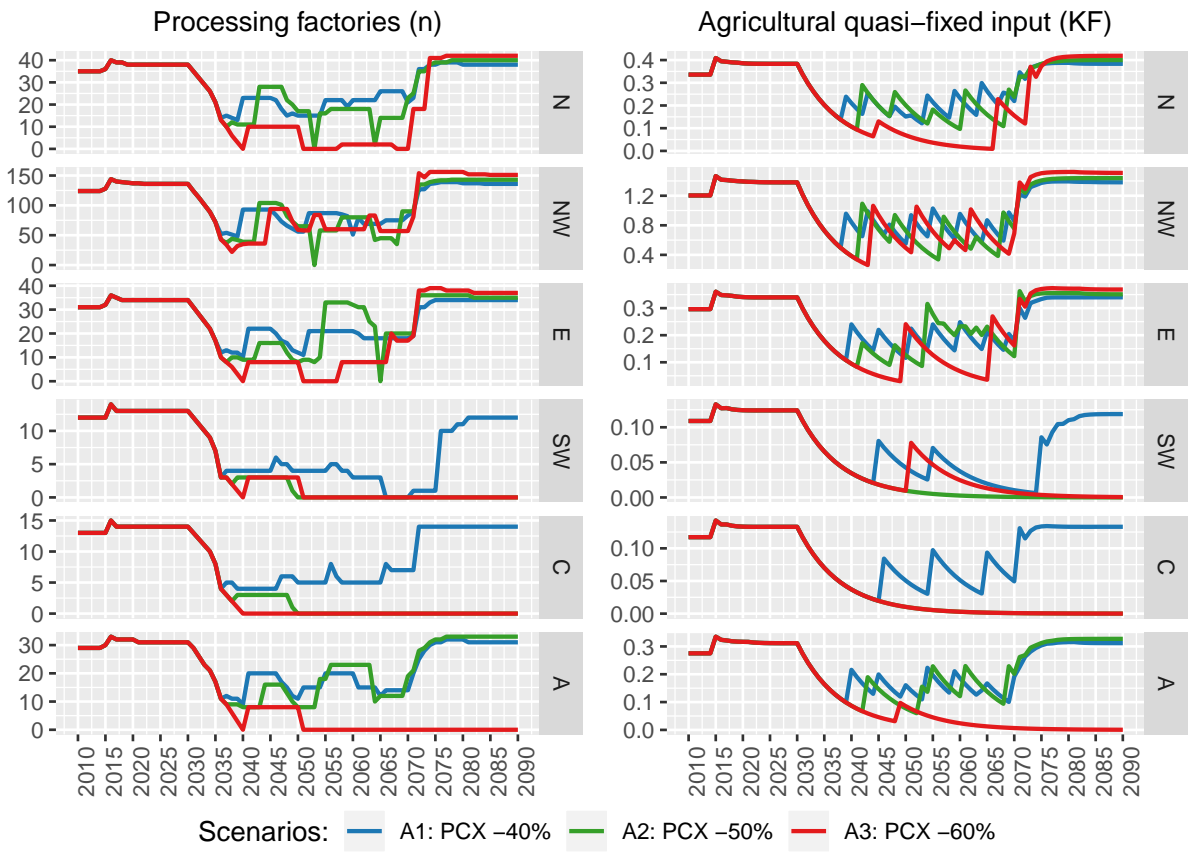
In order to study the resilience of the French dairy sector, we run different set of simulations where we apply a variety of shocks on trade of dairy products and on the transport costs of milk. We run these simulations on a horizon from 2014 (the base year) to 2090 to be able to represent policy changes and observe their long-run consequences. First, we study the reaction of the system to different magnitude of a prolonged decrease of the world price of dairy products. Second, we look at the role of the duration of the shock. Third, we study the reaction of the system to different levels of increase of the transport costs of milk (intra- and inter-regional). Finally, we test the ability of a tariff protection to increase the resilience of the French dairy sector in comparison with different scenarios where targeted investments are applied to help the reconstruction of dairy value chains in regions durably affected by adverse shocks.

2.5.1 Reaction of regional dairy sectors to shocks of foreign dairy products

We run a first set of simulation where we shock the world price of dairy product for 40 years starting in 2030. This corresponds to an identical decrease of the reference price of the foreign dairy product PC^X and of the price of dairy products imports PC^M . Therefore, we represent more of a structural shock on market's average price than the short-run volatility. We run three simulations numbered A1, A2 and A3 where prices are decreased of respectively 40, 50, and 60%.

Figure 2.3 presents the evolution of the number of dairy processing factories and of the quantity of quasi-fixed agricultural inputs from 2014 to 2090. Until 2030 when shocks are applied, all scenarios are identical. In 2015, we observe in every region an increase of the investments in agricultural quasi-fixed input due to the disappearance of milk production quotas. It is followed by an increase of the number of dairy factories in 2016 to process this extra supply. However, we observe a slight downward correction in the following years as imperfect expectations have led to an initial over-investment in production and processing. The system reaches an apparent steady state equilibrium before any shock is applied in 2030.

Figure 2.3: Regional evolution of the number of processing factories and of the quantity of agricultural quasi-fixed input to shocks on the price of foreign dairy products



We notice that for scenario A1, the 40% shock on the price of foreign dairy product affect the processing and the agricultural sector in a similar magnitude across regions. The number of factories and the quantity of quasi-fixed input decline of about 50% in a few years as they reach obsolescence and depreciated capital is not replaced. The system then enters a cyclical behavior for the remaining of the shock. Imperfect expectations and the high-elasticity of the long-run milk production function when prices are reduced leads to periods of under- and over-investment that transmit to the processing sector (Chavas and Pan, 2019). No regional sector is brought to a full collapse at any point. After the shock, the system fully recovers and the pre-shock original steady-state equilibrium is reached after a few years.

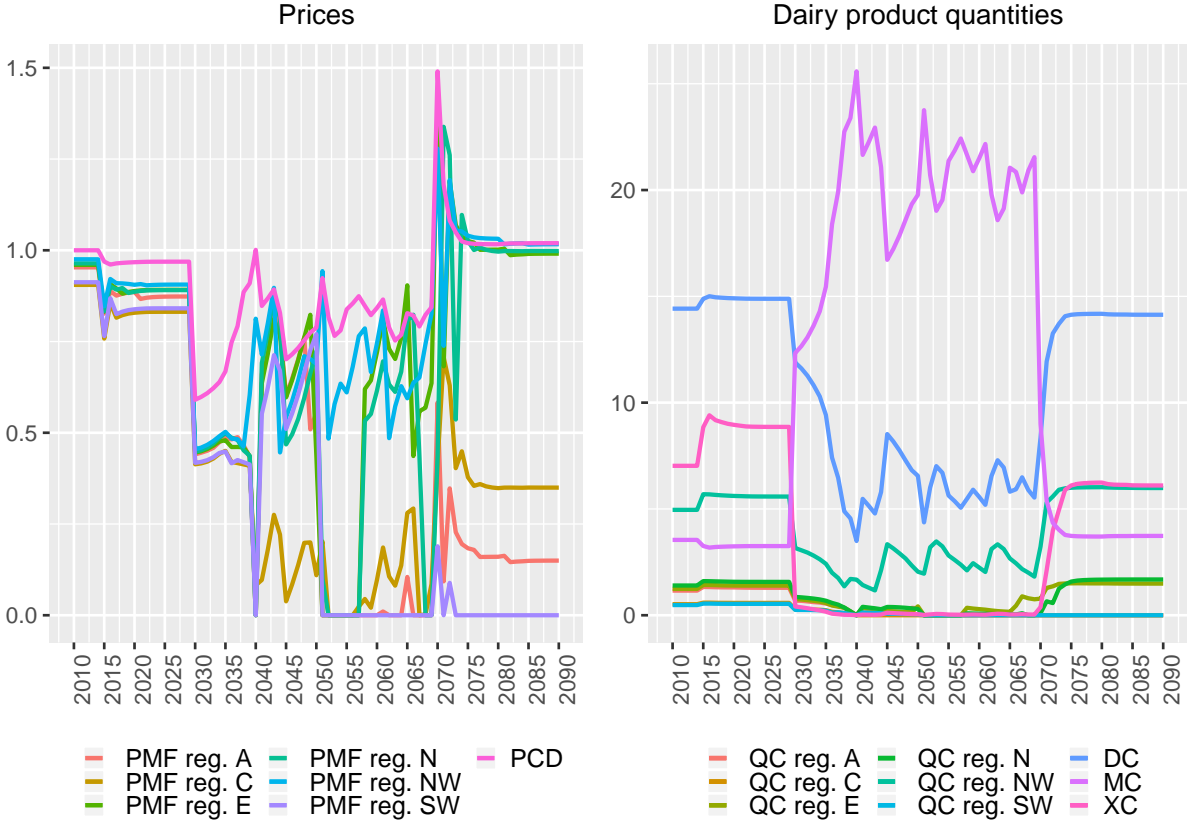
However, during scenario A2, the harder shock leads to a further decrease of the number of processing factories. In the regions that have a smaller milk production density, transport costs start to play a significant role and lead to a tipping point as we observe the full disappearance of the dairy sector in regions C and SW. The dynamics in other regions appear fairly chaotic

as they reach steeper and uncorrelated periods of over- and under-investment. At the end of the shock, the dairy production never recovers in regions *C* and *SW*. Inter-regional transport costs are too large for the local price of milk to be high enough to allow new investments and without local supply, no processing factory settles again. Dairy sectors in other regions get back to a steady equilibrium after the shock. However, it reaches a slightly higher production level in comparison to the pre-shock equilibrium. This is a first example of the hysteretic behavior that the integration of agglomeration economics allows to represent in the model.

We observe a similar behavior for scenario A3, the larger shock leads to the hysteretic disappearance of the dairy sector in region *A* as well as in regions *C* and *SW*. Figure 2.4 presents the evolution of prices of milk and dairy products as well as the quantity of dairy product produced, consumed and traded in this scenario. We notice that during the shock, foreign and domestic demands for the domestic dairy product drop while imports of foreign dairy products increase and over-compensate this loss in the domestic consumption. All prices of milk and dairy products drop. Production prices of milk further decrease in regions where all processing factories disappear (*C*, *SW* and *A*) as intra-regional transport costs increase. We observe a steep increase of all prices in the first year post shock as the demand for domestic products gets back to its original level. Most prices reach higher levels than in the initial year, except in the regions where the dairy sector has disappeared as inter-regional transport costs remain. After a few years the system reaches a new steady-state equilibrium. The supply deficit from regions *C*, *SW* and *A* leads to higher dairy prices and higher milk prices in other regions. This explains why we observe further investments for production and processing leading to higher supply of dairy products in other regions *N*, *NW* and *E*. However, this supply does not compensate for all the production lost, keeping overall demand for domestic dairy products lower in the long term.

From a resilience point of view, we can conclude that the resistance of value chain to small shocks appears to be similar across regions. It is for larger shock that we observe differences with a tipping point mechanisms. Dairy sectors in regions with a higher milk production seems more robust. In others, when too many processing factories disappear, transport costs become significant and lead to the further collapse of the regional value chain. Even when conditions come back to normal, they cannot recover as it is not profitable for agents to invest again in any

Figure 2.4: Evolution of regional milk production prices, domestic dairy product price, regional dairy productions and domestic, importation and exportation demands



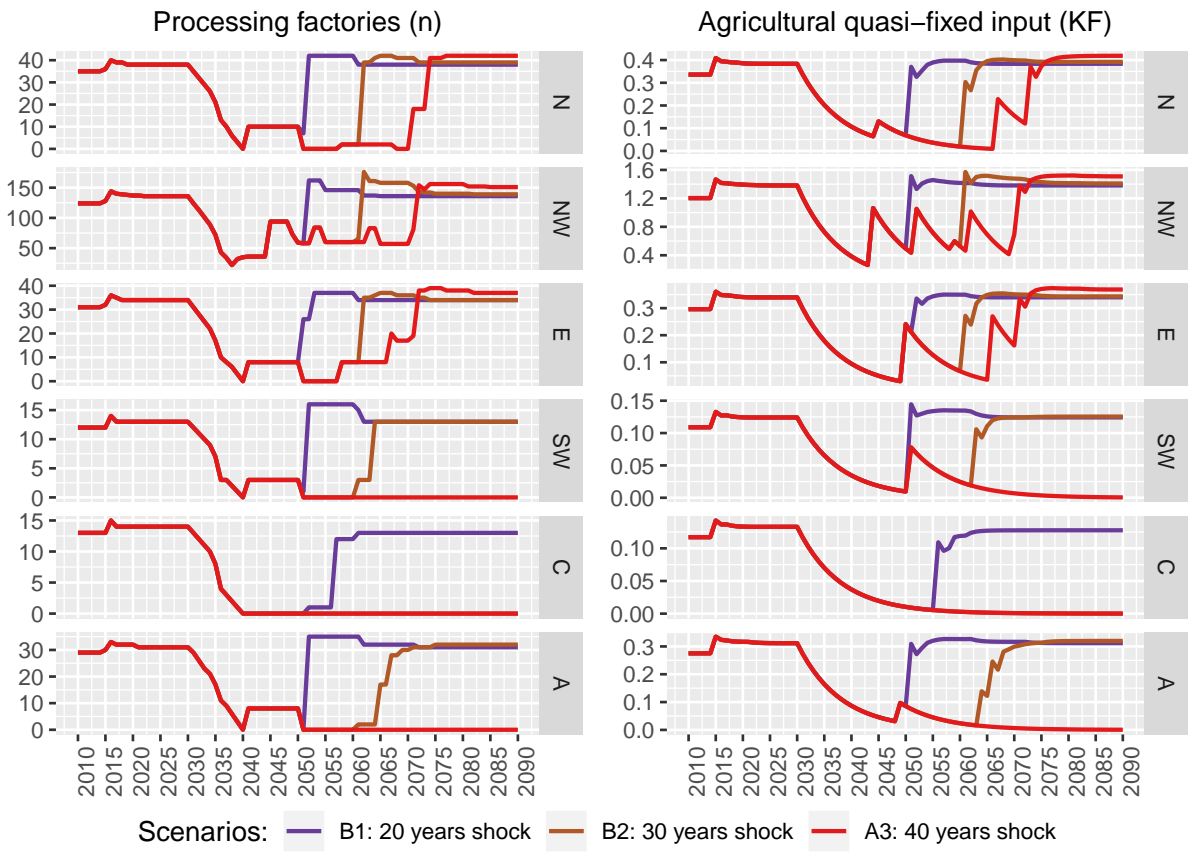
stage of these value chain as they will lack supply or demand.

2.5.2 Role of the shock length

In this set of simulations, we apply the same 60% shock on the price of foreign dairy products (PC^X and PC^M) beginning 2030 as in scenario A3. However, the shocks only last 20 years for simulation B1 and 30 years for scenario B2. Figure 2.5 presents the evolution of the number of dairy processing factories and of the quantity of quasi-fixed agricultural inputs from 2010 to 2090 for scenarios B1, B2 and A3.

We notice that for scenario B1, dairy sectors reach back to their pre-shock steady-state equilibrium in all regions contrary to scenario A3 when they disappeared irreversibly in regions C, SW and A. There is no hysteretic consequences in this case. Indeed, this shock is too short for the capital to depreciate enough to lead to an irreversible disappearance of the sector. Even in region C where all processing factories have disappeared at the end of the shock, there

Figure 2.5: Regional evolution of the number of processing factories and of the quantity of agricultural quasi-fixed input to shocks of various duration

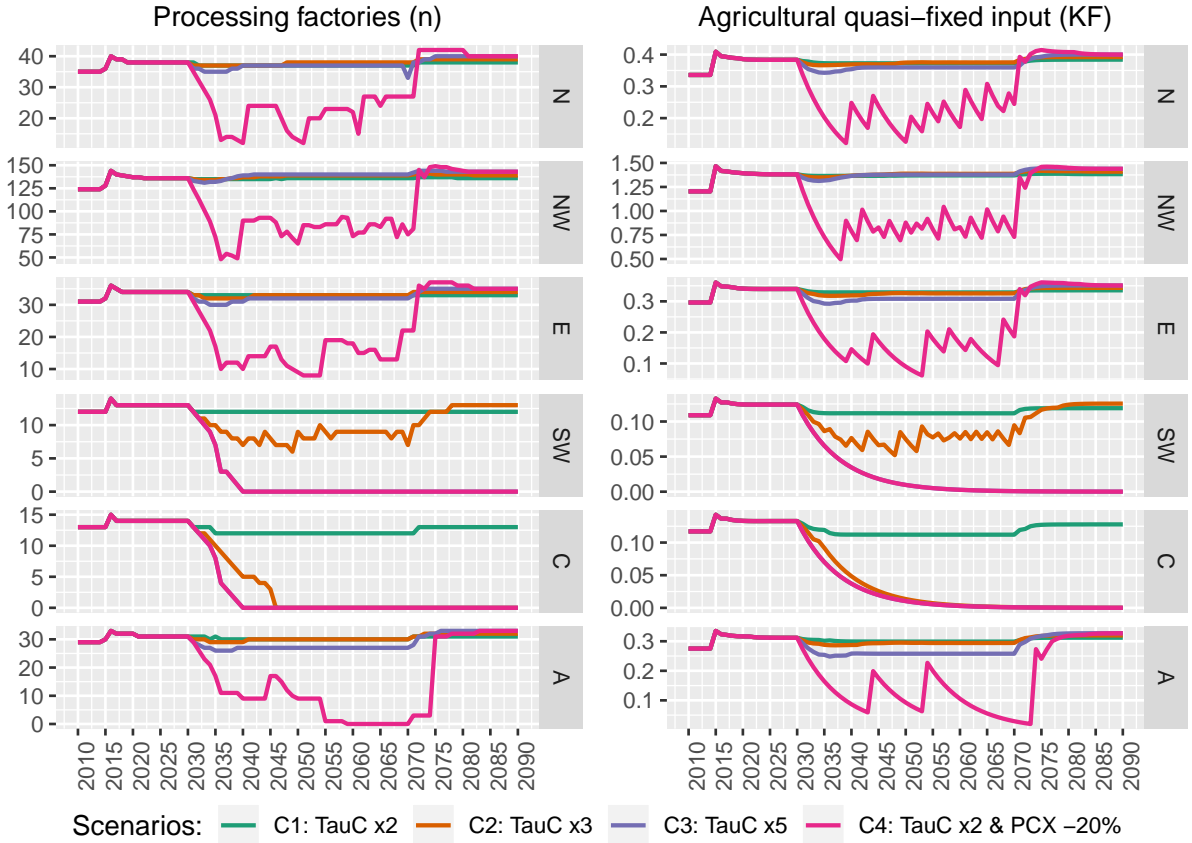


remains enough agricultural quasi-fixed input for the sector to bounce back after it. We notice that with a longer shock in scenario B2, the dairy sector in region C disappears. In regions C and A there was an initial rebound of investments in quasi-fixed input that we observed also on scenario A3 that postponed the time when the dairy sector would irreversibly disappear in these regions. Therefore, these simulations highlight the role of capital durability that will strengthen the resistance of dairy sectors to shocks in the short run and help their long-run resilience. If adverse shocks are short enough they are not likely to irreversibly affect the system. However, we must recall that there is no possibility of disinvestment by the agents in this model. In real conditions, this is likely to limit the resistance of the system as it speeds the decrease of capital at both stages of the value chain in the face of adverse conditions. Ultimately, value chains in regions with more transport costs would be more likely to collapse irreversibly.

2.5.3 Reaction of regional dairy sectors to shocks on transport costs of milk

We now look at the consequences of shocks on transport costs on regional dairy sectors. We increase the cost of transport τ_C^l for 40 years beginning in 2030. We respectively double it in scenario C1, triple it in scenario C2 and it is multiplied by 5 in scenario C3. In scenario C4, we double it for the period of the shock and apply simultaneously a 20% decrease of price of foreign dairy products (PC^X and PC^M), in a similar way as in scenarios A and B. Figure 2.6 presents the evolution of the number of dairy processing factories and of the quantity of quasi-fixed agricultural inputs from 2010 to 2090 for scenarios B1, B2 and A3.

Figure 2.6: Regional evolution of the number of processing factories and of the quantity of agricultural quasi-fixed input to shocks on milk transport costs



We notice first that in scenario C1, the doubling of milk transport costs barely affect the system in any region. However, in scenario C2 when transports cost are tripled, the dairy sector quickly disappears in regions C and the dairy sector in region SW appear to be affected though it does not disappear. In scenario C3, when transport costs are multiplied by 5, dairy sectors in

these two regions quickly disappear. On the other side, other regions seem to be barely affected by these increases of transport costs. They even recover a higher production after the shock as they benefit from higher prices due to the lack of supply from regions C and SW.

We again observe a tipping point mechanism. Indeed, in the regions with a high production density, distances between farms and factories are reduced and the importance of transport cost per km is reduced. On the contrary, in regions with smaller milk production density, transport costs are initially more important and an increase is more likely to bring them to their collapse tipping point.

We notice on scenario C4 that the combined doubling of transport costs and the 20 % decrease of the foreign dairy prices lead to the irreversible collapse of dairy sectors in regions SW and C. Other regions are also affected but make a full recovery. We know from scenario C1 that this increase of transport cost alone is not responsible for this disappearance and from scenario A1, that even a 40% decrease of world price would not have such consequences alone. Therefore, the increase of transport cost largely increases the vulnerability of regional dairy sectors. The tipping point past which a sector enters a collapsing dynamic becomes more reachable.

