ADBI Series on Asian and Pacific Sustainable Development

FOSTERING RESILIENT GLOBAL SUPPLY CHAINS AMID RISK AND UNCERTAINTY

Edited by
Dina Azhgaliyeva, John Beirne, Dil B. Rahut, and Yixin Yao

ASIAN DEVELOPMENT BANK INSTITUTE

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Series Editors: Tetsushi Sonobe and Rohini Pande

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ISBN 978-4-89974-291-3 (Print)
ISBN 978-4-89974-292-0 (PDF)
DOI: https://doi.org/10.56506/ATQY8548

ADB recognizes "China" as the People's Republic of China; and "Korea" as the Republic of Korea.

Note: In this publication, "$" refers to United States dollars.

The cover-named editors are listed in alphabetical order.

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Acknowledgments

This book is a product of the Asian Development Bank Institute's (ADBI) Annual Conference on "Fostering Resilient Global Supply Chains Amid Risk and Uncertainty," held on 28–30 November 2022. The editors are grateful to the speakers and participants at the conference. The editors would like to express their gratitude to Tetsushi Sonobe, Dean of ADBI; Adam Majoe for coordinating the editing and production process; Ian Youngs for the design of the book cover; Toby Miller for editing; and Aileen Magparangalan for typesetting the book. The editors also thank Cathy Ng, Mami Yoshida, Kumiko Suzuki, Atsuko Hirakata, Junko Mitsuhashi, Ruth Anne Gonocruz, Davaatseren Narmandakh, Hai V. Le, Panharoth Chhay, and Pradeep Panthi of ADBI for their support in organizing the conference and appreciate the help of Lian Liu and Shengchi Ma for assisting the review and revision process and reviewing the overview chapter.

Executive Summary

Fostering Resilient Global Supply Chains Amid Risk and Uncertainty comprises selected papers presented at the Asian Development Bank Institute's Annual Conference held on 28–30 November 2022. This book examines the current trends in global trade, the impact of global supply chain disruptions and uncertainties on the global economy, and the undergoing supply chain transformation. The book aims to explore current supply chain challenges and their implications and identify policy recommendations for fostering resilient supply chains for developing Asia and the Pacific.

Challenges

The book is set against the context of global supply chain disruptions that are dragging down the global economy. Global and regional value chains in Asia and the Pacific have been key drivers of economic progress over the past 2 decades. Firms and countries are now involved throughout the value process, forming what is sometimes referred to as "Factory Asia."[1] However, the COVID-19 pandemic and geopolitical tensions have significantly disrupted global supply chains, reverberating through commodity markets and trade channels, threatening food and energy security, and weighing on sustainable economic recovery. Due to supply chain disruptions, food and energy prices surged in Asia and the Pacific, pushing up inflation in the region. The inflation rate in 2022 was extremely high globally with an average of 8.3% (World Bank 2023). In Asia and the Pacific, some regions still experience high inflation, with the Caucasus and Central Asia leading at 12.9% and South Asia, Southeast Asia, and the Pacific reaching 8.2%, 5.0% and 5.2%, respectively, in the same year (Asian Development Bank 2023). Supply chain disruption in food triggered food export restrictions in several countries, which led to a global prisoners' dilemma of food trade ("it's in everyone's interest to keep exports flowing, but no one wants to run short by being the only country that does" Beattie 2022). With increasing economies implementing food export restrictions (World Bank 2022), the world is

[1] Factory Asia refers to the model of regional production networks connecting factories in different Asian economies, producing parts and components that are then assembled, with the final products shipped mainly to advanced economies (see Ando and Kimura [2005]).

trapped in an untrustful setting similar to a prisoner's dilemma, with unilateral food export bans resulting in soaring food prices. High food prices have triggered a food crisis that is driving millions into extreme poverty, magnifying hunger and malnutrition. According to a recent Food and Agriculture Organization report (WFP and FAO 2022), some Asian developing countries, such as Afghanistan, the Lao People's Democratic Republic, Pakistan, and Bangladesh, are facing severe localized food insecurity. In South Asia alone, 1.33 billion people lack healthy diets due to poverty and increasing food prices (FAO 2022). On the other hand, skyrocketing energy prices (coal, crude oil, and natural gas surged by 176%, 51%, and 94%, respectively, between 24 February and 13 September 2022) drove the total energy cost of households by 62.6%–112.9% (Guan et al. 2023), with detrimental food and energy availability pushing millions of people into extreme poverty, especially in developing economies.

Solutions

Economic diversification for Asian countries is significantly influenced by the evolving global trade environment, while the risks to people's lives and means of sustenance have been increasing because of the supply chain crisis and shortages, causing more economic uncertainty in the region. Building supply chain resilience is vital to enhancing the economic outlook for all, particularly in trade-reliant developing Asia and the Pacific. With various definitions of supply chain resilience proposed in recent decades (Christopher and Peck 2004; Ponomarov and Holcomb 2009; Hosseini, Ivanov, and Dolgui 2019), this book focuses on two fundamental compositions of a resilient supply chain: robustness and resilience, the adaptive power of a supply chain in maintaining operation with future shocks and recovering in a timely manner. On the pathway to resilient supply chains, structural transformation driven by technologies and policy tools are both essential (OECD 2023) and examined in this book. In addition, this work highlights significant roles that digitalization could play in enhancing supply chain resilience and proposes possible solutions to build resilient supply for food and energy security in developing Asia and the Pacific.

The book is organized into five parts: (i) International Trade and Global Value Chains, (ii) Food Security and Global Food Supply Chain, (iii) Supply Chain Disruptions and Energy Security (iv) Global Supply Chain Transformation, and (v) Digitalization for Resilient Supply Chains.

Part I: International Trade and Global Value Chains explores the trends in global trade and provides policy recommendations for Asia and the Pacific economies that will facilitate regional trade to best pursue their development goals. This part comprises two chapters.

Chapter 1, "Shifts in Global Supply Chains in United States–People's Republic of China Trade and Implications for Asian Developing Economies," examines the trends in the global supply chain for Asia and Pacific economies. To date, there has been no generalized manufacturing re-shoring (moving the production of goods back to the company's original country) to the United States or near-shoring (moving the production of goods to a nearby country from one of greater distance) to North America, nor is there any sign of mass production moving out of the People's Republic of China (PRC). However, there is some tendency toward near-shoring in the PRC as the country trades more with its Regional Comprehensive Economic Partnership (RCEP) partners and relatively less with the United States (US) and Europe. The decline in trade between the PRC and the US has been concentrated in a few high-tech areas, and thus it is more of a technology conflict than a trade conflict. The final assembly of some high-tech products has shifted to Viet Nam and other Association of Southeast Asian Nations (ASEAN) countries to take advantage of lower wages, bypass US tariffs, and diversify supply chains. This chapter recommends that Asian developing countries strengthen their investment environment, particularly openness to foreign trade and direct investment, logistics, intellectual property protection, and human capital to benefit from increased trade with the PRC and the US by acting as intermediaries between these two giants.

Chapter 2, "Trade Facilitation and Global Value Chains in a Post-Pandemic World," assesses the effects of the implementation of trade facilitation (TF) measures and paperless trade on international trade flows and participation in global value chains (GVCs). The chapter unravels the efficacy of various TF actions implemented at the national level and determines whether they have contributed to creating more sustainable trade flows. Findings from the gravity model of international trade suggest that TF measures concerning transparency, institutions, and formalities hold the highest significance. This chapter highlights that transparency policies will increase trade in manufactured goods more than proportionally, especially in low-income countries in the region. Besides, improving the quality of TF-related institutions will foster participation in GVCs. Some potential actions could include establishing a National Trade Facilitation Committee or a comparable entity or having a well-defined national institutional framework in place for collaboration among border agencies. Finally, for small islands in Asia and the Pacific, public investments directed to improve their logistic performance would be of special relevance.

Part II: Food Security and Global Food Supply Chains examines how global supply chain disruptions and uncertainties affect the region's most vulnerable developing nations and explores possible solutions to build resilient supply for food security in developing Asia and the Pacific. This part contains two chapters.

Chapter 3 is entitled "Integrated Climate Change Assessments on Selected Farming Systems in India, Pakistan, Bangladesh, and Viet Nam." This chapter shares examples from Agricultural Model Intercomparison and Improvement Project (AgMIP) regional integrated assessment studies in Asia. There is a particularly urgent need to transform the food system to feed countries with large populations in the world. The chapter reveals that climate change will negatively impact agriculture even under favorable conditions, affecting farmers differently based on their vulnerabilities, and necessitate a range of adaptation strategies that consider national, regional, and equity-focused goals for climate-resilient development. AgMIP projects in the region lead to three policy recommendations for the Asia and Pacific region: (i) integrate development pathways into climate change assessments via the Representative Agricultural Pathways (RAPs) process, which consists of a holistic set of drivers, metrics, and outcomes that encompasses at the local, regional, and global levels; (ii) explore synergies, trade-offs, and co-benefits of mitigation and adaptation in food systems in order to acquire food security and sustainable livelihoods simultaneously; and (iii) conduct multi-scale assessments that link national and regional stakeholders for enhancing the well-being of farmers both in the present and in the face of evolving climate conditions.

Chapter 4, "When Policy Responses Make Things Worse: The Case of Export Restrictions on Agricultural Products," investigates to what extent agricultural restriction measures disrupt normal trade patterns and impact importing countries and the possibility of forecasting the implementation of agricultural restriction measures. It is found that Asia countries are not immune to these restrictions as the region is home to many food-insecure countries. Countries in South Asia and Southeast Asia are most affected by the trade blockage of food staples. The domestic food price has a higher predictive power than the world price of individual commodities. Among the covariates studied, a country's trade exposure and per capita income influence the imposition of export restrictions. Amid the uncertainty of future commodity supply, it is crucial for Asian countries, whether they are net importers or exporters of food, to exchange information on production forecasts and staple stocks to avoid exacerbating the situation and causing harm to impoverished populations by any unilateral withdrawal from the food trade. The results can help policy makers or the agencies responsible for implementing restrictions pay attention to key price variables and accentuate the need for information-sharing among Asian developing countries regarding commodity supplies and staple stocks to prevent worsening food crises.

Part III: Supply Chain Disruptions: Energy Security and Eco-Innovation discusses the energy trilemma during geopolitical and environmental crises and examines the global trends in eco-innovation for the low-carbon transition. Part III comprises two chapters.

Chapter 5, "Navigating the Energy Trilemma during Geopolitical and Environmental Crises," explains that energy security should focus on two aspects of the energy trilemma (reliability–affordability–cleanliness): reliability and affordability, which are two conflicting parts. There are trade-offs between the two. The Russian Federation's latest invasion of Ukraine highlights some of the problems with energy security, from long-term contracts being broken to supposedly secure supplies being diverted to retired power plants being recommissioned to spillovers to other markets. The transition to carbon-free energy poses new challenges for energy security, from a shift in dependence from some resources (coal, oil, and gas) to others (rare earth, wind, and sunshine) to substantial redundancies in the energy capital stock to undercapitalized energy companies, while regulatory uncertainty deters investment. Renewables improve energy security in one dimension but worsen it in others. This chapter provides policy recommendations on how to deal with the energy trilemma. First, providing energy security requires state intervention. Peak power capacity is a public good, best purchased in a reverse auction.[2] To deliver fuels for energy production, redundancy in transport and transmission network monopolies is best achieved and secured by direct regulation. Second, policies on energy access and poverty should focus on well-targeted income support and investment subsidies.

Chapter 6, "Investment in Innovation: Global Trends, Collaboration, and the Environment" examines the global trends in innovation, collaborative innovation, eco-innovation, and collaborative eco-innovation with an emphasis on the environment. The findings show that innovation and co-innovation have grown substantially, especially in certain technological disciplines. The increase in eco-innovation and collaborative eco-innovation provides some optimism

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2 In a reverse auction, the conventional roles of buyers and sellers are reversed, giving rise to what is also known as a buyer-determined auction or procurement auction. Therefore, there is one buyer and many potential sellers. In a reverse auction, sellers vie for the buyer's business, usually leading to a downward trend in prices as each tries to outbid the others by offering lower rates.

that human ingenuity will be able to mitigate some of climate change and industrial pollution's most detrimental impacts. This chapter indicates that as an increasing proportion of global emissions is attributable to emerging nations, policies that encourage the diffusion of green technological solutions (eco-innovation) between developed and rapidly industrializing economies should be designed. One mechanism by which technologies may spread throughout the world is through collaborative eco-innovation where firms from different countries collaborate on innovation activities. This chapter is suggestive of several policy implications. First, enhanced cooperation can help developing countries, especially in Asia and the Pacific, boost innovation, upgrade industries, and stimulate technology transfer. Pioneering collaborative eco-innovation with a larger number of countries also provides a more robust position to developing countries' economies by minimizing potential vulnerabilities if any single partner experiences an unexpected disruption. Second, governments should identify which green technology field they have an innovation advantage in, and the international differences in eco-innovation indicators, in order to facilitate optimal collaboration among potential member economies. Third, following a rapid increase in global energy prices, it is crucial to promote and fund innovation in green energy-related projects.

Part IV: Global Supply Chain Transformation identifies drivers, trends, and policy recommendations for global supply chain transformation. Part IV comprises two chapters.

Chapter 7, "Global Supply Chain Resilience: Facts and Implications," discusses how the PRC has become a central player in global supply chains over the years but has faced challenges due to events such as the US-PRC trade conflict, the COVID-19 pandemic, and the Russian invasion of Ukraine, resulting in higher inflation and disruptions in supply chains. Companies are now focusing more on resilience than efficiency in their supply chains, and surveys suggest that many are reshuffling their production away from the PRC. Governments of several economies, such as Japan, the Republic of Korea, and also the European Union and the US, are introducing legislation to improve the resilience of global value chains, which is promoting relevant business plans in private sectors. While affected by geopolitical turbulences and the PRC's worsening medium-term economic prospects, much of the companies' decisions to reshuffle production away from the PRC may still be incentivized by the growing needs of diversification. Recent trends, such as the slowdown in mergers and acquisitions in the PRC and the increasing focus on India and ASEAN, suggest that diversifying production away from the PRC is a rational decision based on economic rationale and government action.

Chapter 8, "How Have Recent Global Events Accentuated the Need for Transformation in the Global Supply Chain?" explores the challenges to stability and reliability due to recent global events, such as the COVID-19 pandemic, geopolitical events, supply chain disruptions, and natural disasters, all of which have put enormous stress on globally spread value chains. The disruptions in the supply chain have resulted in a contraction in gross domestic product, inflationary pressures, and trade conflicts. Transformation in the global supply chain and investment in digital capabilities will help organizations tackle human resource shortages, support new business models, and enhance productivity. Changing trade dynamics, complexities of value chains, and increasing global trade barriers have also made regional and global trade within Asia and the Pacific more attractive. However, the research shows that it will be a challenge for organizations and nations to overcome self-serving behavior to enable supply chain partnerships and collaboration. The chapter describes six key policy implications: boosting domestic consumption and regional trade, enhancing diversification and reducing concentration within supply chains, undertaking economic and social upgradation, improving ease of doing business, and strengthening supply chain response to natural disasters. The chapter concludes by suggesting that future studies could explore the challenges, threats, opportunities, and recommendations in further detail, and debate on how organizations, countries, regions, and international bodies could collaborate to create policies and practices that would elevate the challenges of global supply chains will be necessary for future generations.

Part V: Digitalization for Resilient Supply Chains examines the significant roles that digitalization could play in enhancing supply chain resilience and proposes possible digital solutions for building a resilient global supply chain. Part V consists of three chapters.

Chapter 9, "Building Supply Chain Resilience with Digitalization," explains that a lack of end-to-end visibility is one of the key reasons behind the supply chain vulnerability. As digitalization could offer accuracy and transparency to enhance overall resilience across all members of supply chain networks, i.e., from raw material suppliers to customers, this chapter explores how to develop digital technologies' capabilities to strengthen the supply chain resilience to withstand future uncertainties. It proposes the building blocks for digitalization capabilities: an enhanced digital workforce (upskilling of workers' digital capabilities), a robust digital backbone (digital architecture that comprises smart platforms, cloud-based applications, automation, and lean processes), and a digital twin (a digital replica of the physical supply chain). Further, this chapter provides policy recommendations for developing Asia and the Pacific: (i) as the premise of digitalization, significant efforts and progress should be made in rolling out telecommunications and digital infrastructures; (ii) the establishment of comprehensive legislation for digital data security is the key for global competition; policy makers need to ensure that data protection laws align with regional and international standards to build a trusted digital economy for economic growth; and (iii) nurturing digital talents by expanding the scale of digital education and job demands. Policy makers can also collaborate with firms to construct a suitable organizational structure for digitalization and further foster an innovative digital culture for better adaptation.

Chapter 10, "The Surprising Developments of Digital Supply Chains to Raise Resilience in the Face of Disruptions," identifies different types of disruptions that have challenged the resilience of supply chains and proposes a new framework to understand which digital solutions are effective against which types of disruptions. This framework is based on documented examples and experiences from executives. The most effective digital tools for increasing supply chain resilience are systems integration of digital platforms, artificial intelligence (AI) empowerment, and simulation of supply chain scenarios, and the combination of these three can provide more efficiency. However, other digital technologies seem to have a marginal effect on resilience. The findings suggest that regulators should consider fostering standards development for making compatible systems that can be seamlessly integrated. The research also indicates that tools that increase resilience could reduce the need for companies to move manufacturing away from Asia and the Pacific under disruptions in the global supply chains. The chapter concludes with the suggestion that Asia and Pacific economies should embrace digitalization by encouraging the adoption of systems integration, AI, and simulation within regional businesses to enhance supply chain resilience, and this will subsequently attract global companies to maintain their sourcing from the Asia and Pacific region.

Chapter 11, "Bespoke Supply Chain Resilience Facilitated by Dedicated and Shared Resources," offers a characterization of resilience-enhancing measures. Resilience-enhancing measures are either based on dedicated resources (dedicated resilience lever) or shared resources (shared resilience lever). Typically, shared resources not only help build resilience but also help meet customer demand in the absence of disruptions. Furthermore, this chapter provides examples of how supply chain finance solutions empowered by digitalization, such as reverse factoring and dynamic discounting (both finance solutions that help to stabilize the supply chain by improving access to cash for suppliers), can be considered as a shared resource that helps build resilience and efficiency simultaneously. The chapter concludes that shared resilience levers are particularly helpful for supply chains that focus on cost-efficiency and that produce basic/functional products. In contrast, dedicated resilience levers are particularly helpful for supply chains that are less exposed to cost pressure and that produce innovative products.

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PART I

International Trade and Global Value Chains

1

Shifts in Global Supply Chains in United States–People's Republic of China Trade and Implications for Asian Developing Economies

David Dollar

1.1 Introduction

Global supply chains have faced serious challenges in the past few years. The COVID-19 pandemic, in particular, caused disruptions in both supply and demand. Demand shifted from services to goods, especially ones used to work and enjoy leisure at home. There were many specific supply shocks as some factories closed temporarily and workers at ports, and in transportation and warehousing, were in short supply. The strongest image from these combined shocks was the 100+ ships waiting off the coast of Southern California to unload. But COVID-19 has just been one of many disruptions. Weather shocks are becoming greater as a result of climate change. The drought and unprecedented heat in Southwest People's Republic of China (PRC) is a recent example, as were floods in many parts of the world. The 2021 deep freeze in Texas, which shut down the power grid, is another important example. On top of these environmental shocks, the world has seen growing geopolitical tension between the United States (US) and the PRC, the two biggest economies, as well as Russia's invasion of Ukraine. The PRC and the US are not just the biggest economies, they are the biggest trading nations: PRC the biggest exporter and the US the biggest importer. The supply chains of many products involve both the PRC and the US, as well as many third countries.

In light of the successive shocks to supply chains, there has been much speculation as to how they will shift; that is, how the role in global production of different nations will change. In the US, there are calls for onshoring or reshoring of manufacturing and "Buy American" provisions added to several pieces of legislation aimed at restoring infrastructure and industry. The next section of the chapter examines whether there is any evidence of reshoring or near-shoring to the US. It accounts for macroeconomic factors that would make it difficult for the US to see a generalized reshoring of manufacturing. In particular, any significant reduction in America's manufacturing trade deficit would require the country to consume less and save more, a stance that is not likely to be politically popular.

The last section focuses on how developing Asia can benefit from these developments. Factors that have made the PRC such a manufacturing powerhouse include the size of the domestic market, policy openness to foreign trade and investment, excellent infrastructure and logistics, relatively good intellectual property protection compared to other developing countries, and excellent human capital (Xing 2022). It is difficult for any other single country to duplicate this success. Only India has the size, and it has mixed policies toward openness (it has not joined RCEP, for example), as well as weaknesses in infrastructure and educational attainment. Viet Nam probably comes closest to matching the PRC recipe for success, with excellent human capital and even more openness than the PRC has shown. Its logistics are adequate but need to be upgraded if it wants to play a larger role in value chains. Viet Nam has 100 million people but its economy is dwarfed by that of the PRC. Other large ASEAN countries such as the Philippines, Indonesia, or Thailand have weaknesses in openness, logistics, and human capital. Mexico has deficiencies in infrastructure, logistics, intellectual property protection, and human capital that make large-scale near-shoring unlikely. As supply chains evolve in response to economic and political forces, these developing countries could benefit strongly from policy reforms that address the weaknesses. The countries that can create a very good investment climate are likely to experience a deepening role in global supply chains, helping with their growth and poverty reduction objectives.

1.2 Reshoring and Near-Shoring

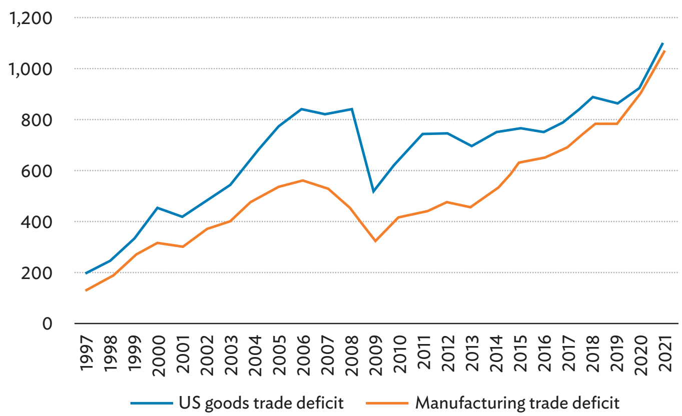
Reshoring of manufacturing to the US has become an important focus of policy. In his 2022 State of the Union address, President Biden stated that "it's time to bury the label rust belt. It's time to see what used to be called the rust belt become the home of a significant resurgence of manufacturing. Instead of relying on foreign supply chains, let's make it in America." So-called "Buy American" provisions have been included in recent legislation such as the infrastructure bill and the climate-focused bill that is mis-named the Inflation Reduction Act. President Trump used similar rhetoric to praise protectionist policies such as import tariffs on steel and aluminum or the 25% tariff on about half of what the US imports from the PRC. These policies have been in place since 2018, long enough to see whether they are having the effect of promoting a generalized reshoring of manufacturing. Generalized reshoring would involve a widespread trend toward greater manufacturing production in the US that is visible in the macroeconomic data. It would be seen in a rising share of manufacturing in GDP and a declining manufacturing trade deficit.

As of mid-2022, there was no evidence of such a generalized reshoring of manufacturing. The index of real manufacturing output from the St. Louis Federal Reserve shows remarkable stability in US manufacturing production. There was some decline in the early days of COVID-19, but then a quick rebound. As for trends: real manufacturing output was 4% higher in mid-2022, compared to a decade earlier. Growth of 4% over a decade means that manufacturing grew slowly and continued a long trend of declining as a share of the US economy. While manufacturing output has stagnated, manufactured imports have surged. It used to be that the manufacturing trade deficit was just one part of the overall US trade deficit, but there were other important factors as well, notably imports of crude oil. But now the US is largely self-sufficient in energy, and has a balance in trade in primary products like food and minerals, exporting some and importing others. So, the overall trade deficit has come to consist almost entirely of the manufacturing trade deficit, which reached $900 billion in 2020 (Figure 1.1). That trade deficit indicates that the US consumes $900 billion more in manufactured goods than it produces.

This overall trade deficit equals the gap between investment and savings in the US. The trade deficit enables the US to invest more than its saves. For there to be generalized reshoring of manufacturing to the US, there would have to be a change in this savings-investment balance. The US could invest less, but that would be bad for long-run growth and no politician is advocating this. Holding the investment rate constant, savings would have to rise to reduce the manufacturing trade deficit. That is, Americans would have to consume less of their income. The most direct path to achieve this would be to increase taxes and reduce government spending in order to bring down America's unsustainable fiscal deficit. However, fiscal tightening of sufficient scale to reduce the US trade deficit is not feasible. So, significant reshoring of manufacturing and a reduction of the US trade deficit is unlikely.

One factor that makes this US savings-investment balance sustainable is that the US dollar is still the premier reserve currency,

Figure 1.1: US Manufacturing Trade Deficit
($ billion)



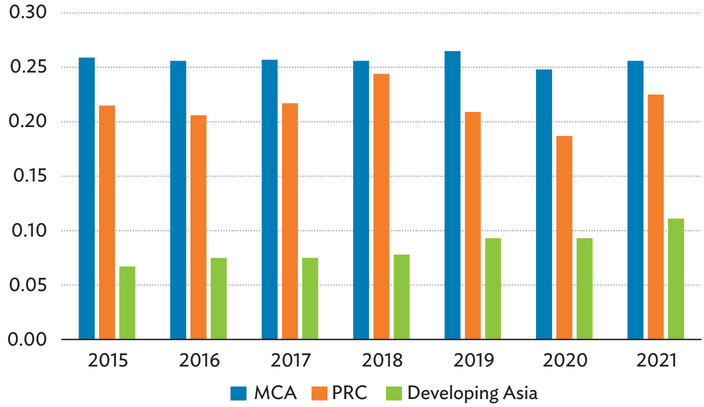
Source: EPI analysis of Census Bureau and USITC trade data.

and that reduces the American cost of overseas borrowing and makes the large external deficit sustainable. While there is continuing talk of other currencies challenging the primary role of the dollar, the reality is that the status of the dollar is well-entrenched. It is based on underlying fundamentals such as open and deep capital markets, flexible exchange rates, and reliable rule of law (Prasad 2014).

While generalized reshoring is unlikely, it is still possible to subsidize the expansion of particular industries, such as semiconductors or electric vehicles. But without a change in the macroeconomic stance, it is likely that these policies will crowd out other manufacturing sectors, with the result that the overall size of US manufacturing is unaffected. Subsidizing particular industries could bid up wages for certain types of labor and/or appreciate the exchange rate, with the result that other sectors become less competitive and hence contract. Also, the subsidies must be paid for, either directly through taxation (or cutting other expenditures) or indirectly through inflation. Either way, paying for the subsidies will tend to reduce other consumption and hence lead to some contraction of other parts of the economy. There is no free lunch, so subsidizing the expansion of, say, semiconductors will lead to contraction of other sectors.

There is also talk in the US about "near-shoring," that is, bringing back some manufacturing production from Asia to the nearby economies,

Figure 1.2: Share of US Manufactured Imports



PRC = People's Republic of China, MCA = Mexico-Canada agreement.