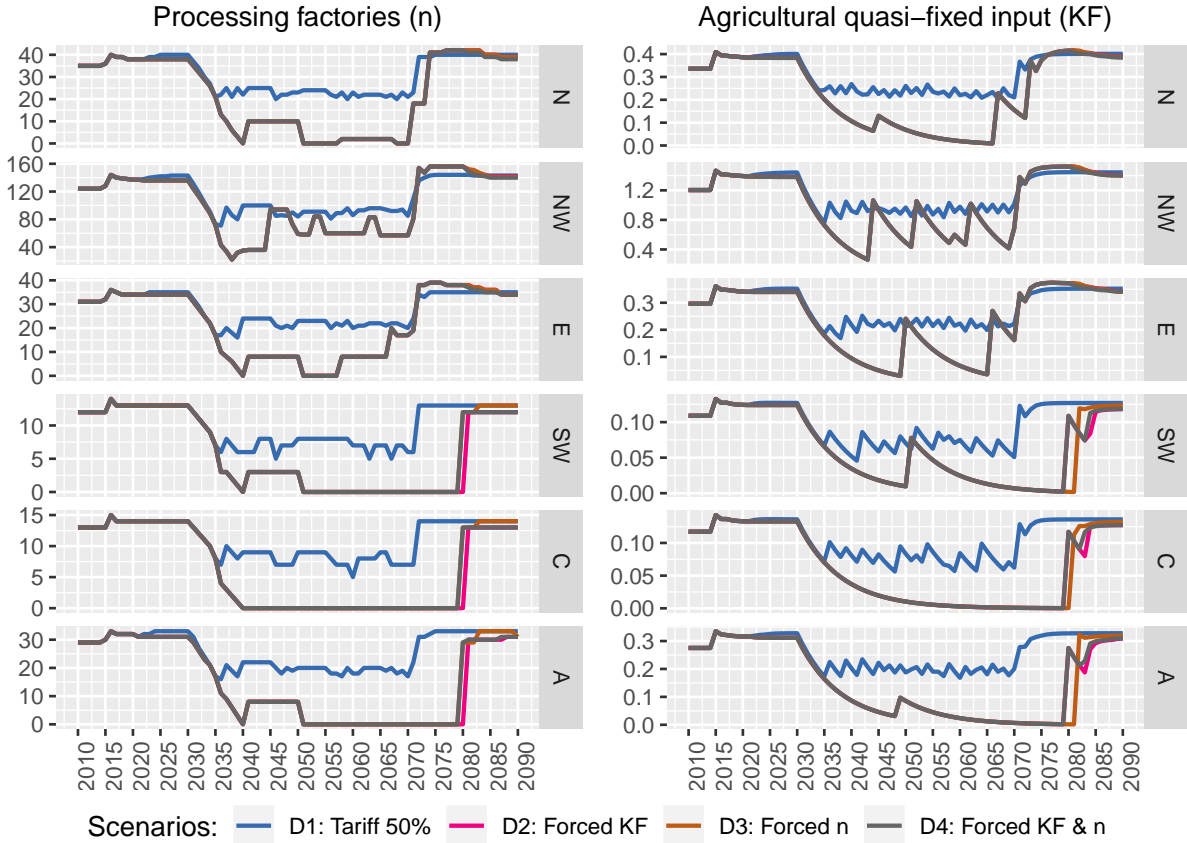
2.5.4 Effects of tariff protection and targeted investment on the resilience of regional dairy sectors and surpluses

In this section we first look at the ability of a trade protection to limit the irreversible consequences of an adverse trade shock on the French dairy sector. We apply the same 60% shock on the world price of dairy, for 40 years beginning 2030 as in scenario A3. However, in this scenario D1, we now apply a specific import tariff equal to 50% of the initial price of initial dairy products beginning in 2020. We have, for all year $t \geq 2020$, $PC_t^M = PC_t^X + 0.5 \cdot PC_{2014}^X$.

We compare the results of this scenario with three initial *laissez-faire* scenarios with no tariffs, where the system is left free for all the period of the shock but some investments are then forced, 10 years after the end of the shock in 2080. In scenario D2, we force on the model an investment in agricultural quasi-fixed input in regions C, SW and A of the same amount as their initial quantity of quasi-fixed input in 2014. We select these three regions as they are the ones that see their dairy sector irreversibly disappear in scenario A3. In scenario D3, we force

an investment in dairy factories in regions *C*, *SW* and *A* equal to their initial number of dairy factories. Scenario D4 combined these last two scenarios with similar simultaneous forced investment in milk production and processing factories in regions *C*, *SW* and *A*.

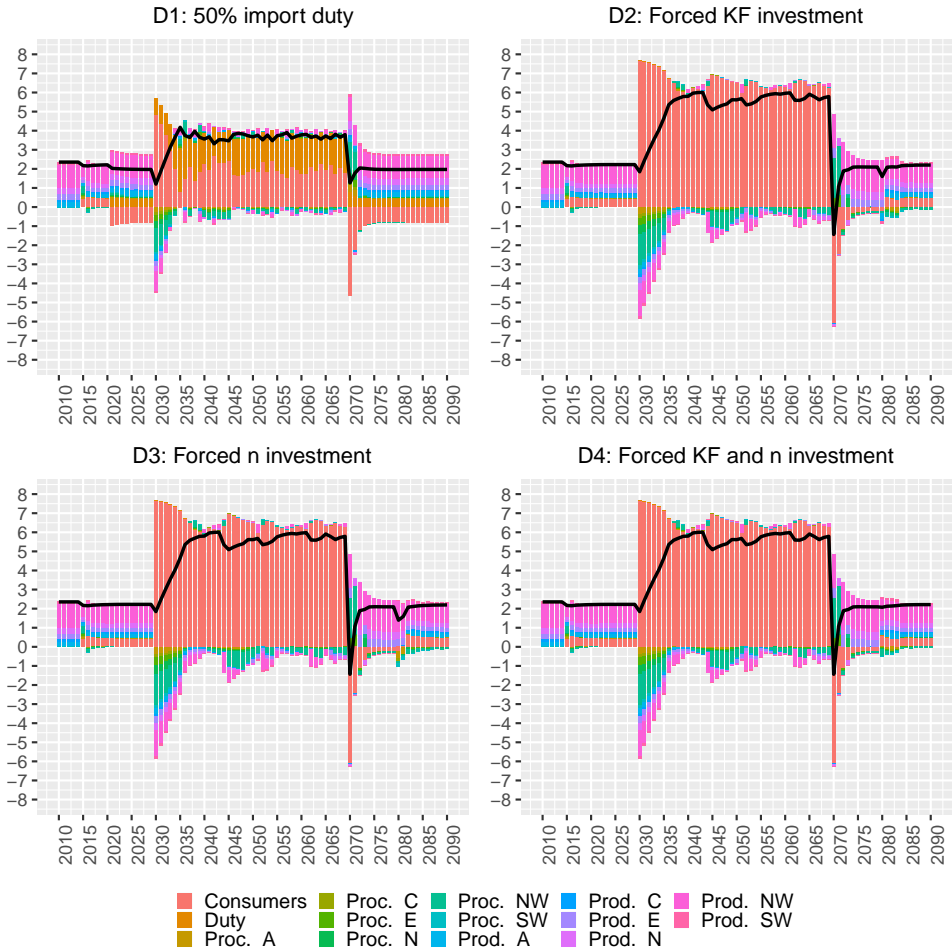
Figure 2.7: Regional evolution of the number of processing factories and of the quantity of agricultural quasi-fixed input under different resilience focused policies



We can see on figure 2.7 the evolution of the number of dairy processing factories and of the quantity of quasi-fixed agricultural inputs from 2010 to 2090 for scenarios D1, D2, D3 and D4. We notice that during scenario D1, the dairy sector of all regions are affected during the shock but at a minor magnitude in comparison to other scenarios and they all make a full recovery directly after the end of the shock reaching back to their pre-shock steady state equilibrium. In scenarios D2, D3 and D4, dairy sectors collapse in regions *C*, *SW* and *A* following scenario A3. However, in all three scenarios, the forced investment allows the regions to recover a fully productive equilibrium in a few years. Indeed, even when investment is forced on only one stage of the value chain, the created supply or demand leads to new investments in the complementary stage.

We now look at the evolution of domestic surpluses during these scenarios. Figure 2.8 presents the evolution of the total national surplus in four scenarios D and its different regional components for production and processing, as well as national consumer surplus and the tax revenue from the duty applied. Method of calculation for each surplus are available in Appendix B.4.

Figure 2.8: Evolution of the total national surplus and its components (Billion euros)



We observe on all scenarios that the end of quotas in 2015 leads to surplus losses by the producers in all regions as the price of dairy products and the price of milk decrease. This loss is mostly offset by gains by the domestic consumers. However, as part of the production is exported, reduced prices are also likely to benefit foreign consumers. Overall, we observe a minor decrease of the total national surplus. In scenario D1, when the tariff is implemented in 2020, we observe a major loss of consumer surplus of about 1.5 billion euros. The price increase partially benefits the producers, however even when including tax revenues, we observe a small

decrease of the total national surplus.

During the shock, we observe in all scenarios big losses for the producers and processors in all regions during the shocks. These losses are largely offset by massive consumer gains due to the decrease of domestic and import prices. In scenario D1, these effects are attenuated and overall the total national surplus increase of about 2 billion euros more in scenarios D2, D3 and D4. At the end of the shock, surpluses reach back to their pre-shock level in scenario D1. However, in scenarios D2, D3 and D4, we notice that before any forced investment is applied, the total national surplus is at a similar level as pre-shock, however its distribution has changed. Producers and processors surpluses have obviously disappeared in regions where the dairy sector has collapsed. Consumers' surplus is below its initial level, pre-disappearance of quota, as the price of domestic dairy products is higher. On the other hand, producers in regions that made a full recovery gained about 1 billion euros in surplus. We notice temporary total surplus losses the year forced investment are made in scenarios D2 and D3. Indeed with the other part of the value chains initially missing, these investment cannot be profitable immediately. However, once the rest of the value chain catches up, all the surpluses quickly reach back to their pre-shock level. The coordination of investments in production and processing in scenario D4 avoid these temporary losses.

To sum-up, we can conclude that tariff protection is efficient at protecting value chains from adverse trade shocks and improve their resilience overall. However, they correspond to an important redistribution from consumers to producers. Even with tax revenues, they lead to a decrease of the total national surplus that is higher when foreign prices are low. On the other hand, targeted investment, preferably coordinated between production and processing can help the recovery in regions where value chain have collapsed during a shock and where economic agents may not reinvest by themselves without an intervention. However, this would require either an investment by the state or to change the expectation mechanism of the agents, so that they believe in the restoration of the rest of the regional value chain following their investment. This could possibly be achieved by some guarantee on the supply or the demand of milk in the region or by the coordination of the producers and processors, for example by contractualization or by vertical integration of the value chain. In any case, one would have to know if the

economic conditions are indeed sufficiently favorable for a value chain to be profitable again.

2.6 Conclusion

The model presented in this paper is a first attempt at representing the economies of agglomeration economies that can arise in agri-food sectors in an applied simulation framework . We show that the specification of internal economies of scale in the processing industry and transport costs of the primary agricultural product for trade between a domestic region and another can generate external economies of scale across the value chains. We show that such economies of agglomeration can be the source of an hysteretic behavior of the agri-food system at the regional level. The dynamic simulations realized in this paper highlight how the representation of these phenomena could change much the results of dynamic simulations in comparison to classical equilibrium models. Such dynamic applied models could therefore play a role in analyzing policies related to agri-food sectors from a resilience point-of-view. It could help emphasize the importance of the option-value of conserving sectors subject to hysteresis when they are at risk. It could also feed the discussion on adjustment costs in such sectors subject to large sunk costs.

The calibration of this model on the French dairy sector has helped highlight how production density is an important driver of the resilience of dairy production at the regional level. Indeed, the lower the density is, the larger transport costs are. This reduces the robustness of regional value chain as adverse shocks are more likely to lead them into a vicious circle when the decrease of the production leads to more collection costs and the ultimate collapse of the regional sector. Once a regional sector has disappeared, inter-regional transport costs prevent its recovery as potential entrants on the production side have no demand and processors have no supply. A tariff protection policy could help the resistance and robustness of dairy value chains. However, this is a very costly policy for consumers. It could be preferable to allow the system to freely adapt to shocks but to implement investment coordination policies to help the recovery of value chains when market conditions are favorable again.

Overall, the French dairy sector appears to be mostly resilient according to the dynamic simulations made in this article. Only some important and prolonged adverse shocks could lead to irreversible consequences in regions where the production density is smaller in the cen-

ter and South-West of the country. This possible collapse could have some long-run adverse consequences for producers in these regions but it would limit only marginally the national supply of dairy product as other regions could increase their production. Final consumers may however still experience a subsequent price increase. Nevertheless, we highlight that important shocks could still massively disturb the French dairy sector leading to more volatility and cycles of over- and under-investment due to the imperfect expectations of the agents in dairy value chains. Furthermore, an increase of transport costs could largely increase the vulnerability of regional dairy sectors.

We must note that such models are subject to many modeling choices and their results can be highly sensitive to their original calibration. Krugman (1991a) has shown the importance of expectations in the determination of the equilibrium toward which an economy with multiple potential equilibria will evolve. Chapter 1 highlights the role of market structure, expectations formation, capital access and depreciation, as well as the types of returns to scale, in the determination of the dynamic of value chains with irreversible investment. In particular, the ability of the agents of the value chain to coordinate horizontally and vertically is a key determinant of the dynamic behavior of the system, as it will allow them to avoid sub-optimal equilibria or cyclical disequilibria and always reach back to the most profitable equilibrium for given exogenous conditions. In this paper, the results are largely driven by the limited expectations of the agents. We do not represent tools of coordination, such as contractualization, that may help prevent such hysteretic phenomena. As much as it invites us to be cautious when discussing the credibility of our results for real applications, it also highlights the potential importance of these coordination issues and how they could justify in some cases, some specific policies to help initiate agri-food value chains.

Chapter 3

Agglomeration Patterns in an Open World: Introducing Local Value Chains in a CGE model

3.1 Introduction

The representation of global value chains in trade models has received increasing scrutiny in the past decade. However, a number of value chains remains limited to a local scale, at least on some of their stages, due to the importance of transport costs. This is particularly the case for some agricultural value chains with bulky or fresh primary products (Daniel, 2007). We have shown in the previous chapter how such agri-food sectors with economies of scale in the processing stage can display economies of agglomeration creating potential hysteretic behaviors with a multiplicity of equilibria. If the output of local value chains can be traded, as processed product are often less costly to transport, local value chains are likely to be affected not only by domestic policies but also by foreign policies and the development of similar value chains abroad. Agglomeration may lead to conflicting interests across countries, but also across regions of a same country as factors are not perfectly mobile. The regional distribution of activities may also have inter-temporal consequences that can become a burden for future periods (Irwin et al., 2010). This makes the analysis of policies increasingly complex as their consequences spread

across space and time (Desmet and Rossi-Hansberg, 2010; Irwin, 2010).

These dynamic interactions between local value chains across regions have mostly been omitted in the literature as most trade models lack the regional disaggregation or the ability to represent economies of agglomeration and the dynamic behaviors they create. This chapter offers a first representation of such local value chains in a dynamic Computable General Equilibrium (CGE) trade model. We do so by integrating the multi-regional agri-food sector structure developed in Chapter 2 into the existing MIRAGRODEP CGE trade model. This leads to a partially bottom-up regional CGE model, with intra- and inter-regional transport costs of unprocessed products creating economies of agglomerations. We apply this local value chains disaggregation on the milk sector in 7 countries in the model, including 5 of the European Union to compare the consequences of support, trade and environmental policies on the regional distribution of agri-food sector inside and outside of the European Union. We provide three illustrations of the types of analysis this model can bring. First, we show how the chronology of trade policy implementation can have a significant impact on the steady-state distribution of local value chains across regions and countries. Second, we show how two types of supports to the dairy sector can lead to different patterns of regional agglomeration. Finally, we study the consequences of an environmental tax on petroleum and coal products, which affects the regional distribution of the dairy sector by increasing transport costs.

More and more CGE models are built with an improved representation of value chains, with increased differentiation of products based on their origin and their usage as inputs or final consumption (Athukorala et al., 2018; Antimiani et al., 2018; Walmsley and Minor, 2017; Bellora and Fontagne, 2019). However, most of these models are at the national scale. The representation of local value chains requires a regional model that allows a sub-national disaggregation of all or parts of the economy (Giesecke and Madden, 2013). Many general equilibrium models have been developed to incorporate some form of economies of agglomeration. However, following the work of Krugman (1991b), they mostly rely on the use of a monopolistic competition framework (Francois et al., 2013; Kilkeny, 1999). This framework relies on product differentiation and taste for diversity to integrate economies of agglomeration. It therefore doesn't appear suitable for the type of value chains we wish to represent, in which raw products are mostly ho-

mogeneous. Moreover, although a number of CGE model are dynamic, often through the use of recursive dynamic, the consequences on dynamic of economies of agglomeration inside CGE models have not been extensively studied. The integration of the multi-regional agri-food sector model of Chapter 2 into the recursively dynamic global trade CGE MIRAGRODEP allows us to create a model able to take into account the different specificities of local value chains. This provides us with a framework in which we are able to represent the spatial dynamics of local value chains and analyze the consequences of a range of policies on their distribution across time.

The three topics we study allow us to highlight the different literature such type of models can contribute to. First, by studying the role of the chronology of trade opening, we complement the literature on trade hysteresis (Baldwin, 1990; Gullstrand and Persson, 2015) . We show how economies of agglomeration can create further trade hysteresis besides sunk costs and capital accumulation. This demonstrates the potential need for a more strategic perception of trade policy chronology with a careful attention to phase-in periods (Genicot and Ray, 2006; Olivero and Yotov, 2012). Second, we complement the literature on the reaction of the distribution of the agricultural production to a set of policies (Daniel and Kilkenny, 2009; Bagoulla et al., 2010). In particular, we show how a support targeted on the price of the raw production can lead to further agglomeration than a support to the price of final food products. Finally, we study the consequences of an environmental taxation policy to highlight how such model can be used to explore the question of the optimal level of agglomeration in face of environmental challenges. We show that such policy would encourage further agglomeration of production as it aims at reducing transport emissions in a supply-oriented industry. However, this would lead to a substantial economic redistribution as it would penalize the regions with a production density too low to reach agglomeration. Moreover, this further production agglomeration might lead to other environmental damages as it could concentrate negative production externalities in some regions.

In the next section, we present the methodology with the description of the MIRAGRODEP model and the modifications applied, the data and the scenarios we simulated. We then discuss the results of these scenarios and their implications before concluding.

3.2 Methodology

3.2.1 The MIRAGRODEP Model

The MIRAGRODEP model (Robichaud et al., 2013) is a multi-sector, multi-regional CGE trade model with a recursive dynamic. It allows for a full and detailed representation of the World economy based on the GTAP database which describes 65 sectors and 141 countries (Aguiar et al., 2019). In each country, it features one representative consumer who maximizes a LES-CES (Linear Expenditure System-Constant Elasticity of Substitution) demand function over the different products. This allows to represent different income elasticities for each product. Separate demand systems with respectively Cobb-Douglas and CES (Constant Elasticity of Substitution) functions are included to represent demands for government consumption and investment purpose. On the supply side, a representative agent in each sector in each country maximizes its production program. The production function is composed of a Leontieff function, between a value added aggregate and an intermediate consumption aggregate. The value added is a CES aggregate of land, natural resources low-skilled labor, and another CES aggregate of high-skilled labor and capital. Intermediate consumption is a CES aggregate of the different inputs. The origin of goods for total demand (consumption, government, investments and intermediate consumption) of each product is determined by a nesting of CES functions following the Armington assumption, with the total demand distributed over a domestic variety and a CES aggregate of imported varieties.

Skilled labor is perfectly mobile across sectors whereas imperfect mobility is assumed for unskilled labor between agricultural and other sectors with the use of a CET (Constant Elasticity of Transformation) aggregator. The total skilled and unskilled labor available in each country evolve exogenously each period following active population projections. The available quantity of natural resources in each sector is fixed. The total supply of land in each country is an isoelastic function of the rate of return to land. Imperfect mobility of land across sectors is assumed through the use of a CET aggregator. Between every period, the capital in every sector depreciates at fixed rate. A putty-clay assumption is made such that only new investments are mobile across sector while installed capital is immobile. The distribution of savings into

new investments across sector depends on respective rate of returns and relative quantities of installed capital and reflect initial investment patterns and a given speed of adjustments. Concerning macroeconomic closures, households are assumed to save a fixed proportion of their available income. Government savings are fixed share of countries GDP. The exchange rate is flexible to adapt to exogenously fixed current account balances (CAB).

3.2.2 Modifications for the representation of local value chains

We modify the MIRAGRODEP model to implement a structure that allows the representation of local value chains. To do so, we use the structure of the multi-regional model of agri-food sector of Chapter 2.