Source: US Department of Commerce, Bureau of the Census.

especially Mexico and Canada. The renewal of the North American Free-Trade Arrangement under the United States-Mexico-Canada Agreement fueled this talk. But note that the renewed trade agreement did not involve any new trade liberalization of significance; in fact, it introduced protectionist measures in the form of domestic content requirements in the auto sector. So far, there is no evidence of "near-shoring." The combined Mexico-Canada share of US manufacturing imports has been high for a long time. Between 2015 and 2021, it did not budge from its 26% level (Figure 1.2). There is good reason for this. Canada is a high-wage economy not well suited to the kinds of products that the US imports from Asia. Mexico is a low-wage developing country, but it has a lot of weaknesses in its investment climate. For example, in considering Mexico's potential as a manufacturing hub, Schott (2021) finds it hampered by investment climate weaknesses: "intrusive Mexican business regulations, inadequate and irregular power supplies, and clogged road and rail networks." The State Department's 2021 assessment of Mexico's investment climate likewise notes that "uncertainty about contract enforcement, insecurity, informality, and corruption continue to hinder sustained Mexican economic growth." Mexico's investment climate, along with those of developing Asia, will be examined in more detail in the final section of the chapter. Suffice it to say at this point that there is no evidence of a surge in Mexican manufacturing as a result of shifts in value chains. Such a surge could yet develop, but we have not seen it so far.

1.3 The PRC's Industrial Policy and Trade Liberalization

PRC leaders have not used the language of reshoring, but they have similarly pursued an interventionist industrial policy aimed at making the PRC less dependent on imported technology and machinery. Naughton (2021) provides a detailed study of the PRC's industrial policy over time, noting that the shift to a more interventionist industrial policy starts with the 2006 "Medium and Long-Term Plan for Science and Technology Development" (MLP), which laid out a strategy for building PRC technical prowess and introduced the program of indigenous innovation. The aim was to reduce the PRC's use of foreign technology and build up innovation capability at home. At the heart of this plan was direct investment by the state, equivalent to tens of billions of dollars, to spur innovation in major technological categories. The key targeted sectors included aeronautics, high-end semiconductors, machine tools, power plants (including nuclear), a satellite navigation system, and new technologies for health and environmental protection.

In 2015, the PRC incorporated this push for indigenous innovation into the "Made in China 2025" program. Made in China 2025 aimed to improve the technology level of all PRC manufacturing and, in some key areas, to achieve technological leadership. The plan included numerical targets for PRC firms' share of domestic and global markets for key products.

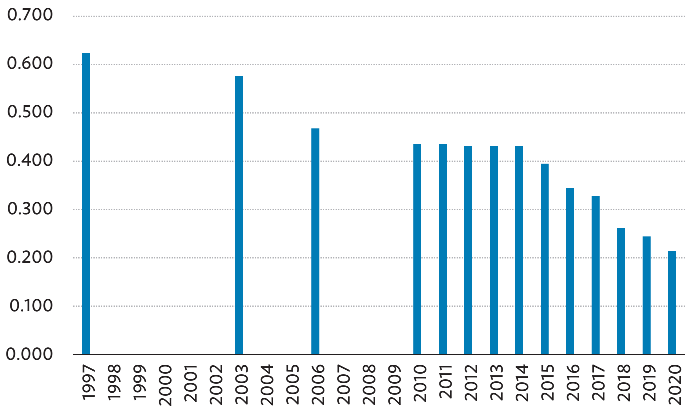
While the PRC used substantial intervention to boost particular industries, the overall results so far have been uneven. Advances in sectors such as electric vehicles and solar energy are impressive. But there has been a sharp decline in total factor productivity (TFP) growth for the whole economy. TFP measures how much output growth countries get from increases in capital and labor inputs. TFP growth depends on several factors such as reallocation of labor from less productive to more productive sectors. But it is also the best measure of the overall technology level of the economy. PRC growth in inputs, especially capital, has continued at a high rate over time, slowing only a minor amount, but the impact of these inputs has diminished; that is, GDP growth has slowed from 10.6% in the 2002 to 2012 period to 6.5% since then. As for TFP growth, in the 2000s, it averaged 3.5% per year, but in the 2010s dropped to 0.7% (International Monetary Fund 2021). The slowdown of TFP growth is consistent with the notion that technological upgrading, either through innovation or via borrowing, has slowed, as have improvements in the efficiency with which resources are used.

If PRC industrial policy succeeds in producing self-sufficiency and indigenous technology in areas that are seen as crucial for the future, this self-sufficiency implies less reliance on imports and foreign investment, hence some turning away from outward orientation, i.e., a kind of on-shoring. At the same time, the PRC economy has become more open as a result of trade and investment liberalization. PRC trade policy did not change much in the 2000s. The average applied tariff rate, for example, fell from 14.7% to 7.7% when the PRC joined the WTO, but then was stable around 6% for 10 years. A new wave of trade liberalization began in the 2010s, with the tariff rate falling to 2.5% in 2020 (Dollar 2022). The tariff reductions have been part of bilateral free-trade agreements that the PRC signed with most of its neighbors, including the Republic of Korea, Australia, New Zealand, ASEAN, and Singapore. Further tariff reductions went into effect in 2022 as the PRC was one of the founding members of the RCEP, the largest free-trade agreement in history. This agreement reduces trade barriers among the PRC, ASEAN, Japan, the Republic of Korea, Australia, and New Zealand. This agreement eliminates tariffs on 90% of items and has simple rules of origin that will put the Asian economies at the heart of global value chains (Petri and Plummer 2020).

Beyond RCEP, the PRC has applied to join the Comprehensive and Progressive Trans-Pacific Partnership (CPTPP), a more ambitious agreement among 11 Asia-Pacific economies, including Japan. If the PRC and other major economies such as Republic of Korea and Indonesia join CPTPP, it will become the primary foundation for trade and investment in the Asia and the Pacific region. The US, meanwhile, dropped out of CPTPP before it reached implementation and is not pursuing any new large trade agreements, either in Asia or in other regions.

There has been a similar pattern in the closely related area of PRC policy toward inward direct investment. Most global supply chains are organized and overseen by multinational firms, with the result that trade is closely related to direct investment. As the PRC was preparing to join the WTO, it made initial steps to liberalize inward investment. Sectors such as textiles and consumer electronics were opened to 100% foreign-owned firms. These were the sectors in which the PRC's initial export successes took place. But many key parts of the economy remained at least partially restricted, including modern services such as finance and telecommunications and hi-tech manufacturing. In autos and financial services, for example, foreign investors could only enter as minority investors, usually paired with state enterprises.

Figure 1.3: FDI Restrictiveness Index
(1=Closed, 0=Open)



FDI = foreign direct investment.

Source: OECD, *FDI Regulatory Restrictiveness Index*, 2021.

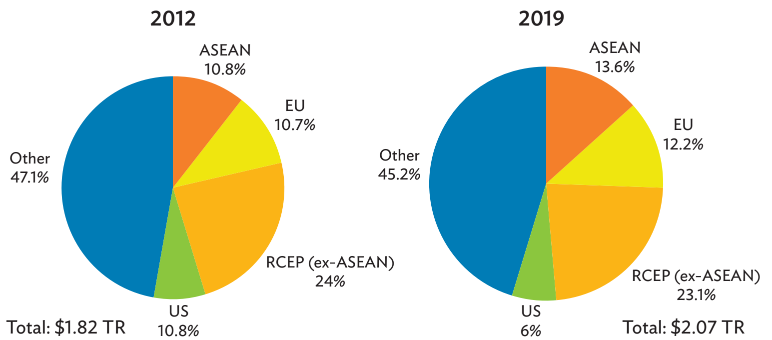
The Organisation for Economic Co-operation and Development (OECD) calculates an index of foreign direct investment (FDI) restrictiveness for major economies, starting in 1997, with zero being completely open to investment and 1.0 being completely closed. PRC restrictiveness at the beginning of this period, above 0.6, reflected its history as a mostly closed economy that had begun to open up. This level of restrictiveness was far above OECD levels and also compared unfavorably to most other large emerging markets. During 1997–2020, the index shows three distinct periods. Between 1997 and 2006, as the PRC prepared to join WTO and then actually joined, quite a few sectors were opened to foreign investment, and the restrictiveness index declined from 0.63 to 0.47. From 2006 until 2014, there was little further liberalization, and the index declined only a small amount, to 0.43. In the most recent 6 years, in contrast, the level of restrictiveness has been cut in half, reaching 0.21 by 2020 (Figure 1.3). Concretely, this reflects the opening of sectors such as autos and financial services to 100% foreign-owned firms. The PRC now is more open to direct investment than other Asian emerging markets such as India, Indonesia, or Thailand, according to this OECD measure. These opening moves are reflected in the data on FDI. In the last few years, the PRC has surpassed the US as the number one destination for direct investment: $253 billion of inflows in 2020 compared to $211 billion for the US FDI surged further in 2021, powered by services and hi-tech sectors. FDI has held up strongly despite the repeated COVID-19 outbreaks on the mainland, the strict zero-tolerance policy, and the chaos in some supply chains. Most likely, investors were sticking with the PRC because of its large and increasingly open domestic market and ability to handle the supply chain snarls as well as anyone.

The notion that all supply chains would leave the PRC was never realistic given the size of its industrial sector and its pre-eminent role in world exports. Supply chains linking the PRC with the US, Europe, and others developed because of mutual benefit, and they will not be dislodged easily. Supply chains in electronics and automobiles are particularly complex, involving many nations and different locations within countries. This division of production has proved to be extremely efficient and has led to continual decreases in prices for these goods (Xing et al. 2021). The COVID-19 pandemic and Russia's invasion of Ukraine have led to a surge in global inflation, which is worrisome. Restricting trade, however, only exacerbates inflation. Major central banks are taking forceful action and it is likely that inflation will be brought under control. Many of the specific shortages that emerged during the pandemic have now been addressed.

While supply chains have generally held up well in this turbulent era, one of the lessons from the recent years of pandemic and geostrategic competition is that firms need to pay more attention to supply-chain resilience. As noted, this is not leading to wholesale reshoring to the US or near-shoring to Mexico and Canada. But many international firms are building more resilience into their supply chains. For some firms, this involves a strategy of "China plus one" in which the firm maintains its production in the PRC but hedges by adding capacity in one other Asian developing country, most commonly Viet Nam. Firms are also holding more inventory and building more redundancy into their supply chains, having been burned by shortages of key inputs during the pandemic years. All of this amounts to some alteration in supply chains, but not a large-scale move away from globalization. One of the main conclusions of the most recent US-PRC Business Council survey of American firms operating in the PRC is that firms are hedging with investments in other Asian countries but not leaving the mainland in any significant way. Only 8% of firms had moved some production back to the US (US-PRC Business Council 2022).

PRC policy of stepped-up industrial policy interventions combined with greater trade and investment openness is itself a kind of hedging, combining state direction with the efficiency of market competition. But it does entail some risks. The US objects to its subsidies for hi-tech sectors and has been reluctant to accept large-scale PRC exports in these areas. This has been the case with solar panels, an industry whose development was subsidized by the PRC government. Governments have not been particularly good at picking winners among technologies and firms, but it is certainly plausible given the track record so far that the PRC will have some failures and some successes as it promotes particular technologies. The risk for the PRC then is that the successes will be kept out of some major markets. The US has already previewed some of the tools that it can use: countervailing duties to counteract subsidies, export controls on hi-tech machinery and parts; investment restrictions on PRC firms in the US and US firms in the PRC; and a broad across-the-board 25% tariff to reduce PRC market share in the US. The European Union (EU) has introduced some similar export and investment restrictions. It is likely that these measures are part of the explanation for the slowdown in productivity growth in the PRC. An International Monetary Fund (IMF) study finds that complete tech decoupling would hurt both the PRC and American economies, but the PRC most of all (IMF 2021). This makes sense because the PRC still has considerable catch-up potential and decoupling would make catch-up more difficult. But it is important to note that the IMF study also finds losses for the US from decoupling, because the benefits of innovation in such a world would be smaller, and hence there would be less incentive for R&D and less actual progress. In other words, decoupling is a lose-lose proposition.

Figure 1.4: PRC Imports by Region

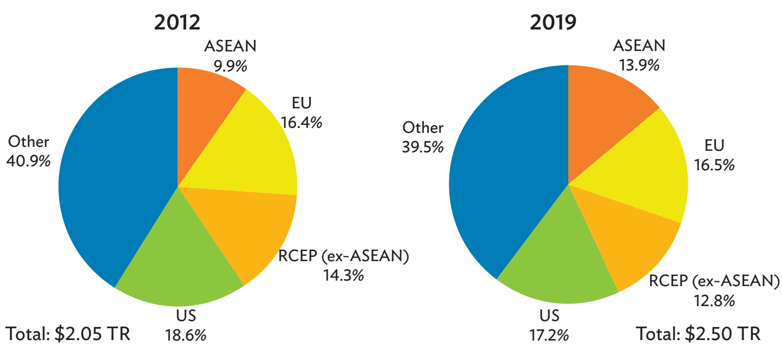


ASEAN = Association of Southeast Asian Nations, EU = European Union, PRC = People's Republic of China, RECP = Regional Comprehensive Economic Partnership, US = United States.

Source: World Bank, *World Integrated Trade Solution.*

While PRC trade and investment with the US and the EU have hit some political bumps, its relations with the developing world have continued to thrive. In terms of PRC imports, which consist mostly of natural resources plus hi-tech parts and machinery, there has been a gradual shift away from the West to RCEP partners. The PRC now imports more than twice as much from its regional partners as it does from the US and EU combined (Figure 1.4). In terms of markets for PRC exports, there has also been a gradual shift away from a focus on the US market. In 2012, the US was the largest market for PRC exports (19%). By 2019, PRC exports to RCEP partners were 56% more than exports to the US, while exports to the EU were at about the same level as the US (Figure 1.5). In this sense the PRC is experiencing some near-shoring, which is logical given the rapid growth of developing Asia as well as the fallout from the tension with the US and Europe. These changes happened before RCEP came into implementation. The mutual tariff cutting now underway is likely to strengthen this trend towards greater intra-Asian trade.

Figure 1.5: PRC Exports by Region



ASEAN = Association of Southeast Asian Nations, EU = European Union, RECP = Regional Comprehensive Economic Partnership.

Source: World Bank, *World Integrated Trade Solution*.

But two aspects of this pattern of trade may raise some concerns for the PRC. First, there is evidence that, for a developing country like the PRC, trade with more advanced economies has spillover benefits in terms of technology upgrading, compared to South-South trade (Xing et al. 2021). PRC firms that are suppliers to global value chains are exposed to advanced technology and absorb some of it. The MNEs that manage supply chains put pressure on all links of the chain to improve productivity and reduce costs. If the PRC decouples from the advanced economies, this will cut off an important source of technological upgrading at a time when it is still has much catch-up potential. This was essentially the finding of the IMF study cited above.

A second concern is the sustainability of PRC trade with developing world partners. Some PRC exports to other developing countries are connected to its Belt and Road Initiative. This initiative was launched in 2013 in an effort to promote connectivity among the partner countries, primarily via infrastructure development. The PRC has been providing about $100 billion per year of financing to other developing countries, with the resulting infrastructure projects mostly using PRC construction companies, steel, machinery, etc. Hence BRI helps promote PRC exports. But quite a few countries that have borrowed from the PRC are now facing debt sustainability problems. The loans are largely commercial, though at rates somewhat more favorable than countries can get from the private market. Much of this lending is in US dollars at floating interest rates. With the COVID-19 pandemic, global slowdown, and Federal Reserve moves to increase interest rates during 2022–23, economic and financial conditions are becoming difficult for many poor countries. They cannot service the debt that they have taken on from the PRC and from others, and they will struggle to take on new debt. About 60% of low-income countries are in debt distress or at high risk of debt distress, according to the IMF (2022). For these countries, the PRC is the largest bilateral official creditor, holding 18% of their external debt. Private creditors hold a similar 19%. Most of these countries will need debt relief, and it has proved challenging to get the PRC, private creditors, and the traditional donors (multilateral institutions and the Western countries) to cooperate on this. As a result of these debt problems, the level of activity in BRI seems to be slowing down. The difficulties that developing countries now face with a slowing global economy, rising dollar interest rates, and higher energy and food prices, may make them less attractive partners for the next few years. The early data from 2023 show weakening external demand for PRC exports, probably resulting from cyclical downturn as well as structural problems such as geostrategic tensions and developing country debt problems.

1.4 Developments in US-PRC Trade

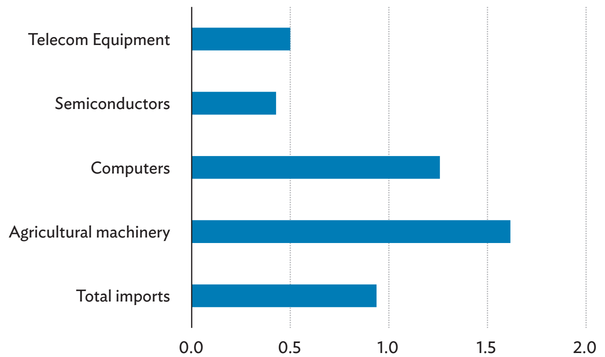
Prior to the trade conflict starting in 2018, the US and the PRC were major trading partners. According to US statistics, 2018 was the peak year of US-PRC trade before the trade war. Focusing on merchandise, the US imported $539 billion of PRC goods, and exported $120 billion.

The large imbalance has been a sensitive issue for years, but is just one piece of a large overall deficit that reflects US macroeconomic policies as well as the dollar's role in the world currency system, as explained in the first section. The US has a surplus on services in its trade with the PRC, which includes the PRC students at high schools and universities in the US, the large number of tourists (pre-COVID-19), services from the financial industry, royalties on the licensing of technology, and profits of multinational firms. Adding these factors into the equation cuts the bilateral deficit by about one-third, but it is still the case that there is a large imbalance because of the macroeconomic and currency factors (Xing et al. 2021). The fact that there was such a large volume of trade between the PRC and the US indicates that the two economies are complementary and the complex supply chains that developed are highly efficient and mutually beneficial. The US is the most technologically advanced economy and also is resource rich in terms of arable land and fossil fuels. The PRC's endowments are quite dissimilar. For example, it is the largest consumer of oil, but only ranks thirteenth in terms of proven reserves of petroleum (Li et al. 2022). Similarly, it has one-fifth of the world's population but only 7% of the globe's arable land. It has a large land mass, but water shortage limits the amount of arable land (Dollar et al. 2020). These differences in factor endowments provide a basis for trade. The PRC tends to export manufactured products and import hi-tech machinery as well as energy and food. The US tends to export hi-tech products, services, food, and energy. In turn, it imports mostly manufactured goods.

As noted, one impetus for the trade war was a concern in the Trump administration about the large bilateral trade deficit that the US has with the PRC. But there has also been a growing concern in the US security community about the PRC's rising technological prowess. These national security concerns were certainly a factor in policies such as putting PRC firms on the entity list and strengthening US export controls over hi-tech products that might have dual use, including high-end semiconductors, telecommunications equipment, and inputs into super-computers.

Despite the 25% tariffs being in place for 4 years, they have had relatively little effect on US-PRC trade, as evidenced in Figure 1.6. The tariffs have certainly had some effect as US imports from the PRC declined modestly after 2018 and there has clearly been diversion of certain production to Southeast Asia. But it can be seen in the figure that, as of 2021, US imports from the PRC were down only 6.2% from the 2018 peak. In 2022, through August, US imports from the PRC were up 18%, so 2022 is likely to be a new record year for US-PRC trade. While overall imports have held up well, there is a lot of variation by product category. US imports of PRC telecommunication equipment or semiconductors are down 50%–60%, and surely this reflects in part the technology war. On the other hand, imports of other products such as computers or agricultural machinery have risen briskly.

Figure 1.6: US 2021 Imports from PRC Relative to 2018 Peak

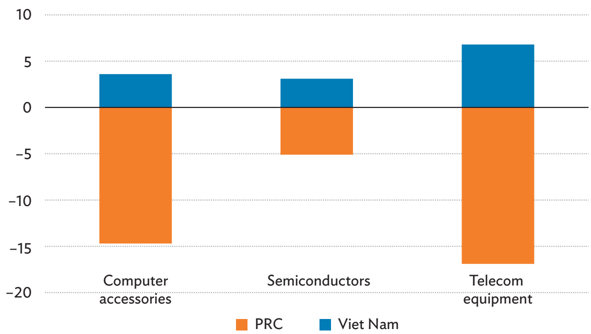


US = United States, PRC = People's Republic of China.

Source: US Department of Commerce, Bureau of the Census.

For the sensitive products, there is evidence that, to some extent, production shifted out of the PRC to other Asian developing economies, Viet Nam in particular, but also other countries such as Cambodia, Malaysia, and Thailand. The increase in US imports from Viet Nam was more than 100% between 2018 and 2021, reaching $100 billion and making Viet Nam America's sixth-largest trading partner on the import side. Referring back to Figure 1.2, the PRC share of US manufactured imports fell four percentage points between 2018 and 2021, while imports from other Asian developing countries rose an equivalent amount, with Viet Nam jumping the most. The large increase in imports came in quite a few categories, particularly some of the labor-intensive items that the PRC has specialized in: furniture, toys, sporting equipment, and cell phones. But particularly large increases were registered in the three product lines where US imports from the PRC declined: computer accessories, semiconductors, and telecommunication equipment. Viet Nam is a much smaller economy than the PRC; it can be seen in Figure 1.7 that additional imports from Viet Nam made up about 40% of the shortfall in PRC imports in these product lines. Some production has moved to other ASEAN countries as well, such as Thailand and Malaysia, but Viet Nam so far has been the big winner.

Figure 1.7: Change in US Imports 2018 to 2021 for Select Hi-Tech Products
(in billion $)

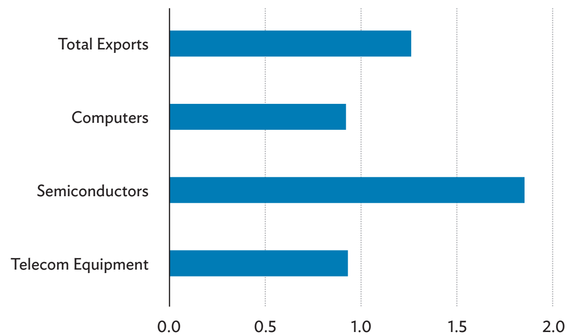


US = United States, PRC = People's Republic of China.

Source: US Department of Commerce, Bureau of the Census.

Concerning US exports, the PRC imposed reciprocal tariffs in the face of the 25% tariffs from the US, but for much of the time since then they have been suspended (Grant 2022). As a consequence, total US exports to the PRC have risen by 26% from the time of the initial trade war (2018) until 2021 (Figure 1.8). There is also some evidence of the American technology controls in the data on exports by detailed product categories. American semiconductor exports nearly doubled, whereas exports of computers or telecommunications equipment declined. This makes sense given the restrictions on American exports of certain technologies. Another factor is the Phase 1 trade deal agreed between the Trump administration and Beijing. The heart of this deal was a commitment that the PRC would increase its imports from the US by a total of $200 billion compared to 2017 levels, during 2020 and 2021. The deal was unrealistic from the start because it would have required US exports to increase by more than 40% in 2020 and then 40+% again in 2021. Macroeconomic variables do not normally vary by such magnitudes within a short period of 2 years. A further complication was the COVID-19 pandemic's disruptions to trade. These disruptions made the ambitious targets impossible (Cooray and Palanivel 2021). Not surprisingly, actual PRC purchases have fallen short of the target. American exports to the PRC increased in a healthy way, but the total amounts reached only 60% of the two-year target (Bown 2022).

Figure 1.8: US 2021 Exports to the PRC Relative to 2018

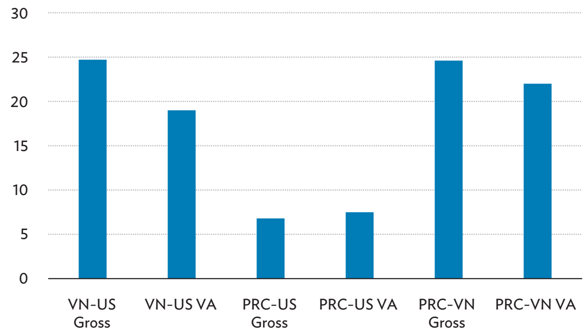


US = United States, PRC = People's Republic of China.

Source: US Department of Commerce, Bureau of the Census.

The economic conflict between the US and the PRC is more of a technology competition than a trade war in the sense that a few specific hi-tech categories have been affected a lot, while overall trade has continued at a high level. But some hi-tech products have been sharply affected by tariffs, subsidies, and other protection. A good example is the solar industry. The US imposed tariffs on PRC solar products in 2012 to counteract subsidies that the industry had gotten as it developed (DiPippo et al. 2022). Since then, PRC exports of solar panels to the US have fallen to nearly zero, while those from Southeast Asia soared, with Viet Nam the main supplier.

Figure 1.9: Average Growth Rates of Exports, 2010–2021



PRC = People's Republic of China, US = United States, VN = Viet Nam, VA = value added.

Source: Asian Development Bank, Trade in Value Added database.

These adjustments in supply chains are visible in the data, especially when one considers value added exports. For example, Viet Nam's gross exports to the US have been growing rapidly, at 24.7% per year over 2010–2021. The growth rate of the value added in Viet Nam's exports to the US was distinctly slower, at 19.0% (Figure 1.9). The latter figure is calculated using trade in value added data from the Asian Development Bank. The difference between the two figures indicates that the imported content in Viet Nam's production is on the rise. Furthermore, the PRC share of the imported content in Viet Nam's exports has risen rapidly, according to the same source.

In 2017, the PRC accounted for 10.8% of the imported content in Viet Nam's exports; by 2021 that figure had nearly doubled to 20.3%. These trends are consistent with some parts of value chains shifting out of the PRC to Viet Nam, but remaining connected to the home economy because it is PRC firms making the new investment and/or PRC firms supplying key intermediate inputs. Notice also, in Figure 1.9, that over the same period PRC exports to Viet Nam, both gross (24.6%) and value added (22.0%) have been rising rapidly. Finally, the figure also includes PRC gross and value-added exports to the US. Here, the pattern is reversed, with value-added exports rising faster (7.5%) than gross exports (6.8%). This indicates that some of the value added exported from the PRC to the US is going through other countries. It is also consistent with the PRC producing more of the value added in the products that it does ship directly to the US. Both are examples of shifts in supply chains.

The Biden administration has introduced new restrictions on the sale of semiconductor technology to the PRC, limiting PRC companies' access to US intellectual property and equipment. Though the US justifies this policy on national security grounds, the move will have a far wider set of consequences. Because the military and civilian application of these technologies cannot be cleanly separated, these restrictions risk damaging growth and innovation in the PRC high-tech commercial sector, deepening US–PRC tension and leading to "de-coupling" at least in this hi-tech part of the economy.

The PRC market accounts for nearly one-quarter of global demand for semiconductors. The US restrictions are likely to accelerate the PRC push for self-sufficiency in this sector, damaging the interests of individual American businesses. If the US is strict on extraterritorial enforcement of these restrictions, companies from third countries could potentially face a choice between following the US restrictions and enjoying access to the PRC market. This is likely to create tensions between the US and allied countries that do not want to make such a choice.

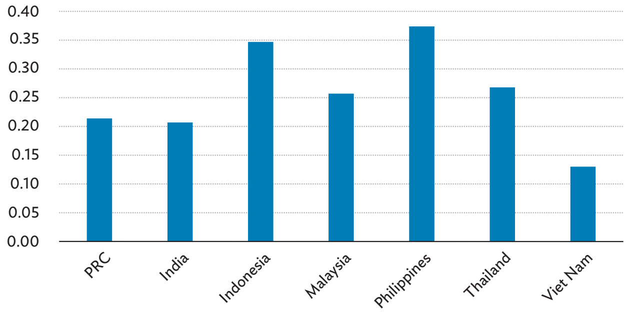
At the same time Congress passed the Creating Helpful Incentives to Produce Semiconductors and Science (CHIPS) Act, aimed at strengthening overall R&D and, specifically, to subsidize semiconductor production in the US with a budget of $52 billion. In 2022, Congress also passed the Inflation Reduction Act, a somewhat mis-named bill that primarily finances new investments related to climate change, especially promotion of solar and wind energy and a shift of the vehicle fleet from gas-powered to electric. This bill has raised some tension with key US allies in Europe and Asia. The crux of the international dispute centers on more than $50 billion in tax credits to encourage American households to purchase electric vehicles. The law restricts the credit to vehicles that are assembled in North America. It also has strict requirements surrounding the components that go into powering electric vehicles, including batteries and the critical minerals that are used to make them. That is creating new incentives for battery makers to build recycling and production facilities in the US. Foreign companies that manufacture cars and car parts in the US can also qualify for the credit. But some foreign carmakers, particularly those from Asia, tend to import more components for electric vehicles from outside the US, meaning that their models will not qualify for the subsidies. That has sparked accusations that the terms of the law were written to benefit US companies like General Motors or Ford, rather than foreign companies like Toyota and Honda, even though these foreign companies have invested heavily in the US. These subsidies for electric vehicles and components such as batteries would discourage auto companies from using PRC parts.

1.5 How Can Developing Asia Benefit?

Evolution of supply chains up to now cannot be characterized with a single generalization. There is no generalized onshoring or near-shoring to the US, though there might be some specific products for which such a characterization would be valid. US efforts to subsidize specific industries such as semiconductors or electric vehicles are not likely to increase total manufacturing production in the US as long as the macroeconomic stance is unchanged. In other words, the US is likely to import more of other manufactured products, providing opportunities to developing countries that are prepared to seize the growing opportunities. Some value chains are getting shorter, but others are getting longer. For example, the products whose final assembly moved to Southeast Asia now have longer supply chains since production starts with minerals, machinery, and components from PRC, which then travel to Southeast Asia for further processing, before finally heading to consumer markets in the US and EU. Many developing countries in Asia have wages below those of the PRC, as PRC wages have risen with productivity and with the emerging decline in the PRC labor force. Asian developing countries can potentially attract more investment and have a greater role in supply chains, but abundant low-cost labor is not enough, as evidenced by the many low-income countries that cannot get a foothold in supply chains. What are some of the factors that determine where production moves?

Global supply chains are largely organized by multinational companies, hence openness to direct foreign investment is critical. Most countries have gotten this message and are open to direct investment in manufacturing. But manufacturing supply chains also increasingly rely on service inputs—finance, transportation, telecom, for example. Many developing countries are still quite closed in key service sectors, with the result that their overall openness is only partial. Large ASEAN countries such as Indonesia, Malaysia, Thailand, and the Philippines are significantly less open to FDI than the PRC is (Figure 1.10). Only Viet Nam among the large ASEAN countries has gone in the other direction and is more open than PRC.

Figure 1.10: OECD FDI Restrictiveness Index by Country 2020
(Index, 0=open, 1=closed)



FDI = foreign direct investment, OECD = Organisation for Economic Co-operation and Development, PRC = People's Republic of China.

Source: OECD, FDI Regulatory Restrictiveness Index, 2021.

Table 1.1: Investment Climate Indicators, Mexico and East Asia

	Logistics Performance Index (LPI) (1–5)	Intellectual Property Rights Index (1–7)	Tertiary School Enrollment Rate (% gross)	Programme for International Student Assessment (PISA) Math Mean Score
	2018	2022	2019	2018
Viet Nam	3.27	4.497	28.6	496
Philippines	2.90	4.495	31.6	353
Indonesia	3.15	4.799	36.3	379
PRC	3.61	5.594	53.8	5911
Thailand	3.41	4.735	n.a.	419
Mexico	3.05	4.623	42.8	409
Malaysia	3.22	6.3	43.1	440
Rep. of Korea	3.61	6.384	98.4	526
Japan	4.03	7.677	64.1	527
Singapore	4.00	7.967	91.1	564
India	3.18	5.143	29.4	n.a.

PRC = People's Republic of China.

Source: The data for LPI are from the "World Development Indicators," 2018, the World Bank. The data for intellectual property are from the "International Property Rights Index 2022," 2022, the Property Rights Alliance. The data for Tertiary School Enrollment Rate are from "World Development Indicators," 2019, the World Bank. The data for PISA Math Mean Score are from the "PISA 2018 Results," 2018, the Organisation for Economic Co-operation and Development.

There are other important aspects of the investment climate. Multinational firms are looking for a good economic environment in which they can source inputs either domestically or internationally. Some of the key ingredients into this kind of environment are logistics, IPR protection, and quality and extent of education. Table 1.1 shows some relevant indicators for the ASEAN countries plus Mexico, PRC, and India. High-income countries such as Japan, Republic of Korea, and Singapore are listed for comparison. Among the developing countries, the PRC stands out as having the best logistics and human capital. Its measure on the Logistics Performance Index is the same as Republic of Korea, even though the latter country is at a much higher level of development. Among the lower wage economies, Viet Nam stands out as having relatively good logistics. India has poor performance in this area, a reason why Indian manufacturing continues to punch below its weight. As noted earlier, Mexico also has serious problems with logistics.

Another important issue is intellectual property protection. Multinational corporations (MNCs) are bringing their intellectual property to the value chains and reasonably good protection is one factor that attracts them to particular locations. Developing countries typically have weaker protection than advanced economies, but among developing countries there is much variation. The PRC stands out with relatively good intellectual property protection. At the other end of the spectrum, Mexico is rather poor. This hampers the potential for significant near-shoring back to North America. Viet Nam looks good on all the measures, which is why it has received the most of the shift in production occasioned by the tech war. But it would need to improve in all areas if it wants to keep expanding its role in supply chains, especially hi-tech ones.

There is also the important issue of human capital. The table includes two indicators: tertiary school enrollment rate and Programme for International Student Assessment (PISA) math scores. The PRC stands out as having outstanding human capital indicators, with tertiary enrollment and PISA scores analogous to developed countries such as Japan and Republic of Korea. The PISA testing covers only Beijing, Shanghai, and some coastal provinces, but still these areas have a population of hundreds of millions. The outstanding human capital, plus excellent logistics and relatively good intellectual property protection, explains the PRC position at the center of manufacturing value chains. Human capital weaknesses hold back countries such as India, Indonesia, Thailand, the Philippines, and Mexico.

A final consideration is carbon footprint. Climate change is a global issue, and at the moment the world is not making enough progress with carbon reduction to meet the target to limit the increase in average temperatures to 1.5 degrees Celsius. Advanced economies led by Europe are considering border adjustment taxes that would mostly hit developing countries. The logic of border tax adjustment is that production of particular items in the South is often more carbon intensive than similar production in advanced economies. Global welfare is improved if that negative externality is taxed. However, this approach could easily turn into an excuse for more general protection against poor countries that hampers their development opportunities. In particular, such a tax could limit opportunities for developing countries' participation in supply chains. Developing countries should look for opportunities to reduce carbon emissions in a way that is cost-effective and not harmful for their development. It would help if rich countries provided the financial and technological assistance that has been promised at previous climate summits. It is in developing countries' interest to get out ahead of this issue and to prevent carbon footprint from becoming an excuse for protectionism.

1.6 Conclusion

The review of trends in global supply chains reveals a complex picture with different shifts in different sectors. There is no evidence of generalized manufacturing re-shoring to the US, or near-shoring to North America. There is some tendency towards near-shoring in the PRC data as that country trades more with its RCEP partners and relatively less with the US and Europe. The decline in trade between the PRC and the US is concentrated in a few, hi-tech sectors, so it is more of a tech war than a trade war. There is no large-scale shift of production out of the PRC, but in some tech products final assembly has shifted to Viet Nam and other ASEAN countries to get around US tariffs and to diversify supply chains. Many international firms are hedging by retaining much of their production in the PRC but adding capacity elsewhere, especially Viet Nam. Asian developing countries can benefit from increased trade with both the PRC and the US, and in some cases will be intermediaries between the two giants. To garner these benefits developing countries need to strengthen their investment climates, especially openness to foreign trade and direct investment, logistics, intellectual property protection, and human capital.

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2

Trade Facilitation and Global Value Chains in a Post-Pandemic World

Inmaculada Martínez-Zarzoso

2.1 Introduction

In the 2000s, the world economy experienced a sharp increase in international trade flows, as well as an increasing diversification of traded goods and services. Substantial improvements in information technology and sustained economic growth have been important factors contributing to this increase in trade (Xing, Gentile, and Dollar 2021). In particular, part of this new trade has been in intermediate products with the development of global value chains (GVCs). However, this trend was interrupted by the outbreak of the economic crisis of 2008–2009 and more so by that of the COVID-19 pandemic in 2020. One consequence of the latter crisis was the disruptions in GVCs driven by the lockdowns and the subsequent wish to relocate production to nearby countries. On the one hand, these disruptions were related to the pandemic outbreaks happening in different countries simultaneously and the lack of workers in important industries related to GVCs, such as logistics and transport. On the other hand, these phenomena could have accelerated the ongoing transformation in the logistics branch with reinforced support for paperless trade, electronic documents, and the automation of customs procedures. In relation to this, the ratification of the Trade Facilitation Agreement in 2017[1] should have started to pave the road that countries have to follow to adopt the required measures for implementation.

[1] WTO members ended their negotiations at the 2013 Bali Ministerial Conference with the landmark Trade Facilitation Agreement (TFA). The agreement entered into force on 22 February 2017, after its ratification by two thirds of the WTO members. See https://www.wto.org/english/tratop_e/tradfa_e/tradfa_e.htm for more details.

The main contribution of this chapter is quantifying the advantages derived from improving trade facilitation measures that help reduce trade barriers among countries, including time delays and administrative burdens for the products and services exchanged. This quantification should help to disentangle the effect of different components of trade facilitation in increasing gross trade and trade in value added after COVID-19, particularly in Asia and the Pacific countries. The main question to be answered is whether a number of trade facilitation measures implemented by countries have contributed to increasing bilateral and aggregated trade, as well as to the participation of countries in GVCs, and if so, to what extent.

There is scant empirical research covering the periods before and after the Trade Facilitation Agreement that includes value-added exports in the analysis. For instance, while some authors focused on the effects of transport infrastructure on trade (Limao and Venables 2001; Márquez-Ramos et al. 2011) and on trade facilitation issues (Wilson, Mann, and Otsuki 2003; Engman 2005; Persson 2007; Martínez-Zarzoso and Márquez-Ramos 2008; Hendy and Zachi 2021; Shepherd 2022; Kareem, Martínez-Zarzoso, and Bruemer 2022), only a few of them focused on value-added exports in developing countries (Xu, Sun, and Jiang 2022; Zhang and Martínez-Zarzoso 2022), and none of them covered recent years and aspects related to trade finance, support for small and medium-sized enterprises (SMEs), agriculture, and women. We will be able to include these factors in the analysis by making use of a new data set based on the UN Global Surveys on Digital and Sustainable Trade Facilitation, covering 144 countries worldwide for the years 2015, 2017, 2019, and 2021.

This chapter aims to narrow this gap in the literature by investigating the relationship between trade facilitation and exports (gross exports and GVC participation) for a global sample of countries and a recent period of time (2015–2021) that covers the COVID-19 pandemic. The empirical methodology consists in applying a gravity model of bilateral trade estimated using panel data methods that control for unobserved heterogeneity using multidimensional fixed effects and panel data models with country-fixed effects for aggregated trade flows and GVC participation and position.

The main results show that most of the trade facilitation indicators considered, namely those related to transparency, paperless trade, institutions, and formalities, have a direct influence on trade flows and some of them on participation in GVCs. However, there are insufficient data to assess the importance of sustainable trade facilitation, given that the data collection for such indicators started in 2020 and there is no information for many countries. Moreover, transparency policies will increase trade in manufactured goods more than proportionally, especially in low-income countries in the Asia and the Pacific region. Second, improving the quality of TF-related institutions will foster participation in global value chains in the region. Finally, public investments directed towards improving their logistics performance would be of special relevance for small islands.

The rest of the chapter is organized into five sections. Section 2.2 presents a review of the literature on trade facilitation. Section 2.3 describes the data and variables used and some stylized facts. Section 2.4 describes the empirical strategy and the econometric estimation techniques used. Section 2.5 presents and discusses the main results from estimating a gravity model of bilateral trade and panel data models for aggregated trade and GVC indicators. Finally, Section 2.6 concludes and presents some policy implications.

2.2 Literature Review

The international trade literature has focused widely on trade facilitation issues since the early 2000s. Seminal contributions by Wilson, Mann, and Otsuki (2003, 2005) used a wide definition of trade facilitation and claimed that trade in the Asia and the Pacific region could increase by 21% if low performers improved their scores halfway to the average. Instead, Engman (2005) used the World Trade Organization (WTO) definition of trade facilitation, simplifying and harmonizing international trade procedures involving activities at the border, while also finding positive impacts on trade. A number of authors[2] investigated the effects of specific measures, including administrative barriers (Hummels and Schaur 2013; Djankov, Freund, and Pham 2010; Hendy and Zaki 2021), information technology (Márquez-Ramos et al. 2007; Rodriguez-Crespo and Martínez-Zarzoso 2021), port efficiency (Limao and Venables 2001; Martínez-Zarzoso and Hofmann 2007; Wilmsmeier, Martínez-Zarzoso, and Fiess 2011), maritime networks (Márquez-Ramos et al. 2011), and the quality of institutions (Gylfason, Martínez-Zarzoso, and Wijkman 2015; Martínez-Zarzoso and Márquez-Ramos 2019). The main takeaway from the existing literature is that advances in trade facilitation actions foster international trade to some extent, with the key issue being quantifying the effects to ascertain what measures are more effective. More recently, some authors have focused on the effects of TF on GVC participation. In this respect, Kumar and Shepherd (2019) find that the full implementation of the TF agreement will increase trade by about 3.5% with respect to 2015 and could lead to changes in the composition

2 See Wilson, Mann, and Otsuki (2005) for a comprehensive review of previous research on specific trade facilitation measures.

of trade, promoting trade in intermediates and hence the development of value chain trade mostly in middle-income economies. Moreover, Shepherd (2022) investigates the effect of changes in trade facilitation performance on changes in GVC trade. He uses the TF indicators computed by the OECD for the period 2015–2019 and finds that in some sectors, the estimated elasticity of TF on trade is higher for intermediates than for total trade, with the quantitative differences being small.

In addition, several works have jointly estimated the effect of trade facilitation variables and policy trade barriers (Márquez-Ramos, Martínez-Zarzoso, and Suárez-Burguet 2012 Hendy and Zachi 2021, among others), showing that the former are in general more important than the latter for trade. Finally, some recent papers have specifically focused on Asia or Asian subregions. More specifically, Central Asia was the focus of Kim, Mariano, and Abesamis (2022) and Cheong and Turakulov (2022), whereas Ismail (2021) investigated digital trade facilitation in selected Asian countries and Ramasamy and Yeung (2019) analyzed the impact of trade facilitation in relation to the People's Republic of China's (PRC) One Belt, One Road initiative. Also, Halaszovich and Kinra (2020) present some insights into trade facilitation in Asia, indicating that the elements of national transportation systems positively influence both trade and foreign direct investment.

With regard to the empirical methodologies, two main modeling strategies have been used. First, a number of authors relied on estimating a gravity model of trade, which includes trade facilitation factors in the specification as proxies for trade easiness (Wilson, Mann, and Otsuki 2003, 2005; Djankov, Freund, and Pham 2010; Nordas, Pinali, and Grosso 2006; Soloaga, Wilson, and Mejía 2006; Persson 2007; Martínez-Zarzoso and Márquez-Ramos 2008; Kumar and Shepherd 2019; Kim, Mariano, and Abesamis 2022; Shepherd 2022). Second, several works (Decreux and Fontagne 2006; Dennis 2006; Cheong and Turakulov 2022, among others) used computable general equilibrium models to estimate the effect of trade facilitation indices on trade flows. Overall, independently of the approach used, the results of the studies show positive and statistically significant effects derived from improved trade facilitation on international trade.

The present chapter departs from existing literature in two respects. First, it focuses on both bilateral and aggregated trade and on GVCs; and second, it analyzes the effect of newly collected TF measures in the most recent years and after the TF agreement with a special focus on developing countries in the Asia and the Pacific region. It also provides policy recommendations for developing Asia and the Pacific derived from the model estimations, disentangling the effectiveness of a wide range of TF actions, taken at a country level.

2.3 Data, Variables, and Stylized Facts

2.3.1 Data and Variables

Export and import data at the bilateral level are from UNCTAD, and data on aggregated exports and imports of goods and services, as well as GDP and GDP per capita at constant prices, are from the World Development Indicators data set. Other gravity variables, namely geographical distance, and whether countries share a common language, common border, and have or have had a colonial relationship, are extracted from the Centre d'Études Prospectives et d'Informations Internationales (CEPII). The Doing Business data set from the World Bank is the source for the number of documents needed to trade, time to trade, and cost to trade across countries, with data available using the new methodology from 2014 to 2019. Data for regional trade agreements (RTAs) are from De Sousa (2012), updated by Martínez-Zarzoso and Chelala (2021), using information from the WTO. Trade facilitation data are from the United Nations Global Surveys on Digital and Sustainable Trade Facilitation.[3] They cover 144 countries worldwide for the years 2015, 2017, 2019, and 2021. The 2021 survey includes 58 questions[4] that are listed in the Appendix (Table A2.1). The implementation stage and rate of implementation for each measure are provided for selected groups of trade facilitation factors. The grouped TF measures are transparency, formalities, institutions, paperless, cross-border, transit, TF for SMEs, agriculture, and women. Each of them varies from zero to 100, indicating the rate of implementation (zero = no implementation),[5] and is composed of a number of subcomponents as indicated in Table A2.1. For instance, the transparency measure includes questions Q2–Q5 and Q9. The first four indicate the advance publication of trade-related regulations on the Internet and stakeholders' consultation, and the fifth whether there is an independent appeal mechanism. The original measures are coded with values from 0 to 3, indicating whether the measure: has been not implemented, is in the pilot stage of implementation, has been partially implemented, or has been fully implemented, respectively.

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3 https://www.untfsurvey.org/.

4 The question numbers correspond to those in the UNTF Survey questionnaire, available at https://www.untfsurvey.org/files/documents/2021-Survey-Questionnaire-English.pdf.

5 The overall implementation rate of each subgroup is defined as: $IR_k = \Sigma(Q_n/3m_k)$, where Q_n is the score of question number n, and m_k is the number of measures included in group m. The methodology used is described here: https://www.untfsurvey.org/files/documents/2021-Survey-Methodology.pdf.

The survey was led and coordinated by ESCAP and jointly conducted in 2021 by five United Nations Regional Commissions: ECA, ECE, ECLAC, ESCAP, and ESCWA. Data for 2021 are duplicated for countries that participated in the 2019 Global Survey but did not answer in 2021 (Antigua and Barbuda, Belize, Brazil, El Salvador, Guyana, Saint Vincent and the Grenadines, Trinidad and Tobago, Tanzania, and Tunisia).

Proxies for GVCs are constructed using information from the UNCTAD-Eora GVC database that covers the period from 1990 to 2018, which is the last year available, to decompose gross exports (see Koopman, Wang, and Wei 2014; Wang et al. 2017; Borin and Mancini 2019). The gross exports' components are value-added exports (VA), foreign value added (FVA), domestic value added (DVA), and domestic value added in exports (DVX), available for 189 countries.[6]

A country's GVC participation (GVCP) is measured as a share of its gross exports (UNCTAD 2013). For country and year, the GVC participation index is given by:

$$GVCP_{it} = \left(\frac{FVA_{it} + DVX_{it}}{Gross\ Exports_{it}}\right) * 100 \qquad (1)$$

where FVA_{it} denotes foreign value added in country i at time t. DVX_{it} denotes domestic value added in exports in country i at time t.

A second variable constructed is the GVC position index, which indicates the relative "upstreamness" of a country in a GVC (Koopman, Wang, and Wei 2014). Examples of upstream activities are branding, design, and research and development, with all of them being capital-intensive pre-production activities that require high-skilled labor. Otherwise, downstream activities are associated with post-production services of high value added, such as sales and marketing. The GVC position of a country in a given year is given by:

$$GVCPosition_{it} = \left[\left(ln\frac{1+DVX_{it}}{Gross\ Exports_{it}}\right) - \left(ln\frac{1+FVA_{it}}{Gross\ Exports_{it}}\right)\right] * 100 \ (2)$$

where FVA_{it} denotes foreign value added in country i at time t. DVX_{it} denotes domestic value added in exports in country i at time t.

Table 2.1 shows the summary statistics of the variables used in the empirical application of the gravity model of trade. The table indicates the number of observations (obs), mean values (mean), standard deviations

[6] For the years from 2016 to 2018, the components are obtained using an imputation technique based on the macroeconomic estimates of the IMF World Economic Outlook (WEO) (Casella et al. 2019).

(Std. dev.), and minimum and maximum values of the dependent (ln exports) and independent (income, distances, gravity variables, and TF indicators) variables used. TF indicators are explained in the next section, focusing specifically on the Asia and the Pacific region. The TF average values shown in Table 2.1 mainly indicate that there is room for improvement for many countries, since they are around 30%–65% out of 100%.

Table 2.1: Summary Statistics

Variable-	Obs	Mean	Std. Dev.	Min	Max
ln exports of manufactures	6,206	5.562	4.080	–6.908	16.574
ln GDP exporter	6,206	24.290	1.645	20.721	28.235
ln GDP importer	6,206	24.298	1.776	20.520	28.235
Ln distance	6,206	8.330	0.900	4.558	9.775
Common language	6,206	0.395	0.489	0	1
Common colony	6,206	0.160	0.366	0	1
Contiguity	6,206	0.074	0.262	0	1
Regional trade agreement (RTA)	6,206	0.260	0.439	0	1
WTO exporter	6,206	0.968	0.177	0	1
WTO importer	6,206	0.971	0.167	0	1
Trade Facilitation Indicators:					
TFI exporter	6,206	0.544	0.186	0.097	0.91
TFI importer	6,206	0.549	0.190	0.097	0.91
Transparency importer	6,206	0.640	0.274	0	1
Transparency exporter	6,206	0.635	0.274	0	1
Formalities importer	6,206	0.659	0.206	0.125	1
Formalities exporter	6,206	0.654	0.206	0.125	1
Institutions importer	6,206	0.525	0.207	0	1
Institutions exporter	6,206	0.523	0.208	0	1
Paperless importer	6,206	0.583	0.240	0.074	1
Paperless exporter	6,206	0.579	0.234	0.074	1
Transit importer	5,509	0.642	0.236	0	1
Transit exporter	5,631	0.639	0.235	0	1
Smes importer	4,658	0.339	0.203	0	0.867
Smes exporter	4,649	0.339	0.206	0	0.867
Agriculture importer	4,427	0.422	0.303	0	1
Agriculture exporter	4,382	0.428	0.298	0	1
Women importer	4,546	0.191	0.244	0	1
Women exporter	4,496	0.195	0.244	0	1

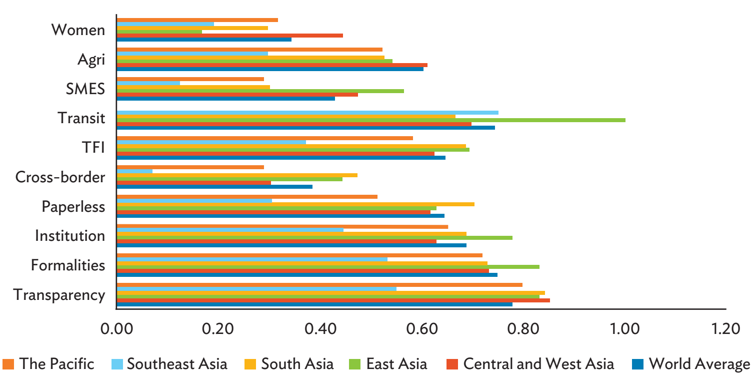
Note: See Table A2.1 for a description of the variables. TFI denotes the trade facilitation index.

Source: Author's elaboration. WTO denotes World Trade Organization.

2.3.2 Stylized Facts

In this section, we present some figures that show the implementation stage of TF measures in 2021. Figures 2.1 and 2.2 show the rate of implementation in 2021 of the TF aggregated indicators in the Asia and the Pacific region by subregions and in the world economy compared with the Asia and the Pacific region, respectively. Figure 2.1 indicates that East Asia is the best performer in terms of transparency, transit, and formalities, with TF measures reaching more than 80% of the full implementation target (scale between 0 and 1), but the same subregion is the worst performer in terms of sustainable TF measures (related to women, sustainable agriculture, and SMEs). Central and West Asia are also doing well in regard to transparency, but not so concerning cross-border TF, as they have the lowest degree of implementation (below 30%). As regards Southeast Asia, sustainable TF is also poorly implemented, whereas transparency and formality TF measures show a better achievement. The Pacific does best in transparency TF and worst in cross-border TF measures, whereas South Asia shows 80% implementation in transparency, and around 70% in formality, institutions, and paperless TF-adopted measures.

Figure 2.1: Trade Facilitation in Asia and the Pacific in 2021

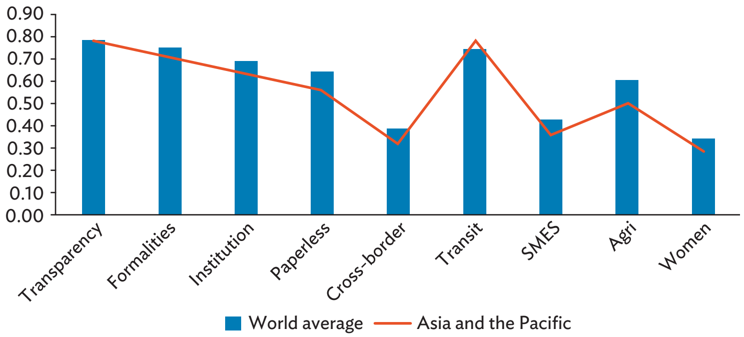


Source: https://www.untfsurvey.org/region?id=ESCAP and author's elaboration. See list of countries in each subregion in Table A2.2 in the Appendix.

Figure 2.2 indicates that countries in Asia and the Pacific generally perform around the global average in some categories, such as transit and transparency, and slightly below concerning border formalities.

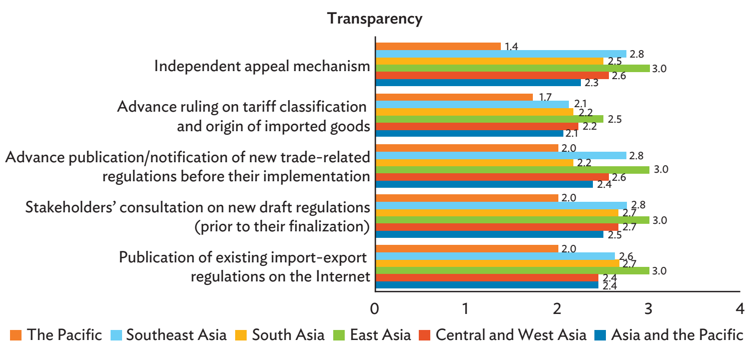
Otherwise, Asia and the Pacific have a worse performance than the world average in the case of paperless trade and institutions, meaning there is room for improvement.

Figure 2.2: Trade Facilitation in the World in 2021



Source: https://www.untfsurvey.org/region?id=ESCAP and author's elaboration.