First, we introduce in the model a new set of sub-regions sub from a selected set of country $rv(r)$ where local value chains are represented. The sub-regions are mapped to their corresponding country using the mapping set $mapsub(rv, sub)$. We also add subsets of sectors. $iv(i)$ is the set of sectors part of the local value chains we represent with $ia(iv)$ and $ip(iv)$ respectively the subsets of primary agricultural sectors and processing sectors. Value chains are described by the mapping $mapvc(ia, ip)$ of primary sectors to the corresponding processing sectors that use them as main inputs.

The production system for primary production sectors and processing stages of value chains is mostly a replicate of the original structure of production of the other sectors in the model but with now one representative agent by sector iv by sub-region sub . Land is considered imperfectly mobile with a CES aggregator over sector and value chain stages of every sub-regions. Natural resources used in these value chains are considered fixed by sector by sub-region. Skilled and unskilled labor remain mobile across sub-regions. Installed capital is considered immobile between sectors and sub-regions while the function that distributes new investments over sectors is extended over stages of local value chains of every sub-regions.

The main novelty in the model is the representation of intra- and inter-regional transport costs of the primary products in local value chains. We inspire from the structure of the model of Chapter 2 by introducing a discrete number of factories in the processing sector of each region $n_{ip,r,sub,t}$. We assume that every processing factory in a sector ip in a country r is identical with

the same fixed quantity of capital per factory $KTOTI_{ip,r}$. Therefore, the number of factories $n_{ip,r,sub,t}$ in the processing sector ip , in region sub of country r at time t is defined by the total quantity of capital, $Kvc_{ip,r,sub,t}$, divided by $KTOTI_{ip,r}$. Therefore, the entry and exit of processing factory is driven by the evolution of capital across period in the processing sectors of each sub-region sub . This number of factories is then mainly used for the computation of intra-regional transport (or collection) costs of the primary production to processing factories. Similarly to Chapter 2, we assume that the primary production is distributed evenly above the territory of each sub-region s , corresponding to a uniform farm price and uniform production capacities of farms in the region. The average distance between farms and factories depends then in LVCs in each region sub only on the number of factories and on the surface area of the regions. We assume that the transport cost per unit of primary input ia in region sub is given by:

$$transC_{ia,r,sub,t} = PICtrans_{ia,ip,r,t} \cdot \tau_{r,t}^I \cdot \sqrt{\frac{areaReg_{r,sub}}{\max(1, \sum_{mapvc(ia,ip)} n_{ip,r,sub,t})}} \cdot \left(\frac{\sqrt{2} + \log(1 + \sqrt{2})}{6} \right), \quad (3.1)$$

With $areaReg_{r,sub}$ the surface area of region sub , $\tau_{r,t}^I$ the quantity of transport unit necessary to haul one unit of primary product over one unit of distance and $PICtrans_{ia,ip,r,t}$ the price of transport. Similarly to Chapter 2, this equation provides the average distance between the center of a square of a surface area of $areaReg_{r,sub} / \max(1, \sum_{mapvc(ia,ip)} n_{ip,r,sub,t})$ and a random point in this square with a uniform density. This is equivalent to approximating that each region at time t is composed of $n_{ip,r,sub,t}$ identical squares with a factory at the center of each.

Therefore, the price $PICag_{ia,ip,r,sub,t}$ of the primary product ia at the processing factory of sector ip in region sub is given by:

$$PICag_{ia,ip,r,sub,t} = PYag_{ia,r,sub,t} \cdot (1 + TaxPag_{ia,r,sub,t}) \cdot (1 + taxicc_{ia,jp,r,t}) + transC_{ia,r,sub,t}, \quad (3.2)$$

With $PYag_{ia,r,sub,t}$, the production price of the primary product, $TaxPag_{ia,r,sub,t}$, the ad-valorem production taxes and $taxicc_{ia,jp,r,t}$, ad-valorem intermediate consumption taxes from product ia for processing in sector ip .

Trade of the primary products is possible between subregions ($subr, subs$) of the same coun-

try r with inter-regional transport costs. We consider that the primary product is homogeneous across regions, therefore exports $Xag_{ia,r,subr,subs,t}$ from region $subr$ to region $subs$ are given by the complementarity condition:

$$Xag_{ia,r,subr,subs,t} \begin{cases} = 0 & \text{if } PICag_{ia,ip,r,subs,t} < PICag_{ia,ip,r,subr,t} - \tau_{ia,r,subr,subs,t}^R \cdot PIC_{trans',ip,r,t} \\ > 0 & \text{if } PICag_{ia,ip,r,subs,t} = PICag_{ia,ip,r,subr,t} - \tau_{ia,r,subr,subs,t}^R \cdot PIC_{trans',ip,r,t} \end{cases} \quad (3.3)$$

With $\tau_{ia,r,subr,subs,t}^R$ the quantity of transport necessary to haul one unit of product ia from region $subr$ to region $subs$ and $PIC_{trans',ip,r,t}$ the price of transport for sector ip .

3.2.3 Data

The MIRAGRODEP model is based on the social accounting matrix (SAM) and trade elasticity parameters from the GTAP database. We use for this study the GTAP 10 database with a 2014 base year. We use a disaggregation with a set i of 15 sectors and a set r of 18 countries and aggregate regions. The list of sectors and countries is available in Table 3.1.

Table 3.1: Countries/aggregates regions and sectors of the model

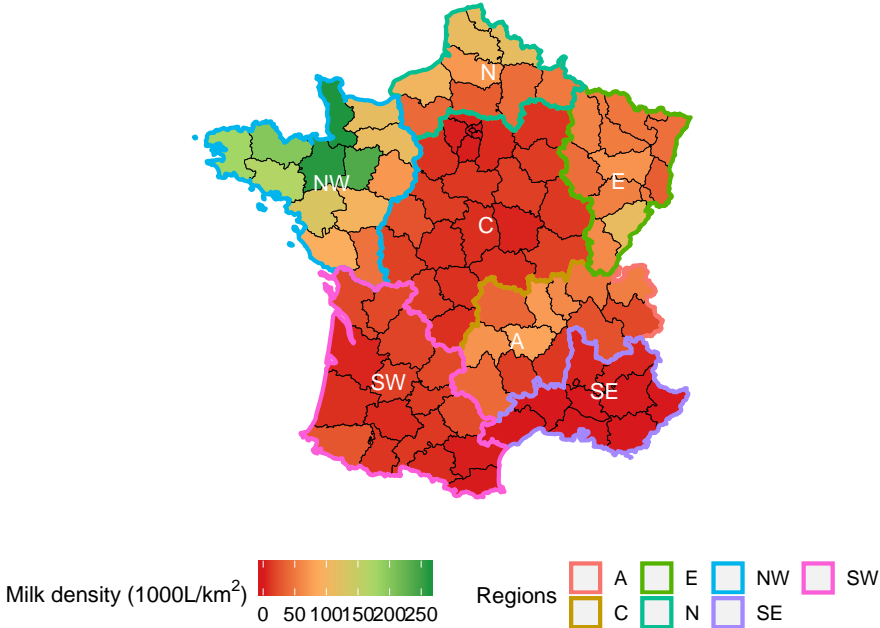
r	Country/region	i	Sector description
AUS	Australia	oap	Other agricultural products
NZL	New-Zealand	ctl	Cattle
ROW	Rest of the World	rmk	Raw milk
CHN	China	Extraction	Extraction products
ASIA	Rest of Asia	cmt	Cattle meat
JPN	Japan	ProcFood	Processed food
CAN	Canada	mil	Processed dairy
USA	United States	TextWapp	Textile and Wearing Apparel
MEX	Mexico	LightMnfc	Light Manufacture
MER	Rest of Mercosur	p_c	Petroleum and Coal Products
LAC	Latin America and Carribean	HeavyMnfc	Heavy Manufacture
BRA	Brazil	Util_Con	Utilities
E28	Rest of EU28	TransComm	Trade, services and communications
FRA	France	trans	Transport (air, sea, land)
DEU	Germany	OthServices	Other services
ITA	Italy		
NLD	Netherlands		
GBR	United Kingdom		

Similarly to Chapter 2 and to allow easier comparison between the two models, we choose

to focus in this study on the representation of dairy value chains only. Indeed, fresh milk is a sensitive product with costly transport. Therefore, processing factories need to be sufficiently close to the producing farms. However, processed dairy products are cheaper to transport, especially if dried and can more easily be traded across country. Therefore, the raw milk sector (*rmk*) is the only in the set of primary agricultural sectors *ia* and the processed dairy sector (*mil*) is the only in the set of processing sectors *ip*. We have the mapping of the dairy value chain $mapvc('rmk', 'mil')$.

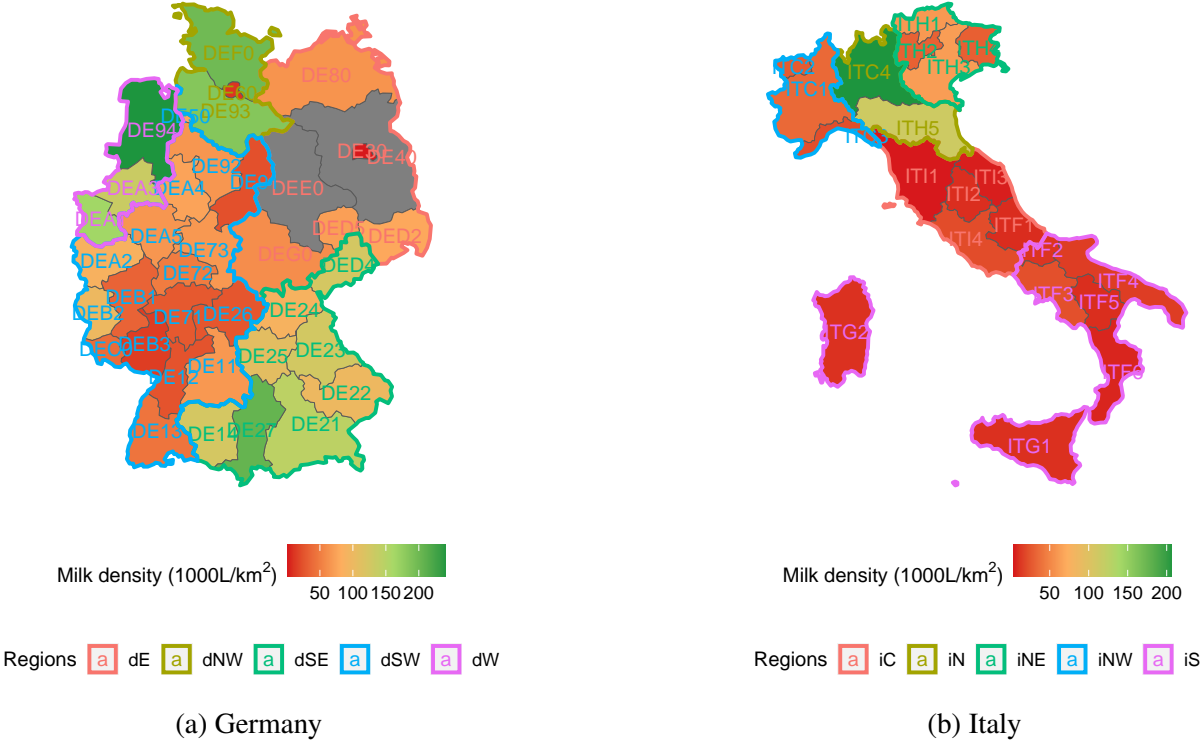
We represent dairy value chains only in a selected set of countries $rv(r)$ composed of France, Italy, Germany, the United States, New-Zealand, Great-Britain and the Netherlands. We choose these countries as they are important producers and exporters of dairy products. Moreover, we will focus on policies at the European Union (EU) level. It is therefore interesting to compare the consequences of these policies on dairy sectors in and outside of the EU. In the other countries and regions of the model where a detailed representation of dairy value chains is not used, the production and trade of raw milk and dairy products follows the original MIRAGRODEP structure.

Figure 3.1: Map of the milk production density in France in 2014 and production regions of the model



Sources: National Statistics Agency (INSEE), Monthly Dairy Survey (FranceAgriMer)

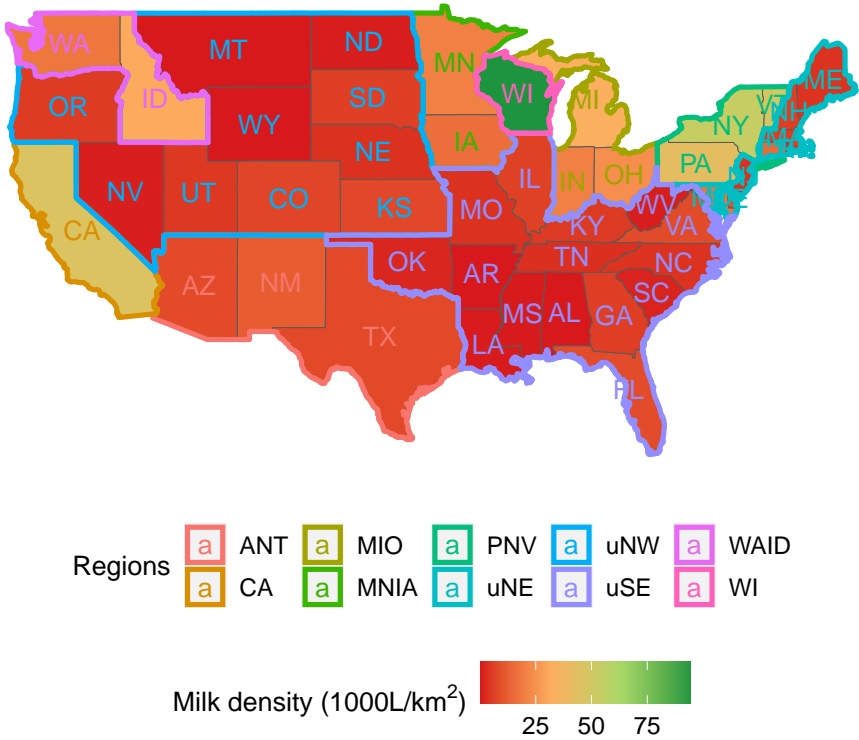
Figure 3.2: Map of the milk production density in 2016 and production regions of the model for Germany and Italy (Source: Eurostat)



We create a regional disaggregation of dairy value chains with 7 regions in France similar to the ones used in Chapter 2. We use milk production data from Eurostat at the Nuts3 level to create regional disaggregation with 5 regions in Germany and Italy. Similarly, we use production data from USDA at the State level to create 10 producing regions in the US. For all of these disaggregations, we create these regions arbitrarily but with the goal of creating geographically cohesive regions with relatively homogeneous density of milk production. Figures 3.1, 3.2a, 3.2b and 3.3 display these regions for France, Germany, Italy and the US. We don't do further regional disaggregation in New Zealand, the United Kingdom and the Netherlands as we lack data and consider these countries sufficiently small and homogeneous in the distribution of their dairy production. This also helps improve the tractability of the model.

A reduced but still significant share of the raw milk in the GTAP database has other uses than processed dairy, some of it is consumed directly, another share goes into other sectors such as "other processed food" and a small share is traded internationally. As these other uses are not represented with a regional disaggregation, we keep a reduced raw milk sector aggregated na-

Figure 3.3: Map of the milk production density in the United States in 2016 and production regions of the model (Source: USDA)



tionally with a classical MIRAGRODEP production structure to supply these other uses even in countries with regional disaggregation. The regionally disaggregated raw milk sector in countries rv only supply the dairy processing sector following the intra- and inter-regional transport costs structure presented in the previous sub-section. We use data from USDA, Eurostat and the French Ministry of Agriculture to compute the total yearly quantity of milk produced in each region. Similarly to Chapter 2, we assume that all the milk is initially processed locally and there is no inter-regional milk trade during the base year. Finally, we assume again that a factory in the model has the size to optimally process 100 million liters of raw milk per year. We showed in Chapter 2 that this number seemed like a good compromise for France and although sources for such data are rare, we find a similar order of magnitude in the U.S. (Dalton et al., 2002). We can then infer the number of factories in each region and the reference size in capital of factories in each country $KTOTI_{ip,r}$.

In order to calibrate initial collection costs and transport costs parameters, we use the data from the GTAP SAM and assume that 70% of initial intermediate consumption of transports by the dairy processing sector in all rv countries is for collection costs. This corresponds to the assumption that most transport costs borne by the processing sectors concerns the handling of raw milk. In the US, we take 70% of the initial intermediate consumption of transports in both the dairy processing and the raw milk production sector, as we assume that collection costs are shared by farmers and dairies (Ye, 2003). Using the initial number of dairy factories per region sub and data on the surface area of each region, we compute in each country the value of the transport cost of a unit of product per km $\tau_{r,t}^I$ so that the initial total collection given through Equation 3.1 matches its target. Initial number of factories and collection costs are available for each region on Table 3.2. We calibrate $\tau_{ia,r,subr,subs,t}^R$, the total quantity of transport necessary to haul one unit of product ia from region $subr$ to region $subs$, using the distances $dist(subr,subs)$ between the centroid of regions such that $\tau_{ia,r,subr,subs,t}^R = \tau_{r,t}^I \cdot dist(subr,subs)$.

Table 3.2: Initial number of factories (n) and collection costs ($TransC$, in % of initial raw milk production price) for all regions of the model

r	sub	n initial	TransC initial	r	sub	n initial	TransC initial
	dE	33	15.86	GBR	GBRr	152	12.17
	dNW	58	6.68	NLD	NLDr	133	4.09
DEU	dSW	59	12.78	NZL	NZLr	219	3.03
	dW	53	6.45		ANT	106	7.65
	dSE	101	7.92		CA	184	3.25
	A	29	7.12		MIO	94	4.22
	C	13	14.41		MNIA	67	5.1
FRA	E	31	6.07	USA	PNV	128	3.17
	N	34	5.53		uNE	12	8.84
	NW	123	3.77		uNW	79	12.21
	SW	12	13.32		uSE	61	12.24
	iN	74	5.83		WAID	97	4.38
	INE	19	10.56		WI	137	2.25
ITA	iNW	10	13.61				
	IS	12	22.53				
	IC	6	24.97				

Initial milk production per region and corresponding regional input and factor demands for milk production and dairy processing are computed from the original data of the MIRA-

GRODEP model for each country, proportionately to the real milk productions of these regions. Factors and input shares are therefore identical in the raw milk production function across regions of a same country. Initial production prices are normalized. The rate of taxes on production and intermediate consumption related to raw milk production and consumption and transport costs are computed to ensure the conservation of the initial amount of incomes from each tax. Therefore, initial input and factors shares and total value of production per factory in dairy processing functions will only differ from the amount of transport costs. All production parameters are computed accordingly considering the base year SAM to be in equilibrium.

3.2.4 Scenarios

We simulate 5 policy scenarios in this Chapter, all beginning in 2021 and ending in 2050. This length allows us to simulate changes of policies and let their consequences stabilize. They are summarized in Table 3.3. The first two, "XM" and "MX" are built to study the possible existence of trade hysteresis and to see if the chronology of trade policy matter on the final regional distribution of production. In the scenario "XM", we first open other countries to EU exports of dairy products with 0% tariffs starting in 2021. Then, we open the EU to imports of dairy products from other countries with a 0% tariff starting in 2036. The "MX" scenario is similar with an opposite chronology, imports of dairy products are open in 2021 and exports in 2036. From 2036, the two scenarios are similar; this will enable us to observe if hysteresis occurs.

Table 3.3: Policy scenarios

Scenario	Rate	Policy	Product	Geography	Period
XM	0%	import tariff	mil	from EU28 to all	2021-2050
	0%	import tariff	mil	from all to EU28	2036-2050
MX	0%	import tariff	mil	from all to EU28	2021-2050
	0%	import tariff	mil	from EU28 to all	2036-2050
PrRmk	+30%	production subsidy	rmk	EU28	2021-2035
PrMil	+10%	production subsidy	mil	EU28	2021-2035
CarbTax	+30%	production tax	p_c	EU28	2021-2035
	+30%	import tariff	p_c	from all to EU28	2021-2035

The next two scenarios, "PrRmk" and "PrMil" are built to study the consequences of two

types of support policies of dairy value chains. In "PrRmk", we simulate a 30% ad-valorem subsidy on the production price of raw milk (rmk) in all EU28 countries from 2021 to 2035. In "PrMil", we simulate a 10% ad-valorem subsidy on the production price of dairy product (mil) in all EU28 countries from 2021 to 2035.

Finally, we test the consequence of an environmental to reduce the use of carbon-intensive products. We apply a 30% ad valorem tax on all production and imports of petroleum and coal products (p_c) in EU28 countries from 2021 to 2035. The scenario is likely to have interesting consequences on the geographical distribution of dairy production as it should increase transport costs.

In those last four policy scenarios, the policies ends in 2035 to see if any hysteretic consequences remain after. We run all two scenarios twice. Once with the model and transport costs as presented in Section 3.2.2 with normal economies of agglomeration. We index these scenarios "Var". We run all the policy scenarios another time and neutralize agglomeration economies in equation 3.1, by keeping the effect of the number of factories $n_{ip,r,sub,t}$ on collection costs fixed over time. The scenarios are indexed "Fix". Finally, we run a base scenario called "BASE" with no policy implemented.