Figure 2.3: Degree of Implementation of Transparency TF Measures in Asia and the Pacific

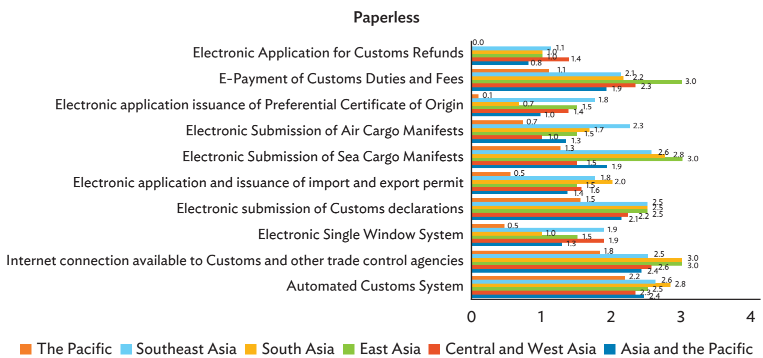


Note: Average scores are calculated only using economies where measure implementation information is available (i.e., not implemented = 0, planning stage = 1, partially implemented = 2, or fully implemented = 3).

Source: https://www.untfsurvey.org.

Figures 2.3–2.5 show specific TF scores (notice that the variations go from 0 to 3) for different subregions in Asia and the Pacific and specific TF indicators. Those are related to transparency (Figure 2.3), paperless trade (Figure 2.4), and formalities (Figure 2.5). Figure 2.3 indicates that the best score in transparency items is for countries in East Asia, whereas the worst refers to countries in the Pacific subregion. This means that while the transparency TF measures have been fully implemented in the former, they are still in the planning stage or have been partially implemented in the latter region. In regard to paperless TF measures, Figure 2.4 shows that there is room for improvement in most subregions concerning the implementation of electronic single windows and several electronic application processes, which are still not fully implemented in any of the considered subregions. Similarly, Figure 2.5 shows that formalities for TF are, at best, partially implemented, indicating that risk management in South Asia is either in the planning stage or partially implemented, as is the case for post-clearance audits in the Pacific.

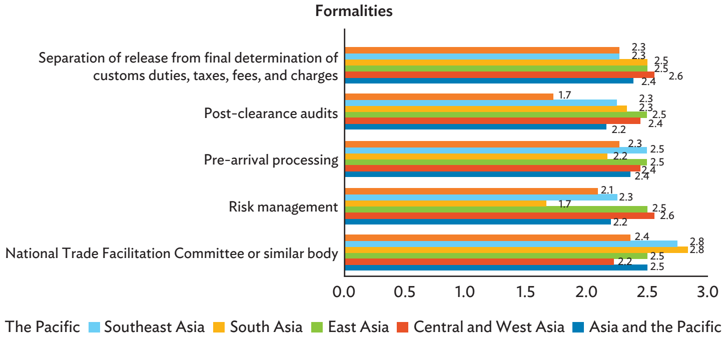
Figure 2.4: Degree of Implementation of Paperless TF in Asia and the Pacific



Note: Average scores are calculated only using economies where measure implementation information is available (i.e., not implemented = 0, planning stage = 1, partially implemented = 2, or fully implemented = 3).

Source: https://www.untfsurvey.org.

Figure 2.5: Degree of Implementation of Formalities TF in Asia and the Pacific



Note: Average scores are calculated only using economies where measure implementation information is available (i.e., not implemented = 0, planning stage = 1, partially implemented = 2, or fully implemented = 3).

Source: https://www.untfsurvey.org.

2.4 Empirical Strategy

To evaluate the effects of TF measures across countries, in light of the TF agreement, the main strategy consists in: first, estimating a gravity model of bilateral trade for the years 2016 to 2021 for a global sample of countries and for exports of primary and manufactured products separately; second, estimating correlations between TF measures and the total exports of goods and services and GVC proxies for a global sample of countries and for specific geographical areas, with a special focus on the Asia and the Pacific region; third, considering the doing business time to exports and cost to export and import as dependent variables.

2.4.1 The Gravity Model of Trade

The gravity model of trade has been extensively used to estimate the factors that explain bilateral trade flows among countries (Feenstra 2004). In the last four decades, being a structural model with firm theoretical foundations, it has been considered the workhorse for international trade analysis, as documented by Eaton and Kortum (2002), Anderson and Van Wincoop (2003), Allen, Arkolakis, and Takahashi (2014), Head and Mayer (2014), and Anderson, Larch, and Yotov (2018), among others. Therefore, it is suitable for evaluating the effects of trade facilitation factors.

The international trade theories in relation to the gravity model were reformulated and modernized by Anderson and Van Wincoop (2003). The model's underlying assumptions are that the elasticity of substitution between goods is constant and products are differentiated by country of origin. Moreover, bilateral trade costs are assumed to be symmetric, so prices differ among countries. According to the gravity model, bilateral exports between two countries are directly proportional to the product of their economic mass and inversely proportional to the costs of trade between them. The multiplicative form of the model is given by:

$$X_{ijt} = \frac{Y_{it}Y_{jt}}{Y_t^W}\left(\frac{t_{ijt}}{P_{it}P_{jt}}\right)^{1-\sigma} \tag{3}$$

where X_{ijt} is the bilateral exports from country i to country j in year t, and Y_{it} (Y_{jt}) and Y^W are the GDP of the exporting (importing) country and the world in year t, respectively. t_{ijt} is the trade costs between the pair of trading countries in year t, and P_{it} and P_{jt} are price indices that reflect the multilateral resistance terms (MRTs). σ is the elasticity of substitution between goods.

The model specification in its log-linear form is given by:

$$\begin{aligned} ln\, X_{ijt} &= ln\, Y_{it} + ln\, Y_{jt} - \ln Y_t^W + (1-\sigma)\ln t_{ijt} \\ &\quad -(1-\sigma)ln\, P_{it} - (1-\sigma)\ln P_{jt} \end{aligned} \tag{4}$$

The presence of trade costs and MRTs in Equation (4) implies that some estimation issues must be considered. For instance, the trade cost function t_{ijt}, is generally assumed to be a function of several trade barriers. These include the geographical distance between countries, the lack of a common border, a common colonial past and common language (all time-invariant), and a number of policy variables, including membership in multilateral agreements such as: regional trade agreements (RTAs), World Trade Organization (WTO), and trade facilitation variables (all time-varying). The trade cost function is given by:

$$\begin{aligned} T_{ijt} = d_{ij}^{\alpha_3} TF_{it}^{\alpha_4}\, TF_{jt}^{\alpha_5} \exp(&\alpha_6 Contig_{ij} + \alpha_7 Comlang_{ij} + \alpha_8 Comcol_{ij} \\ &+\alpha_9 RTA_{ijt} + \alpha_{10} WTO_{ijt}) \end{aligned} \tag{5}$$

Substituting Equation (5) into Equation (4) and extending the model with year dummy variables and an error term gives the next model specification:

$$\begin{aligned}\mathrm{Ln\,X_{ijt}} = {} & \pi_i + \delta_j + \alpha_1 \ln Y_{it} + \alpha_2 \ln Y_{jt} + \alpha_3 \ln D_{ij} + \alpha_4 TF_{it} \\ & + \alpha_5 TF_{jt} + \alpha_6 Contig_{ij} + \alpha_7 Comlang_{ij} + \alpha_8 Comcol_{ij} \\ & + \alpha_9 RTA_{ijt} + \alpha_{10} WTO_{ijt} + \theta_t + u_{ijt} \qquad (6)\end{aligned}$$

where X_{ijkt} denotes exports of shipped from country *i* to country j in year *t*, $\ln D_{ij}$ denotes the natural logarithm of the distance between country *i* and country *j*, and TF_{it} (TF_{ij}) denotes trade facilitation measures taken by country *i* (*j*) at time *t*. $Contig_{ij}$ takes the value of 1 for a pair of countries sharing a border, and 0 otherwise. $Comlang_{ij}$ and $Comcol_{ij}$ take the value of 1 when a pair of countries share an official language or have ever had a colonial relationship, respectively, and 0 otherwise; RTA_{ijt} takes the value of 1 when the trading countries are members of a regional trade agreement, and 0 otherwise; WTO_{ijt} takes the value of 1 if country *i* or country *j* is a WTO member and 2 if both are members. f_t denotes a set of year dummies that proxy for business cycle and other time-variant common factors (globalization) that affect all trade flows in the same manner.

The MRTs are modeled using time-invariant country-specific dummies (p_i, l_j), given the short time span of our sample and the year-time variation of our TF variables. In the final specification, the time-invariant gravity variables that account for trade cost factors are substituted by country-pair fixed effects to control for all bilateral unobserved characteristics. The model is specified as:

$$\begin{aligned} ln\,X_{ijt} = {} & \gamma_{ij} + \beta_1\, ln\,Y_{it} + \beta_2\, ln\,Y_{jt} + \beta_3\, ln\,TF_{it} \\ & + \beta_4\, ln\,TF_{jt} + \beta_5 RTA_{it} + \alpha_6 WTO_{jt} + \theta_t + u_{ijt} \qquad (7)\end{aligned}$$

In this regard, we follow Baier and Bergstrand (2007) and Head and Mayer (2014), who suggested the use of pair fixed effects and time dummy variables to control for bilateral unobserved heterogeneity and common time trends, respectively. For completeness, we also include estimates of the traditional gravity model (6) that include economic and bilateral variables and with common time effects in the Appendix (Table A2.3 for manufactures and Table A2.4 for primary products).

According to Head and Mayer (2014), fixed effects that vary by exporter-time (*it*) and importer-time (*jt*) could be included as a proxy for MRTs. In this case, variables such as GDP and TF cannot be identified directly.[7] As a way to identify the effect of variables that vary by country

[7] The direct effect on exports of variables that change by country and over time is subsumed in the exporter-time and importer-time fixed effects.

and over time, such as TF, a two-stage approach is used (also following Martínez-Zarzoso and Chelala 2020). In the first stage, the country-time fixed effects are estimated from the following gravitational model:

$$lnX_{ijt} = \delta_{ij} + \tau_{it} + \varphi_{jt} + \alpha_1 TP_{ijt} + \varepsilon_{ijt} \tag{8}$$

Exporter-time (τ_{it}) and importer-time (φ_{it}) fixed effects represent trade barriers that are country-specific and vary over time, that is, third-party countries' barriers to trade that affect the costs of trade.

The exporter-time and importer-time fixed effects, extracted from Model (8), are used as dependent variables in the second stage:

$$\hat{\tau}_{it} = \gamma_i + \beta_1 \ln Y_{it} + \beta_2 TF_{it} + \beta_3 X_{it} + \eta_{it} \tag{9}$$

To account for factors such as institutions, infrastructure, and cultural factors that vary slowly, the estimation includes unobservable country effects, γ_i. Y_{it} indicates the exporter's GDP. *TF* takes the value of 1 when the exporting country has applied a given TF improvement in period *t*. X denotes additional control variables that have country-time variation.

In addition to the log-linearized models proposed, and based on the ongoing development of new techniques for estimating the gravity model based on theoretical advances (Head and Mayer 2014; Yotov, Piermartini, and Larch 2016; Egger, Larch and Yotov 2022), we also estimate the model in its multiplicative form using a Poisson pseudo maximum likelihood (PPML) estimator:

$$X_{ijt} = \exp\left(\vartheta_{ij} + \tau_{it} + \varphi_{jt} + \delta_1 TP_{ijt}\right) \varepsilon_{ijt} \tag{10}$$

where the dyadic fixed effects associated with trade, u_{ij}, represent the time-invariant characteristics of the trade relationship between *i* and *j*, as above. TP_{ijt} represents time-variable bilateral factors, such as being a member of the WTO or of an RTA. Finally, ε_{ijt} is the error term and is assumed to be identically or independently distributed. As before, we extract the country-time fixed effects from Model (10) and use them in a second step, similarly to Equation (9).

2.4.2 Effect of Trade Facilitation on Exports and GVCs

In this section, we estimate a panel data model using country-level variables related to trade and GVCs and link them with TF factors. Estimating the models in first differences will also allow us to infer the effect of the pandemic on fostering the use of electronic documents and procedures to decrease trade costs. This, however, will only be possible with trade variables, given that trade-in value added and the related variables are only available until 2018.

As dependent variables, we alternatively consider total trade, trade in goods, and trade in services. Moreover, we also use the participation of countries in GVCs, using the two proxies described in the data and variables section, that is, the GVC participation index and the GVC position of a country. The empirical strategy to infer the effect of trade facilitation improvements on trade and GVC variables consists in estimating a panel data model that controls for country and time unobserved heterogeneity and estimated with the variables in first differences. This method is also known as a "random trend model" (Wooldridge 2010), which is an extension of the standard unobserved effects models for panel data. The model allows each country to have its own time trend. The country-specific trend is an additional source of heterogeneity. The estimated model is given by:

$$\ln y_{it} = \theta_i + g_i t + \delta_1 TF_{it} + \delta_3 T_{it} + \omega_{it} \qquad (11)$$

where y_{it} is the natural log of the trade and GVC variables and g_i is (roughly) the average growth rate over a period (holding the explanatory variables fixed). Since we would like to allow θ_i and g_i to be arbitrarily correlated with the other explanatory variables, our analysis is within a fixed-effects framework. Our approach to estimating Model (11) is to difference away θ_i and estimate the model given by:

$$\Delta \ln y_{it} = g_i + \delta_1 \Delta TF_{it} + \delta_3 \Delta T_{it} + \Delta\omega_{it} \qquad (12)$$

where we have used the fact that $g_i t$ - $g_i(t\text{-}1)$ = g_i and Equation (12) becomes the standard fixed-effects model. In differencing the equation to eliminate θ_i we lose one time period, so that Equation (12) applies to T-1 time periods. We are able to apply fixed-effects methods to Equation (12) since our trade facilitation indicators have at least four distinct waves, and the minimum requirement to estimate this model is T = 3. According to Wooldridge (2010), it is reasonable to assume that the first difference of the residuals is serially uncorrelated, in which case the FE method applied to Equation (12) is attractive.

2.4.3 Cost of Trading Across Countries

The third set of estimations takes the variables from the World Bank Doing Business data set as dependent variables, one by one. These will serve us to answer the question of whether the implementation of the trade facilitation agreement has indeed reduced the cost to export, cost to import, and the number of documents used for export and import, respectively. A similar model to that in the previous subsection will be used, but without exploiting the panel dimension of the data, given that the time variation is almost not there. Another limitation is that these variables are only available until 2019. Therefore, we will be able to show correlations but not causality in this case. A similar exercise is done using the different components of the Logistics Performance Index (LPI), which is also available from the World Bank, but only for the years 2016 and 2018.

2.5 Main Results

Table 2.2 shows the main results from estimating the gravity model of trade given by Equation (7) for trade in manufactured goods.[8] The results, including gravity variables instead of dyadic fixed effects, as in Equation (6), are shown in the Appendix (Tables A2.3 and A2.4). Model (7) includes bilateral and time fixed effects, and hence it controls for bilateral unobserved heterogeneity and common time effects. Column (1) reports the result for the trade facilitation index (TFI). The reported coefficient indicates that a one percentage point increase in the index for exporters increases trade by around 1.34%. The overall TF index includes the above-mentioned components (transparency, formalities, paperless, institutions, and cross-border). First, Columns (2) to (6) present the estimates for each component of the specific TF scores. The highest effect in magnitude is obtained for the transparency rating score (1.97), followed by formalities and institutions, whereas paperless TF and transit TF measures are not statistically significant. Second, Columns (7) to (9) present the coefficients for each component of the sustainable TF scores. Only the agricultural component is statistically significant, whereas the TF for SMEs and for women is not. Interestingly, only the TF indicators for the exporter are statistically significant, whereas those for the importer are not. Similarly, only the GDP of the exporter is statistically significant and shows a more than proportional effect on exports, whereas the GDP for the importer is not. With regard to the RTA dummy variable, it shows a weakly significant effect, indicating that exports are around 44% higher when countries belong to the same RTA according to Column (1): [exp(0.368)-1]*100)].

Next, Table 2.3 presents the results obtained by estimating Equations (8) and (10). Columns (1) and (2) report the results for the specification

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8 The model was also estimated for exports of primary products and none of the TF variables was found to be statistically significant. Results are available on request.

Table 2.2: Results for the Gravity Model of Trade

	Dep. Var: ln Exports in Manufactured Goods								
		TFI Subcomponents							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Variables:	TFI	Transp	Formal	Paperless	Instit	Transit	Smes	Agri	Women
TFI exporter	1.348**	1.973***	0.844**	0.0447	0.807***	0.239	0.151	0.885***	−0.218
	(0.542)	(0.458)	(0.358)	(0.434)	(0.301)	(0.313)	(0.396)	(0.297)	(0.280)
TFI importer	−0.125	−0.253	−0.382	0.507	0.215	0.250	0.189	0.0483	−0.280
	(0.529)	(0.391)	(0.338)	(0.396)	(0.275)	(0.287)	(0.436)	(0.234)	(0.282)
ln GDP exporter	2.027***	2.048***	2.004***	1.866***	1.983***	2.411***	2.545***	2.435***	2.464***
	(0.414)	(0.405)	(0.414)	(0.416)	(0.410)	(0.447)	(0.397)	(0.408)	(0.395)
ln GDP importer	0.152	0.159	0.0900	0.186	0.189	−0.0723	0.374	0.271	0.368
	(0.390)	(0.384)	(0.387)	(0.388)	(0.383)	(0.427)	(0.407)	(0.400)	(0.386)
RTA	0.368*	0.481**	0.369*	0.370*	0.365*	0.423*	0.457*	0.0970	0.331
	(0.191)	(0.194)	(0.192)	(0.191)	(0.190)	(0.226)	(0.276)	(0.316)	(0.265)
2017 dummy	0.117	0.104	0.187**	0.168*	0.0571	0.215**			
	(0.107)	(0.0917)	(0.0921)	(0.0979)	(0.104)	(0.0955)			
2018 dummy	0.0812	0.0608	0.154*	0.135	0.0208	0.129	−0.0895	−0.0259	−0.0369
	(0.107)	(0.0911)	(0.0923)	(0.0967)	(0.104)	(0.0939)	(0.0716)	(0.0953)	(0.0771)
2019 dummy	−0.191	−0.239**	−0.0787	−0.0837	−0.249*	−0.153	−0.283***	−0.723***	−0.165*
	(0.145)	(0.113)	(0.115)	(0.114)	(0.132)	(0.109)	(0.0861)	(0.250)	(0.0845)
2020 dummy	−0.269*	−0.315***	−0.160	−0.166	−0.327***	−0.199*	−0.307***	−0.727***	−0.165*
	(0.140)	(0.108)	(0.109)	(0.107)	(0.125)	(0.106)	(0.0862)	(0.246)	(0.0863)
2021 dummy	−0.204	−0.246*	−0.0508	−0.0630	−0.249	−0.0392	−0.259**	−0.646**	−0.0853
	(0.185)	(0.137)	(0.142)	(0.144)	(0.152)	(0.122)	(0.119)	(0.272)	(0.112)
Observations	6,206	6,206	6,206	6,206	6,206	4,994	4,471	3,901	4,220
R-squared	0.25	0.26	0.24	0.26	0.25	0.22	0.28	0.27	0.28
Number of id	2,405	2,405	2,405	2,405	2,405	2,027	1,752	1,546	1,688

Note: Robust standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. All columns include country-pair and time fixed effects. Trade facilitation variables are described in Appendix A.1. TFI denotes the trade facilitation index of the exporter/importer country. Id denotes the number of bilateral trade relations. GDP denotes the gross domestic product per capita of the exporter/importer in constant USD of 2017. RTA denotes regional trade agreements and takes the value of one when the trading countries belong to the same regional trade agreement and zero otherwise.

Source: Author's elaboration.

with exports in natural logarithms and Columns (3) and (4) in levels for exports of manufactured goods and primary products, respectively. The results for the RTA variable for manufactured goods are consistent with the analysis in Table 2.2 (compare 0.368 with 0.231 in the first columns of Tables 2.2 and 2.3, respectively). From these models, the country-time fixed effects (CTFEs) are extracted and used in a second-step estimation, the results of which are shown in Table 2.4, which presents the outcomes obtained using Column (1) in Table 2.3 as a first step. The correlation between these CTFEs and the TF index (TFI) is shown in Figure 2.6, which shows a clear positive correlation.

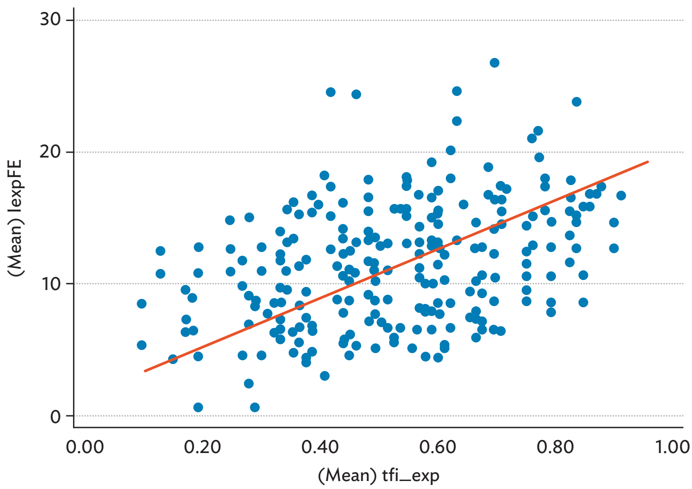
Table 2.3: Gravity Model Estimates with Multidimensional Fixed Effects

	(1)	(2)	(3)	(4)
Dep. Variables	Ln Exp_ma	Ln Exp_pri	Exp_ma	Exp_pri
RTA	0.261**	−0.187*	0.231***	0.179**
	(0.126)	(0.110)	(0.0599)	(0.0866)
it, jt, ij Fixed effects	Yes	Yes	Yes	Yes
Observations	18,939	15,427	19,495	15,969
R-squared	0.900	0.911	0.999	0.995

Note: Robust standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Exp_ma and Exp_pri denote total exports in manufactured and primary products, respectively. RTA denotes regional trade agreements and takes the value of 1 when the trading countries belong to the same regional trade agreement and 0 otherwise. The results in Columns (1) and (2) are obtained with the Stata command *reghdfe* and in (3) and (4) with *ppml_panel_sg*.

Source: Author's elaboration. It, jt, and ij denote exporter-time, importer-time, and bilateral fixed effects.

Figure 2.6: Scatterplot of Country-Time FE from the Gravity Model and Trade Facilitation Scores



Source: Author's elaboration. Using the ln of the exporter-time FE (lnexpFE on y-axes) from Model (3) in Table 2.3; tfi_exp denotes the trade facilitation index of the exporter countries.

It is worth noting that the estimates obtained in Table 2.4 for the TF indicators are similar in general to those in Table 2.2, but slightly smaller in magnitude. In particular, it is confirmed that transparency measures, formalities, and institutions supporting TF are the most effective, whereas paperless TF is only weakly significant, and transit TF does not show a clear effect. In this case, agriculture-related TF shows a significant positive effect concerning sustainable TF indicators. However, the effect of TF measures related to SMEs, in this case, is negative and significant, perhaps reflecting the small cost firms have to incur to adopt the measures in the short term. Likewise, TF for women does not show a significant effect on trade.

Table 2.4: Multilateral Resistance and Trade Facilitation – Second-Step Results

Dep. Var: FE GM	(1) TFI	(2) Tranps	(3) Formal	(4) Paperless	(5) Insti	(6) Transit	(7) SMES	(8) Agri	(9) Women
TFI exporter	0.998***	1.165***	0.485***	0.123*	0.739***	0.0193	−0.731***	0.570***	−0.0911
	(0.0823)	(0.0528)	(0.0455)	(0.0661)	−0.0421	(0.0484)	(0.0594)	(0.0375)	(0.0595)
ln GDP exporter	1.975***	1.953***	1.935***	1.855***	1.955***	2.146***	2.448***	2.331***	2.446***
	(0.0759)	(0.0660)	(0.0749)	(0.0751)	−0.0707	(0.0760)	(0.0801)	(0.0709)	(0.0820)
Obs	10,961	10,961	10,961	10,961	10,961	9,966	8,469	7,960	8,194
R-squared	0.231	0.265	0.225	0.217	0.248	0.251	0.290	0.284	0.252
Number of id	3,139	3,139	3,139	3,139	3,139	2,941	2,682	2,475	2,615

Note: Robust standard errors in parentheses, *** p < 0.01, ** p < 0.05, * p < 0.1. TFI denotes the overall trade facilitation index (TFI) as defined in Table A2.1. GDP exporter denotes the gross domestic product per capita of the exporter in constant USD of 2017. All columns include country and time fixed effects. The number of id refers to the pair of countries included in the sample.

Source: Author's elaboration.

Since the effects could differ by income level, Table 2.5 presents estimates for high-income countries (HICs), low-income countries (LICs), upper-middle-income countries (UMCs), and low-middle-income countries (LMCs). It seems that all income groups benefit from the implementation of transparency TF, formalities TF, and institution TF. In contrast, paperless TF mainly benefits UMCs and LMCs, and transit TF only LICs. As regards the sustainable TF measures, agriculture TF is beneficial for all, but not so SMEs and women TF measures.

Table 2.5: Multilateral Resistance and Trade Facilitation – Second-Step Results (by Income Group)

Country Group:	Transp	Formal	Insti	Paperless	Transit	SMES	Agri	Women
HIC	1.068***	0.409***	1.390***	−1.011***	−0.148***	−0.803***	0.389***	−0.399***
	(0.109)	(0.0865)	(0.113)	(0.220)	(0.0467)	(0.166)	(0.0469)	(0.0336)
LIC	1.582***	0.477***	0.321***	−0.106	0.931***	−0.989***	0.226*	0.113
	(0.0793)	(0.0716)	(0.0416)	(0.103)	(0.0477)	(0.117)	(0.136)	(0.135)
UMC	1.009***	0.450***	1.081***	0.178*	−0.714***	−1.102***	0.281***	−1.098***
	(0.0824)	(0.124)	(0.113)	(0.0915)	(0.0498)	(0.0417)	(0.0621)	(0.118)
LMC	0.940***	0.578***	0.856***	0.691***	0.0525	−0.122	0.551***	0.0759
	(0.0625)	(0.0555)	(0.0477)	(0.0868)	(0.0374)	(0.0786)	(0.0390)	(0.0864)

Note: Robust standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. See Table A2.1 for the definition of the TF variables in the first row. High-income countries (HICs), low-income countries (LICs), upper-middle-income countries (UMCs), and low-middle-income countries (LMCs).

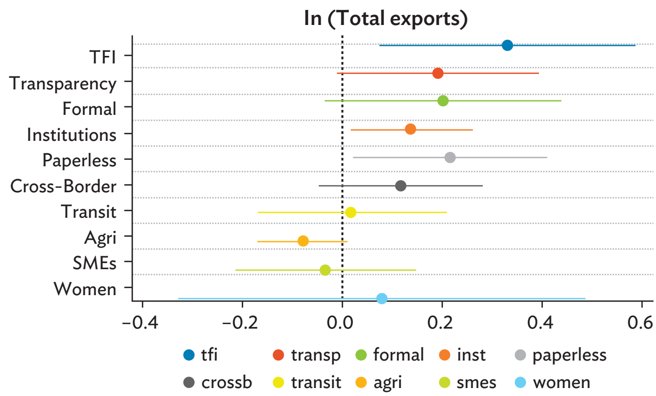
Source: Author's elaboration.

2.5.1 Results from Country-Level Regressions: Trade, GVC, Cost, and Time to Trade

This section presents the results from estimating Equation (12) for trade and GVC variables. The estimated coefficients and the corresponding confidence bands at the 5% significance level are shown in Figures 2.7–2.11 for total trade, trade in goods, trade in services, GVC participation, and the GVC position index.