3.3 Results

3.3.1 Trade chronology

Table 3.4 presents the evolution of the number of dairy factories per region for the scenarios "XM_var" and "MX_var" in 2035 and 2050 in comparison to the base scenario where no policy is implemented on the period. Looking first at the results for 2035, we notice unsurprisingly that the dairy sectors of EU countries seem to gain from the opening of other countries to their exports. The number of dairy factories increase in most regions. Symmetrically, most regions seem to lose from the opening of their imports to foreign products. US regions and New Zealand have the opposite evolution in both scenarios. We now look at the results for 2050, when both EU exports and imports have been open for 15 years in both scenarios. We notice that in both scenarios, almost all dairy value chains inside the EU as well as in New Zealand seem to have

gained from the opening in both scenario. The dairy sectors in the United Kingdom lose in both scenario while US regions are not much affected ultimately. It is interesting to notice that the distribution of dairy factories across regions differ slightly between scenarios. This is proof of some level of hysteresis as in the end, both scenario have the same policy implemented from 2036 to 2050. In Germany, there is one more dairy factory in the South-East and in the North-West (dSE and dSW) in the "MX" scenario compared to the "XM" scenario, while the East (dE) has one less factory. In France, there is one more factory in the North-West (NW) and one less in the center region (C) in the "MX" scenario compared to the "XM" scenario. In Italy, the North (iN) gain 3 factories while the southern regions (iS and iC) lose two each in the "MX" scenario compared to the "XM" scenario. Overall, in the EU, regions with originally larger dairy sector, with denser production, appear to gain in the "MX" scenario while the regions with smaller, less dense dairy sectors appear to lose. The opening of imports before exports therefore seem to leave hysteretic consequences with greater agglomeration of the milk production across regions.

Table 3.4: Number of factories per region in 2035 and 2050 for scenarios BASE, XM_var and MX_var

r	sub	2035			2050		
		Base	XM_var	MX_var	Base	XM_var	MX_var
DEU	dE	29	33	27	27	29	28
	dNW	53	57	51	52	53	54
	dSW	54	59	50	51	54	52
	dW	49	52	46	48	49	49
	dSE	93	100	88	91	93	94
FRA	A	29	31	27	30	31	31
	C	12	14	12	13	14	13
	E	31	33	29	32	33	33
	N	34	37	32	35	36	36
	NW	125	134	118	129	131	132
	SW	11	13	11	12	12	12
GBR	GBRr	144	148	136	145	142	142
ITA	iN	77	81	76	76	78	81
	INE	19	21	19	19	20	20
	iNW	10	10	9	10	10	10
	IS	12	13	11	12	14	12
	IC	6	6	5	6	6	4
NLD	NLDr	118	132	110	114	120	120
NZL	NZLr	265	254	337	296	359	363
USA	ANT	116	115	118	129	129	129
	CA	202	199	204	219	219	219
	MIO	103	102	104	112	112	112
	MNIA	73	72	74	80	80	80
	PNV	140	138	142	152	152	152
	uNE	13	12	13	14	14	14
	uNW	87	86	88	98	98	98
	uSE	67	66	68	76	75	76
	WAID	106	105	108	116	116	116
WI	150	148	152	162	162	162	

Table 3.5 presents the evolution of the raw milk production in every region in 2035 for "Var" and "Fix" versions of the "XM" and "MX" scenarios, relative to the base scenario. Raw milk production follows in every region the direction of the number of dairy factories. The evolution of raw milk production appears to be attenuated in most regions when agglomeration economies are neutralized in "Fix" scenarios. We notice some differences in the evolution of raw milk production across regions of a same country. Regions with lower production density

and therefore higher initial transport costs seem to benefit the most from the opening of other countries to exports ("XM") and be the most affected by the opening of imports ("MX"). This holds true in "Var" scenarios, but also in "Fix" scenarios, though with reduced differences. We notice that it is not verified for the center and South-West regions of France (C and SW) in the "MX_var" scenario. However, we notice on Table 3.4 that in that case, the number of factories does not change for these regions. These regions have a smaller number of factories in the baseline and the reduction of production does not appear sufficient to cause the exit of a factory. We conclude that the opening of exports leads to a deagglomeration of milk production as it benefits mostly regions with higher transport costs while the opening of imports has the opposite effect. These phenomena are reinforced by the agglomeration economies due to the evolution of collection costs with the number of dairy factories as long as initial changes are sufficient to lead to entry or exit of factories.

Table 3.5: Evolution of the raw milk production per region in 2035 in comparison to the baseline scenario (% of variation to "BASE" scenario)

r	sub	Var		Fix	
		XM	MX	XM	MX
DEU	dE	11.07	-7.98	7.37	-5.78
	dNW	6.48	-4.90	7.06	-5.35
	dSW	8.89	-6.91	7.27	-5.64
	dW	6.28	-5.06	7.05	-5.34
	dSE	6.89	-5.35	7.1	-5.41
FRA	A	7.39	-6.09	7.08	-5.57
	C	11.20	-5.28	7.33	-5.84
	E	7.06	-5.89	7.04	-5.53
	N	7.01	-5.74	7.02	-5.51
	NW	6.53	-5.53	6.96	-5.44
	SW	10.76	-5.24	7.29	-5.80
GBR	GBRr	2.78	-5.42	2.69	-5.08
ITA	iN	5.69	-0.75	6.16	-2.64
	INE	7.97	-1.14	6.3	-2.71
	iNW	4.47	-6.28	6.38	-2.76
	IS	11.13	-8.35	6.63	-2.89
	IC	4.71	-17.50	6.7	-2.93
NLD	NLDr	10.78	-6.91	10.51	-6.69
NZL	NZLr	-4.01	24.49	-3.89	23.70
USA	ANT	-1.31	1.41	-1.29	1.25
	CA	-1.19	1.16	-1.26	1.23
	MIO	-1.22	1.20	-1.27	1.23
	MNIA	-1.29	1.24	-1.27	1.24
	PNV	-1.20	1.16	-1.26	1.23
	uNE	-2.42	1.22	-1.3	1.26
	uNW	-1.61	1.59	-1.32	1.27
	uSE	-1.65	1.60	-1.32	1.27
	WAID	-1.24	1.24	-1.27	1.23
WI	-1.14	1.12	-1.25	1.22	

Table 3.6 presents the evolution of the raw milk production in every region in 2035 for "Var" and "Fix" versions of the "XM" and "MX" scenarios, relative to the base scenario. It also features the difference in these evolution between "MX" and "XM" scenarios, both for the "Var" and "Fix" versions. Here again, for the "Var" scenarios, we observe important differences between the milk production levels in the "XM" and "MX" scenarios in 2050 when imports and exports have been opened for 15 years in both scenarios. The difference between scenarios in most regions is greater than one percentage point of the raw milk production in the baseline and

goes up to more than 26 points in the center of Italy (iC). This confirms the important and lasting impacts of differentiated chronologies of trade opening. In the "Fix" scenarios, differences in the regional production of raw milk in 2050 between "MX" and "XM" scenarios are mostly non-existent, none being higher than 1 point. Therefore, it seems that hysteresis is mostly due to agglomeration economies more than capital accumulation effects.

Table 3.6: Evolution of the raw milk production per region in 2050 in comparison to the baseline scenario (% variation of "BASE" scenario production)

r	sub	Var			Fix		
		XM	MX	XM-MX	XM	MX	XM-MX
DEU	dE	6.54	1.01	5.53	2.52	2.35	0.17
	dNW	1.6	3.04	1.44	2.64	2.58	0.06
	dSW	4.31	2.22	2.09	2.56	2.43	0.13
	dW	1.53	2.71	1.18	2.65	2.59	0.06
	dSE	1.91	2.91	1.00	2.63	2.55	0.08
FRA	A	2.56	1.68	0.88	2.26	1.94	0.32
	C	7.38	2.14	5.24	2.26	1.79	0.47
	E	2.2	1.8	0.40	2.26	1.96	0.30
	N	2.02	1.97	0.05	2.26	1.97	0.29
	NW	1.54	1.97	0.43	2.26	2.00	0.26
	SW	4.38	2.34	2.04	2.26	1.81	0.45
GBR	GBRr	-2.22	-2.17	0.05	-2.00	-1.97	0.03
ITA	iN	2.61	6.53	3.92	3.93	3.99	0.06
	INE	5.51	7.3	1.79	4.01	4.04	0.03
	iNW	1.18	1.8	0.62	4.05	4.08	0.03
	IS	15.29	0.08	15.21	4.19	4.17	0.02
	IC	1.26	-25.23	26.49	4.23	4.20	0.03
NLD	NLDr	5.05	4.89	0.16	5.00	4.84	0.16
NZL	NZLr	19.47	20.12	0.65	18.96	19.53	0.57
USA	ANT	-0.15	-0.04	0.11	-0.16	-0.15	0.01
	CA	-0.05	-0.2	0.15	-0.15	-0.14	0.01
	MIO	-0.08	-0.17	0.09	-0.15	-0.14	0.01
	MNIA	-0.12	-0.15	0.03	-0.16	-0.14	0.02
	PNV	-0.05	-0.21	0.16	-0.15	-0.14	0.01
	uNE	-0.91	-0.21	0.70	-0.17	-0.15	0.02
	uNW	-0.44	0.11	0.55	-0.18	-0.16	0.02
	uSE	-0.55	0.07	0.62	-0.18	-0.16	0.02
	WAID	-0.1	-0.17	0.07	-0.15	-0.14	0.01
WI	-0.02	-0.23	0.21	-0.15	-0.14	0.01	

The policy scenarios simulated here are obviously quite unlikely. Trade liberalization usu-

ally concerns a set of products and sectors and occurs reciprocally between a set of countries. However, we can extrapolate from these results for more traditional scenarios. It is likely that the opposite effects of imports and exports opening on the geographical distribution of production would remain if some trade agreements are signed sequentially with countries that are mostly importers or exporters of a given product of local value chains with economies of agglomeration. We can imagine that this chronology in the signing of trade agreements would have similar hysteresis consequences on the final distribution of activities. At a time when the benefits of trade agreements are much discussed politically, in particular for their consequences in less developed regions with less mobile labor and production factors, such type of consideration should become increasingly important. Moreover, it is likely that protectionist policies would have symmetrical effects. The possibility of trade wars create risks that make such type of analysis especially relevant.

3.3.2 Support policies

Table 3.7 displays the evolution of the number of factories per region in 2035 and 2050 for the "PrRmk" and "PrMil" scenarios and in the baseline. Looking at 2035, we first notice that both production subsidies to raw milk ("PrRmk") and to processed dairy products ("PrMil") expand the dairy sector in most European regions, while the increased competition leads to the exit of a number of dairy factories in the US and New Zealand. The effects are in most cases larger in the "PrMil" scenario. We notice however in the center of Italy (iC), that the region actually loses a processing factory in 2035 in the "PrRmk" scenario. It is likely that this region has actually suffered from the increased supply of dairy products from other regions.

Now looking at 2050, 15 years after the implementation of these support policies have been suspended in both scenarios, we notice that differences in the numbers of dairy factories remain in both scenarios in comparison to the baseline, as well as differences between scenarios. Therefore, this shows that both these support policies have hysteretic consequences. We notice that South-West Germany (dSW) and the Netherlands (NLD) see their number of processing factories remaining higher in both scenarios in 2050 in comparison to the baseline. The starkest contrast between scenarios occurs in South-East Germany (dSE), North-West France (NW) and

the North of Germany (dN) which see their number of factories higher in the "PrRmk" scenario than in the baseline, while it is lower in the "PrMil" scenario. The South of Italy (iS) has the opposite evolution. Overall, it seems that the subsidy to the production of raw milk has a lasting agglomerating effect, leading to a concentration of the production in the regions where it is already the densest, while the subsidy to the production of processed dairy product has the opposite distributional effect.

Table 3.7: Number of dairy factories per region in 2035 and 2050 in the "BASE", "PrRmk_var" and "PrMil_var" scenarios

r	sub	2035			2050		
		BASE	PrRmk_var	PrMil_var	Base	PrRmk_var	PrMil_var
DEU	dE	29	35	40	27	27	29
	dNW	53	65	68	52	53	52
	dSW	54	65	71	51	52	53
	dW	49	60	62	48	48	47
	dSE	93	114	119	91	92	90
FRA	A	29	33	34	30	30	30
	C	12	14	15	13	13	13
	E	31	36	36	32	32	32
	N	34	39	40	35	35	35
	NW	125	143	146	129	130	128
	SW	11	13	14	12	12	12
GBR	GBRr	144	161	157	145	145	145
ITA	iN	77	87	87	76	80	75
	INE	19	21	22	19	20	19
	iNW	10	10	11	10	9	10
	IS	12	12	15	12	10	13
	IC	6	5	6	6	4	5
NLD	NLDr	118	161	158	114	115	115
NZL	NZLr	265	257	245	296	296	295
USA	ANT	116	116	114	129	129	129
	CA	202	200	198	219	219	219
	MIO	103	102	101	112	112	112
	MNIA	73	73	72	80	80	80
	PNV	140	139	138	152	152	152
	uNE	13	13	12	14	14	14
	uNW	87	86	85	98	98	98
	uSE	67	67	66	76	76	75
	WAID	106	105	104	116	116	116
WI	150	149	147	162	162	162	

Table 3.8 presents the evolution of the raw milk production in both "Var" and "Fix" versions of the "PrRmk" and "PrMil" scenarios in 2035 and 2050 in comparison to the base scenario. In 2035 for the "Var" scenarios, the evolution of the production of raw milk follows the direction of the one of processing factories from Table 3.7. However, we notice that the effect is now stronger in EU regions for the "PrRmk" scenario. The subsidy that targets directly the primary agricultural production has the strongest effect on it. If we compare the "Var" and "Fix" scenarios, we observe that the global evolution in the milk production of countries is similar. The "PrRmk" scenario has an agglomeration effect in the regions that already have the densest production, even without agglomeration economies ("PrRmK_Fix"). Agglomeration economies only strengthen this effect in the "PrRmk_Var" scenario. However, we notice some opposite distributional effects between the "Var" and "Fix" versions of the "PrMil" scenario. In the "PrMil_Var" scenario, some of the regions with lower density of production (dE, dSW, C, SW, iS) have the largest increase in production while some the densest regions (dW, dNW, E, NW, iN) see smaller increase of production. This is the de-agglomerating effect we noticed in Table 3.7. However, in the "PrMil_Fix" scenario, the distributional effect leads to a concentration of the production in the already densest regions, similarly to the "PrRmk_Fix" scenario, however with smaller inter-regional differences. A likely explanation for this difference in the distributional effect is that when agglomeration economies are represented (Var scenario), the increase in production and number of factories leads to agglomeration economies greater in regions with lower density of production and higher initial transport costs. This de-agglomerating effect offsets the concentrating effect observed when agglomeration economies are neutralized ("PrMil_Fix").

The agglomeration effect that occurs without modeling of economies of agglomeration in "Fix" version of both "PrRmk" and "PrMil" scenarios is likely due to the differences in the calibration of processing production functions and initial collection costs across regions. Indeed, even if collection costs do not evolve in these scenarios, the differences across regions remain. Therefore, the share of the price of raw milk in the overall value added produced by the agri-food sector is higher in the regions with lower transport costs. The regions with the densest production and lower transport costs therefore benefit the most in proportion from the subsidy

on the price of raw milk. The similar effect in the "PrMil_Fix" scenario is likely due to similar causes as processed dairy sectors also use some processed dairy products as inputs. Therefore, the subsidy of these products benefits more to the region with lower initial transport costs, for which these products have a higher initial input share. This explanation is confirmed by the fact that when exports of dairy products are open and their price increase as we can see in the "XM_Fix" scenario in Table 3.5, we observe the opposite distributional effect.

Now looking at 2050 on Table 3.8, we see that the persistent geographical distributional effect in "Var" and "Fix" versions of "PrRmk" and "PrMil" scenarios are similar in directions to the ones observed in 2035 when the support policies were still in place. The difference we observe is that in comparison to the "XM" and "MX" scenarios, some important differences remain in the "Fix" scenarios with neutralized agglomeration economies and are sometimes even larger than in the "Var" scenarios. In these cases, the accumulation and de-accumulation dynamics of capital seem to have larger hysteretic effects than agglomeration economies.

Table 3.8: Evolution of the raw milk production per region in 2035 and 2050 in comparison to base scenario (% of base scenario)

sub	2035				2050			
	Var		Fix		Var		Fix	
	PrRmk	PrMil	PrRmk	PrMil	PrRmk	PrMil	PrRmk	PrMil
dE	31.56	30.28	26.28	19.23	-0.76	6.48	-2.45	-0.93
dNW	37.00	21.02	38.04	22.80	0.84	-1.22	1.76	0.70
dSW	34.56	26.22	30.02	20.41	0.83	2.75	-1.11	-0.39
dW	37.30	20.75	38.36	22.89	0.78	-1.56	1.87	0.74
dSE	36.91	21.85	36.35	22.31	0.87	-0.91	1.15	0.47
A	28.89	14.50	27.91	13.61	0.18	0.39	-0.08	0.05
C	26.11	19.13	21.41	12.53	-0.74	3.68	-3.32	-0.82
E	29.50	13.99	28.91	13.76	0.44	0.07	0.41	0.18
N	29.70	13.84	29.44	13.84	0.56	-0.03	0.66	0.24
NW	30.51	13.24	31.18	14.10	0.94	-0.39	1.51	0.46
SW	27.11	18.68	22.34	12.69	-0.07	3.26	-2.85	-0.69
GBRr	26.83	7.67	26.12	7.32	0.00	-0.12	0.00	-0.11
iN	30.72	10.43	29.72	12.02	5.19	-0.59	2.41	0.71
INE	26.16	12.39	23.51	10.65	3.95	0.87	-0.67	-0.26
iNW	16.61	10.46	19.82	9.78	-7.10	-0.68	-2.52	-0.87
IS	7.35	19.78	10.21	7.27	-19.11	10.93	-7.43	-2.64
IC	0.94	1.84	7.85	6.60	-30.22	-19.25	-8.67	-3.11
NLDr	51.92	28.69	50.62	27.87	0.93	0.43	0.82	0.38
NZLr	-2.94	-7.14	-2.80	-6.89	-0.10	-0.15	-0.09	-0.13
ANT	-0.69	-1.84	-0.66	-1.71	-0.01	-0.08	-0.01	-0.01
CA	-0.65	-1.58	-0.65	-1.67	0.01	0.12	-0.01	0.00
MIO	-0.67	-1.65	-0.65	-1.68	0.01	0.06	-0.01	-0.01
MNIA	-0.66	-1.69	-0.65	-1.68	0.00	0.05	-0.01	-0.01
PNV	-0.65	-1.57	-0.65	-1.67	0.02	0.11	-0.01	0.00
uNE	-0.74	-2.91	-0.67	-1.72	-0.14	-0.91	-0.01	-0.01
uNW	-0.85	-2.16	-0.68	-1.74	-0.13	-0.39	-0.01	-0.02
uSE	-0.69	-2.09	-0.68	-1.74	-0.03	-0.41	-0.01	-0.02
WAID	-0.67	-1.65	-0.65	-1.68	0.00	0.07	-0.01	-0.01
WI	-0.62	-1.53	-0.64	-1.66	0.03	0.14	-0.01	0.00

We can conclude that support policies that target the primary production in local value chains seem to have an agglomerating effect, benefiting mostly the regions that already have the densest production and lower transport costs. This effect is reinforced by agglomeration economies and can last, and sometimes even worsen, after the policy ends. On the contrary, policies that support the price of processed products ("PrMilk" and "XM"), seem to mostly benefit the regions with less dense production and higher transport costs, as higher levels of

production provide them with more economies of agglomeration and set them on a more sustainable path. These differences in distributional effects of policies seem to be mainly pulled by the differences across regions in the relative share of transport costs and primary inputs in the value added of these sectors, as well as by the importance of agglomeration economies. These determinants must therefore be carefully calibrated when studying policy implications from such model. However, these results are interesting to look at in the context of the European Common Agricultural Policy (CAP). Indeed, the move from market price support mechanisms to more direct support of farmers could have had, following this model, a concentrating effect on the distribution of agricultural production across regions. This result seems to be in line with the observed dynamic of the distribution of agricultural production in Europe in the past two decades (Chevassus-Lozza and Daniel, 2006; Ben Arfa et al., 2009; Bagoulla et al., 2010). We can imagine that an increase of "second pillar", rural development programs could help offset this concentration effect.

3.3.3 Tax on petroleum and coal products

We now present the results of the simulation "CarbTax", where a 30% tax on the production and imports of petroleum and coal products is implemented between 2035 and 2050. This policy leads in European countries to a decrease of total consumption of these products between 20 and 25% and leads to an increase of the cost of transport between 5 and 10%. Table 3.9 presents the evolution of the number of dairy factories in 2035 and in 2050 in the "CarbTax_Var" scenario in comparison to the base scenario. If the global number of factories per countries do not look much affected by the policy, we notice a clear agglomeration effect of this policy in 2035 with the region with lowest density of production loosing dairy factories (dE, dSW, iS, iC), while the regions with the higher density of production sometimes even see their number of dairy factories increasing (dNW, dSE, NW, iN). This effect remains in 2050, 15 years after the policy has been suspended, and sometimes even reinforce as can be seen in Italy (iN and iNE against iS and iC).