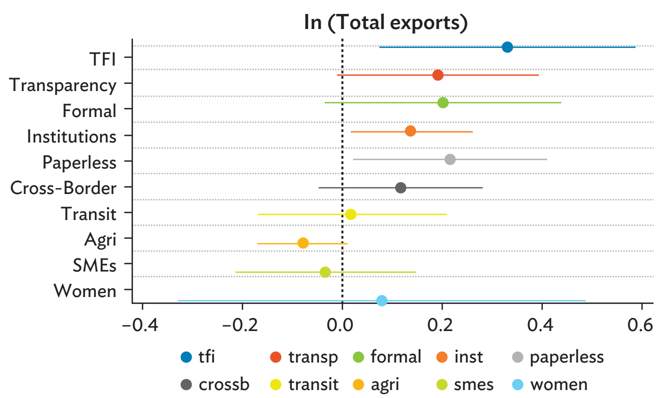
The coefficients shown in Figure 2.7 indicate that TF related to transparency, formalities, institutions, and paperless trade explains total exports of goods and services at the aggregated level. However, cross-border procedures and transit at the border TF do not show any clear effect, as is also the case for sustainable TF indicators (SMEs, agriculture, women). When distinguishing between trade in goods (Figure 2.8) and trade in services (Figure 2.9), we see that most of the effects are due to trade in goods, whereas only the institutions component is weakly significant for trade in services.

Figure 2.7: Dependent Variable Trade in Goods and Services – Global Sample



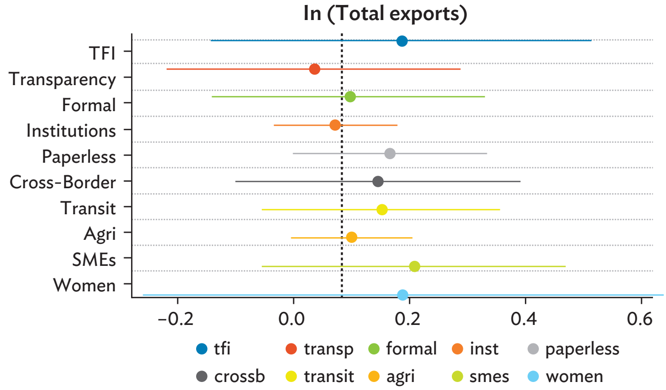
Source: Author's elaboration using the results from estimating Equation (12) for trade and GVC variables. The lines indicate confidence bands at the 5% significance level and the dots indicate estimated coefficients for each of the components of the trade facilitation indicator.

Figure 2.8: Dependent Variable Trade in Goods – Global Sample



Source: Author's elaboration using the results shown in Table A2.5 in the Appendix. The lines indicate confidence bands at the 5% significance level, and the dots indicate estimated coefficients for each of the components of the trade facilitation indicator.

Figure 2.9: Dependent Variable Trade in Services – Global Sample (Trade in Technology-Intensive Goods)

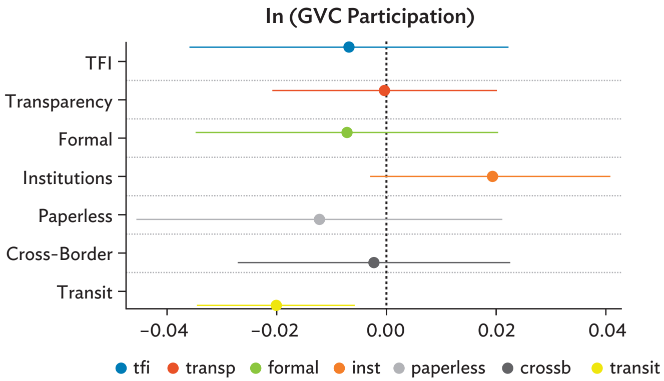


Source: Author's elaboration. The lines indicate confidence bands at the 5% significance level and the dots indicate estimated coefficients for each of the components of the trade facilitation indicator.

Next, Figures 2.10 and 2.11 show the results for the GVC participation and the GVC position index described in the data section. According to the results shown in Figure 2.10, only the subcomponent referring to institutions for TF seems to have a clear effect on GVC participation, whereas the component cross-border TF is significant at the 10% level. When the GVC position is examined as shown in Figure 2.11, however, almost none of the TF components show a significant effect at conventional levels, with only institutions for TF showing a 10% significance.

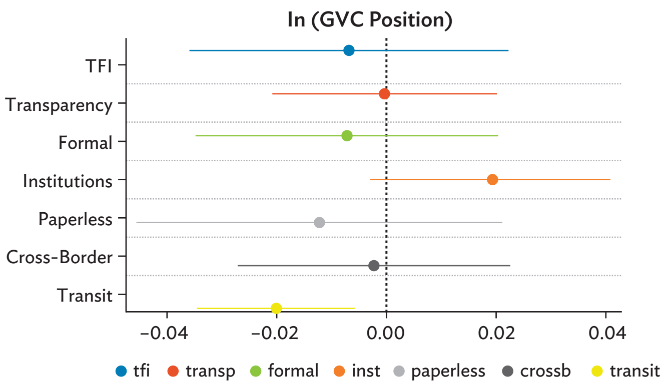
Finally, in order to see whether the implementation of TF measures is helping to reduce the time and cost to trade across borders, we show a graphical representation of the results obtained from simple regressions that do not exploit the panel data structure, and hence show correlations rather than causality.

Figure 2.10: Dependent Variable GVC Participation – Global Sample



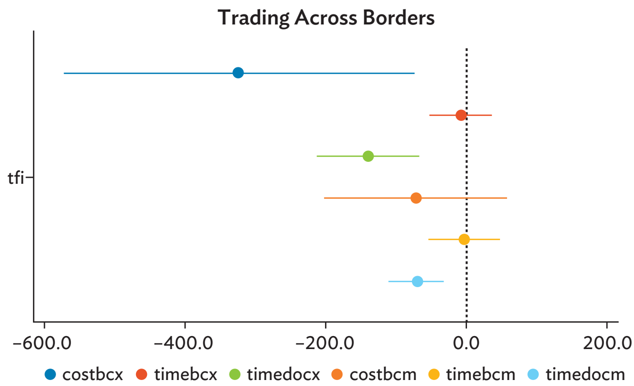
Source: Author's elaboration. The lines indicate confidence bands at the 5% significance level and the dots indicate estimated coefficients for each of the components of the trade facilitation indicator. Point estimates are from Table A2.5 in the Appendix.

Figure 2.11: Dependent Variable GVC Position – Global Sample



Source: Author's elaboration. The lines indicate confidence bands at the 5% significance level and the dots indicate estimated coefficients for each of the components of the trade facilitation indicator.

Figure 2.12: Dependent Variables: Cost and Time to Trade Across Borders – Global Sample



Note: costbcx(m) = cost to export(import), border compliance (US$); timebcx(m) = time to export(import), border compliance (hours); timedocx(m) = time to export(import), documentary compliance (hours).

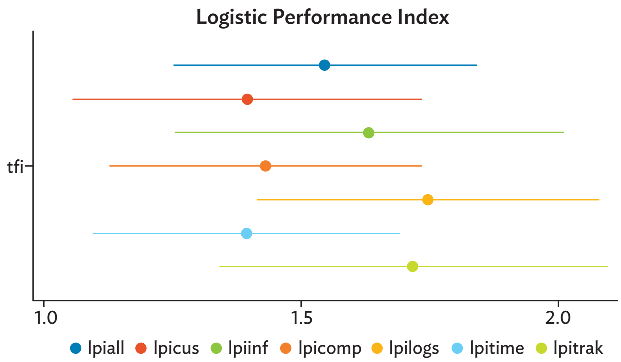
Source: Author's elaboration with data from World Bank Doing Business Indicators (2016–2019). See Table A2.6 for the full regression results. The lines indicate confidence bands at the 5% significance level and the dots indicate estimated coefficients for each of the components of the trade facilitation indicator.

Figure 2.12 shows the results of using three sets of variables for exporters and importers related to trading across borders, namely the cost and time to export and import, and the number of hours needed to fill the documents required to export and import. All these variables are negatively correlated with the TF index (*tfi*), as indicated in Figure 2.12. For instance, an increase in the *tfi* of one percentage point is related to a decrease in the cost involved in border compliance (costbcx) of $323, which doubles the mean value in the sample. Similarly, the same increase in *tfi* is related to a reduction in the hours needed for documentary compliance for exporting 139 (timedocx), with a sample average of 51.

We also consider, as shown in Figure 2.13, whether the TF index is correlated with the LPI and its components, that is: quality of trade and transport-related infrastructure; competence and quality of logistics services (*lpilogs*); ability to track and trace consignments(*lpitrak*); efficiency of the customs clearance process (*lpicus*); ease of arranging competitively priced shipments (*lpicomp*); and frequency with which shipments reach consignees within the time scheduled (lpitime). It can be seen that all the LPI components are positively correlated with the

TF index, and these correlations are all statistically significant. This result indicates that improvements in logistics performance are clearly correlated with better trade facilitation performance and will surely improve trade across borders and reduce trade costs.

Figure 2.13: Dependent Variables: Logistic Performance Index and its Components – Global Sample



Note: lpiall = logistics performance index(lpi): Overall (1 = low to 5 = high); lpiinf = quality of trade and transport-related infrastructure; lpilogs = competence and quality of logistic services; lpitrak = ability to track and trace consignments; lpicus = efficiency of the customs clearance process; lpicomp = ease of arranging competitively priced shipments; lpitime = frequency with which shipments reach consignee within time scheduled.

Source: Author's elaboration. The lines indicate confidence bands at the 5% significance level and the dots indicate estimated coefficients for each of the components of the trade facilitation indicator.

2.6 Conclusions

The combined interlink between economies and the undisputed importance of trading across countries makes the issue of trade facilitation very relevant in the 21st century – more so in a world subject to increasing risks and uncertainties related to pandemics and climatic disasters. This chapter evaluates the degree of implementation of trade facilitation measures in the world economy and its correlation with some measures of globalization, namely exports of goods and services and participation in GVCs. The main methodology relies on the gravity equation of trade and econometric techniques for panel data sets. With the help of newly collected data covering the pre- and post-pandemic periods, this chapter evaluates the relative importance of several developments all directed towards implementing a number of trade facilitation actions that are expected to reduce the cost of trading across borders and to increase trade in goods and services.

The main results from the gravity model indicate that TF measures related to transparency, institutions, and formalities are of utmost importance, whereas sustainable TF actions are still in their infancy, and more data are needed for a proper evaluation of their effectiveness. The TF implementation is related to a reduction in the time and cost to export and import as well as to improvements in logistics performance, which indicates the importance of reducing the time needed to trade, that is, to export and import, with the implementation of targeted policy measures directed towards reducing these times. Moreover, the implementation of TF measures has a significant effect on exports of manufactured goods overall, which is visible for all TFI sub-components.

The implications of the results for developing countries located in the Asia and the Pacific region are manyfold. For instance, the region comprises 12 least-developed countries, of which five are small islands and four are landlocked. For all of them, policies that invest in trade facilitation will contribute more than proportionally to increasing exports of manufactured goods. In particular, measures directed at improving institutional arrangements for border agencies, creating authorized operators, and publishing average release times (transparency) have a more-than-proportional effect on exports. The results from our models indicate that increasing transparency measures will foster exports of manufactured goods more than proportionally for low-income countries. Those include, for example, advanced publication of new trade regulations on the Internet and stakeholders' consultation of new draft regulations. Moreover, policies directed towards improving the quality of institutions will favor the development and deepening of global value chains. Some examples of actions could be the creation of a National Trade Facilitation Committee or similar body or the existence of a clear national institutional arrangement for border agency cooperation.

The main limitation is related to the lack of data in the last two waves of the survey for sustainable trade facilitation measures, which does not allow us to draw conclusions in this respect. Further work should focus on country-specific analysis in the Asia and the Pacific region using firm-level data. This will enable us to disentangle whether the effects of the trade facilitation measures affect differently large and small firms in the region.

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Appendix

Table A2.1: Trade Facilitation Indicators

Variable	Description (short name)	Link to WTO TFA*	Group*	Subgroup*
Q1	National Trade Facilitation Committee or similar body	Section 3, Article 23: Institutional Arrangements	General	Institution
Q2	Publication of existing import-export regulations on the internet	Section 1, Article 1.2: Information Available Through Internet	General	Transparency
Q3	Stakeholders' consultation on new draft regulations (prior to their finalization)	Section 1, Article 2.2: Consultations	General	Transparency
Q4	Advance publication/ notification of new trade-related regulations before their implementation	Section 1, Article 2.1: Opportunity to Comment and Information Before Entry into Force	General	Transparency
Q5	Advance ruling on tariff classification and origin of imported goods	Section 1, Article 3: Advance Rulings	General	Transparency
Q6	Risk management	Section 1, Article 7.4: Risk Management	General	Formalities
Q7	Pre-arrival processing	Section 1, Article 7.1: Pre-arrival Processing	General	Formalities
Q8	Post-clearance audits	Section 1, Article 7.5: Post-Clearance Audit	General	Formalities
Q9	Independent appeal mechanism	Section 1, Article 4: Procedures for Appeal and Review	General	Transparency
Q10	Separation of release from final determination of customs duties, taxes, fees, and charges	Section 1, Article 7.3: Separation of Release from Final Determination of Customs Duties, Taxes, Fees, and Charges	General	Formalities
Q11	Establishment and publication of average release times	Section 1, Article 7.6: Establishment and Publication of Average Release Times	General	Formalities

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Table A2.1 *continued*

Variable	Description (short name)	Link to WTO TFA*	Group*	Subgroup*
Q12	TF measures for authorized operators	Section 1, Article 7.7: Trade Facilitation Measures for Authorized Operators	General	Formalities
Q13	Expedited shipments	Section 1, Article 7.8: Expedited Shipments	General	Formalities
Q14	Acceptance of copies of original supporting documents required for import, export, or transit formalities	Section 1, Article 10.2: Acceptance of Copies (10.2.1)	General	Formalities
Q15	Automated Customs System	n/a	Digital	Paperless
Q16	Internet connection available to Customs and other trade control agencies	n/a	Digital	Paperless
Q17	Electronic Single Window System	Section 1, Article 10.4: Single Window	Digital	Paperless
Q18	Electronic submission of Customs declarations	n/a	Digital	Paperless
Q19	Electronic application and issuance of import and export permit	n/a	Digital	Paperless
Q20	Electronic Submission of Sea Cargo Manifests	n/a	Digital	Paperless
Q21	Electronic Submission of Air Cargo Manifests	n/a	Digital	Paperless
Q22	Electronic application and issuance of Preferential Certificate of Origin	n/a	Digital	Paperless
Q23	E-Payment of Customs Duties and Fees	Section 1, Article 7.2: Electronic Payment	Digital	Paperless
Q24	Electronic Application for Customs Refunds	n/a	Digital	Paperless
Q25	Laws and regulations for electronic transactions	n/a	Digital	Cross-border

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Table A2.1 *continued*

Variable	Description (short name)	Link to WTO TFA*	Group*	Subgroup*
Q26	Recognized certification authority	n/a	Digital	Cross-border
Q27	Electronic exchange of Customs Declaration	n/a	Digital	Cross-border
Q28	Electronic exchange of Certificate of Origin	n/a	Digital	Cross-border
Q29	Electronic exchange of Sanitary and Phyto-Sanitary Certificate	n/a	Digital	Cross-border
Q30	Paperless collection of payment from a documentary letter of credit	n/a	Digital	Cross-border
Q31	National legislative framework and/ or institutional arrangements for border agency cooperation	Section 1, Article 8: Border Agency Cooperation	General	Institution
Q32	Government agencies delegating border controls to Customs authorities	n/a	General	Institution
Q33	Alignment of working days and hours with neighboring countries at border crossings	Section 1, Article 8: Border Agency Cooperation (8.2(a))	General	Institution
Q34	Alignment of formalities and procedures with neighboring countries at border crossings	Section 1, Article 8: Border Agency Cooperation (8.2(b))	General	Institution
Q35	Transit facilitation agreement(s)	n/a	General	Transit
Q36	Limit the physical inspections of transit goods and use risk assessment	Section 1, Article 10.5: Pre-shipment Inspection	General	Transit

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Table A2.1 *continued*

Variable	Description (short name)	Link to WTO TFA*	Group*	Subgroup*
Q37	Supporting pre-arrival processing for transit facilitation	Section 1, Article 11: Freedom of Transit (11.9)	General	Transit
Q38	Cooperation among agencies of countries involved in transit	Section 1, Article 11: Freedom of Transit (11.16)	General	Transit
Q39	Trade-related information measures for SMEs	n/a	Sustainable	SMEs
Q40	SMEs in AEO scheme	n/a	Sustainable	SMEs
Q41	SMEs access Single Window	n/a	Sustainable	SMEs
Q42	SMEs in National Trade Facilitation Committee	n/a	Sustainable	SMEs
Q43	Other special measures for SMEs	n/a	Sustainable	SMEs
Q44	Testing and laboratory facilities available to meet SPS of main trading partners	n/a	Sustainable	Agriculture
Q45	National standards and accreditation bodies to facilitate compliance with SPS	n/a	Sustainable	Agriculture
Q46	Electronic application and issuance of SPS certificates	n/a	Sustainable	Agriculture
Q47	Special treatment for perishable goods	Section 1, Article 7.9: Perishable Goods	Sustainable	Agriculture
Q48	TF policy/strategy to increase women's participation in trade	n/a	Sustainable	Women
Q49	TF measures to benefit women involved in trade	n/a	Sustainable	Women

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Table A2.1 *continued*

Variable	Description (short name)	Link to WTO TFA*	Group*	Subgroup*
Q50	Women membership in the National Trade Facilitation Committee or similar bodies	n/a	Sustainable	Women
Q51	Single window facilitates traders' access to finance	n/a	Others	Trade-finance
Q52	Authorities engaged in blockchain-based supply chain project covering trade finance	n/a	Others	Trade-finance
Q53	Variety of trade finance services available	n/a	Others	Trade-finance
Q54	Agency in place to manage TF in times of crises and emergencies	n/a	Others	Crisis
Q55	Online publication of emergency TF measures	n/a	Others	Crisis
Q56	Coordination among countries on emergency TF measures	n/a	Others	Crisis
Q57	Additional trade facilitation measures to facilitate trade in times of emergency	n/a	Others	Crisis
Q58	Plan in place to facilitate trade during future crises	n/a	Others	Crisis

Variable	Description (short name)
transparency (*transp*)	Transparency (Q2–Q5, Q9) [unit: rate of implementation; 0% = no implementation, 100% = full implementation]
Formalities (*formal*)	Formalities (Q6–Q8, Q10–Q14) [unit: rate of implementation; 0% = no implementation, 100% = full implementation]
Institution (*inst*)	Institution (Q1, Q31 and Q32) [unit: rate of implementation; 0% = no implementation, 100% = full implementation]
Paperless (*paperless*)	Paperless trade (Q15–Q19, Q21–Q24) [unit: rate of implementation; 0% = no implementation, 100% = full implementation]

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Table A2.1 *continued*

Variable	Description (short name)
Crossborder (*crossb*)	Cross-border paperless trade (Q25–Q30) [unit: rate of implementation; 0% = no implementation, 100% = full implementation]
Trade Facilitation Index (tfi)	Total trade facilitation implementation: transparency, formality, institution, paperless trade, and cross-border paperless trade [unit: rate of implementation; 0% = no implementation, 100% = full implementation]
Transit TF (transit)	Transit (Q35–Q38) [unit: rate of implementation; 0% = no implementation, 100% = full implementation]
TF for SMEs (smes)	Sustainable TF: Trade facilitation for SMEs (Q39–Q43) [unit: rate of implementation; 0% = no implementation, 100% = full implementation]
Agricultural TF (agri) =	Sustainable TF: Agricultural trade facilitation (Q44–47) [unit: rate of implementation; 0% = no implementation, 100% = full implementation]
TF for women (women)	Sustainable TF: Women in trade facilitation (Q48–Q50) [unit: rate of implementation; 0% = no implementation, 100% = full implementation]

Note: For details, see questionnaire and methodology at https://www.untfsurvey.org/about. * (Only applicable for Q1–58.)

Source: Author's elaboration.

Table A2.2: List of Countries in Subregions (Figures 2.1 to 2.5)

East Asia	South Asia	Southeast Asia	The Pacific	Central and West Asia
Mongolia	Bangladesh	Cambodia	Cook Islands	Afghanistan
People's Republic of China	Bhutan	Indonesia	Federated States of Micronesia	Armenia
	India	Lao People's Democratic Republic	Fiji	Azerbaijan
	Maldives	Myanmar	Kiribati	Georgia
	Nepal	Philippines	Marshall Islands	Kazakhstan
	Sri Lanka	Thailand	Nauru	Kyrgyz Republic
		Timor-Leste	Niue	Pakistan
		Viet Nam	Palau	Tajikistan
			Papua New Guinea	Turkmenistan
			Samoa	Uzbekistan
			Solomon Islands	
			Tonga	
			Tuvalu	
			Vanuatu	

Source: ADBI website and author's elaboration.

Table A2.3: Gravity Model Estimations with Bilateral Variables for Manufactures

Variables	(1) TFI	(2) Transp	(3) Formal	(4) Paperless	(5) Inst	(6) Transit	(7) SMES	(8) Agri
tfi_exp	2.245***	1.790***	1.576***	0.979***	0.0563	0.450**	0.177	0.667***
	(0.313)	(0.202)	(0.242)	(0.231)	(0.204)	(0.195)	(0.250)	(0.239)
tfi_imp	0.237	0.253	0.487**	−0.260	0.104	0.155	−0.203	−0.0743
	(0.313)	(0.194)	(0.239)	(0.219)	(0.190)	(0.178)	(0.265)	(0.197)
lgdp_exp	0.968***	0.976***	0.980***	1.041***	1.087***	1.063***	1.109***	1.103***
	(0.0365)	(0.0353)	(0.0363)	(0.0352)	(0.0337)	(0.0377)	(0.0390)	(0.0426)
lgdp_imp	0.642***	0.641***	0.618***	0.660***	0.645***	0.624***	0.680***	0.665***
	(0.0343)	(0.0322)	(0.0346)	(0.0317)	(0.0304)	(0.0345)	(0.0357)	(0.0371)
ld	−2.033***	−2.044***	−2.029***	−2.003***	−1.990***	−1.933***	−1.912***	−1.983***
	(0.0791)	(0.0780)	(0.0792)	(0.0795)	(0.0798)	(0.0910)	(0.0964)	(0.107)
comlang_off	1.275***	1.233***	1.326***	1.374***	1.435***	1.586***	1.482***	1.353***
	(0.130)	(0.129)	(0.126)	(0.132)	(0.127)	(0.137)	(0.151)	(0.157)
comcol	−0.257	−0.202	−0.289*	−0.433**	−0.538***	−0.580***	−0.437**	0.0169
	(0.169)	(0.166)	(0.162)	(0.168)	(0.159)	(0.175)	(0.194)	(0.200)
contig	0.968***	0.950***	0.974***	0.972***	0.969***	1.029***	1.162***	1.017***
	(0.202)	(0.200)	(0.200)	(0.204)	(0.205)	(0.212)	(0.237)	(0.258)
rta	0.632***	0.637***	0.646***	0.676***	0.693***	0.760***	0.659***	0.556***
	(0.118)	(0.117)	(0.117)	(0.119)	(0.120)	(0.134)	(0.146)	(0.159)
wto_o	0.267	0.694***	0.125	0.614***	0.694***	1.090***	0.719***	0.711***
	(0.243)	(0.238)	(0.251)	(0.237)	(0.242)	(0.283)	(0.260)	(0.258)
wto_d	0.465	0.512	0.361	0.533	0.529	0.503	0.904**	0.805**
	(0.331)	(0.327)	(0.335)	(0.331)	(0.332)	(0.387)	(0.357)	(0.349)
2017.year dummy	0.0219	0.0855	0.0398	0.159**	0.180**	0.217***		
	(0.0830)	(0.0768)	(0.0789)	(0.0792)	(0.0858)	(0.0840)		
2018.year dummy	0.00268	0.0636	0.0188	0.136*	0.155*	0.139*	−0.0491	−0.0127
	(0.0772)	(0.0709)	(0.0727)	(0.0738)	(0.0803)	(0.0775)	(0.0692)	(0.0921)
2019.year dummy	−0.301***	−0.213***	−0.223***	−0.0718	−0.0153	−0.0907	−0.164**	−0.344*
	(0.0912)	(0.0753)	(0.0766)	(0.0816)	(0.0949)	(0.0833)	(0.0772)	(0.192)
2020.year dummy	−0.389***	−0.301***	−0.312***	−0.157*	−0.0988	−0.150*	−0.226***	−0.373*
	(0.0938)	(0.0784)	(0.0797)	(0.0835)	(0.0956)	(0.0858)	(0.0774)	(0.194)
2021.year dummy	−0.396***	−0.243***	−0.311***	−0.0797	0.00824	3.45e−07	−0.116	−0.154
	(0.109)	(0.0830)	(0.0878)	(0.0935)	(0.105)	(0.0878)	(0.0932)	(0.203)
Observations	6,206	6,206	6,206	6,206	6,206	4,994	4,471	3,901
Number of id	2,405	2,405	2,405	2,405	2,405	2,027	1,752	1,546

Note: Robust standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. tfi_exp (tfi_imp) denotes trade facilitation measures of the exporter (importer) country; lgdp_exp (lgdp_imp) denotes the natural log of the gross domestic product of the exporter (importer) country; ld is the natural log of the distance between countries; *Contig* takes the value of 1 for a pair of countries sharing a border, and 0 otherwise. *Comlang_off* and *Comcol* take the value of 1 when a pair of countries share an official language or have ever had a colonial relationship, respectively, and 0 otherwise; rta takes the value of 1 when the trading countries are members of a regional trade agreement, and 0 otherwise; wto_o (_d) takes the value of 1 if country i (country *j*) is a WTO member.

Source: Author's elaboration.