Table 3.9: Number of dairy factories per region in 2035 and 2050 and evolution in the "BASE" and "CarbTax" scenarios

r	sub	2035		2050	
		Base	CarbTax_Var	Base	CarbTax_Var
DEU	dE	29	28	27	26
	dNW	53	54	52	53
	dSW	54	52	51	50
	dW	49	49	48	48
	dSE	93	94	91	91
FRA	A	29	29	30	30
	C	12	12	13	12
	E	31	31	32	32
	N	34	34	35	35
	NW	125	127	129	130
	SW	11	11	12	11
GBR	GBRr	144	143	145	145
ITA	iN	77	79	76	80
	INE	19	19	19	20
	iNW	10	10	10	10
	IS	12	10	12	9
	IC	6	4	6	3
NLD	NLDr	118	119	114	113
NZL	NZLr	265	264	296	296
USA	ANT	116	116	129	129
	CA	202	201	219	219
	MIO	103	103	112	112
	MNIA	73	73	80	80
	PNV	140	140	152	152
	uNE	13	13	14	14
	uNW	87	87	98	98
	uSE	67	67	76	75
	WAID	106	106	116	116
WI	150	150	162	162	

Table 3.10 presents the evolution of the production of raw milk per region in 2035 and 2050 in the "Var" and "Fix" versions of the "CarbTax" scenario in comparison to the base scenario. We notice similar trends than what we could observe on the number of dairy factories. In most regions, the effects of the tax seem of the same order of magnitude between "Var" and "Fix" scenarios, with slightly less hysteretic consequences in the "CarbTax_Fix" scenario. However, we observe some larger effects that deepen over time, even after the tax ended, in some regions

with low density of production (SW, iS, iC) when economies of agglomeration are represented ("CarbTax_Var").

Table 3.10: Evolution of the raw milk production per region in 2035 and 2050 in the "CarbTax_Var" and the "CarbTax_Fix" scenarios in comparison to the baseline scenario (variation in % of baseline scenario)

r	sub	2035		2050	
		CarbTax_Var	CarbTax_Fix	CarbTax_Var	CarbTax_Fix
DEU	dE	-4.61	-4.05	-3.94	-1.39
	dNW	1.42	1.37	1.23	0.59
	dSW	-2.53	-2.28	-1.43	-0.75
	dW	1.42	1.51	1.09	0.64
	dSE	0.78	0.61	0.75	0.31
FRA	A	0.14	0.17	-0.33	-0.51
	C	-3.34	-4.09	-4.82	-3.17
	E	0.62	0.81	0.05	-0.11
	N	0.90	1.14	0.28	0.09
	NW	1.82	2.24	0.90	0.77
	SW	-2.87	-3.47	-4.38	-2.78
GBR	GBRr	-0.53	-0.63	0.06	0.05
ITA	iN	3.94	2.71	6.13	1.92
	INE	0.54	-1.17	4.04	-0.52
	iNW	-1.22	-3.54	1.78	-2.02
	IS	-15.15	-9.98	-22.45	-6.13
	IC	-27.63	-11.61	-49.87	-7.18
NLD	NLDr	0.97	1.25	-0.27	-0.36
NZL	NZLr	-0.54	-0.70	-0.01	-0.01
USA	ANT	-0.14	-0.21	-0.02	-0.06
	CA	-0.04	-0.06	0.05	0.03
	MIO	-0.07	-0.09	0.02	0.01
	MNIA	-0.09	-0.12	0.02	-0.01
	PNV	-0.02	-0.05	0.05	0.03
	uNE	-0.17	-0.25	-0.14	-0.08
	uNW	-0.28	-0.36	-0.16	-0.15
	uSE	-0.29	-0.36	-0.32	-0.15
	WAID	-0.06	-0.10	0.02	0.01
WI	0.00	-0.02	0.07	0.05	

This spatial agglomeration effect is not surprising as the tax increases the cost of coal and petroleum products and therefore of transports. It is expected to increase concentration and to reduce transport demand. However, this has important distributional effects, benefiting the production in regions with the already most developed sectors while affecting the less developed

regions. If factors are not mobile across regions, their owners could see substantial income losses in these regions. For example, in Italy for the scenario "CarbTax_Var", rental rate of land decreases of respectively 11 and 19% in the South and in the center (iS and iC) while it increases by 0.5% in the North (iN). We see similar evolution in other countries. Labor is mobile in this model but we could expect similar results if it was not. Therefore, complementary support policies could be necessary to go along such a tax. Moreover, we haven't represented in this model other production externalities. The increased concentration of production may have other adverse consequences for example on ecosystems. The benefits of such a policy regarding carbon emissions and climate may therefore need to be balanced with other environmental and rural development goals.

3.4 Conclusion

We have provided in this Chapter an original implementation of local value chains with economies of agglomeration inside a dynamic CGE trade model. We simulated a variety of policy scenarios affecting directly or indirectly the dairy sector. In every case, the representation of local value chains brings light to substantial effects of these policies on the spatial distribution of production across time. We show that the representation of agglomeration economies is essential as they have important consequences on the level of geographical concentration of local value chains. In some case, their omission can even lead to the inversion of the direction of the agglomeration effect. Moreover, we show that they lead to hysteretic consequences, larger than the ones observed solely due to capital accumulation dynamics. Therefore, such models appear to be of prime importance to analyze the consequences across time and space of policies affecting local value chains.

With respects to policy implications, we have shown that the chronology of trade liberalization policies can have significant and lasting spatial distribution effects. The opening of domestic markets leads to the further concentration of production across regions while the opening of foreign markets has the opposite effects. Therefore, trade policy agenda should be built carefully to account optimally for these effects. We have also shown that the design of a support policy of local value chains matters for their geographical distribution effects. Primary producer

supports seem to lead to increased agglomeration of production while supports of the price of processed product seem to partially reverse existing production concentration. Finally, we have shown that an environmental tax that increases the price of petroleum and coal products and subsequently of transports, leads to the agglomeration of local value chains.

These three examples show how different policies can have important consequences on the geographical distribution of activities inside countries. Moreover, we have shown how these consequences can last long after they have been suspended, due to agglomeration economies and capital dynamics. At a time with growing uncertainty around trade and production capabilities due to environmental, health and political concerns, it seems critical to understand the dynamic effects of policies in these areas to not hinder any future option. It appears equally important to account for the distributional effects of policies when a number of factors, including labor, are not much mobile across space and sectors. Lingering in this work is the issue of the "optimal" level of agglomeration. If factors are mobile, the agglomeration of all production in a single region would not be a problem. However, when factors are fixed, the right level of concentration will depend on the relative importance of agglomeration economies and factor use. Finally, the concentration of production may lead to other negative externalities, for example effluent management and ecological concerns in agriculture, that may counter-balance the benefits from agglomeration.

General Conclusion

This thesis provides a framework for the better understanding and modeling of the dynamics of regional agri-food sectors. We develop a first dynamic CGE global trade model that features agri-food sectors disaggregated at the regional scale and that allows the representation of economies of agglomeration and the associated hysteresis.

In the first chapter, we present a simple model that allows to isolate the main determinants of the dynamics and the resilience of agri-food sectors. In particular, we highlight the role of economies of scale, access to other markets, capital flexibility, market structure and agents expectations. Depending on these characteristics, we show that these sectors can display a multiplicity of steady-state equilibria, leading to a potential hysteretic behavior. It will be important to appropriately represent these characteristics in dynamic models of agricultural value chains to provide accurate evaluations of the long-run consequences of policies and exogenous shocks. These determinants can also be seen as potential policy levers to improve the performance and resilience of agri-food sectors. We highlight potential vertical coordination issues that could justify policy interventions, either to protect value chains during crises or to ease their recovery after. The choice between conservation and recovery policies will depend on the expected length of the crisis and the respective costs of these policies. We also show how more integrated value chains can help the coordination of its agents toward more profitable equilibria. However, we highlight how it may increase adjustment costs and the risks of bottlenecks if it locks farmers and processors into more isolated and specialized value chains.

In the second chapter, we build a first calibrated multi-regional dynamic model of agri-food sectors with economies of agglomeration and asset fixity. We show that both a shock on the World price of dairy products or a shock on milk transport costs can lead to the irreversible

collapse of some regional dairy sectors. We emphasize the role of the density of milk production as it seems to limit the vulnerability of regional dairy sectors. We also show how a tariff on dairy imports can help protect regional sectors but represents an important cost for consumers. A policy supporting investments in damaged sectors to help their recovery seems to be more efficient.

In the last chapter, we integrate the model developed in the second chapter into the global CGE trade model MIRAGRODEP. This allows us to provide a comprehensive response to our initial goal: representing the regional dynamics of agri-food sectors in a global framework. We provide three examples of topics such models can contribute to. First, we show how the representation of economies of agglomeration in agri-food sectors emphasize the importance of hysteresis in trade policies, signaling a potential need to pay more attention to the chronology of these policies. Then, we demonstrate that two agricultural support policies with supposedly similar goals can have lasting and contradicting consequences on the distribution and concentration of agricultural production. Finally, we show how the taxation of coal and petroleum products may inflict lasting damages to the agricultural sectors of less productive regions and may lead to the further agglomeration of agricultural production, with potentially adverse environmental consequences.

We hope that this work can help shed light on the importance to better account for agglomeration effects and the hysteretic behavior of agri-food sectors considering the current shifts and uncertainty the global food system is facing. We highlight a number of adjustment costs and option value to the preservation of agricultural value chains at the regional scale. In a changing and uncertain context, it seems important to understand and measure these effects to choose policies that are collectively desirable and improve the food system today without hampering its resilience for tomorrow. The tools developed in this thesis can help in the task of better understanding the consequences of policies and shocks on regional agri-food sectors as they spread in time and space.

The research presented in this thesis nevertheless contains a number of limits that are avenues for further research. We just scratch the surface of the complex interactions at play between local agricultural value chains across the World and their policy implications regarding

the current environmental, social and political challenges.

First, we compared the resulting dynamics of the geographic distribution of agricultural production to a variety of scenarios and have been able to evaluate their consequences in terms of prices, consumption and profits. However, we have not been able to search for the optimal dynamic geographic distribution of agri-food sectors. The non-convexities in this system and its complexity in space and time makes this problem especially complicated to solve. If some reduced models may be tractable at a national scale on a reduced period, it would become quickly impossible to solve as it expands. However, this remains an interesting question for the future. In particular, regarding the growing uncertainty that production systems face, it would be interesting to know the optimal distribution between an agglomerated sector in a single region that would take maximum advantage of economies of agglomeration, and scattered smaller sectors that may be less productive but may provide a more resilient overall supply. This may raise some interesting political economy issues as the answer may be different for an individual country or from a collective point of view. That may call for a different set of policies depending on the ability of countries to cooperate.

Second, we haven't explicitly represented risk in the models we developed. We believe that the introduction of such noise in these models would have made them significantly harder to apprehend as they already lead to nearly chaotic dynamics. In addition, we believe this would have required many additional assumptions on the uncertainty profiles of various exogenous variables, as well as on the risk perceptions of the agents. Indeed, as we have shown the complex consequences of any shock and how they depend on the characteristics of the production system and in particular the ability of the agent to coordinate; the explicit introduction of such uncertainty would have required further assumptions on how the agent perceive these risks and their consequences on the market. Finally, looking at the literature on investment under uncertainty and option value, we believe this would have only reduced the levels of investment of the agent according to their option value in response to a given state (Dixit and Pindyck, 1994; Moschini and Hennessy, 2001). Although accounting for risk could have changed the number of steady-state equilibria and their levels in some situation, we don't believe this would have significantly affected the behavior of the models we developed.

Third, as we discussed at different point throughout this work, agents expectations and their ability to coordinate is a key determinant of our results as in most cases, the hysteretic behavior of the agri-food sectors we observe depend on the limited rationality assumptions we made. As shown by (Krugman, 1991b), even in a system with multiple possible equilibria, expectations can be more important than history in the determination of the final outcome. We mostly assumed that agents had backward looking expectations, either myopic or adaptive. This choice was made for the sake of simplicity, as perfect expectations would have been analytically challenging to represent. Moreover, such assumptions are commonly used in agricultural economics and CGE models and the hypothesis of limited rationality seems to hold in the context of agricultural agents (Nerlove and Bessler, 2001; Femenia and Gohin, 2011). However, this makes our models unable as such to represent the reaction of the agents on information on future market conditions. This may have important consequences if the agents anticipate a given policy change. This seems to have occurred for example with the end of milk productions quotas in the European Union as many countries had started increasing their herd and overshot their quota the year prior to the reform (Matthews, 2015).

Fourth, we highlighted the role of the market structure on the ability of the agents to coordinate vertically in value chains and on the equilibrium levels of prices. However, in most models we chose a competitive short-run structure, whereas the reduced number of processing factories and the importance of transport costs generally gives market power to the processors in agricultural markets. This choice was made for the sake of simplicity. It quickly appeared that the representation of a monopsonistic or oligopsonistic structure would be less tractable, even in simple analytical models and would quickly become impossible to solve in more complex models, where the addition of local supply and inter-regional trade create non-convexities in the total inverse supply function. We showed in the Appendix A.3 to the first chapter that an oligopsonistic structure may not significantly change the behavior of a regional value chain. This would mostly change the repartition of the value added in the agri-food chains and the levels of investment, production and prices. More importantly, in relation with the discussion on agents' expectations, we haven't represented some specific structures that may provide more information to the agents and ease their coordination. We can think for example to the cases of

cooperatives, contractualization and futures market that can be seen in many agricultural value chains. The growing literature on dynamic coordination games shows the key role of timing and information in such problems (Gale, 1995; Morris and Shin, 2003; Yang, 2010; Jorge and Rocha, 2015). This calls for caution on the external validity of our results and invites more work to allow the representation and analysis of these structures in our framework.

Fifth, if we have represented some degree of heterogeneity between regions in their geography, transport costs and factors distribution, we still have omitted a number of particular features that could affect the dynamic of their agricultural sectors. In particular, we haven't represented any vertical and horizontal differentiation. In some countries where geographic appellations are important, this may be a supplementary asset for some region that may be worth studying. We also have not represented much heterogeneity in production systems and market structures inside and across regions as it would have made models increasingly complex. However, looking at the multiplication and cohabitation of different forms of agriculture (organic, local market oriented, export oriented, family-owned or with foreign capital) with different scales, it would be interesting to see how this might provide different types of solutions to regions with different characteristics.

Finally, our representation of agglomeration economies and of the dynamic location choices of agricultural and processing activities remains simplistic. We make a strong assumption in particular on the homogeneous distribution of the agricultural production inside regions and on the shape of the intra-regional transport costs function. This assumption was made because it reduced the amount of data required to calibrate these models and it simplified their resolution. The evolution of the location of agricultural activities in relation to the location of processing factories will determine the size of these agglomeration economies. However, this is a complex question as both are influenced by the other. A number of papers study this question in location theory (Parr and Kim Swales, 1999; Kilkenny and Thisse, 1999). However, they often provide complex solutions, highly dependent on the geographical distribution of factors and on market characteristics. The pricing strategy appears especially important as the resulting location will depend on the share of transport costs the processors and the farmers pay. The size of production per farm will also affect milk transport costs (Freije, 2011). Moreover, we used a very rough

calibration of the amount of milk transport costs and the size of economies of scale of processing factories. More work is therefore required to know the actual behavior of the agents regarding their location and to better measures the size of agglomeration economies and their evolution. This is an important next step to significantly strengthen the accuracy of such models.

These limits invite more work to improve the fit of trade models to the differing features of agri-food sectors across the World. We focused mainly on the representation of the dairy sector in our examples but such treatment would be interesting on many other sector with important transport costs and economies of scale in processing. Most animal productions correspond to these characteristics, but also some plant based ones, such as sugar production. The complexity of the interactions we highlighted raises many questions to determine optimal policies in the current context, with new consumer and citizen demands and environmental and health challenges. We believe this thesis provides a good base framework to integrate this complexity and pursue this research. This work is necessary to continue to increase our understanding of the evolution of local agricultural value chains and to create the policy environment required for their success and resilience in an open World.

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Appendices

Appendix A

Supplementary material to Chapter 1

A.1 Convergence of the agricultural capital dynamic when factories are fixed

We have a recursive sequence $(u_t)_{t \geq 0}$ described by $u_{t+1} = h(u_t) = a \cdot (u_t)^\rho$. We have $\rho < 0$ and $a > 0$, therefore h is decreasing and the even and odd sequences (u_{2t}) and (u_{2t+1}) are monotonous. We have $u_{2t+2} = h \circ h(u_t) = a^{1+\rho} \cdot (u_{2t})^{\rho^2}$.

The points $u_E = a^{\frac{1}{1-\rho}}$ and 0 are the two unique fixed points of both h and $h \circ h$.

(u_{2t}) is increasing if for all $t \geq 0$:

$$\begin{aligned} u_{2t+2} &> u_{2t} \\ a^{1+\rho} \cdot (u_{2t})^{\rho^2} &> u_{2t} \\ (u_{2t})^{\rho^2-1} &> a^{-1-\rho} \end{aligned} \tag{A.1}$$

Therefore, (u_{2t}) is increasing if $\rho < -1$ and $u_{2t} > a^{\frac{-(1+\rho)}{\rho^2-1}} = u_E$ or if $\rho > -1$ and $u_{2t} < a^{\frac{-(1+\rho)}{\rho^2-1}} = u_E$. Similarly we show that (u_{2t}) is decreasing if $\rho < -1$ and $u_{2t} < a^{\frac{-(1+\rho)}{\rho^2-1}} = u_E$ or if $\rho > -1$ and $u_{2t} > a^{\frac{-(1+\rho)}{\rho^2-1}} = u_E$.

h is decreasing and $h \circ h$ is increasing. Therefore, if $0 < u_{2t} < u_E$, we have: $u_{2t+1} = h(u_{2t}) > u_E = h(u_E)$ and $0 < u_{2t+2} = h \circ h(u_{2t}) < u_E = h \circ h(u_E)$. Then, by recursion, we show that if $0 < u_0 < u_E$, the even and odd sequence (u_{2t}) and (u_{2t+1}) are bounded and for all $t \geq 0$,

$0 < u_{2t} < u_E$ and $u_{2t+1} > u_E$. In the same way, we show that if $u_0 > u_E$, we have: $0 < u_{2t+1} < u_E$ and $u_{2t+2} > u_E$.

Then, if $\rho < -1$ and $u_0 < u_E$, we have (u_{2t}) increasing and bounded by the unique fixed point u_E . Therefore, (u_{2t}) converge towards u_E . We also have (u_{2t+1}) decreasing and bounded by the unique fixed point u_E . Therefore, (u_{2t+1}) converge towards u_E . Therefore, the sequence (u_t) is converging toward $u_E = a^{\frac{1}{1-\rho}}$. We show symmetrically that (u_t) converges toward u_E if $u_0 > u_E$. (u_t) is stable at u_E if $u_0 = u_E$. Then, for any initial value $u_0 > 0$, (u_t) is converging toward u_E if $\rho < -1$.

If $\rho > -1$, the even and odd sequences (u_{2t}) and (u_{2t+1}) don't have the same limits, therefore, (u_t) do not converge.

We have the sequence (K_t) with n_E fixed described by the recursive relation in equation 1.22:

$$K_{t+1} = A_t \cdot B_t^{\frac{1}{1-\alpha-\beta}} \cdot n_E^{\frac{(1-\sigma)(\beta-1)}{(\beta \cdot \sigma - 1) \cdot (1-\alpha-\beta)}} \cdot K_t^{\frac{\alpha \cdot (1-\sigma)}{(\beta \cdot \sigma - 1) \cdot (1-\alpha-\beta)}} \quad (\text{A.2})$$

Therefore, we have:

$$\alpha = A_t \cdot B_t^{\frac{1}{1-\alpha-\beta}} \cdot n_E^{\frac{(1-\sigma)(\beta-1)}{(\beta \cdot \sigma - 1) \cdot (1-\alpha-\beta)}}$$

$$\rho = \frac{\alpha \cdot (1-\sigma)}{(\beta \cdot \sigma - 1) \cdot (1-\alpha-\beta)}$$

We conclude that (K_t) converges if:

$$\frac{\alpha \cdot (1-\sigma)}{(\beta \cdot \sigma - 1) \cdot (1-\alpha-\beta)} > -1 \quad (\text{A.3})$$

We can rearrange this condition as:

$$2 \cdot \alpha + \beta - \sigma \cdot \alpha \beta \cdot \sigma - \alpha \cdot \beta \cdot \sigma - \beta^2 \cdot \sigma < 1 \quad (\text{A.4})$$

If the sequence (K_t) converges, it is toward the point:

$$\begin{aligned}
K_E &= \left[A_t \cdot B_t^{\frac{1}{1-\alpha-\beta}} \cdot n_E^{\frac{(1-\sigma)(\beta-1)}{(\beta \cdot \sigma - 1)(1-\alpha-\beta)}} \right]^{\frac{1}{1-\frac{\alpha \cdot (1-\sigma)}{(\beta \cdot \sigma - 1)(1-\alpha-\beta)}}} \\
&= \left[A_t^{1-\alpha-\beta} \cdot B_t \right]^{\frac{\beta \cdot \sigma - 1}{(\beta-1)(1-\alpha \cdot \sigma - \beta \cdot \sigma)}} \cdot n_E^{\frac{1-\sigma}{1-\alpha \cdot \sigma - \beta \cdot \sigma}}
\end{aligned} \tag{A.5}$$

A.2 Existence of one steady-state equilibrium of the value chain

We look for a solution of equation 1.25:

$$n_E = \lfloor C_t \cdot \left(\left[A_t^{1-\alpha-\beta} \cdot B_t \right]^{\frac{\beta \cdot \sigma - 1}{(\beta-1)(1-\alpha \cdot \sigma - \beta \cdot \sigma)}} \cdot n_E^{\frac{1-\sigma}{1-\alpha \cdot \sigma - \beta \cdot \sigma}} \right)^{\frac{\alpha}{1-\beta}} \rfloor \tag{A.6}$$

We simplify this expression to $n = \lfloor E \cdot n^\gamma \rfloor$, with:

$$E = C_t \cdot \left(A_t^{1-\alpha-\beta} \cdot B_t \right)^{\frac{\alpha \cdot (1-\beta \cdot \sigma)}{(1-\beta)^2 \cdot (1-\alpha \cdot \sigma - \beta \cdot \sigma)}}, \tag{A.7}$$

And:

$$\gamma = \frac{\alpha \cdot (1-\sigma)}{(1-\beta) \cdot (1-\alpha \cdot \sigma - \beta \cdot \sigma)}. \tag{A.8}$$

This condition is equivalent to finding a natural integer n , such that:

$$\begin{aligned}
E \cdot n^\gamma - 1 &\leq n < E \cdot n^\gamma \\
(E - n^{-\gamma})^{\frac{1}{1-\gamma}} &\leq n < E^{\frac{1}{1-\gamma}}
\end{aligned} \tag{A.9}$$

If $E \leq 1$, we have $n < 1$ so the only possible equilibrium is $n = 0$. The value chain do not admit any productive stable equilibrium. If $E > 1$, we can prove that there is at least one positive solution, $n = \lfloor E^{\frac{1}{1-\gamma}} \rfloor$. Indeed, if $n = \lfloor E^{\frac{1}{1-\gamma}} \rfloor$, we have: $E^{\frac{1}{1-\gamma}} - 1 \leq n < E^{\frac{1}{1-\gamma}}$. So, the second side of inequality A.9 is verified and we have $n^\gamma < E^{\frac{\gamma}{1-\gamma}}$, which implies: $E \cdot n^\gamma - 1 < E^{\frac{1}{1-\gamma}} - 1 \leq n$. So the first inequality is verified. We see on inequality A.9 that $n = \lfloor E^{\frac{1}{1-\gamma}} \rfloor$ is the highest possible

solution to this problem.

Replacing A_t , B_t and C_t by their expression in A.7, we have:

$$\begin{aligned}
E_t &= \left[\left(\frac{F_t}{1-\sigma} \right)^{\beta \cdot \sigma - 1} \cdot \frac{P_{Y,t} \cdot \beta \beta \cdot \sigma}{\sigma \beta \sigma \cdot P_{V,t}^{\beta \cdot \sigma}} \right]^{\frac{1}{\sigma \cdot (1-\beta)}} \\
&\cdot \left[\left(\left[\left(\frac{P_{K,t}}{\alpha} \right)^{1-\beta} \cdot \left(\frac{P_{V,t}}{\beta} \right)^\beta \right]^{\frac{1}{\alpha+\beta-1}} \right)^{1-\alpha-\beta} \cdot \left(\frac{P_{V,t}}{\beta} \right)^{\frac{\beta \cdot (\sigma-1)}{\beta \cdot \sigma - 1}} \cdot (\sigma \cdot P_{Y,t})^{\frac{\beta-1}{\beta \cdot \sigma - 1}} \right]^{\frac{\alpha \cdot (1-\beta \cdot \sigma)}{(1-\beta)^2 \cdot (1-\alpha \cdot \sigma - \beta \cdot \sigma)}} \\
&= \left(\frac{F_t}{1-\sigma} \right)^{\frac{\beta \cdot \sigma - 1}{\sigma \cdot (1-\beta)}} \cdot \left[\left(\frac{P_{V,t}}{\beta} \right)^{\beta \cdot (\beta \cdot \sigma - 1)} \cdot \left(\frac{P_{K,t}}{\alpha} \right)^{\alpha \cdot (\beta \cdot \sigma - 1)} \cdot \sigma^{\alpha - \beta + \alpha \cdot \beta \sigma + \beta^2 \cdot \sigma} \cdot P_{Y,t}^{\frac{1-\beta \cdot \sigma}{\sigma}} \right]^{\frac{1}{(1-\beta) \cdot (1-\alpha \cdot \sigma - \beta \cdot \sigma)}}
\end{aligned} \tag{A.10}$$

And we have the highest possible equilibrium:

$$\bar{n} = \left[\left(\frac{F_t}{1-\sigma} \right)^{\frac{\alpha \cdot \sigma + \beta \cdot \sigma - 1}{\sigma \cdot (1-\alpha - \beta)}} \cdot \left[\left(\frac{P_{V,t}}{\beta} \right)^{\beta \cdot (\beta \cdot \sigma - 1)} \cdot \left(\frac{P_{K,t}}{\alpha} \right)^{\alpha \cdot (\beta \cdot \sigma - 1)} \cdot \sigma^{\alpha - \beta + \alpha \cdot \beta \sigma + \beta^2 \cdot \sigma} \cdot P_{Y,t}^{\frac{1-\beta \cdot \sigma}{\sigma}} \right]^{\frac{1}{(1-\alpha - \beta) \cdot (1-\beta \cdot \sigma)}} \right] \tag{A.11}$$

A.3 Dynamic with an oligopsonistic processing sector

According to equation 1.3, we have the inverse agricultural supply function:

$$\begin{aligned}
P_Q &= \left(K^{\frac{\alpha}{1-\beta}} \cdot \left(\frac{P_V}{\beta} \right)^{\frac{\beta}{\beta-1}} \cdot \frac{1}{Q} \right)^{\frac{\beta-1}{\beta}} \\
&= \frac{Q^{\frac{1-\beta}{\beta}}}{K^{\frac{\alpha}{\beta}}} \cdot \frac{P_V}{\beta}
\end{aligned} \tag{A.12}$$

We now assume that the processing factories are not price takers but take into account the reaction of the price of the agricultural commodity P to their demand d . We are in the symmetrical oligopsonistic case than a Cournot oligopolistic model. The short-run processing program

is now:

$$\max \pi_y = d^\sigma \cdot P_Y - d \cdot P_Q(d) = d^\sigma \cdot P_Y - d \cdot \frac{(D^- + d)^{\frac{1-\beta}{\beta}}}{K^{\frac{\alpha}{\beta}}} \cdot \frac{P_V}{\beta}, \quad (\text{A.13})$$

With D^- the demand from other processing factories. The first order condition is:

$$\begin{aligned} \sigma \cdot d^{\sigma-1} \cdot P_Y - \frac{(D^- + d)^{\frac{1-\beta}{\beta}}}{K^{\frac{\alpha}{\beta}}} \cdot \frac{P_V}{\beta} - d \cdot \frac{1-\beta}{\beta} \cdot \frac{(D^- + d)^{\frac{1-\beta}{\beta}-1}}{K^{\frac{\alpha}{\beta}}} \cdot \frac{P_V}{\beta} &= 0 \\ \sigma \cdot d^{\sigma-1} \cdot P_Y - P_Q \cdot \left(1 + \frac{d}{d+D^-} \cdot \frac{1-\beta}{\beta}\right) &= 0 \end{aligned} \quad (\text{A.14})$$

As all the factories are identical, we have $D^- = (n-1) \cdot d$. Then, we have:

$$\begin{aligned} \sigma \cdot d^{\sigma-1} \cdot P_Y - P_Q \cdot \left(1 + \frac{1}{n} \cdot \frac{1-\beta}{\beta}\right) &= 0 \\ d &= \left[\frac{P_Q}{\sigma \cdot P_Y} \cdot \left(1 + \frac{1}{n} \cdot \frac{1-\beta}{\beta}\right) \right]^{\frac{1}{\sigma-1}} \\ d &= \left(\frac{P_Q}{\sigma \cdot P_Y} \cdot \frac{(n-1) \cdot \beta + 1}{n \cdot \beta} \right)^{\frac{1}{\sigma-1}} \end{aligned} \quad (\text{A.15})$$

Then, if we write the market clearing condition $Q = n \cdot d$ to find the equilibrium price of the agricultural commodity P_Q , we have:

$$K^{\frac{\alpha}{1-\beta}} \cdot \left(\frac{P_V}{\beta \cdot P_Q} \right)^{\frac{\beta}{\beta-1}} = n \cdot \left(\frac{P_Q}{\sigma \cdot P_Y} \cdot \frac{(n-1) \cdot \beta + 1}{n \cdot \beta} \right)^{\frac{1}{\sigma-1}}. \quad (\text{A.16})$$

We find:

$$P = B \cdot n^{\frac{(1-\sigma)(\beta-1)}{\beta \cdot \sigma-1}} \cdot K^{\frac{\alpha \cdot (1-\sigma)}{\beta \cdot \sigma-1}} \cdot \left(\frac{n \cdot \beta}{n \cdot \beta + 1 - \beta} \right)^{\frac{\beta-1}{\beta \cdot \sigma-1}}. \quad (\text{A.17})$$

If we compare with equation 1.7, we notice that the equilibrium price of the commodity is lower under this oligopsonistic structure than in the competitive case. However, it converges back to the competitive price when the number of factories increases. Following the reaction function 1.12 of the agricultural capital to the expected price, we have the reaction function of the agricultural capital to its previous level and the number of factories in an oligopsonistic

market:

$$K_{t+1} = A_t \cdot B_t^{\frac{1}{1-\alpha-\beta}} \cdot n_t^{\frac{(1-\sigma)(\beta-1)}{(\beta \cdot \sigma - 1) \cdot (1-\alpha-\beta)}} \cdot K_t^{\frac{\alpha \cdot (1-\sigma)}{(\beta \cdot \sigma - 1) \cdot (1-\alpha-\beta)}} \cdot \left(\frac{n \cdot \beta}{(n-1) \cdot \beta + 1} \right)^{\frac{\beta-1}{(\beta \cdot \sigma - 1) \cdot (1-\alpha-\beta)}} \quad (\text{A.18})$$

Similarly, to the case of the competitive market, we show that if the number of processing is fixed at n_E , the agricultural capital will converge toward a point K_E given by the following function f_o if $2 \cdot \alpha + \beta - \sigma \cdot \alpha \beta \cdot \sigma - \alpha \cdot \beta \cdot \sigma - \beta^2 \cdot \sigma < 1$. We have:

$$f_o : n_E \mapsto K_E = \left[A_t^{1-\alpha-\beta} \cdot B_t \right]^{\frac{\beta \cdot \sigma - 1}{(\beta-1) \cdot (1-\alpha \cdot \sigma - \beta \cdot \sigma)}} \cdot n_E^{\frac{1-\sigma}{1-\alpha \cdot \sigma - \beta \cdot \sigma}} \cdot \left(\frac{n_E \cdot \beta}{(n_E-1) \cdot \beta + 1} \right)^{\frac{1}{1-\alpha \cdot \sigma - \beta \cdot \sigma}} \quad (\text{A.19})$$

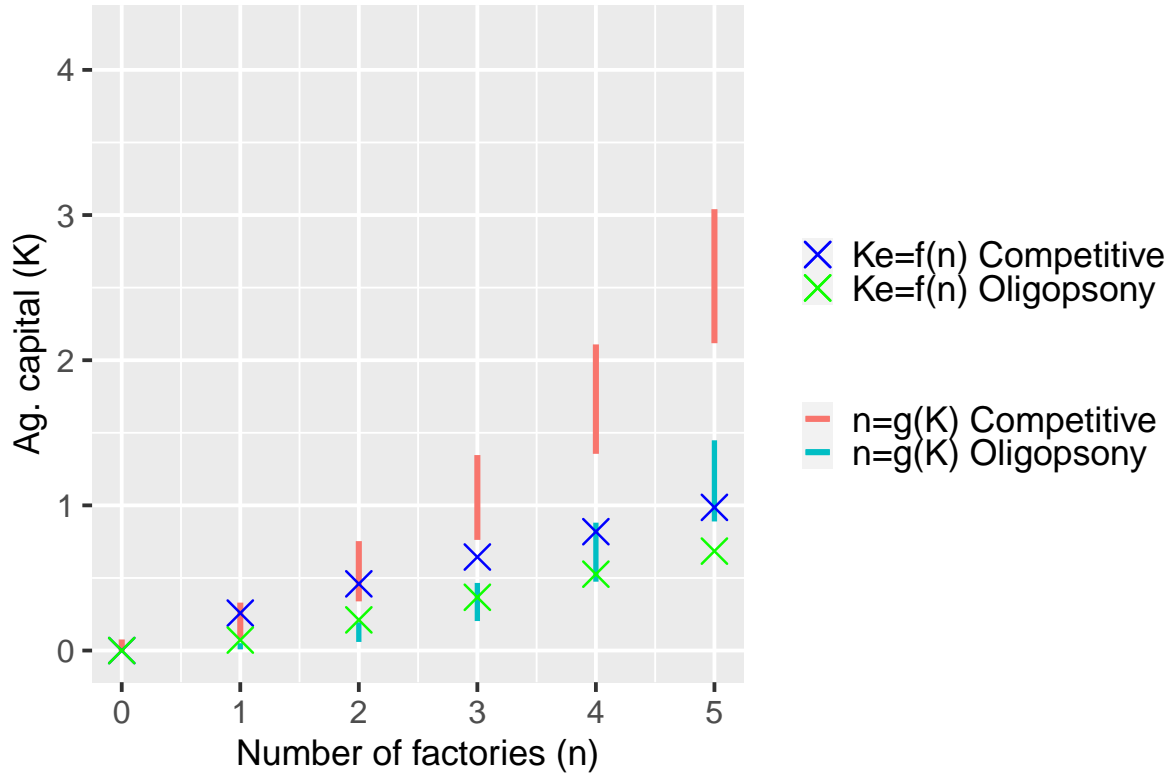
We notice that for any $n_E > 0$, $f_o < f$. The equilibrium level of the agricultural capital for a given number of factories is lower under an oligopsonistic market structure than a competitive market. This is logical as the equilibrium price of the commodity is lower when the processors have more market power.

The profit per factory is now:

$$\pi_y = (\sigma \cdot P_Y)^{\frac{1}{1-\beta \cdot \sigma}} \cdot \left(\frac{(n-1) \cdot \beta + 1}{n \cdot \beta} \right)^{\frac{1}{\beta \cdot \sigma - 1}} \left[\frac{(n-1) \cdot \beta + 1}{\sigma \cdot n \cdot \beta} - 1 \right] \cdot \left(\frac{P_V}{\beta} \right)^{\frac{\beta \cdot \sigma}{\beta \cdot \sigma - 1}} \cdot n^{\frac{\sigma \cdot (1-\beta)}{\beta \cdot \sigma - 1}} \cdot K^{\frac{\alpha \cdot \sigma}{1-\beta \cdot \sigma}}$$

If we compare with equation 1.9, we notice that the profit of processing factories is larger under the oligopsonistic market structure than in a competitive market for a given level of agricultural capital. Due to the zero-profit condition, more processing factories will enter in an oligopsonistic market as they are able to get a lower commodity price. We can solve $\pi_y = 0$ numerically to find the reaction function g_o of the number of factories. Then we are able to draw the new reaction diagram of the dynamic system. Figure A.1 presents the reaction functions g and g_o of the number of processing factories and the equilibrium functions of the agricultural capital f and f_o under a competitive and an oligopsonistic market structure. We find similar behavior of the model between the two configurations. However, the existing equilibria in the oligopsonistic structure have less agricultural capital and more processing factories.

Figure A.1: Example of equilibrium diagram with the equilibrium function of agricultural capital (f) and the reaction function of the number of factories (g) under competitive and oligopsonistic market structure



Parameters: $\alpha = 0.3$, $\beta = 0.4$, $\sigma = 0.4$, $P_Y = 3$, $F = 1.1$, $P_V = P_K = 1$.

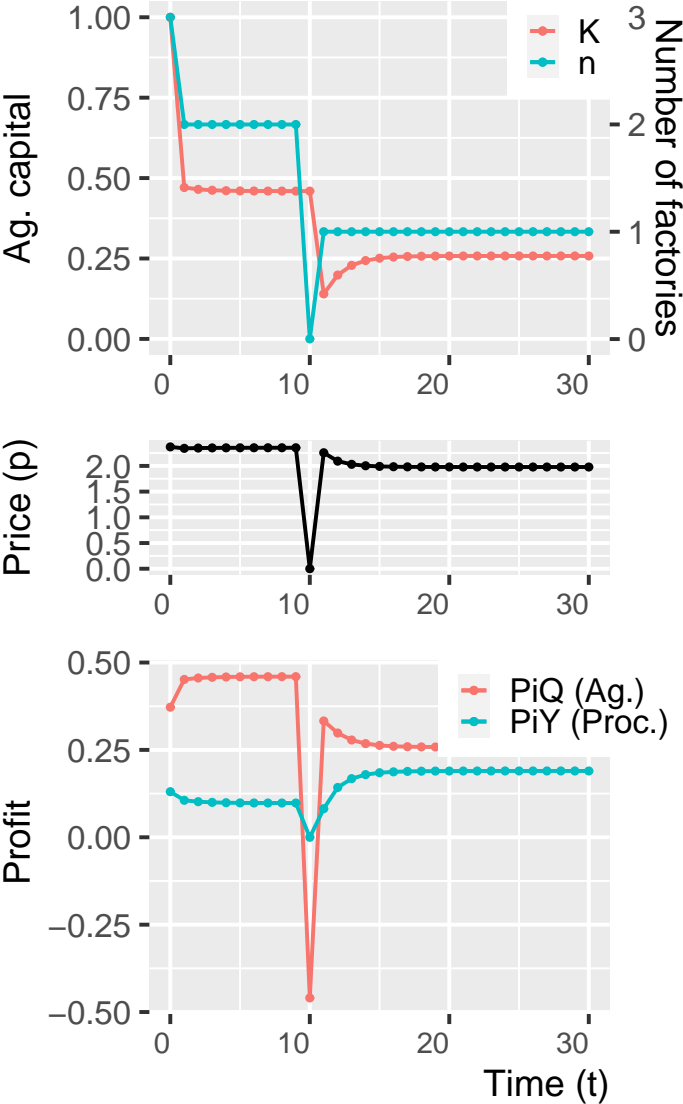
A.4 Dynamic with adaptive expectations

We now assume that the agricultural representative agent uses adaptive expectations to decide of its capital for the next period. Its expectation of the price of agricultural commodity is: $\hat{P}_{Q,t} = \mu \cdot P_{Q,t-1} + (1 - \mu) \cdot P_{Q,t-1}^{\hat{}}$ with $\mu \in [0, 1]$. When the system is at a steady-state equilibrium, P_t is stable and $\hat{P}_{Q,t}$ converges toward $P_{Q,t} = P_{Q,t-1}$. Therefore, the reaction function of the agricultural capital becomes similar to the one observed under a myopic expectation assumption. This implies that adaptive expectations do not change the potential equilibria of an agricultural value chain. However, they will change the speed of adjustment of agricultural capital, with similar consequences to the ones highlighted when discussing the flexibility of capital.

Figure A.2 presents an example of dynamic with a similar scenario to the one presented in figure 1.3a, but we use adaptive expectation of the agricultural representative agent with

$\mu = 0.3$. We observe that the price collapse provoked by the exit of factories during the shock do not lead to a full disinvestment of the agricultural capital as the agent still expects a higher price. We also notice a smoother return to the initial equilibrium after, with less over-investment as the adaptive expectation dampens the reaction of the capital.

Figure A.2: Dynamic of the agricultural capital, the number of factories, commodity price and profits of an agricultural value chain facing a shock, under adaptive expectation of the farmers ($\mu = 0.3$)



Parameters: $\alpha = 0.3, \beta = 0.4,$
 $\sigma = 0.4, P_Y = 3$ (normal) and $P_Y = 2$ (shock), $F = 1.1, P_V = P_K = 1$. One period shock at $t = 10$.