Table A2.4: Gravity Model Estimations with Bilateral Variables for Primary Products

Variables	(1) TFI	(2) Trans	(3) Formal	(4) Paperless	(5) Instit	(6) Transit	(7) SMEs	(8) Agri
tfi_exp	2.241***	1.415***	0.636**	1.978***	0.0113	0.628***	−0.167	0.379
	(0.387)	(0.247)	(0.289)	(0.310)	(0.258)	(0.239)	(0.272)	(0.299)
tfi_imp	0.385	0.112	0.0525	0.481*	−0.599***	0.153	0.335	−0.112
	(0.362)	(0.230)	(0.271)	(0.282)	(0.232)	(0.209)	(0.259)	(0.272)
lgdp_exp	1.026***	1.055***	1.115***	1.017***	1.146***	1.133***	1.207***	1.167***
	(0.0486)	(0.0464)	(0.0468)	(0.0475)	(0.0436)	(0.0481)	(0.0495)	(0.0522)
lgdp_imp	0.591***	0.599***	0.601***	0.580***	0.600***	0.627***	0.636***	0.670***
	(0.0418)	(0.0399)	(0.0395)	(0.0417)	(0.0382)	(0.0438)	(0.0436)	(0.0454)
ld	−1.511***	−1.494***	−1.491***	−1.528***	−1.491***	−1.431***	−1.449***	−1.444***
	(0.0876)	(0.0874)	(0.0884)	(0.0873)	(0.0887)	(0.103)	(0.112)	(0.119)
comlang_off	0.743***	0.762***	0.851***	0.787***	0.930***	0.923***	0.971***	0.747***
	(0.173)	(0.174)	(0.175)	(0.167)	(0.168)	(0.182)	(0.201)	(0.209)
comcol	−0.250	−0.295	−0.459**	−0.252	−0.580***	−0.584**	−0.350	0.129
	(0.232)	(0.233)	(0.234)	(0.228)	(0.224)	(0.252)	(0.268)	(0.281)
contig	1.638***	1.636***	1.636***	1.626***	1.629***	1.765***	1.748***	1.576***
	(0.227)	(0.225)	(0.228)	(0.225)	(0.228)	(0.233)	(0.279)	(0.306)
rta	0.882***	0.910***	0.909***	0.902***	0.918***	0.914***	0.812***	0.824***
	(0.118)	(0.117)	(0.118)	(0.117)	(0.118)	(0.128)	(0.141)	(0.155)
wto_o	0.851**	1.318***	1.280***	0.494	1.328***	1.822***	1.427***	1.179***
	(0.400)	(0.395)	(0.397)	(0.409)	(0.396)	(0.462)	(0.429)	(0.421)
wto_d	0.808	0.881*	0.892*	0.723	1.001**	1.883***	0.932*	0.950*
	(0.502)	(0.499)	(0.505)	(0.498)	(0.504)	(0.689)	(0.559)	(0.539)
2017.year dummy	−0.208**	−0.0980	−0.0671	−0.202**	0.0564	−0.0222		
	(0.0838)	(0.0788)	(0.0791)	(0.0804)	(0.0819)	(0.0778)		
2018.year dummy	−0.255***	−0.148*	−0.119	−0.250***	0.00354	−0.146*	−0.0618	−0.0108
	(0.0868)	(0.0814)	(0.0837)	(0.0832)	(0.0864)	(0.0850)	(0.0706)	(0.0870)
2019.year dummy	−0.335***	−0.154*	−0.0851	−0.282***	0.127	−0.109	−0.0410	−0.0417
	(0.102)	(0.0870)	(0.0903)	(0.0874)	(0.107)	(0.0923)	(0.0871)	(0.290)
2020.year dummy	−0.331***	−0.148*	−0.0759	−0.278***	0.138	−0.0811	0.00478	0.0175
	(0.104)	(0.0870)	(0.0910)	(0.0898)	(0.108)	(0.0942)	(0.0879)	(0.289)
2021.year dummy	−0.402***	−0.133	−0.0521	−0.351***	0.235**	0.0244	0.0589	0.207
	(0.121)	(0.0933)	(0.105)	(0.103)	(0.119)	(0.0957)	(0.104)	(0.298)
Observations	5,242	5,242	5,242	5,242	5,242	4,255	3,768	3,342
Number of id	2,020	2,020	2,020	2,020	2,020	1,702	1,456	1,306

Note: Robust standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. tfi_exp (tfi_imp) denotes trade facilitation measures of the exporter (importer) country; lgdp_exp (lgdp_imp) denotes the natural log of the gross domestic product of the exporter (importer) country; ld is the natural log of the distance between countries; Contig takes the value of 1 for a pair of countries sharing a border, and 0 otherwise. *Comlang_off* and *Comcol* take the value of 1 when a pair of countries share an official language or have ever had a colonial relationship, respectively, and 0 otherwise; rta takes the value of 1 when the trading countries are members of a regional trade agreement, and 0 otherwise; wto_o (_d) takes the value of 1 if country i (country *j*) is a WTO member.

Source: Author's elaboration.

Table A2.5: Random Trend Model Estimations for GVC Participation

Dep. Var.: GVC participation	(1) TFI	(2) Transp	(3) Formal	(4) Inst	(5) Paperless	(6) Crossb	(7) Transit	(8) Agri	(9) SMES	(10) Women
Ind. Variables:										
FD.lgdppck	2.415***	2.446***	2.443***	2.787***	2.430***	2.463***	2.489***	2.734***	2.660***	2.711***
	(0.186)	(0.186)	(0.183)	(0.201)	(0.192)	(0.181)	(0.207)	(0.256)	(0.244)	(0.325)
FD.tfi	0.331**									
	(0.129)									
FD.transp		0.191*								
		(0.101)								
FD.formal			0.201*							
			(0.119)							
FD.inst				0.137**						
				(0.061)						
FD.paperless					0.215**					
					(0.097)					
FD.crossb						0.116				
						(0.083)				
FD.transit							0.017			
							(0.097)			
FD.agri								−0.080*		
								(0.045)		
FD.smes									−0.035	
									(0.091)	
FD.women										0.079
										(0.205)
Observations	364	364	364	629	364	364	317	198	210	183
R-squared	0.494	0.490	0.490	0.573	0.491	0.488	0.435	0.633	0.591	0.583
Number of iso3c	90	90	90	132	90	90	80	71	77	69

Notes: Robust standard errors in parentheses***, $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. FD denotes variables in first differences. Country and time fixed effects included in all models; not shown to save space. Variables are described in Table A2.1.

Source: Author’s elaboration.

Table A2.6: Cost and Time to Trade Across Borders and Trade Facilitation

	(1)	(2)	(3)	(4)	(5)
Dep. Var:	**Costbx**	**Timedocx**	**Costbm**	**Timebm**	**Timedocm**
Ind. Var:					
Ln GDP per head	0.816	−8.600	−82.839***	−40.531***	−24.065***
	(16.320)	(5.698)	(15.436)	(6.520)	(3.745)
TFI	−323.196**	−139.930***	−71.761	−3.626	−69.513***
	(126.721)	(36.424)	(65.718)	(25.567)	(19.838)
Constant	297.537***	209.366***	971.716***	453.603***	323.287***
	(85.839)	(38.125)	(131.219)	(52.902)	(32.384)
Sample Mean	120.779	58.291	51.122	158.448	73.010
Observations	359	359	359	359	359
R-squared	0.100	0.241	0.232	0.291	0.298

Note: Robust standard errors in parentheses, *** p < 0.01, ** p < 0.05, * p < 0.1. costbcx(m) = cost to export(import), border compliance (US$); timebcx(m) = time to export(import), border compliance (hours); timedocx(m) = time to export(import), documentary compliance (hours). TFI = Trade Facilitation Index.

Source: Author's elaboration.

PART II

Food Security and Global Food Supply Chains

3

Integrated Climate Change Assessments on Selected Farming Systems in India, Pakistan, Bangladesh, and Viet Nam[1,2]

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3.1 Introduction

Early work on climate change and agriculture was often limited to site-based crop modeling without addressing farming systems at regional scales and socio-economic outcomes (Rosenzweig and Parry 1994;

[1] Some of this material has been previously published in *Handbook of Climate Change and Agroecosystems - Climate Change and Farming System Planning in Africa and South Asia: AgMIP Stakeholder-driven Research (Vol. 5)*. 2021. *World Scientific*.

[2] **Acknowledgments:**
All figures from the *Handbook of Climate Change and Agroecosystems* are used with permission from World Scientific. All other figures were created by the chapter authors. The authors would like to acknowledge the financial aid from the United Kingdom's Department for International Development in support of the "AgMIP Regional Integrated Assessments in Sub-Saharan Africa and South Asia" project and from the Australian Centre for International Agricultural Research in support of the "Mitigation and Adaptation Co-Benefits (MAC-B)" trial project in Bangladesh. This research is also funded by Vietnam National University HoChiMinh City (VNU-HCM) under grant number TX2023-16-01 for staff salary at Climate Change Institute. The authors also acknowledge the contributions from all the AgMIP Regional Research Teams in South Asia and Dr. Carolyn Z. Mutter, former AgMIP International Program Manager.

Iglesias, Rosenzweig, and Pereira 2000; Saarikko 2000). To fill these gaps, the Agricultural Model Intercomparison and Improvement Project (AgMIP) was founded in 2010. AgMIP has built a network of 1,200+ transdisciplinary scientists and decision-makers and developed a portfolio of climate, biophysical, and socioeconomic models and assessments to understand and respond to current and future challenges in agriculture and food security (Rosenzweig et al. 2013; Rosenzweig and Hillel 2015; Rosenzweig, Mutter, and Mencos Contreras 2021; Ruane et al. 2017).

There is a further gap with regard to the evidence base required by policy makers to adopt agricultural adaptation policies and undertake resilience programs for the agricultural sector. To fill this gap, AgMIP is developing tools and methods that help decision-makers, and policy-makers create multiple-scale interventions and policies to offset the negative impacts of climate change (Jägermeyr et al. 2021; Müller et al. 2021; Ruane et al. 2018; Rosenzweig et al. 2018). The AgMIP tools and methods can aid in the more equitable implementation of agricultural development strategies to ensure that all farmers will benefit (Valdivia et al. 2015).

Finally, there is a large gap or "siloization" of responses between mitigation and adaptation actions by countries. As many countries are now seeking to implement strategies for both climate change mitigation and adaptation as part of their Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs), interventions in farming systems can address both reductions in greenhouse gas (GHG) emissions and improvement in resilience. AgMIP projects are addressing this siloization in Bangladesh, Viet Nam, and India by testing the co-benefits and trade-offs between mitigation and adaptation in regard to elements of the sustainable rice intensification management system, including alternate wetting and drying (AWD).

AgMIP has developed protocols for regional integrated assessments (RIAs) that bring together climate, biophysical, and economic modelers to work together on farming system scales. The purpose of this chapter is to synthesize and evaluate the results of RIAs that have been done at subnational scales in India and Pakistan, to present crop modeling results from Viet Nam, and illustrate a pilot study in Bangladesh on combined mitigation and adaptation.

In this chapter, we share examples from AgMIP regional integrated assessment studies in South Asia, illustrate the AgMIP mitigation and adaptation co-benefits protocols with an example from Bangladesh, and present major overall findings (Rosenzweig, Mutter, and Mencos Contreras 2021). We then build on the AgMIP project results to formulate policy recommendations for development pathways in Asia and the Pacific region, as well as implications for global food supplies and food security.

3.2 Implementation of the AgMIP Regional Integrated Assessments[3]

AgMIP's regional activities (Figure 3.1), such as those in South Asia, have substantially improved our understanding of the likely impacts of future climate change on agricultural production and farming systems in the region (Rosenzweig, Mutter, and Mencos Contreras 2021). The AgMIP RIA framework (Antle et al. 2015) is a helpful tool not only for assessing how smallholder farming is affected by current climate extremes and how it will be affected by climate change in the future, but also for developing and testing adaptation strategies. Studies were conducted in the Indo-Gangetic Plain, Andhra Pradesh, and Tamil Nadu in India, and the Punjab region in Pakistan to assess climate change, to co-generate with stakeholders Representative Agricultural Pathways (RAPs), and to evaluate agricultural adaptation packages to the projected impacts in these regions. Earlier AgMIP work was conducted in Sri Lanka (Zubair et al. 2015). These assessments characterized the main challenges that will be faced by government planners and farmers in regard to both development and climate change.

Challenges in bringing the AgMIP projects to practice include the need to engage stakeholders at scales that range from local or sub-national to national. Decision-making related to climate change adaptation and resilience occurs at both scales, with financing for resilience projects often generated at national scales. To address this challenge, AgMIP has developed an approach called Integrated National and Regional Assessments (InaRA) that interacts with stakeholders at national scales, through surveys and workshops, and that conducts analyses at both local and regional scales.

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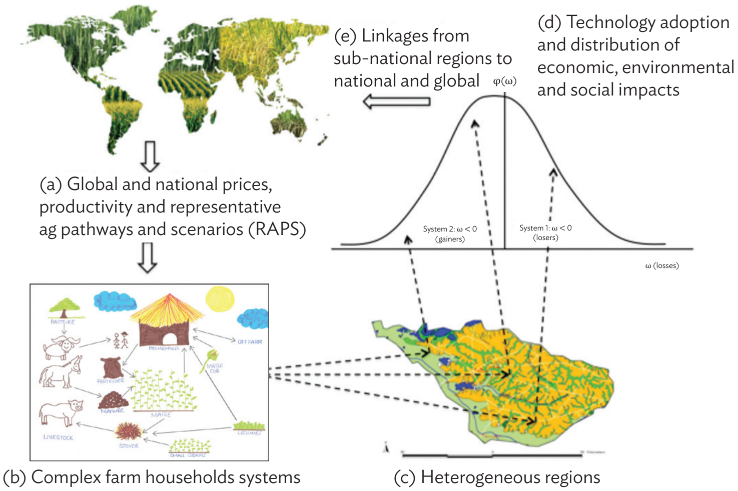
3 Regional studies are conducted at the sub-national scale.

Figure 3.1: AgMIP Regional Integrated Assessment (RIA) Framework



AgMIP = The Agricultural Model Intercomparison and Improvement Project.

Source: Antle et al. (2015).

Climate change will bring changes to many agricultural regions around the world. In South Asia, heatwaves and humid heat stress are projected to become more intense and frequent during the 21st century (IPCC 2021b). The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) brought forward the role of multiple stresses that exacerbate vulnerability and called out the climate sensitivity of food security in South Asia (IPCC 2022). Highly vulnerable places are located where poverty is widespread, institutions are weak, and conflict rages. The IPCC AR6 emphasizes the 2°C global warming threshold above which risks of severe climate change impacts to food security will grow, bringing threats through production challenges as well as to nutritional status (IPCC 2022).

Climate changes are already detectable in South Asia as exemplified by observed alterations in monsoon timing and strength, but uncertainty in long-term monsoonal trends warrants a multi-climate model and greenhouse gas scenario approach to bracket potential ranges and best/worst outcomes (Singh et al. 2019; Roxy et al. 2017). Heat waves and heavy downpours are occurring more frequently and more intensely, bringing threats to food security and the livelihoods of smallholder farmers. Recent devastating examples are the floods in Pakistan and recent heat waves in India, both occurring in 2022.

In the next section, we present results from several regional integrated assessments in Asia, including from farming systems in India, Pakistan, and Viet Nam.

3.3 Case Studies from India, Pakistan, and Viet Nam

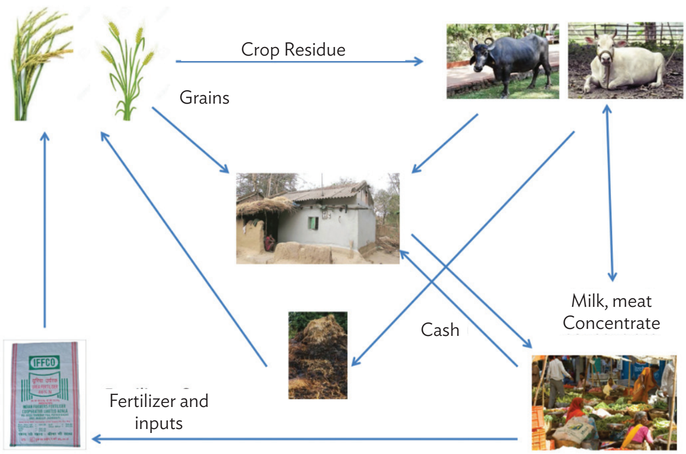
3.3.1 India—Indo-Gangetic Plain

Meerut and Karnal Districts were selected as the study areas. They are located in the Upper Gangetic region of the Indo-Gangetic Plain in India (Subash et al. 2021). The current climate is semi-arid subtropical, with hot dry summers and cold winters. The main farming systems in the region are rice-wheat and sugarcane-wheat production. Most households, even those with the smallest land holdings, raise cows and buffalos to produce milk. This study focused on smallholder farms that engage in rice, wheat, and milk production.

Livestock serves a dual purpose for households. While milk is either consumed by the family or sold to earn extra income, livestock dung is used as farmyard manure, which helps improve soil health. Thus, on-farm recycling of crop byproducts enhances resource use efficiency and also reduces farm households' dependence on farm input (e.g., fertilizers) purchased from the market. However, due to small holdings, farm households are also engaged in non-farm activities (wage earning, small grocery shops, employment in formal and informal sectors, etc.) to support their livelihoods. A schematic of the smallholder farming system in the Indo-Gangetic Plain is shown in Figure 3.2.

Results show relatively small declines in net farm returns and per capita income (Subash et al. 2021). However, negative effects of climate change are found in half to three-quarters of the farms. Adaptation packages were tested utilizing the Agricultural Production Systems sIMulator (APSIM) and Decision Support System for Agrotechnology Transfer (DSSAT) crop models: With these packages, rice yields increased by 6%–14% and wheat yields were augmented by 11%–18%. When these increases were evaluated using the Trade-Off Analysis for Multi-Dimensional Impact Assessment (TOA-MD) economic model, farmers gained in net farm returns (11%–14%) and per capita income (7%–8%). The TOA economic model calculated that 57%–62% of farm households would adopt the portfolio of strategies under the current production system.

Figure 3.2: A Farming System in the Indo-Gangetic Plain



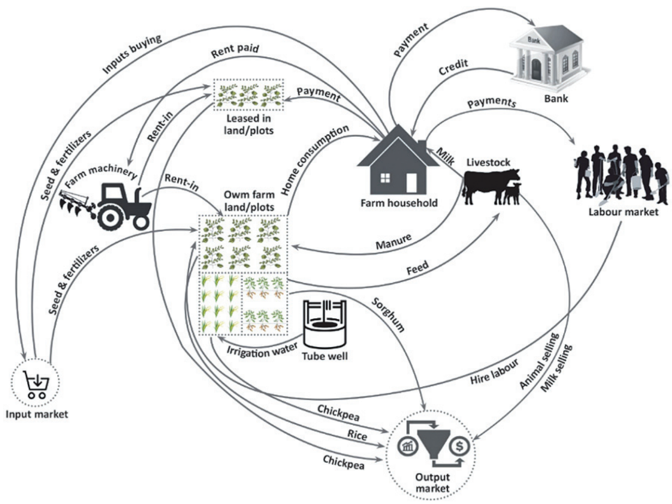
Source: Subash et al. (2021).

The TOA-MD regional farming system economics model was also used to simulate different Representative Agricultural Pathways (RAPs) that were developed with stakeholders to envision alternate agricultural development trajectories in the region. The stakeholders and scientists named one of the RAPs the "Sustainable Development Pathway" and the other one the "Unsustainable Development Pathway" (Subash et al. 2021). These were tested under five different climate change scenarios and two price scenarios (low and high). Results again show that many farming households are vulnerable to climate change, even under the Sustainable Development Pathway, especially under the hottest and driest climate scenarios and when prices of their products are low. Overall, however, the Sustainable Development Pathway was most favorable in regard to confronting the challenges of climate change for the smallholder farmers of the Indo-Gangetic Plain.

3.3.2 India—Andhra Pradesh

The Kurnool District is located in a dry zone, with only 500 to 750 mm rainfall per year. Most of the rainfall (about 70%) is associated with the southwest monsoon, with the remaining amount coming from the northeast monsoon. How climate change may affect both monsoons is of critical importance for the smallholder farmers there who mostly practice rainfed farming. Even in the current climate, the scarce rainfall is barely sufficient and its distribution throughout the growing period erratic, making agricultural production highly risky (Figure 3.3) (Nedumaran et al. 2021).

Figure 3.3: A Farming System in Andhra Pradesh, India



Source: Nedumaran et al. (2021).

More frequent and deeper droughts, poor timing of precipitation through the crop-growing period, and reduced potential for groundwater recharge are critical concerns linked to looming alterations in long-term conditions. Availability and uptake of improved crop varieties (including genetic resources targeting drought- and disease-tolerance) are both low. Lack of markets and low commodity prices plague the system and often lead to farm household economic losses. Vegetable and fruit production is subject to a lack of good handling techniques and, thus to post-harvest losses. Livestock productivity suffers from poor feed availability and practices. Furthermore, institutional systems are weak, and farmers has little access to programs such as insurance and credit sources.

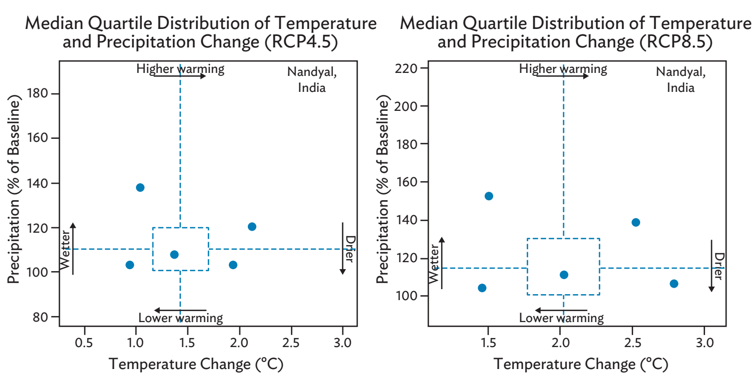
Black soil is widespread in Andhra Pradesh, making cultivation difficult during the rainy season. Thus, most smallholder farmers keep their fields fallow during the rainy season and plant their crops in moist soil when it is over. Chickpea is the major crop, accounting for up to

70% of the cropping area in the district. Although raising chickpea is highly profitable, most farm households also engage in other income-producing activities, including livestock raising and off-farm labor.

RAPs and climate change scenarios formed the basis of the AgMIP Regional Integrated Assessment of chickpea farming systems in Kurnool, Andhra Pradesh (Nedumaran et al. 2021). The RIA method includes stratifying households according to prominent differences across the farms. In this case, rainfall was selected as the stratifying component, with low and medium/high precipitation dividing the study population.

The climate change scenarios all projected higher temperatures and increased rainfall for the district, especially in the high greenhouse gas emissions scenario (Figure 3.4) (Ruane and McDermid 2017). In regard to rainfall, the downscaled global climate models showed a range of increases from 3% to nearly 30% in the climate scenario associated with medium increases in GHGs and from 6% to 40% in the climate scenario with the highest emissions (Nedumaran et al. 2021).

Figure 3.4: GCM Selection for Study Region in Andhra Pradesh



GCM = global climate model, RCP = Representative Concentration Pathway.

Source: Nedumaran et al. (2021).

The RIA found that vulnerability is not uniform across the Kurnool district, with impacts varying across climate and price scenarios, and future pathways. Under current production regimes, most of the chickpea farm households are vulnerable to climate change, with greater impacts projected for the warmer scenarios and lower impacts for the wetter ones. Even under a less extreme climate scenario, losses were found among smallholder farming households.

When utilizing the DSSAT model projections, the per capita income and poverty were negatively impacted in most scenarios regardless of the representative concentration pathway (RCP).[4] The higher percentage changes in per capita income and poverty were found in the hottest and driest scenario (RCP8.5) with about −18% and 15% change, respectively. The magnitudes were comparatively lower (−12% and 5%), with RCP4.5, the dry but less warm scenario.

The RIA methods call for the development of sets of practices that can build resilience to both current and future climate extremes. The climate-smart adaptation package developed for the Kurnool District in Andhra Pradesh consisted of short-duration cultivars in the drier parts of the region and medium-duration cultivars in the wetter parts (Nedumaran et al. 2021). Other elements of the adaptation package included use of harvested rainwater for irrigation, adequate levels of fertilizer application, introduction of foxtail millet, and promulgation of mechanical harvesters. Adoption of the climate-smart adaptation package was tested using the TOA-MD economic model; results showed that almost 80% of smallholder farmers could improve their livelihoods if the package were to be adopted.

3.3.3 India—Tamil Nadu

Tamil Nadu is one of the 29 states in India; it is located in the southern part of the country and shares borders with Pondicherry and the South Indian states of Kerala, Karnataka, and Andhra Pradesh (Vellingiri et al. 2021). This study focused on the region of Tiruchirappalli and the district of Vaiyampatti. Agriculture provides the major source of income to the population of the district. The major crops are paddy, sorghum, cotton, groundnut, and maize. In addition, dairy, sheep, and goats, and inland fishing contribute to the district's economy and act as a major source of livelihood for improving the income and standard of living of the people. The major challenges are the large number of resource-poor farmers, fragmentation of holdings, dependence on monsoon rain, and low productivity due to saline and alkaline soils. Low adoption of optimum seeding rates and lack of awareness and availability of new technologies are other challenges.

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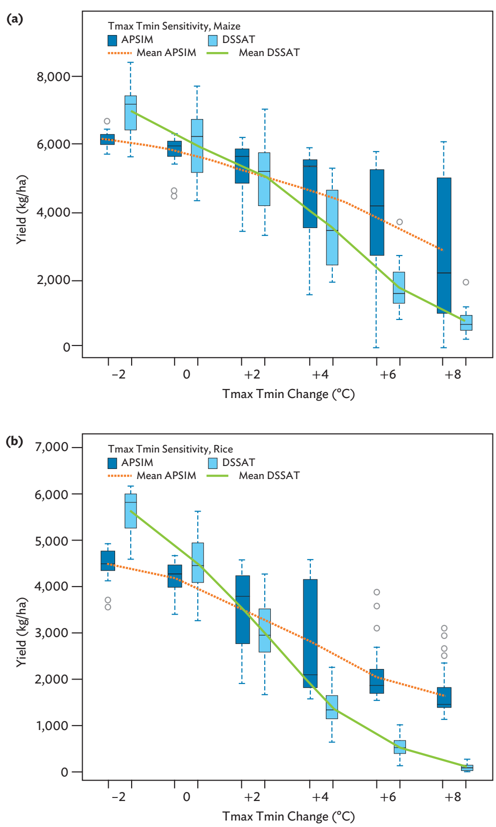
4 RCPs are scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases and aerosols and chemically active gases, as well as land use/land cover. RCP4.5 is an intermediate stabilization pathway in which radiative forcing is limited at approximately 4.5 W m-2 in 2100, while RCP8.5 is a high-emissions pathway for which radiative forcing reaches greater than 8.5 W m-2 in 2100 (IPCC 2021a).

Results of the AgMIP RIA found more negative effects from the higher greenhouse gas emissions climate scenario than the lower one (Vellingiri et al. 2021). Maize yields were lowered in the most severe scenario, which is characterized by a very hot and dry climate. Reductions in maize productivity ranged from 14% to 24% depending on climate change scenario (Figure 3.5a). Rice yields are also projected to be negatively affected (Figure 3.5b). The adaptation package for the Tamil Nadu region included an optimum sowing window and increased application of nitrogen fertilizer. These practices had positive effects on both maize and rice yields.

Figure 3.5: Response to Changes in Temperature for (a) Maize and (b) Rice



Source: Vellingiri et al. (2021).

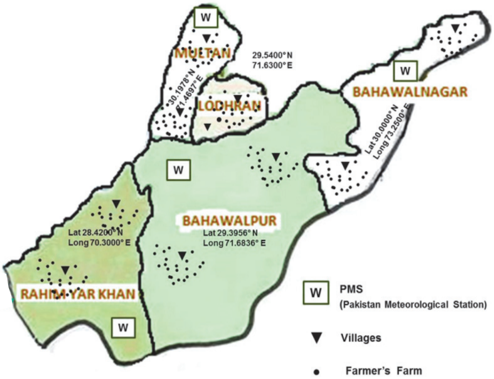
As agricultural technology advances and climate change progresses, improvements in crop genetics, such as longer growth-stage durations and higher temperature tolerance, will be important. Upgrades to crop and livestock management are also important; for example, increasing manure applications can enhance resilience through improvement of soil quality and water-holding capacity. However, even with those improvements, the changing climate is likely to bring detrimental effects. Under the hottest climatic conditions, maize yields are projected to decline by ~9% with the co-generated RAP known as the Sustainable Development Pathway and ~10% with the RAP known as the Unsustainable Development Pathway (Vellingiri et al. 2021). In the Sustainable Development Pathway, climate change is projected to reduce rice yields by ~14%; in the Unsustainable Development Pathway, rice yields decline by ~4%, both under the hottest climatic conditions.