Appendix B

Supplementary material to Chapter 2

B.1 Resolution of the short-run optimization program of the agricultural sector

$$\max_{QM_{r,t}, VI_{r,t}} QM_{r,t} \cdot PM_{r,t}^F - VI_{r,t} \cdot CV_t, \quad (\text{B.1})$$

Under constraint

$$QM_{r,t} = \alpha_{M,r} \cdot \left(\beta_{F,r} \cdot (KF_{r,t})^{\theta^M} + \beta_{V,r} \cdot (VI_{r,t})^{\theta^M} + \beta_{A,r} \cdot (AL_r)^{\theta^M} \right)^{\frac{1}{\theta^M}}, \quad (\text{B.2})$$

The Lagrangian of this program is:

$$\mathcal{L}_{r,t} = QM_{r,t} \cdot PM_{r,t}^F - VI_{r,t} \cdot CV_t - \lambda \cdot \left[QM - \alpha_{M,r} \cdot \left(\beta_{F,r} \cdot (KF_{r,t})^{\theta^M} + \beta_{V,r} \cdot (VI_{r,t})^{\theta^M} + \beta_{A,r} \cdot (AL_r)^{\theta^M} \right)^{\frac{1}{\theta^M}} \right]. \quad (\text{B.3})$$

So we have:

$$\frac{\partial \mathcal{L}_{r,t}}{\partial QM_{r,t}} = PM_{r,t}^F - \lambda, \quad (\text{B.4})$$

and

$$\frac{\partial \mathcal{L}}{\partial VI_{r,t}} = -CV_t + \lambda \cdot \alpha_{M,r} \cdot \beta_{V,r} \cdot (VI_{r,t})^{\theta^M - 1} \left(\beta_{F,r} \cdot (KF_{r,t})^{\theta^M} + \beta_{V,r} \cdot (VI_{r,t})^{\theta^M} + \beta_{A,r} \cdot (AL_r)^{\theta^M} \right)^{\frac{1 - \theta^M}{\theta^M}}, \quad (\text{B.5})$$

By substituting λ we get:

$$-CV_t + PM_{r,t}^F \cdot (\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r} \cdot (VI_{r,t})^{\theta^M-1} \cdot QM^{1-\theta^M} = 0. \quad (\text{B.6})$$

So the consumption of variable input is:

$$VI_{r,t} = \left(\frac{CV_t}{PM_{r,t}^F \cdot (\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r} \cdot QM^{1-\theta^M}} \right)^{\frac{1}{\theta^M-1}} = QM^{\frac{1-\theta^M}{\theta^M-1}} \cdot \left(\frac{CV_t}{PM_{r,t}^F \cdot (\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r}} \right)^{\frac{1}{\theta^M-1}}. \quad (\text{B.7})$$

By substituting in the production function, we get:

$$QM = \alpha_{M,r} \cdot \left(\beta_{F,r} \cdot (KF_{r,t})^{\theta^M} + \beta_{V,r} \cdot \left(QM \cdot \left(\frac{CV_t}{PM_{r,t}^F \cdot (\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r}} \right)^{\frac{1}{\theta^M-1}} \right)^{\theta^M} + \beta_{A,r} \cdot (AL_r)^{\theta^M} \right)^{\frac{1}{\theta^M}}, \quad (\text{B.8})$$

$$\Rightarrow \frac{QM^{\theta^M}}{(\alpha_{M,r})^{\theta^M}} = \beta_{F,r} \cdot (KF_{r,t})^{\theta^M} + \beta_{V,r} \cdot \left(QM \cdot \left(\frac{CV_t}{PM_{r,t}^F \cdot (\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r}} \right)^{\frac{1}{\theta^M-1}} \right)^{\theta^M} + \beta_{A,r} \cdot (AL_r)^{\theta^M}, \quad (\text{B.9})$$

$$\Rightarrow QM^{\theta^M} \cdot \left(\frac{1}{(\alpha_{M,r})^{\theta^M}} - \beta_{V,r} \cdot \left(\frac{CV_t}{PM_{r,t}^F \cdot (\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r}} \right)^{\frac{\theta^M}{\theta^M-1}} \right) = \beta_{F,r} \cdot (KF_{r,t})^{\theta^M} + \beta_{A,r} \cdot (AL_r)^{\theta^M}, \quad (\text{B.10})$$

$$\Rightarrow QM = \left(\frac{\beta_{F,r} \cdot (KF_{r,t})^{\theta^M} + \beta_{A,r} \cdot (AL_r)^{\theta^M}}{\frac{1}{(\alpha_{M,r})^{\theta^M}} - \beta_{V,r} \cdot \left(\frac{CV_t}{PM_{r,t}^F \cdot (\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r}} \right)^{\frac{\theta^M}{\theta^M-1}}} \right)^{\frac{1}{\theta^M}}. \quad (\text{B.11})$$

So the agricultural production is given by:

$$QM = \alpha_{M,r} \cdot \left(\frac{\beta_{F,r} \cdot (KF_{r,t})^{\theta^M} + \beta_{A,r} \cdot (AL_r)^{\theta^M}}{1 - (\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r} \cdot \left(\frac{CV_t}{PM_{r,t}^F \cdot (\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r}} \right)^{\frac{\theta^M}{\theta^M - 1}}} \right)^{\frac{1}{\theta^M}}. \quad (\text{B.12})$$

We have at all time $QC_{r,t} > 0$, so:

$$QM_{r,t} = \alpha_{M,r} \cdot \left(\frac{\beta_{F,r} \cdot (KF_{r,t})^{\theta^M} + \beta_{A,r} \cdot (AL_r)^{\theta^M}}{\max \left(0, 1 - (\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r} \cdot \left(\frac{CV_t}{PM_{r,t}^F \cdot (\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r}} \right)^{\frac{\theta^M}{\theta^M - 1}} \right)} \right)^{\frac{1}{\theta^M}}, \quad (\text{B.13})$$

B.2 Resolution of the short-run optimization program of a processing factory

$$\max_{QC_{r,t}, DM_{r,t}, L_{r,t}} Pi_{r,t} = QC_{r,t} \cdot PC_t^D - \frac{DM_{r,t}}{n_{r,t}} \cdot PM_{r,t}^F - L_{r,t} \cdot PL_t, \quad (\text{B.14})$$

Under the constraint:

$$QC_{r,t} = \alpha^C \left(\beta_{K,r} \cdot K^{\theta^C} + \beta_{M,r} \cdot \left(\frac{DM_{r,t}}{n_{r,t}} \right)^{\theta^C} + \beta_{L,r} \cdot L_{r,t}^{\theta^C} \right)^{\frac{1}{\theta^C}}. \quad (\text{B.15})$$

The Lagrangian of this system is:

$$\begin{aligned} \mathcal{L}_{r,t} = & QC_{r,t} \cdot PC_t^D - \frac{DM_{r,t}}{n_{r,t}} \cdot PM_{r,t}^F - L_{r,t} \cdot PL_t \\ & - \lambda \cdot \left[QC_{r,t} - \alpha^C \left(\beta_{K,r} \cdot K^{\theta^C} + \beta_{M,r} \cdot \left(\frac{DM_{r,t}}{n_{r,t}} \right)^{\theta^C} + \beta_{L,r} \cdot L_{r,t}^{\theta^C} \right)^{\frac{1}{\theta^C}} \right]. \end{aligned} \quad (\text{B.16})$$

We have:

$$\frac{\partial \mathcal{L}_{r,t}}{\partial QC_{r,t}} = PC_t^D - \lambda = 0, \quad (\text{B.17})$$

So $\lambda = PC_t^D$. We have:

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial DM_{r,t}} &= -PM_{r,t}^P + \lambda \cdot \alpha_{C,r} \cdot \beta_{M,r} \cdot \left(\frac{DM_{r,t}}{n_{r,t}} \right)^{\theta^C - 1} \left(\beta_{K,r} \cdot (K)^{\theta^C} + \beta_{L,r} \cdot (L_{r,t})^{\theta^C} + \beta_{M,r} \cdot \left(\frac{DM_{r,t}}{n_{r,t}} \right)^{\theta^C} \right)^{\frac{1-\theta^C}{\theta^C}} \\ &= 0 \end{aligned} \tag{B.18}$$

So

$$PM_{r,t}^P = PC_t^D \cdot \beta_{M,r} \cdot \left(\frac{DM_{r,t}}{n_{r,t}} \right)^{\theta^C - 1} \cdot (\alpha_{C,r})^{\theta^C} \cdot (QC_{r,t})^{1-\theta^C} \tag{B.19}$$

So:

$$\frac{DM_{r,t}}{n_{r,t}} = QC_{r,t} \cdot \left(\frac{PM_{r,t}^P}{PC_t^D \cdot \beta_{M,r} \cdot (\alpha_{C,r})^{\theta^C}} \right)^{\frac{1}{\theta^C - 1}} \tag{B.20}$$

Similarly, we get:

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial L_{r,t}} &= -PL_t + \lambda \cdot \alpha_{C,r} \cdot \beta_{L,r} \cdot (L_{r,t})^{\theta^C - 1} \cdot \left(\beta_{K,r} \cdot (K)^{\theta^C} + \beta_{L,r} \cdot (L_{r,t})^{\theta^C} + \beta_{M,r} \cdot \left(\frac{DM_{r,t}}{n_{r,t}} \right)^{\theta^C} \right)^{\frac{1-\theta^C}{\theta^C}}, \\ &= 0 \end{aligned} \tag{B.21}$$

So:

$$L_{r,t} = QC_{r,t} \cdot \left(\frac{PL_t}{PC_t^D \cdot \beta_{L,r} \cdot (\alpha_{C,r})^{\theta^C}} \right)^{\frac{1}{\theta^C - 1}} \tag{B.22}$$

Substituting in the constraint we get:

$$\begin{aligned} \left(\frac{QC_{r,t}}{\alpha^C} \right)^{\theta^C} &= \beta_{K,r} \cdot K^{\theta^C} + \beta_{M,r} \cdot \left(QC_{r,t} \cdot \left(\frac{PM_{r,t}^P}{PC_t^D \cdot \beta_{M,r} \cdot (\alpha_{C,r})^{\theta^C}} \right)^{\frac{1}{\theta^C - 1}} \right)^{\theta^C} \\ &\quad + \beta_{L,r} \cdot \left(QC_{r,t} \cdot \left(\frac{PL_t}{PC_t^D \cdot \beta_{L,r} \cdot (\alpha_{C,r})^{\theta^C}} \right)^{\frac{1}{\theta^C - 1}} \right)^{\theta^C} \end{aligned} \tag{B.23}$$

So:

$$QC_{r,t} = \left(\frac{\beta_{K,r} \cdot K^{\theta^C}}{\frac{1}{(\alpha^C)^{\theta^C}} - \left[\beta_M \cdot \left(\frac{PM_{r,t}^P}{(\alpha^C)^{\theta^C} \cdot \beta_M \cdot PC_t^D} \right)^{\frac{\theta^C}{\theta^C-1}} + \beta_L \cdot \left(\frac{PL_t}{(\alpha_{M,r})^{\theta^M} \cdot \beta_L \cdot PC_t^D} \right)^{\frac{\theta^C}{\theta^C-1}} \right]} \right)^{\frac{1}{\theta^C}} \quad (\text{B.24})$$

We have at all time $QC_{r,t} > 0$, so:

$$(QC_{r,t})^{\theta^C} = \frac{(\alpha^C)^{\theta^M} \cdot \beta_{K,r} \cdot (K)^{\theta^C}}{\max \left(0, 1 - (\alpha^C)^{\theta^M} \cdot \left[\beta_M \cdot \left(\frac{PM_{r,t}^P}{(\alpha^C)^{\theta^C} \cdot \beta_M \cdot PC_t^D} \right)^{\frac{\theta^C}{\theta^C-1}} + \beta_L \cdot \left(\frac{PL_t}{(\alpha_{M,r})^{\theta^M} \cdot \beta_L \cdot PC_t^D} \right)^{\frac{\theta^C}{\theta^C-1}} \right] \right)}, \quad (\text{B.25})$$

B.3 Resolution of the long-run agricultural program

The representative agent in a region r at time t decides of its investment $I_{r,t}$ for next period, under the expectation that the price of capital remains at PKF_t and the price of milk is at program:

$$V(KF_{r,t}) = \max_{(I_{r,t'}, VI_{r,t'}^{opt})_{t' \geq t}} \sum_{t'=0}^{\infty} \frac{1}{(1+r)^{t'-t}} \cdot \left[\pi(KF_{r,t'}, VI_{r,t'}^{opt}) - I_{r,t'} \cdot PKF_t \right], \quad (\text{B.26})$$

subject to: $KF_{r,t+1} = (1 - \delta) \cdot KF_{r,t} + I_{r,t}$.

With $\pi_{r,t}(KF_{r,t'}, VI_{r,t'}^{opt}) = QM(K_{t'}, VI_{r,t'}^{opt}) \cdot PM_{r,t}^{F,exp} - VI_{r,t'}^{opt} \cdot CV_t^{exp}$.

The Bellman equation is:

$$V(KF_{r,t}) = \max_{I_{r,t}, VI_{r,t}^{opt}} \pi(KF_{r,t}, VI_{r,t}^{opt}) - I_{r,t} \cdot PKF_t + \frac{1}{(1+r)} \cdot V((1 - \delta) \cdot KF_{r,t} + I_{r,t}). \quad (\text{B.27})$$

First order condition:

$$\frac{1}{(1+r)} \cdot \frac{\partial V}{\partial K_{t+1}} = PKF_t, \quad (\text{B.28})$$

And:

$$\frac{\partial \pi}{\partial VI_{r,t}^{opt}} = \frac{\partial QM}{\partial VI_{r,t}^{opt}} \cdot PM_{r,t}^{F,exp} - CV_t^{exp} = 0. \quad (\text{B.29})$$

We have by the envelope theorem:

$$\frac{\partial V(KF_{r,t})}{\partial KF_{r,t}} = \frac{\partial \pi}{\partial KF_{r,t}} + \frac{1 - \delta}{(1 + r)} \cdot \frac{\partial V}{\partial K_{t+1}}. \quad (\text{B.30})$$

So by substituting the FOC:

$$\frac{\partial V}{\partial KF_{r,t}} = \frac{\partial \pi}{\partial KF_{r,t}} + (1 - \delta) \cdot PKF_t. \quad (\text{B.31})$$

Updating from one period:

$$\frac{\partial V}{\partial KF_{r,t+1}} = \frac{\partial \pi}{\partial KF_{r,t+1}} + (1 - \delta) \cdot PKF_t. \quad (\text{B.32})$$

Substituting in the FOC:

$$\frac{1}{(1 + r)} \cdot \left(\frac{\partial \pi}{\partial KF_{r,t+1}} + (1 - \delta) \cdot PKF_t \right) = PKF_t. \quad (\text{B.33})$$

So:

$$\frac{\partial \pi}{\partial KF_{r,t+1}} = (\delta + r) \cdot PKF_t. \quad (\text{B.34})$$

$$\frac{\partial QM}{\partial KF_{r,t+1}} \cdot PM_{r,t}^{F,exp} = (\delta + r) \cdot PKF_t. \quad (\text{B.35})$$

So we have with the two FOC:

$$\left\{ \begin{array}{l} (\alpha_{M,r})^{\theta^M} \cdot \beta_{F,r} \cdot (KF_{r,t+1})^{\theta^M - 1} \left(QM_{r,t+1}^{opt} \right)^{1 - \theta^M} \cdot PM_{r,t}^{F,exp} = (\delta + r) \cdot PKF_t, \end{array} \right. \quad (\text{B.36})$$

$$\left\{ \begin{array}{l} (\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r} \cdot (VI_{r,t+1}^{opt})^{\theta^M - 1} \left(QM_{r,t+1}^{opt} \right)^{1 - \theta^M} \cdot PM_{r,t}^{F,exp} = CV_t^{exp}, \end{array} \right. \quad (\text{B.37})$$

$$\left\{ \begin{array}{l} KF_{r,t+1} = QM_{r,t+1}^{opt} \cdot \left((\delta + r) \cdot \frac{PKF_t}{(\alpha_{M,r})^{\theta^M} \cdot \beta_{F,r} \cdot PM_{r,t}^{F,exp}} \right)^{1/\theta^{M-1}}, \end{array} \right. \quad (B.38)$$

$$\left\{ \begin{array}{l} VI_{r,t+1}^{opt} = QM_{r,t+1}^{opt} \cdot \left(\frac{CV_t^{exp}}{(\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r} \cdot PM_{r,t}^{F,exp}} \right)^{1/\theta^{M-1}}. \end{array} \right. \quad (B.39)$$

$$\begin{aligned} \left(\frac{QM_{r,t+1}^{opt}}{\alpha_{M,r}} \right)^{\theta^M} &= \beta_{F,r} \cdot \left(QM_{r,t+1}^{opt} \cdot \left((\delta + r) \cdot \frac{PKF_t}{(\alpha_{M,r})^{\theta^M} \cdot \beta_{F,r} \cdot PM_{r,t}^{F,exp}} \right)^{1/\theta^{M-1}} \right)^{\theta^M} \\ &+ \beta_{V,r} \cdot \left(QM_{r,t+1}^{opt} \cdot \left(\frac{CV_t^{exp}}{(\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r} \cdot PM_{r,t}^{F,exp}} \right)^{1/\theta^{M-1}} \right)^{\theta^M} + \beta_{A,r} \cdot (AL_r)^{\theta^M}, \end{aligned} \quad (B.40)$$

$$(QM_{r,t+1}^{opt})^{\theta^M} = \frac{\beta_{A,r} \cdot (AL_r)^{\theta^M}}{\left(\frac{1}{\alpha_{M,r}} \right)^{\theta^M} - \left[\beta_{F,r} \cdot \left((\delta + r) \cdot \frac{PKF_t}{(\alpha_{M,r})^{\theta^M} \cdot \beta_{F,r} \cdot PM_{r,t}^{F,exp}} \right)^{\frac{\theta^M}{\theta^{M-1}}} + \beta_{V,r} \cdot \left(\frac{CV_t^{exp}}{(\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r} \cdot PM_{r,t}^{F,exp}} \right)^{\frac{\theta^M}{\theta^{M-1}}} \right]}, \quad (B.41)$$

B.4 Surpluses

The national consumer surplus at time t is defined in reference to the base year. It is computed as :

$$SurC_t = \int_{P_t}^{P_{2014}} P_t \cdot a_U \cdot (P_t)^{\sigma_U} dP_t = -\frac{a_U}{\sigma_U + 1} \cdot \left(P_t^{\sigma_U + 1} - P_{2014}^{\sigma_U + 1} \right). \quad (B.42)$$

The regional producer surplus at time t in region r is:

$$PiF_{r,t} = QM_{r,t} \cdot PM_{r,t}^F - VI_{r,t}^{opt} \cdot CV_t - KF_{r,t} \cdot PKF_{r,t} \cdot (r + \delta). \quad (B.43)$$

The regional processors surplus at time t in region r is:

$$SurPT_{r,t} = n_{r,t} \cdot \left[QC_{r,t} \cdot PC_{r,t}^D - \frac{DM_{r,t}}{n_{r,t}} \cdot PM_{r,t} - L_{r,t} \cdot PL_t - K \cdot PK_t \cdot \frac{1+r}{T_{proc}} \right]. \quad (B.44)$$

The tariff revenues at time t are:

$$Duty_{r,t} = (PC_t^M - PC_t^X) \cdot MC_t. \quad (\text{B.45})$$

B.5 Description of the computable model

The computable model is composed of six GAMS files: simulation.gms, modelsetup.gms, calibration.gms, newEntrants.gms, SRresolution.gms and re_init.gms. The file "simulation.gms" is the script file to launch simulations. It calls the set-up file "modelsetup.gms", then the calibration file "calibration.gms". Then the scenarios are implemented. The scenario loop and time loop then begin for the actual resolution of the model. Each time the evolution of the agricultural quasi-fixed input is computed. Then a loop on every regions of the model calls the file "newEntrants.gms" to find the number of new entering processing factories in each regions. Then the short-run model is solved by calling the file "SRresolution.gms". Finally, surpluses are computed and a number of variables are scaled back to their proper value. Throughout the model, the file "re_init.gms" is called a number of times to re-initiate variables before the resolution of the short-run or the long-run model.

B.5.1 Equations of the short-run model

Some equations including some max functions are replaced by a set of sub-equations to get to the form $\max(0, X) = 0.5 \cdot \sqrt{X + X^2}$. We have $\tau_{r,s,t}^R = \tau_t^I \cdot D_{r,s}$ (see equation 2.13). Because of the law-of-one-price and the equalization of milk prices across markets at the difference of inter-regional transport costs when trade occur, milk exports are a function of prices difference across regions with a large multiplier to limit all arbitrage possibility (see equations $Eq_Trsimp(r, s, t)$ and $Eq_Tr(r, s, t)$). Equations $Eq_QC(r, t)$, $Eq_CntrlQC$, $Eq_CntrlQCpos$, Eq_Pi , Eq_DM and Eq_L are only part of the short-run model at time t in regions where some processing factories are present at the time ($n_{r,t} > 0$).

The short-run model is solved each time t on the set of all the model's regions $r = s$.

B.5.2 Long-run processing entry model

The long-run processing entry model is solved independently for each region r , each time t , while the regional set s include all the regions of the model excluding r . The long-run model include all equations from the short-run model except equations: Eq_U , Eq_P , Eq_{DC} , Eq_{MC} , Eq_{XC} , $Eq_{ClosureCh}$. Equations Eq_{NPV} (see equation 2.36) and Eq_{ndv} (see equation 2.32) are added to compute the expected net present value per processing factory in the region and the number of factories related to the number of entrant. They are respectively defined as:

$$NPV_{r,t}(newC_{r,t}) = -K \cdot PK_t + \sum_{t'=t}^{t+T_{proc}-1} Pi_{r,t} \cdot (1+r)^{t'-t},$$

and:

$$n_{r,t} = n_{t-1} + newC_{r,t} - newC_{r,t-T_F}.$$

Some of the endogenous variables are replaced during the resolution by their expected value: $\tau_t^I = \tau_t^{I,exp}$ (see equation 2.34), $PC_t^D = PC_t^{D,exp}$ (see equation 2.33) and $PM_{s,t}^P = PM_{s,t-1}^P$.

First, the number of new entrants $newC_{r,t}$ in the region r is fixed at one. If this results in a positive expected profit by entrant $NPV_{r,t}$, we then optimize the model to find $newC_{r,t}$ such that $NPV_{r,t} = 0$. We then take the truncation of this number of entrant to get an integer number. If the numerical resolution do not converge with this method, which is possible due to the complexity of the model, we find recursively the number of new entrant, by resolving the model with one more new entering factory in the region until we get $NPV_{r,t} < 0$. The number of new entrant is then $newD_{r,t}$ in the last resolution that resulted in $NPV_{r,t} \geq 0$.

Table B.1: Equations in the short run computable model

Name	Equation	Corresponding equation in the paper
$Eq_QM(r,t)$	$QM_{r,t} = \left(\beta_{F,r} \cdot (KF_{r,t})^{\theta^M} + \beta_{A,r} \cdot (AL_r)^{\theta^M} \right) \cdot CntrlQMpos_{r,t}^{\frac{-1}{\theta^M}}$	2.2
$Eq_CntrlQM(r,t)$	$CntrlQM_{r,t} = (\alpha_{M,r})^{-\theta^M} - \beta_{V,r} \cdot \left(\frac{CV_t}{PM_{r,t}^F \cdot (\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r}} \right)^{\frac{\theta^M}{\theta^M - 1}}$	2.2
$Eq_CntrlQMpos$	$CntrlQMpos_{r,t} = 0.5 \cdot \sqrt{CntrlQM_{r,t} + (CntrlQM_{r,t})^2}$	2.2
$Eq_VI(r,t)$	$VI_{r,t}^{opt} = QM_{r,t} \cdot \left(\frac{CV_t}{PM_{r,t}^F \cdot (\alpha_{M,r})^{\theta^M} \cdot \beta_{V,r}} \right)^{\frac{1}{\theta^M - 1}}$	2.4
Eq_PiF	$PiF_{r,t} = QM_{r,t} \cdot PM_{r,t}^F - VI_{r,t}^{opt} \cdot CV_t - KF_{r,t} \cdot PKF_{r,t} \cdot (r + \delta)$	B.43
$Eq_QC(r,t)$	$QC_{r,t} = \alpha^C \cdot \beta_{K,r} \cdot K^{\frac{1}{\theta^C}} \cdot (CntrlQCpos_{r,t})^{-\frac{1}{\theta^C}}$	2.8
$Eq_CntrlQC(r,t)$	$CntrlQC_{r,t} = 1 - (\alpha^C)^{\theta^M} \cdot \left[\beta_M \cdot \left(\frac{PM_{r,t}^P}{(\alpha^C)^{\theta^C} \cdot \beta_M \cdot PC_t^D} \right)^{\frac{\theta^C}{\theta^C - 1}} + \beta_L \cdot \left(\frac{PL_t}{(\alpha_{M,r})^{\theta^M} \cdot \beta_L \cdot PC_t^D} \right)^{\frac{\theta^C}{\theta^C - 1}} \right]$	2.8
$Eq_CntrlQCpos(r,t)$	$CntrlQCpos_{r,t} = 0.5 \cdot \sqrt{CntrlQC_{r,t} + (CntrlQC_{r,t})^2}$	2.8
$Eq_Pi(r,t)$	$Pi_{r,t} = QC_{r,t} \cdot PC_{r,t}^D - \frac{DM_{r,t}}{n_{r,t}} \cdot PM_{r,t} - L_{r,t} \cdot PL_t$	2.7
$Eq_DM(r,t)$	$\frac{DM_{r,t}}{n_{r,t}} = QC_{r,t} \cdot \left(\frac{PM_{r,t}^P}{PC_t^D \cdot (\alpha^C)^{\theta^C} \cdot \beta_L} \right)^{\frac{1}{\theta^C - 1}}$	2.9
$Eq_L(r,t)$	$L = QC_{r,t} \cdot \left(\frac{PL_t}{PC_t^D \cdot (\alpha^C)^{\theta^C} \cdot \beta_L} \right)^{\frac{1}{\theta^C - 1}}$	2.10
$Eq_PMP(r,t)$	$PM_{r,t}^P = PM_{r,t}^F + \tau_t^I \cdot \sqrt{\frac{S_r}{\max(1, n_{r,t})}} \cdot 0.3836$	2.11 & 2.12
$Eq_Trsimp(r,s,t)$	$Trsimp_{r,s,t} = INF \cdot (PM_{s,t}^P - PM_{s,t}^P - \tau_{r,s,t}^R)$	2.14
$Eq_Tr(r,s,t)$	$Tr_{s,t} = 0.5 \cdot \sqrt{Trsimp_{r,s,t} + (Trsimp_{r,s,t})^2}$	2.14
$Eq_U(t)$	$U_t = a_U \cdot (P_t)^{\sigma^U}$	2.16
Eq_P	$U_t \cdot P_t = DC_t \cdot PC_t^D + MC_t \cdot PC_t^M$	2.17
$Eq_DC(t)$	$DC_t = a_D^{\sigma^A} \cdot U_t \cdot \left(\frac{P_t}{PC_t^D} \right)^{\sigma^A}$	2.18
$Eq_MC(t)$	$MC_t = a_M^{\sigma^A} \cdot U_t \cdot \left(\frac{P_t}{PC_t^M} \right)^{\sigma^A}$	2.19
$Eq_XC(t)$	$XC_t = a_X \cdot \left(\frac{PC_t^X}{(PC_t^D)} \right)^{\sigma^X}$	2.20
$Eq_ClosM(r,t)$	$QM_{r,t} + \sum_s Tr_{s,t} = DM_{r,t} + \sum_s Tr_{r,s,t}$	2.21
$Eq_ClosC(t)$	$\sum_r QC_{r,t} = DC_t + XC_t$	2.22

Appendix C

Supplementary material to Chapter 3

Table C.1: Initial trade flows of dairy products in the model (\$Billions, source: GTAP10)

		Destination									Total X
		AUS	BRA	CAN	CHN	DEU	FRA	GBR	ITA	JPN	
Origin	AUS	0	0	0	0.33	0	0	0	0	0.39	2.17
	BRA	0	0	0	0	0	0	0	0	0	0.36
	CAN	0	0.01	0	0.01	0	0	0.01	0	0.01	0.38
	CHN	0.01	0	0	0	0.01	0.01	0.01	0	0.01	0.24
	DEU	0.02	0	0.01	0.27	0	0.83	0.56	2.02	0.05	11.2
	FRA	0.04	0.02	0.05	0.38	1.28	0	0.9	0.81	0.1	8.92
	GBR	0.01	0	0.01	0.03	0.13	0.2	0	0.06	0	2.09
	ITA	0.05	0.01	0.05	0.02	0.65	0.7	0.29	0	0.09	3.55
	JPN	0	0	0	0.01	0	0	0	0	0	0.05
	MEX	0	0	0	0	0	0	0	0	0	0.17
	NLD	0.02	0.01	0.02	0.1	1.75	0.7	0.26	0.25	0.06	7.71
	NZL	0.35	0.01	0.04	4.24	0.02	0.06	0.05	0	0.39	12.4
	USA	0.15	0.02	0.26	0.58	0.02	0.02	0.02	0	0.32	5.79
	ROW	0.04	0.02	0.07	0.1	0.41	0.13	0.06	0.11	0.05	8.17
	ASIA	0.02	0.01	0.01	0.09	0.02	0.01	0.02	0.01	0.18	1.81
	MER	0	0.34	0	0.18	0	0	0	0	0.02	2.18
	LAC	0	0.02	0.01	0.05	0.01	0.01	0.01	0	0.01	1.07
E28	0.11	0.01	0.04	0.36	3.57	1.7	2.16	1.76	0.1	21.3	
Total M	0.81	0.48	0.56	6.76	7.88	4.36	4.35	5.04	1.75		
		MEX	NLD	NZL	USA	ROW	ASIA	MER	LAC	E28	Total X
Origin	AUS	0	0.01	0.05	0.03	0.42	0.9	0	0.02	0	2.17
	BRA	0	0	0	0.01	0.11	0.01	0.01	0.21	0	0.36
	CAN	0.02	0	0	0.14	0.06	0.08	0	0.03	0	0.38
	CHN	0	0	0	0.02	0.05	0.1	0	0	0.02	0.24
	DEU	0.01	1.23	0.01	0.06	0.97	0.31	0	0.04	4.83	11.2
	FRA	0.01	0.3	0.01	0.23	1.35	0.53	0	0.04	2.88	8.92
	GBR	0	0.16	0	0.07	0.3	0.06	0	0.04	1.01	2.09
	ITA	0	0.1	0	0.32	0.32	0.05	0	0.02	0.88	3.55
	JPN	0	0	0	0	0	0.03	0	0	0	0.05
	MEX	0	0	0	0.1	0.01	0.02	0	0.04	0	0.17
	NLD	0.02	0	0.01	0.11	1.31	1.08	0	0.09	1.93	7.71
	NZL	0.15	0.08	0	0.35	3.15	2.94	0	0.51	0.09	12.4
	USA	1.49	0.01	0.06	0	0.73	1.61	0.01	0.47	0.02	5.79
	ROW	0.01	0.03	0	0.26	6.41	0.23	0.01	0.03	0.21	8.17
	ASIA	0	0.01	0.01	0.06	0.44	0.89	0	0.02	0.03	1.81
	MER	0.04	0	0	0.03	0.66	0.1	0.04	0.76	0	2.18
	LAC	0.06	0	0	0.06	0.08	0.03	0	0.7	0.02	1.07
E28	0.03	0.94	0.02	0.38	3.78	0.73	0	0.23	5.36	21.3	
Total M	1.85	2.88	0.18	2.2	20.2	9.7	0.09	3.24	17.3		

Table C.2: Initial ad-valorem duty on dairy products in the model (% , source: GTAP 10)

		Destination									
		AUS	BRA	CAN	CHN	DEU	FRA	GBR	ITA	JPN	
Origin	AUS	0.6	18.2	23.4	10.7	85.7	46.7	41	52.7	28.3	
	BRA	0	0	14	0	18.9	54.8	0	0	25.2	
	CAN	1.69	14	0	11.1	55.7	50.3	36.3	0	34.3	
	CHN	0	0	7.9	0	45.6	42.8	0	0	27.7	
	DEU	1.67	18.4	3.25	9.73	0	0	0	0	33.8	
	FRA	0.68	20.6	2.96	7.89	0	0	0	0	34.8	
	GBR	0.46	21.4	0.77	9.09	0	0	0	0	37.6	
	ITA	0.94	21.3	0.55	11.7	0	0	0	0	28.9	
	JPN	3.54	17	8	19	22.4	57	0	0	0	
	MEX	0.68	0	4.72	0	40.5	31.4	0	38.2	0	
	NLD	0.69	21.9	1.45	5.49	0	0	0	0	37.5	
	NZL	0	14.3	6.94	3.99	66.8	62.8	44.6	80.9	28	
	USA	0	22	14	6.07	40.7	57.3	34.3	36.6	32.2	
	ROW	0.68	2.6	2.4	7.02	3.16	14.1	9.69	3.76	24.8	
	ASIA	0.02	6.05	28.2	7.53	22.1	18.1	14.3	1.42	24.2	
	MER	0.32	0	0.44	6.94	29.4	0	0	0	32.4	
	LAC	0.22	0.16	29.7	5.82	9.19	2.05	8.28	15.3	25.7	
	E28	0.72	15.3	1.6	6.52	0	0	0	0	32.8	
			MEX	NLD	NZL	USA	ROW	ASIA	MER	LAC	E28
	Origin	AUS	7.91	39.2	0	0.62	7.09	12.8	15.1	4.05	22.4
BRA		0	18.5	0.06	11.2	6.23	3.12	0	8.88	11.7	
CAN		6.16	86.2	0	4.51	9.37	14.3	4.67	8.99	28.6	
CHN		0	0	0	19.4	9.14	4.14	0.58	4.21	17.1	
DEU		13	0	1.81	13.5	8.74	20.5	27.3	14.1	0.34	
FRA		11.4	0	3.72	11.1	7.26	14.7	17.9	12	0.02	
GBR		5.66	0	0.07	11.6	4.91	7.61	10	5.32	0	
ITA		33.3	0	0.92	11.7	12.7	13.3	19.9	11.4	0.27	
JPN		0	18.5	5	19.3	4.03	5.04	0	0	27.4	
MEX		0	0	0	0.07	2.15	7.08	0	9.93	3.93	
NLD		34.3	0	3.36	10.8	7.38	3.92	23.4	9.4	0.09	
NZL		11.3	51	0	9.08	8.03	5.8	15.5	11.3	61.5	
USA		0	47.2	1.99	0	8.66	12.5	17.2	14.7	47.6	
ROW		6.09	17.6	1.57	9.05	1.95	8.52	3.9	8.13	16	
ASIA		4.88	12.6	0.73	9.82	7.97	5.08	3.49	6.81	9.1	
MER		2.69	0	3.97	11.1	9.47	6.63	0	1.71	7.59	
LAC	14.2	8.92	0.77	1.14	6.99	11.9	0.2	5	11.3		
E28	10.7	0	2.53	10.8	10.1	8.78	7.6	12.4	0.36		

Résumé long en français

Les filières agricoles sont par de multiples aspects ancrées dans le temps sur leurs territoires. Ce constat vient d'abord de la fixité de la plupart des facteurs de production en agriculture et dans la transformation. En effet, la terre est restée un facteur de production important malgré le développement de modes de productions intensifs. Le capital agricole et dans la transformation est souvent peu malléable du fait de coûts d'ajustement importants. Enfin, l'agriculture requiert toujours une main d'œuvre spécialisée, dont les compétences particulières sont difficilement valorisables dans d'autres secteurs. Par ailleurs, on observe souvent d'importantes économies d'échelles dans les usines agroalimentaires qui nécessitent une taille relativement importante pour opérer efficacement. Les matières premières agricoles étant souvent couteuses à transporter du fait de leur périssabilité, leur poids, et leur encombrement, on observe alors des économies d'agglomération. Il doit y avoir suffisamment de production agricole à proximité des usines de transformation pour que la filière dans son ensemble soit profitable. La littérature en économie géographique montre que la présence d'économies d'agglomération peut mener à l'existence d'une multiplicité d'équilibres potentiels et à un comportement hystérique des systèmes. Selon les conditions initiales, une filière s'agrègera dans une région ou une autre selon ce processus auto-renforçant. On peut donc décrire une filière agricole comme un écosystème, formé par la réunion d'un nombre de producteurs et de transformateurs sur un même territoire, et stabilisé par la fixité des facteurs de production et la présence d'économies d'agglomération. Toutefois un choc pourra remettre en cause la stabilité d'une filière dans une région, la faisant passer alors dans un cercle vicieux de déprise jusqu'à un effacement potentiellement irréversible. Dans ce contexte, l'instabilité et les changements rapides amenés par le changement climatique, l'émergence de nouveaux risques sanitaires (COVID-19, peste porcine), de nouvelles demandes des consommateurs et citoyens (agriculture biologique, bien-être animal), et l'émergence de politiques protectionnistes et d'un nouveau risque de guerre commerciale, apparaissent comme autant de défis pour les filières agricoles. En outre, les marchés agroalimentaires sont devenus de plus en plus mondialisés ces dernières décennies. Les filières sont désormais interconnectées à travers le monde. Cela rend l'appréhension de ces problèmes de plus en plus compliquée car toute action sur une filière dans une région pourra

avoir des conséquences durables sur les filières des autres régions et des autres pays. Pourtant, nous manquons encore d'outils satisfaisants pour modéliser et comprendre les dynamiques des filières à l'échelle locale et leurs interactions complexes à l'échelle mondiale. Les modèles de commerce international actuels manquent souvent d'un niveau de détail régional, les relations verticales au sein des filières ne sont pas ou peu détaillées, leur aspect dynamique est très simplifié et leur représentation des économies d'agglomération est peu adaptée au contexte agricole. Ainsi, nous proposons dans cette thèse des solutions pour améliorer la représentation des dynamiques des filières agricoles régionales dans les modèles de commerce international.

Dans le premier chapitre nous développons un cadre théorique simple et original pour analyser les dynamiques et la résilience des filières agricoles. Nous présentons un modèle analytique dynamique de filière agricole, permettant de représenter une production agricole avec différents niveaux de fixité des facteurs ainsi que des usines de transformation présentant des économies d'échelle. Nous utilisons ce cadre pour discuter des conséquences à court et long terme des perturbations entraînées par la pandémie de COVID-19 sur les filières agricoles. Nous démontrons que ces différentes perturbations sont susceptibles d'entraîner un écroulement durable de certaines filières. Nous montrons que les filières isolées du reste des marchés du fait des coûts de transports ou des spécificités de leur production sont plus vulnérables. Si un échelon de la chaîne de valeur est en difficulté, c'est toute la filière qui est en crise par manque de débouchés ou de fournisseurs. La flexibilité et la capacité à trouver des marchés alternatifs sont donc apparues essentielles pendant la crise liée au COVID-19. Par ailleurs, nous montrons que si la rigidité du capital dans la production agricole et la transformation entraînent d'important coûts d'ajustement pendant la crise ; elle permet aussi de préserver la structure des filières et leur permet de mieux rebondir ensuite. En effet, si un désinvestissement rapide permet de limiter certains coûts pendant la crise, il risque de déstabiliser durablement les filières. Enfin, nous discutons de l'importance des problèmes de coordination verticale observés dans les filières. En effet, l'hystérèse et les difficultés des filières à se reconstruire après une crise viennent d'abord dans notre modèle des difficultés à coordonner dans le temps les investissements dans la production et la transformation. Aucun agent n'a intérêt à réinvestir sans garantie de débouchés ou d'approvisionnement ce qui rend difficile le redémarrage des filières. Une plus forte inté-

gration, par exemple par de la contractualisation pourrait permettre de pallier à ces problèmes. Toutefois, cela peut aussi présenter le risque de rapprocher encore plus les acteurs des filières et de les enfermer dans des relations de dépendances, moins résilientes en cas de chocs. Une politique de préservation des filières en temps de crise ou pour favoriser leur reconstruction ensuite pourrait donc être judicieuse pour pallier à ces problèmes. Le choix dépendra alors du coût respectif de ces politiques et de la durée estimée de la crise.

Dans le second chapitre, nous développons un modèle multirégional dynamique de filière agricole qui permet la représentation d'économies d'agglomération. Nous représentons des coûts de collecte de la matière première agricole vers les usines de transformations, ainsi qu'un coût fixe d'installation de ces usines donnant lieu à des économies d'échelle. Nous calibrons ce modèle sur le secteur laitier français que nous désagrégeons en 7 bassins de production. Nous simulons une variété de chocs sur les cours mondiaux des produits laitiers et sur les coûts de transports du lait. Nous montrons que les dynamiques régionales des filières laitières en réponse à ces chocs peuvent être chaotiques et parfois hystérétiques. En effet, on observe parfois l'effondrement irréversible des filières dans certaines régions. Les régions où la production laitière est plus dense ont des secteurs laitiers plus résilients du fait de la moindre importance des coûts de collecte. Nous montrons qu'une protection tarifaire du secteur laitier pourrait permettre de protéger les filières les plus fragiles. Toutefois, cette politique représente une importante redistribution de la valeur des consommateurs vers les producteurs. Une politique favorisant l'investissement pour reconstruire les filières sinistrées après un choc pourrait donc apparaître plus pertinente.

Enfin, dans le troisième chapitre, nous modifions le modèle de commerce international en équilibre général calculable MIRAGRODEP en y intégrant la représentation des filières régionales avec économies d'agglomération développée dans le chapitre 2. Nous focalisons là encore notre calibration sur la description du secteur laitier en utilisant une désagrégation régionale pour la France, l'Italie, l'Allemagne et les États-Unis. Nous étudions trois sujets pour montrer la diversité des littératures auxquelles un tel type de modèle peut contribuer. D'abord, nous étudions l'importance de l'hystérèse dans le commerce en simulant des scénarios avec différentes chronologies de libéralisation des marchés des produits laitiers. Nous montrons que

la distribution régionale de la production laitière restera durablement différente selon que le marché domestique ou que les marchés extérieurs s'ouvrent en premier. Cela souligne donc le besoin potentiel d'adopter une vision stratégique de la chronologie dans la mise en place de politiques commerciales. Ensuite, nous comparons les effets de deux politiques de soutien au secteur laitier sur la distribution géographique de la production. Nous montrons qu'un soutien direct du prix du lait par une subvention à la production tend à concentrer la production dans les régions où elle est déjà la plus importante. Au contraire, un soutien plus en aval au prix des produits laitiers transformés semble avoir un effet favorisant plutôt l'essor des régions où la production est plus en retrait initialement. Enfin, nous étudions les conséquences d'une politique environnementale de taxation des sources d'énergies carbonées. Nous montrons qu'une telle politique mène à l'augmentation des coûts de transport du lait ce qui mène à la concentration des filières dans les régions où la production est la plus dense et à leur écroulement dans les régions moins productrices. Cette redistribution est persistante même après la suspension d'une telle politique.

Cette thèse fournit ainsi des d'outils permettant d'appréhender la complexité des interactions entre filières agricoles régionales et de mieux évaluer les conséquences dans le temps et dans l'espace d'une diversité de politiques et de chocs. Nous montrons l'importance des effets d'agglomération et le besoin de prendre en compte leur rôle dans l'équilibre de long terme des filières.