3.3.4 Punjab, Pakistan

Climate change poses a looming challenge to crop production and farmer livelihoods in Pakistan (Ahmad et al. 2021). Cotton–wheat is a long-established crop production system in the northwestern plains of the Indian subcontinent, and this rotation occupies a prominent place in the agricultural growth of India and Pakistan (Figure 3.6). Cotton and wheat contribute largely to the economic well-being of many people engaged in farming, value chain processing, and the textile industry. The cotton–wheat cropping system is a grain-plus-cash enterprise that contributes to farmers' livelihoods by cultivating cotton as an industrial product and wheat as a constituent of food security. Being a cash and grain cropping system, it is extremely remunerative with secure returns. The total agricultural area under the cotton–wheat cropping system in Pakistan is 8.83 mha, which is 37% of the total cropped area of Pakistan. The AgMIP downscaled climate scenarios for maximum temperature in the Punjab in the 2050s ranged from 2.5°C to 3.6°C; minimum temperature projections were from 2.7°C to 3.8°C.

Results of the AgMIP RIA showed that projected changes in climate are considerable in the Punjab. Rainfall declines in the hottest and driest climate scenario show that cotton-growing season precipitation is lowered by about 30%–50%; for the wheat-growing season in the same worst-case scenario, rainfall declines are projected to be about 35% to 40%. When these changes are used to project impacts on cotton and wheat, results show 7%–42% declines in cotton yield and 2%–5% declines in wheat yield (Figure 3.7). The cotton crop was found to be more sensitive to climate change than the wheat crop. Cotton is likely to be particularly hard hit because cotton yields in the Punjab are projected

Figure 3.6: Map of Study Region in Punjab, Pakistan

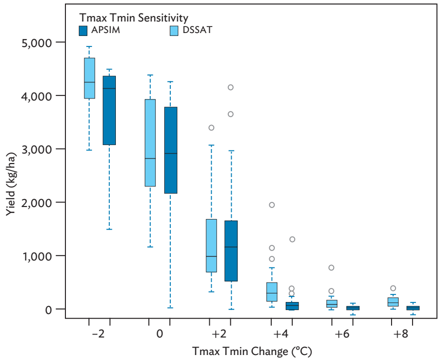


Source: Ahmad et al. (2021).

to decline while cotton production is projected to increase in other global cotton regions (Rosenzweig et al. 2018; Ruane et al. 2018). This causes a local reduction in both cotton yields and prices – a situation of great concern.

These climate and crop outcomes result in major effects on the incomes of farm households as projected by the TOA-MD economic model (Ahmad et al. 2021). Higher temperatures and humidity levels are simply not good the cotton-wheat cropping system in the Punjab. Under current growing conditions, a massively large percent of farming households (78%) are vulnerable to climate change: poverty levels increase by nearly 70% and net returns decline by almost 30%. Adaptation packages to reduce these impacts include management strategies such as higher density of sowing rates and greater applications of fertilizer in cotton and better- adjusted sowing dates as well as greater fertilizer applications in wheat. Those management interventions would increase net returns by 15% and reduce poverty for about 70% of farm households (slightly less in the case of the stakeholder co-generated RAPs Sustainable Development Pathway and slightly more in the Unsustainable Development Pathway) in the future. The TOA-MD model results show that over 50% of farmers would adopt the adaptation package and that poverty levels would be reduced by almost 40%.

Figure 3.7: DSSAT and APSIM Responses to Changes in Temperature on Cotton Yield



APSIM = Agricultural Production Systems Simulator, DSSAT = Decision Support System for Agrotechnology Transfer.

Source: Ahmad et al. (2021).

3.3.5 Viet Nam

In Viet Nam, the SIMPLE crop model was applied to assess crop responses to future climate change. The test case was black sesame (*Sesamum orientale L.*) (Vaughan and Geissler 2009). The study area is in the Hoa Binh commune, Cho Moi district, An Giang province, which is an islet in the Mekong Delta (Cho Moi People's Committee 2018).

This study conducted experiments for ADB1 black sesame (a local variety of the Mekong Delta), which grows to 116–120 m in height (Phạm 2012) and has a growing period of 70–75 days (Nguyễn and Võ 2013). This variety is tolerant to droughts, harmful pests, and diseases and can grow productively in a range of soil types. Measured data were used to create the inputs for the SIMPLE application.

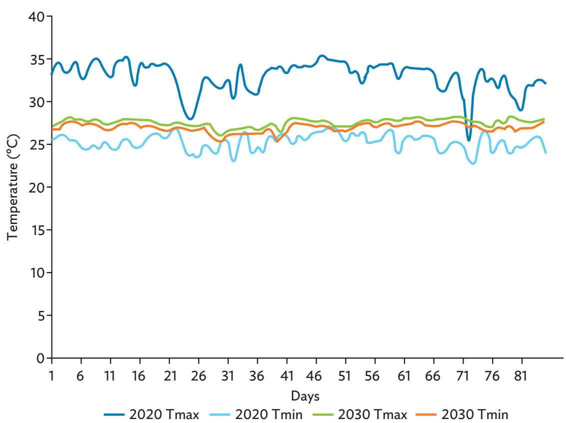
Sowing density was one individual per 30 cm x 20 cm in an area of 62.5 m^2 with ridge size of 20 cm height x 1.2 m wide, and furrow width of 20–30 cm. This experiment provided enough fertilizer and complete plant protection against harmful pests and diseases. Fertilizer was applied in the field with 90 kgN/ha; 50 P_2O_5: 50 K_2O kg/ha + 300 kg organic compounds/ha. Chemical compounds of Hopsan, Bassa, Trebon, Copper-B, Aliette, and Ridomil were used for plant protection. The crop was irrigated on a daily basis.

Biomass and yield were measured by crop stages of leaves, from formation to 50% of total area, and maturity dates. Date records include germination, leaves reaching 50% by area, flowering, harvest, senescence, irrigation (with amount), and fertilization (with amount). Biomass was weighed every 10 days (from a cutting of 4 m^2). The black sesame crop was harvested when three-quarters of the leaves turned yellow. Soil was analyzed for deep dynamic compaction, root zone depth, and available water capacity. Rainfall, temperature, and CO_2 were measured in the field.

We selected the climate change scenario SSP5-8.5 of GFDL-ESM4 to project future temperatures (European Union 2021). This study conducted a simulation run of black sesame yield regarding temperature in 2030. The projected data was in the range of 25–30°C (Figure 3.8). This application predicted a lower yield in 2030 than in 2020 (Figures 3.9 and 3.10). This difference is due to the projected temperature change in 2030.

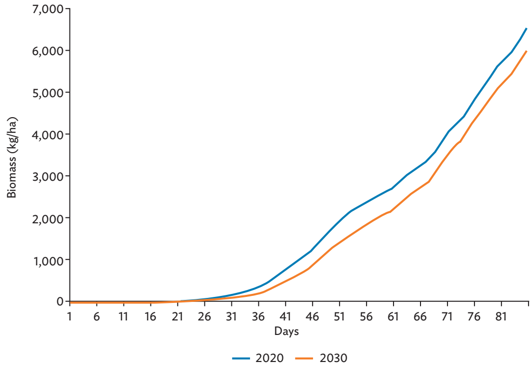
The combination of downscaled data and site data in this study showed that crop modeling with projected climate data could provide useful scenarios for developing and testing climate change adaptation.

Figure 3.8: Observed (2020) and Projected (2030) Temperature



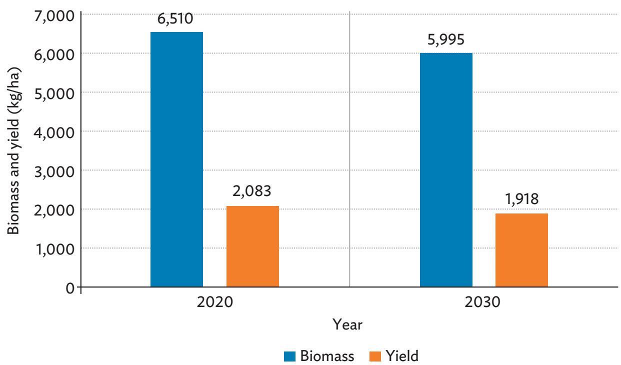
Source: Authors.

Figure 3.9: Biomass Simulated by SIMPLE Crop Model in 2020 and 2030



Source: Authors.

Figure 3.10: Biomass and Yield Simulated by SIMPLE Crop Model in 2020 and 2030



Source: Authors.

3.4 Synthesis of Regional Study Results

3.4.1 Vulnerability and Economic Impact

The global area harvested to cereals is expected to grow about 3% by 2031, with expansion mainly experienced in Asian countries (OECD-FAO 2022). For example, global rice production is expected to reach more than 580 Mt by 2031 with pronounced production growth in Asia. The bulk of global rice output in Asia is expected to continue to be robust. At the same time, global wheat production is expected to increase by 70 Mt to 840 Mt by 2031, of which 35 Mt is projected to come from Asia (OECD-FAO 2022). However, crops in many regions of Asia are projected to face strong negative impacts from climate change (Jägermeyr et al. 2021). Therefore, the projected changes presented in this chapter (see Table 3.1) can have a significant impact on global food security.

Table 3.1: Summary of Results from AgMIP Study Regions in South Asia

Study Region	Vulnerability to Climate Change	Economic Impacts
Indo-Gangetic Plain, India	33%–51% of farm households vulnerable to adverse impacts under Sustainable Development Pathway	49%–74% of farms decline in net farm returns and per capita income
Andhra Pradesh, India	42%–68% of chickpea-based farm households under current system vulnerable	18% reduction in per capita income and 15% increase in poverty rates
Punjab, Pakistan	78% of cotton-wheat farm households vulnerable to climate change	69% increases in poverty and 27% reductions in net farm returns

AgMIP = Agricultural Model Intercomparison and Improvement Project.

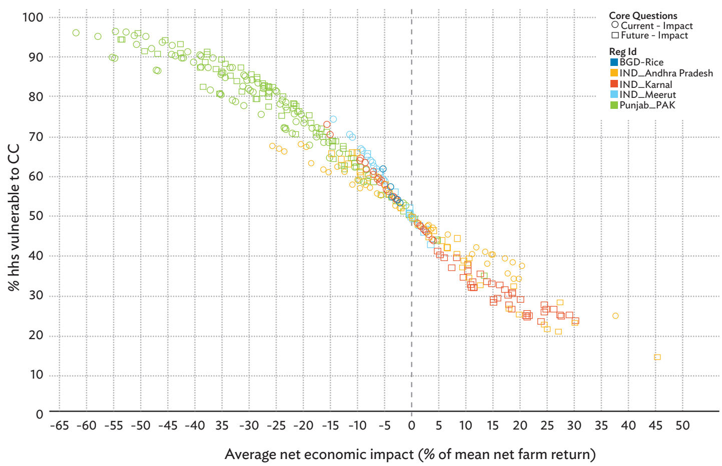
Note: The AgMIP Regional Integrated Assessment in Tamil Nadu, India did not include an economic analysis.

Source: Rosenzweig et al. (2021).

While the results described in the previous section and Table 3.1 show that most scenarios would cause losses to farmers, in some cases, climate change and/or the combination of agricultural pathways and climate change can benefit smallholder farmers. When this occurs, it means that, on average, the gains are larger than the losses, so the net economic impact is positive. However, these mean results do not take into consideration the vulnerability of the poorest households under climate change, so the aggregated results were further disaggregated using the TOA-MD economic model (Figure 3.11).

Figure 3.11 shows the net economic impact (NEI) as a proportion of mean net farm income (x-axis) and the proportion of households that are vulnerable to climate change (y-axis). The figure shows the results for all countries by strata, crop models and climate and socio-economic scenarios. Results demonstrate a range from losses (i.e., negative NEI) to gains (i.e., positive NEI). But in all cases, including the cases with gains, the proportion of farms that are vulnerable to climate change is high, between 20% to almost 100% of the population. The Punjab region in Pakistan has the highest losses and vulnerability rates. Future conditions under the Representative Agricultural Pathways increase the range of negative and positive outcomes. While high NEI tends to decrease the vulnerability levels, a large proportion of households who gain from climate change are still at risk of losing income.

Figure 3.11: Vulnerability and Net Economic Impacts for AgMIP Sites in South Asia



AgMIP = Agricultural Model Intercomparison and Improvement Project, Hhs = Households.

Note: Data from Bangladesh are included.

Source: Authors.

3.4.2 Research Gap—Sole Focus on Adaptation

Responses to climate change involve either mitigation, i.e., reduction in atmospheric concentrations of greenhouse gases, or adaptation, i.e., autonomous and planned interventions to reduce climate change impacts (IPCC 2021a). The first set of AgMIP regional integrated assessments only considered vulnerability and adaptation to climate change, but did not consider mitigation of greenhouse gas emissions from farming systems. Because mitigation interventions can affect adaptation responses and vice versa, AgMIP expanded on its RIA protocol-based methodology to include analysis of both mitigation and adaptation interventions. Furthermore, national stakeholders are involved in both mitigation and adaptation responses to climate change through their NDCs, so research is needed to analyze the interactions between mitigation and adaptation interventions. The new set of AgMIP protocols is called Mitigation and Adaptation Co-Benefits (MAC-B).

3.5 Mitigation and Adaptation Co-Benefits

There is increasing interest across research, stakeholder, and policy-making communities in identifying agriculture and food system interventions that contribute to both climate mitigation and adaptation, and to evaluate the resulting co-benefits, in order to promote and enable their implementation. The recent IPCC Special Report on Climate Change and Land highlighted the importance of conducting this type of assessment (IPCC 2019a).

Co-benefits span a range of outcomes, from biophysical/chemical (e.g., water conservation or biodiversity) to socio-economic (e.g., resilience to shocks). They can be global (e.g., targeting planetary boundaries) and/or highly regionally dependent (e.g., relevant to state-specific policies and goals). Several interventions for agriculture are shown to have mitigation and adaptation co-benefits at the global scale (IPCC 2019a). One reason for limited knowledge is that much of the research to date focuses on empirical research about individual interventions and the co-benefits they may provide. AgMIP's MAC-B methodology is a set of models, processes, and techniques for modeling co-benefits to significantly accelerate the innovation pathway, which is vital considering the increasing rate of climate change and increasing calls for more rapid and more ambitious action.

Intensive rice production in South Asia involves transplanting seedings into puddled soil, which is continuously flooded for much of the growing season. Continuously standing water in rice fields emits methane (CH_4), a potent GHG. CH_4 is generated by methanogensis when the amount of water and decomposing organic matter such as glucose is oxidized to CO_2, and O_2 is reduced to H_2O. This limits oxygen to the soil and in the water itself; instead of bonding with oxygen and leaving the soil as CO_2, methanogenic microbes, which thrive in low-oxygen environments, process the carbon into CH_4. Climate change could exacerbate this as temperatures rise and metabolisms of these microbes start to increase. Further, intensive tillage, puddling, and continuous irrigation in rice production consumes more production resources and energy than required and has raised concerns about production efficiency, environmental sustainability and profitability of rice production in the region, including energy-related GHG emissions. Rice alone consumes 80% and 81% of the energy and water use of monsoon cereals, respectively, and is responsible for 90% of the total GHG emissions of all monsoon cereals (Davis et al. 2019).

Nearly 3 billion people rely on rice as a staple crop (FAO 2019). The importance of rice for food security is such that it may directly feed more people daily than any other crop currently cultivated, providing approximately 20% of dietary energy (CGIAR 2013). This is partly due to the diversity of conditions in which rice may be grown—there are over 40,000 rice varieties, and as a species it can tolerate a wide range of temperature and moisture conditions. As a result, rice serves as the primary staple crop across vast expanses of South, Southeast, and East Asia, and is increasingly grown across Africa and Latin America by over 144 million producers. Global demand for rice is expected to increase by 28% in the next 3 decades (Chen et al. 2020). Thus, rice has a large global "footprint" and there exist many opportunities to identify and transfer improvements in rice-based farming systems.

AgMIP is currently testing this methodology in Bangladesh, Viet Nam, and India. In the next section, we describe the pilot MAC-B project in Bangladesh.

3.5.1 Pilot MAC-B Project in Bangladesh

Building on earlier work in Bangladesh (Ruane et al. 2013), we conducted a pilot RIA of sustainable rice systems in Bangladesh and evaluated the current and future efficacy to simultaneously boost yields and improve rural livelihoods; adapt to a changing climate; and mitigate GHG emissions and unsustainable use of water. To do this, we adapted the AgMIP RIA protocols to include mitigation components. The resulting RIA methodology was used to estimate the linked mitigation-adaptation co-benefits of rice systems in Bangladesh.

The study regions were Lalmonirhat and Rangpur in the north, Faridpur and Gopalganj in the south, Kishoreganj in the east, and

Rajshahi in the west. The method retained the multi-disciplinary, climate-crop-livestock-socioeconomic evaluation framework that combines comprehensive data collection for a population of diverse farming households and crop field trials with state-of-the-art climate, crop, livestock, and economic modeling techniques—and the data and modeling tools were again used in conjunction with scenarios of future climate, policy, and socio-economic conditions. However, in the MAC-B RIA approach, we incorporated a process-based biogeochemical modeling of the land surface. This allowed us to resolve current and potential future soil carbon storage, GHG fluxes, and nutrient dynamics alongside crop yield and water productivity under different sustainable rice management packages. In particular, we analyzed improved water management, through AWD.

We evaluated the rice production systems under current and future climate conditions and assessed the potential mitigation and adaptation co-benefits of AWD. This study served as an initial proof of concept for applying these methods more broadly and systematically to evaluate sustainable rice interventions across many domains using AgMIP approaches.

We did not directly consider future socio-economic conditions or policy changes related to agricultural development. Instead, we focused our efforts on modelling co-benefits under future climate conditions. This study, however can be the foundation to extend the analysis under a broader suite of future conditions (i.e., developing and applying AgMIP Representative Agricultural Pathways).

We utilized the AgMIP RIA methodology, which poses questions that lead to simulation analyses conducted by the combined model suite of the DNDC-ORYZA rice crop model and TOA-MD economic regional farming system model. The scale of the simulations is a regional farming system that is characterized by distributions of climate, soils, crops, livestock, and economic variables. Climate data are for a baseline period of 30 years; future climate scenarios are from the Sixth Phase of the Coupled Model Intercomparison Project (CMIP6).

Outcomes to be examined and models used are:

- GHG emissions
  - o N_2O, CO_2, and CH_4 flux rate (kg C/ha, kg N/ha)
  - o Model: DNDC
- Yields
  - o Yield per hectare (kg/ha)
  - o Models: ORYZA, APSIM
- Yield stability
  - o Coefficient of variation of crop model outputs
  - o Models: ORYZA, APSIM

- Economic performance
  - Farmer income and percent poverty by strata
  - Sensitivity to costs for aspects of production that contribute strongly to GHGs, such as water management
  - Model: TOA-MD

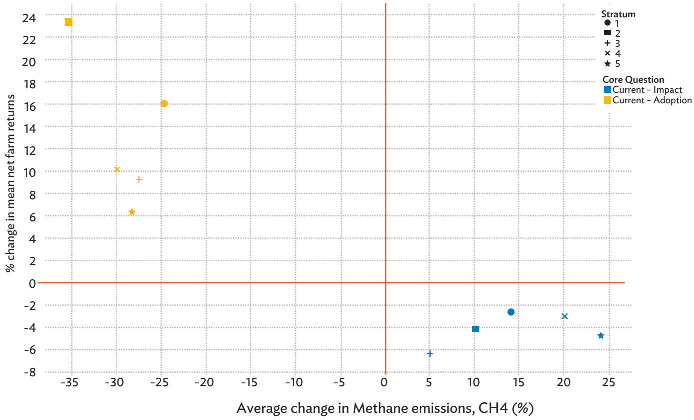
Early results show that AWD technology under future climate change results in strong reductions, not only on water requirements for irrigation, but also methane emissions. Crop model simulations project a slight decrease in yields at the regional scale for non-site-specific AWD compared to conventional rice systems, but this may be ameliorated by efficient fertilization. Irrigation water savings and lower CH_4 emissions were confirmed by simulation results. Increased yields in many individual fields also confirmed that some degree of positive change in yields is achievable due to the decreases in irrigation water requirements and CH_4 emissions, if site-specific AWD can be applied.

However, when using observed data, most farms that had control over water access show an increase in yields (with AWD). Preliminary results show increases in yields and decreases in poverty rates. In addition, they show that climate change is projected to increase CH_4 emissions due to warmer temperatures, but that adoption of AWD can reduce CH_4 emissions in the farming system tested.

Figure 3.12 shows preliminary results of how a change in rice production management (in this case AWD) can be used as an adaptation strategy, while at the same time capturing mitigation benefits. Climate change is likely to reduce net farm income between 2% to 8%, but also is likely to increase methane emissions on conventional rice farming systems (blue points on the figure).

In this case study, CH_4 increases between 4% to 25%. The preliminary results show that the AWD increases yields and mean net farm returns (6% to 24%), but also reduces methane emissions between 24% and 35%. This suggests that it is possible to achieve mitigation-adaptation co-benefits in rice-based systems.

Figure 3.12: Change in Mean Net Farm Returns and Methane Emissions in Bangladesh Rice Systems



Note: Blue indicates methane emissions under current production systems and orange indicates adoption of improved management, both under climate change scenarios.

Source: Authors.

Next steps are to incorporate algorithms to provide irrigation automatically when the rice crop experiences water deficits, as well as other crop model improvements. Additional analysis is required to assess the potential socio-economic (e.g., gender, labor, poverty), biophysical (e.g., soil fertility) and environmental (e.g., N_2O, and other GHGs) trade-offs and co-benefits of alternative rice management systems.

The MAC-B pilot study in Bangladesh also considered that the vulnerability contexts and benefit structures are different for men, women, and youth. This is because different groups have differing capacity to influence farm household decision-making and differing opportunities to participate in farm activities. Interventions that result in equal access and benefits will impact livelihoods overall. Key social variables that should be considered in future MAC-B research include age, education, land ownership, household headship, gender roles, gendered decision making, migration, ethnicity and language, and intra-household consumption patterns (Gartaula 2022).

3.5 Discussion and Conclusions

New insights emerged from the AgMIP studies in India, Pakistan, Bangladesh, and Viet Nam. First, the changing climate will exert negative pressure even under favorable circumstances of agricultural development. Second, in any given region, climate change will affect farmers differently depending on underlying vulnerabilities in regard to biophysical (e.g., soils and microclimate) and socioeconomic (assets) resources. Attention to the most vulnerable groups of farmers is critical. Third, there are many adaptation strategies available now that can be employed to reduce the brunt and burden of climate change impacts. These include management options such as adoption of differing cropping systems, upping fertilization rates, and establishing irrigation systems, as well as development of new markets. Investments will be needed in crop breeding program to improve cultivars in regard to heat and drought tolerance.

Specific to the mitigation and adaptation co-benefits work, control of and access to water is critical for rice-based systems in South Asia. Improved technologies that rely on controlled and intermittent irrigation (e.g., AWD) may not achieve potential yields when farmers cannot control when to irrigate. While the results are preliminary, they show the importance of capturing the heterogeneity inherent to these production systems. In the case of Bangladesh, the regional differences among farm types and smallholder households indicate that some do better than others with respect to climate change, and some may have larger benefits by adopting practices like AWD. Further analysis that incorporates other regions and more detailed production costs is needed.

Agricultural development based on policy and interventions that consider both national goals and regional (sub-national) needs, as well as mitigation and adaptation, is likely to improve farmers' livelihoods at present and in the future. The IPCC AR6 WGII empathized the need for climate-resilient development that integrates adaptation measures and their enabling conditions with mitigation to advance sustainable development for all (IPCC 2021a). As increases in climate extremes are becoming more prevalent in many regions of the world, national and sub-national action to ensure climate resilient development is becoming more and more urgent. But each country needs to determine its own set of mitigation and adaptation strategies that can maximize opportunities, minimize vulnerability, and enhance development. These three goals need to be entwined rather than siloed, and trade-offs need to be fully understood and reduced. Equity, social inclusion, and climate justice all must be taken into account in development planning (IPCC 2021a).

To advance climate change action even as the challenges of sustainable development are being addressed, a range of actors from all walks of society needs to be engaged. However, there are barriers to action to be recognized and overcome. These barriers include economic costs of adaptation, lack of technological capacity, and undeveloped institutional settings. A multiscale approach that includes portfolios of measures by a range of stakeholders is recommended by the IPCC (IPCC 2019b).

Exploration and adoption of the AgMIP methodologies are greatly benefited by the process of co-development of RAPs, policy briefs, and infoguides written in the language of stakeholders. The co-creation of engagement and communications in an iterative approach by stakeholders and scientists results in co-ownership of the results, which can then be broadly and confidently shared by scientists and stakeholders alike via documents, presentations, and well-designed, user-friendly web-based platforms.

Many developing countries in the Asia and the Pacific region face rapid development and serious risks due to climate change. There is a particularly urgent need for transformation to feed countries with some of the largest populations in the world, as well as to reduce greenhouse gas emissions from food systems. AgMIP projects in the region and work under development lead to three policy recommendations:

(i) **Integrate climate resilient development pathways into climate change assessments via the RAPs process.**
The development of agriculture-specific pathways and scenarios is motivated by the need for a stakeholder-driven and protocol-based approach to climate impact, vulnerability, and adaptation assessment. RAPs are comprised of a logically consistent set of drivers and outcomes that encompass local, regional, and global scales. Stakeholders and scientists work together to create coherent and agreed-upon potential agricultural development futures that serve as both a visioning and concrete testing methodology. AgMIP's experience with the implementation of RAPs in the countries highlighted in this chapter has shown that it is a highly constructive process that brings together decision-makers and scientists to create policy-relevant research and decision outcomes. AgMIP RAPs are composed of future biophysical, socio-economic, and policy conditions that are then tested in impact and adaptation assessments. They are also useful in creating a set of metrics that can be tracked to evaluate outcomes of decisions and policies.

(ii) **Explore synergies, trade-offs, and co-benefits of mitigation, adaptation, and development in food systems.**
Mitigation actions may not be feasible in many developing countries if attention is not paid simultaneously to food security and attainment of sustainable farmer livelihoods. The key concept is co-benefits that achieve multiple objectives. This requires linking local, regional, national, and international scales of governance to ensure achievement that benefits food security and farmer livelihoods at the base of the food system. It is at the local and regional scales where agriculture fundamentally takes place that women's roles and nutritional outcomes for all are critically important. However, there is major gap in knowledge at these scales regarding how to realize the potential for co-benefits. Much more research is needed on topics such as ease of adoption, roles of women, nutrition, and health outcomes. Projects such as the AgMIP MAC-B can fill these research gaps to help national decision-makers develop integrated mitigation and adaptation policies.

(iii) **Conduct multi-scale assessments that link national and regional stakeholders.**
Agricultural development based on policies that consider both national goals and regional (sub-national) needs is likely to improve farmers' livelihoods at present and in the future under changing climate conditions. AgMIP is developing an Integrated National and Regional Assessment methodology that is designed to facilitate a step change in climate change adaptation and resilience planning in both developed and developing countries. This is accomplished by understanding system-level climate impacts and adaptation options, decision processes, applications research, and communications supporting science-based policy and investment planning (Antle et al. 2015; Valdivia et al. 2015; 2021).

Engaging policymakers early and often in the research process creates shared learning and common interests, and provides opportunities to co-produce knowledge, as well as trust in the information. Thus, relationship-building is critical to effective long-term climate action in agriculture. Knowledge jointly produced through deliberative dialogue with researchers, policymakers, and local communities provide new viewpoints and contextualize findings. Stakeholder dialoguing also contributes to more effective adaptation to climate impacts by improving the relevance and robustness of research results.

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4

When Policy Responses Make Things Worse: The Case of Export Restrictions on Agricultural Products

David Laborde and Abdullah Mamun

4.1 Introduction

Export restrictions on food commodities are often used by countries that are net exporters of food in the wake of either commodity price booms (e.g., the 2006–2008 and 2010–2011 food price crises) or in response to sudden shocks, such as extreme weather or wars (e.g., the Russian invasion of Ukraine in 2022). Among the objectives of this trade policy tool, the most common is to insulate domestic prices from the world price level and thus avoid political repercussions from external shocks in the adopting countries (Bouët and Laborde 2010; Martin and Anderson 2012; Tadesse et al. 2014). Although the impacts of these trade measures have been extensively studied, the drivers and likelihood of export restrictions by a country on a specific commodity have been underinvestigated. In this study, we first investigated the impact of export restrictions during three crises (the 2006–2008 global food crisis, COVID-19, and the Russian invasion of Ukraine in 2022) on normal trade patterns globally, and in Asia in particular, and then examined the role of various drivers of adoption of these policies.

We started by investigating the price movement of key commodities, export measures, trade patterns, and the share of trade as measured by calories affected. Our specific objectives were to understand how food trade affected Asian countries and to examine the trade volume restricted by countries imposing these restrictions. Focusing on Asia, we were interested in examining how countries in the region that are net importers of food, often developing countries, are made vulnerable to bilateral trade shocks. We attempted to fit a probabilistic model to find the drivers of export restriction because we have a rich data set on the trade measures implemented in different episodes of crisis. The study examined the individual country model for selected countries in Asia to check for the consistency of results with results at the global level.

Whenever international prices of staple commodities surge, governments receive a signal of market turmoil and react immediately by imposing trade-restricting measures. During the global food price crisis of 2006–2008, such behavior was observed among many governments, particularly in exporting countries, in response to impending food security shocks. Bouët and Laborde (2010) built an initial database compiling restriction measures that various governments put in place to bar the export of cereals and vegetable oils. As many as 16 countries imposed some form of export restriction, such as a ban or export tax, on commodities including rice, wheat, maize, other grains, and vegetable oils. Later, Laborde, Mamun, and Parent (2020) complemented the data set with additional information, such as data on the volume of exports and calories of traded commodities affected by those restrictions.

During the COVID-19 pandemic, the world faced another round of supply shocks as increasingly more countries implemented export restrictions to secure their food supply. This time, in addition to export restrictions imposed by governments, the food supply chain was heavily disrupted. As the pandemic receded, countries opened their markets to facilitate the trade of foods and other commodities. Laborde, Mamun, and Parent (2020) continued to gather and validate data on export restrictions on agricultural commodities.

In 2021, as the world was returning to normal after COVID-19, the Russian invasion of Ukraine sent shock waves across the world in February 2022, particularly because these two countries together account for 12% of the total calories traded globally (Glauber and Laborde 2022a). The Russian Federation and Ukraine are also the top suppliers of wheat, barley, sunflowers, and maize. As Laborde and Mamun (2022) extend the tracking of export restrictions related to the ongoing crisis, as many as 28 countries have put restrictive measures on a range of products, including food and fertilizers. With world food stocks already low in 2021, the Russian invasion of Ukraine put an additional strain on the food supply and prompted fears of price increases beyond the initial increases driven by COVID-19 (Glauber and Laborde 2022a). The crisis has been exacerbated by the fact that increasingly more countries that are not dominant in the world market have followed the restrictions imposed by major exporting countries, creating a domino effect (Bouët and Laborde 2012).

The question arises as to why these trade measures are so frequently implemented as policy tools by governments during periods of food crisis. The economic rationales behind this pattern have been discussed extensively in the literature, both theoretically and empirically. Bouët and Laborde (2010) present details of justifications for the use of export restrictions. Most cited justifications refer to the terms of trade, food security, price impact, and price insulation. Countries' exploitation of the terms of trade through export restrictions is similar to raising import tariffs, because both improve the terms of trade, influencing the world price in their favor. This rationale works well when a country has a very large share in the world market for a specific commodity. When food prices spike, noncooperative behavior also exists between large net food exporting countries and large net food importing countries (Bouët and Laborde 2012). In the absence of international coordination, this behavior hurts small net food importing countries, which usually respond by reducing import tariffs.

On the other hand, with low food stocks, concerns about food availability and price stabilization in the domestic market were seen as the major drivers for governments to undertake various export restrictions. During the period 2006–2008, many countries, including Bangladesh, India, Indonesia, and Pakistan, adopted these policies amid a growing fear of price surges for products including wheat, rice, and palm oils. They either implemented a complete ban on exports of commodities or used variable tax rates to limit exports. Adjemian, Petroff, and Robe (2022) presented the political economy of export bans and argued, both theoretically and empirically, that forward-looking price volatility in agricultural markets plays a key role in export bans by top producer countries.

Many prior studies have focused primarily on the key drivers of export restrictions and have analyzed the direct impact of these policies on price, distribution of income, and food security. However, it is also important to understand the dynamics of export restrictions to ensure sufficient international coordination and thus avoid unilateral withdrawal from trading. It is important to understand how much is already known about which variabilities are repeatedly exploited by exporting countries.

It is important to investigate the structure of a food system, such as the trade position for a given product, the role of other crops, and the product's share in global markets. For a given product, it is important to study the issue of variability in stocks across countries and the concentration of exports. Additionally, some products are targeted for export bans more than others. Time is another critical dimension: In past episodes of food price crisis, a few countries started with restrictions and, within a few weeks, increasingly more countries had presented restrictive policies.

Starting by analyzing the direct impact of export restrictions in the world, and in Asia in particular, this study aimed to investigate the possibility of forecasting export restrictions in an econometric framework that captures all of these phenomena. Furthermore, the study investigated the extent to which normal trade patterns are disrupted by the trade policies observed during different episodes of export restriction. The next section provides a literature review. We then discuss the direct impact of export bans and taxes. Section 4.4 analyzes the disruption of global food trade induced by export restrictions on commodities, focusing on several commodities. The economic model for forecasting export restrictions and the identification of the drivers of such restrictions are discussed in Section 4.5. The study concludes with a discussion on the key findings and the contributing drivers of export restriction measures.

4.2 Literature Review

Understanding export restrictions as the outcome of a process is important for optimal trade policies. Such an understanding can help limit the spread of restrictions being imposed and allow coordination between net food exporting and net food importing countries. Instead of examining the outcomes of export restrictions, which are widely studied in trade literature, this study aimed to investigate the forecasting power of various economic variables—including price change, the share of export in the global market, openness to trade, product forecasts, and stock-to-use ratio—in predicting the adoption of export restrictions. In this section, we discuss previous studies that have identified drivers of export restriction and the economic models used. This section also reviews studies on the impacts of export restriction, focusing in particular on trade patterns and price transmission.

Until recently, economic rationales for export restrictions have been studied more from a political-economic perspective and less in a complete economic framework. Identification of the contributing factors and an explanation of their power to predict export restrictions have been missing. He (2021), in an interesting paper that closely matches our study objectives, presented a probabilistic model for predicting export restrictions with a six-digit Harmonized System (HS) product and used a set of political and economic indicators as explanatory variables. Among these indicators, the most important were the market power of a commodity, the number of the country's regional trade agreement partners, and the market power of the downstream sector, which purchases inputs.

He (2021) used data on export restrictions from 2005 to 2015, and thus had a gap in data coverage. Moreover, episodes of export restriction are often driven by either production shocks or significant price spikes. Although a price spiral was observed in 2021, the 2022 Russian invasion of Ukraine appears to be a purely exogenous shock, and thus any econometric model must address endogeneity bias. Also, the paper did not include any price variable as an explanatory variable and thus suffered from selection bias.

However, a large body of literature exists on the impacts of export restrictions on increased price volatility, food security, and poverty (Ivanic and Martin, 2008, 2014; Bouët and Laborde 2010, 2012; Martin and Anderson 2012; Pieters and Swinnen 2016; Laborde, Lakatos, and Martin 2019; Nguyen et al. 2023). Several of these papers have attempted to understand why countries resort to trade policies that hinder the flow of goods across borders and explain the spread of such restrictions to other countries (Bouët and Laborde 2010, 2012; Anderson, Ivanic, and Martin 2014; Ivanic and Martin 2014; Adjemian, Petrott, and Robe 2022). Nguyen et al. (2023) included insightful discussion on the interconnected issues of conflict and food insecurity and emphasized global policy actions for mitigating the challenges caused by war.

Adjemian, Petrott, and Robe (2022) examined the market reaction to export restrictions and proposed a theoretical model for examining risk associated with future price shocks in staple food products. They used options-implied volatilities (IVols) for corn and wheat as indicators of price uncertainty and presented econometric estimation results based on a daily data set of export restrictions for predicting price volatility. They showed that, when an export ban is imposed, IVols are significantly high on the day and immediately after the ban is announced. This study focused mainly on the power of export restrictions on market instability, instead of factors that determine the imposition of export restrictions in the first place. Moreover, the study examined only a few staple foods, not a complete set of commodities.

Bouët and Laborde (2010) illustrated all possible reasons for the popular use of export taxes during price spikes on the basis of the 2006–2008 episode of export restriction. They showed that, with the implementation of export taxes, countries engage in trade retaliation and thus face a noncooperative policy equilibrium that hurts world welfare. Nonetheless, their study did not address the predictive power of economic and production variables in export restriction. Now that the data on export restriction include three important time periods, a more robust data set can be used to investigate the forecasting power of economic indicators and thus to shed light on when a particular export restriction measure is likely to be used and how long it is likely to remain in effect.

Governments introduce export bans or impose high taxes with the objective of insulating domestic prices from the world level. Ivanic and Martin (2014) explored the nature of price transmission during the food price crisis and showed how these protectionist policies pursued by governments exacerbate the situation by increasing world prices, which are further raised by subsequent adjustments to trade policies. Their study was based on the 2006–2008 and 2010–2011 episodes of food price spikes. In a more recent paper, Martin and Minot (2022) investigated the impact of price insulation on global wheat markets during the 2022 food price crisis induced by the Russian invasion of Ukraine. They showed that these export restrictions almost doubled world wheat prices and increased price volatility.

Rude and An (2015) also examined the price volatility of grain and oilseeds during the 2006–2008 and 2010–2011 food price crises and how export restrictions created price instability. Their results indicated increased price volatility for wheat and rice during these periods but showed no evidence of volatility in maize and soybean prices. Estrades, Flores, and Lezama (2017) analyzed the period between 2005 and 2014 and estimated a disaggregated gravity model of trade to study the role of export restrictions and reduced import tariffs in price increases. They found that export restrictions have a price effect on a limited number of sectors, namely a positive price effect for vegetables, fats, and oils and a strong effect of export taxes for oilseeds.

Many authors have investigated the impact that trade policy responses to price spikes and weather shocks have on poverty, reaching the general conclusion that the impact is exacerbated by export restrictions because there are many relatively poor net food buyers and net food sellers (Ivanic and Martin 2008; Laborde, Lakatos, and Martin 2019; Koo, Mamun, and Martin 2021). Ivanic and Martin (2008) conducted one major study analyzing the impact on poverty during food price crises. They analyzed household survey data on nine low-income countries and found that, overall, higher food prices during the period 2006–2008, when many countries imposed either higher export taxes or bans on the export of goods, had an adverse effect on poverty. They argued that the magnitude of the impact depends on the distribution of net food buyers and net food sellers and found that poverty increased for most countries because of higher wheat prices, followed by rice, dairy, and maize prices.

Laborde, Lakatos, and Martin (2019) investigated the problem of collective action concerning the spread in trade policy actions during the 2010–2011 food price crisis. Their analysis shed light on the policies that contribute to world price volatility and that hurt poor consumers. Their findings revealed that price insulation policies adopted by many countries accounted for 40% of the increase in the world wheat price and

25% in the price of maize. Furthermore, they showed that global poverty had increased by 1% because of a combination of higher food prices overall and subsequent trade policy responses by many governments.

Koo, Mamun, and Martin (2021) conducted a country study to investigate the impact that weather shocks and subsequent trade intervention by Zambia had on poverty. They used household survey data and crop models to assess the average yield shock in maize due to the El Niño event in 2015. The impact on poverty was exacerbated by the fact that yield shock occurred first, and then the government imposed an export ban, which was seen as a policy based on food availability. Their findings showed that the government of Zambia successfully lowered the domestic price of maize relative to neighboring countries, which hurt poor net food sellers. The study observed that yield shock and lower prices magnify small adverse impacts on poverty.

We found that the available literature that identifies the drivers of export restrictions and assesses their predictive power fell short on (1) accounting for all recent episodes of export restrictions (2006–2008, 2010–2011, COVID-19, and the 2022 food crisis due to the Russian invasion of Ukraine) and (2) considering all possible explanatory variables, such as world price changes by commodity and period, a country's market share in the export of a specific commodity, the consumer price index for food, and production forecasts. We aimed to fill the gap in the literature by using an econometric model. We also studied the impact of export restrictions on normal trade patterns and downstream intermediate sectors that purchase inputs from the main or initial commodity where an export restriction is in place.

4.3 Coverage And Direct Impact Of Export Restrictions

In this section, we discuss various episodes of export restriction, their evolution, the commodities being restricted, and their direct impact on the share of global trade, measured in terms of billion kilocalories. We then discuss how these episodes affected Asia in particular.

4.3.1 Export Restrictions: Evolution and Impact at the Global Level

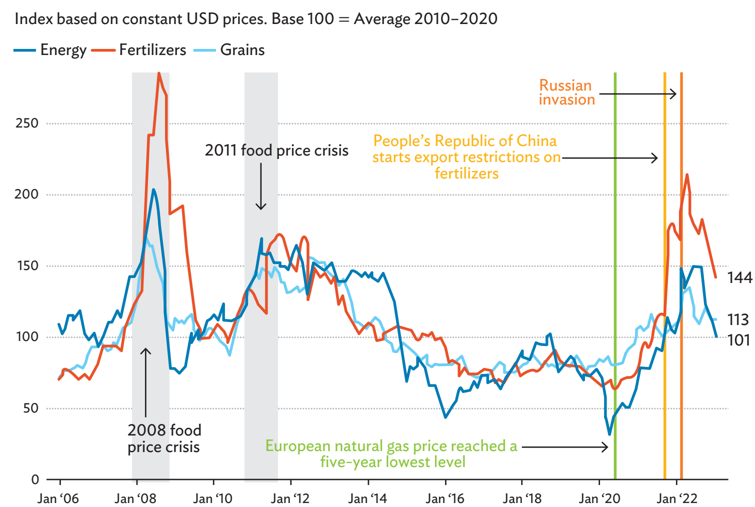
As millions of people face poverty and undernourishment, food security concerns are at the heart of the development agenda for most countries. Food price spikes, often induced by bad weather shocks, bring much misery to poor consumers. Over the past 15 years or so, the world has experienced various periods of food crisis: the 2006–2008 and

2010–2011 food price crises, the COVID-19 pandemic in 2021, and now the 2022 Russian invasion of Ukraine. Suffering has been exacerbated by the imposition of various trade policy measures that exporting countries implement to lower domestic prices and appease consumers. This section focuses on the coverage of agricultural products, the time period, and the most direct impact of these episodes of export restriction. We analyze the impact at the global level first, and then address Asia in particular, where the poverty rate is high. (More than 180 million people lived under $2.15 a day in 2019, according to the World Bank's Poverty and Inequality Platform database.)

We start by analyzing the timeline of the food price crisis, beginning in 2006. Monthly price movements of three major commodities—energy, grains, and fertilizers—are depicted in Figure 4.1. Evidently, in every episode of export restriction, the price of grains peaked compared with the preceding periods. Interestingly, fertilizer had much higher prices than the other two commodities. Prices have receded since then, but slowly.

As a result of the Russian invasion of Ukraine in February 2022, export blockages of key grains and oilseeds created by the war put severe strain on the supply of food to countries that are heavily reliant on import from these two nations, particularly countries in the Middle

Figure 4.1: Prices for Grains, Fertilizer, and Energy



Source: World Bank, US Bureau of Labor Statistics.

East, Africa, and South and East Asia (Glauber and Laborde 2022a). As Figure 4.1 indicates, prices were already high starting from late 2021, with an increase of 95% for fertilizer from January 2021 to January 2022.

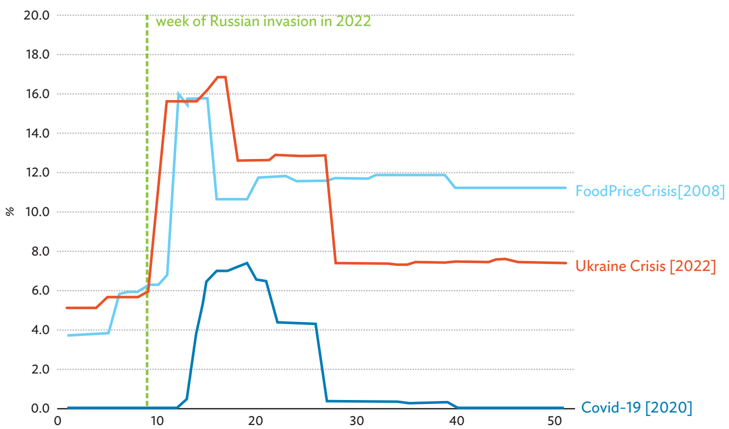
The price of grains increased by 23% from March 2021 to March 2022, the period immediately after the war broke out. Starting in September and October 2021, export restrictions on fertilizer were imposed, first by the People's Republic of China (PRC) and then by the Russian Federation. The war in 2022 blocked the supply of fertilizers from Ukraine too. Although there are always short-term concerns related to supply constraints, the prospect of medium- and longer-term impacts due to a fertilizer supply shock is severe and dangerous to global food security (Hebebrand and Laborde 2022).

It is important to understand how export restrictions evolve over a short period of time because this information can help determine the duration of each restriction. As Figure 4.2 shows, a clear trend emerges in the evolution of global trade being restricted by either export bans, taxes, or licensing during all three episodes of food crisis. In quick succession, the number of countries imposing export restrictions rose sharply, producing a cascading effect described by Glauber, Laborde, and Mamun (2022b).

As shown in the International Food Policy Research Institute's food and fertilizer export restriction tracker, we observed that export

Figure 4.2: Evolution of the Share of Global Food and Feed Trade, in Calories, Impacted by Export Restrictions

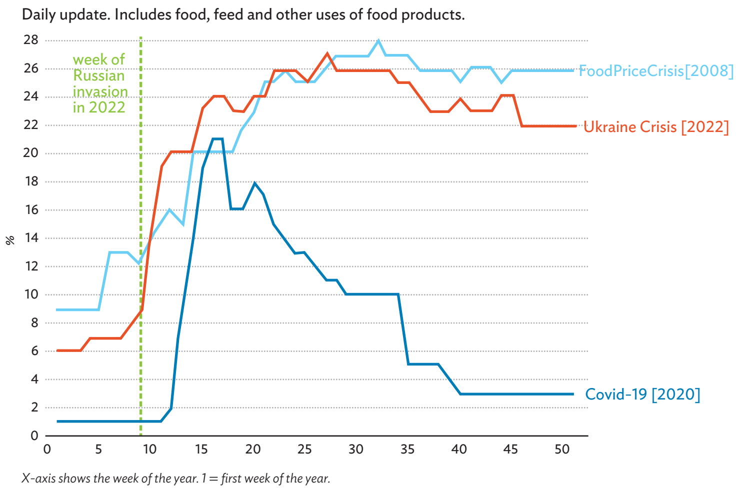
Daily update. Includes food, feed and other uses of food products.



X-axis shows the week of the year. 1 = first week of the year.

Source: IFPRI.

Figure 4.3: Evolution of the Number of Countries with New or Increased Export Restrictions on Global Food and Feed Trade, in Calories



Source: Food and Fertilizer Export Restriction Tracker, IFPRI.

restrictions were imposed by as many as 27 countries during the 2008 food price crisis and 25 countries in 2022—similarly to in 2008. During the COVID-19 pandemic, the number of countries that opted for restrictions was smaller—20 countries at the peak.

In the 2008 global food price crisis, the share of trade rose sharply, measured in calories affected by export restrictions between weeks 10 and 15. A slightly higher peak was observed in 2022, which stretched from weeks 10 to 18. During this time, more than 16% of globally traded calories were affected by export restrictions. Compared with these periods, the period encompassing the COVID-19 pandemic experienced a much lower impact—less than 8% of global trade measured in calories affected. The reason for the high impact in 2022 was that most of the large food exporting countries, such as Argentina, India, Indonesia, Kazakhstan, the Russian Federation, Türkiye, and Ukraine, imposed restrictions during the 2022 crisis. Documentation of these trade volumes measured in billion kilocalories can be found in Laborde and Mamun (2022).

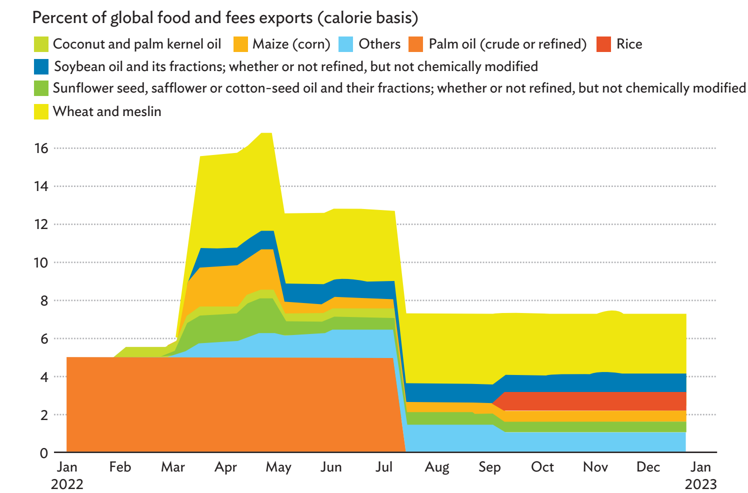
Although the share of restricted calories could decrease quickly when key exporters decide to remove their restrictions, the total number of countries implementing such measures displays much more hysteresis; many small and medium-sized countries will maintain restrictions for a longer period, including minor exporters in global markets. However, these lingering policies could have more pronounced consequences at a regional scale or in the business climate in these countries.

Grains and vegetable oils largely comprise the list of commodities targeted for export restrictions. When broken down by individual commodities, as shown in Figure 4.4, wheat and palm oil account for a large share of traded calories being restricted, and the restrictions remained for much of 2022. In the case of wheat, it was mainly the Russian Federation and Ukraine that imposed export restrictions, and for palm oil, Indonesia alternately imposed both an export ban and taxes. Restrictions on soybean oil (mainly led by Argentina) and maize (mainly the Russian Federation and Ukraine) were two other major commodities that came under export restrictions in 2022.

New commodities, such as rice and sugar, were included in restrictions later in the year. India, a large rice exporter, announced an export ban at the beginning of September 2022 that jolted the global rice market. The country also imposed export restrictions on wheat and sugar. Since mid-2022, the extent of export restrictions has eased with Indonesia's withdrawal of restrictions on palm oil. The Russian Federation and Ukraine reached an agreement in July 2022 to allow uninterrupted passage of grains and oil through selected Black Sea ports because the storage capacity of both new and old harvests of wheat and other agricultural products, amounting to approximately 20 million metric tons, had reached its limit (Glauber and Laborde 2022b).

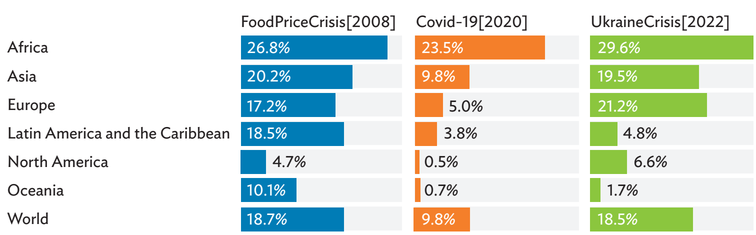
Two important questions arise: Who is most affected by these trade restrictions? and Which group of countries impose these restrictions? Since the global food price crisis in 2008, developing countries have mostly used these policy tools, and, unfortunately, these trade restrictions also affect developing countries (Glauber et al. 2022). Two issues closely related to food security received attention at the World Trade Organization's (WTO) 12th Ministerial Conference, which recently concluded in June 2022: export restriction and public stockholding programs. Yet, countries continue to use export bans or taxes because they are easily implementable and make their constituents happy. Unfortunately, poorer countries and regions, which are often net food importers, suffer the most, as shown in Figure 4.5.

Figure 4.4: Food and Feed Export Restrictions in 2022 Broken Down by Product



Source: Food and Fertilizer Export Restriction Tracker, IFPRI.

Figure 4.5: Share of Imported Calories Restricted by Export Restrictions by Regions



Source: Food and Fertilizer Export Restriction Tracker, IFPRI.

Figure 4.5 shows how export restrictions in different periods have affected different geographic regions. It is evident that Africa has been hit hardest by export restrictions on foods, particularly staple foods. In 2008, around 27% of total traded calories were affected in Africa, followed by Asia. Latin America, North America, and Oceania were seen as the least affected regions. In the current Russian invasion of Ukraine, Africa has been the most affected region (about 30% of food trade has been affected), followed by Europe and Asia. Notably, a huge amount of trade, particularly for grains, takes place between Europe and Ukraine, and the Russian Federation. Similarly, Asia has been affected because of export bans or restrictions on wheat, maize, barley, and sunflower oil by Ukraine and the Russian Federation.

4.3.2 Direct Impact of Export Restrictions in Asia

Asia, the most populous continent in the world, is home to millions of people facing poverty and food insecurity. According to the 2022 State of Food Security and Nutrition Report, more than half of the world's people affected by hunger in 2021 were from Asia (425 million people). Any disruption to the food supply or price spike in staple food commodities makes Asia vulnerable to food insecurity.

Unfortunately, some of the big exporting countries in the region also frequently implement trade restrictions that hinder the flow of goods to neighboring countries. Countries including the PRC, India, Indonesia, Kazakhstan, Pakistan, and Viet Nam have put some form of export restriction on key commodities for domestic price control. Because the Russian invasion of Ukraine had already rattled the global market for wheat, maize, and sunflower oil, these countries' decision to place export restrictions brought further miseries to net food importing countries such as Bangladesh, Nepal, and Sri Lanka (Mamun, Glauber, and Laborde 2022). Since 2005, Bangladesh has increasingly relied on wheat imports from the Russian Federation and Ukraine, as Mamun, Glauber, and Laborde (2022) have reported.

Table A4.1 in the appendix to this chapter shows the share of restrictions on imported calories, focusing on Asian countries only. Countries including Azerbaijan, Bangladesh, Georgia, Nepal, Pakistan, Tajikistan, and Uzbekistan saw the largest share of imported calories being restricted. Countries in Central Asia rely heavily on wheat, maize, barley, and sunflower oil from the Russian Federation and Ukraine.

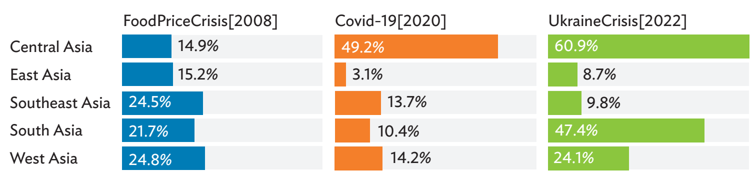
At the aggregate level, Asian countries are affected more than any other region except for Africa, because they account for a large share of the consumption of grains and vegetable oils. In the 2008 and 2022 food price crises, Asia's import share affected by trade restrictions stood at 20%, compared with the world's average of 18% (Figure 4.5). These findings indicate that the region's dependence on cereals from the PRC, India, Kazakhstan, the Russian Federation, Ukraine, and Viet Nam makes them vulnerable to any supply shock.

On the other hand, Asian countries were highly dependent on the import of vegetable oils from a few large exporting countries, such as Argentina, Brazil, Indonesia, and Malaysia. Furthermore, the impact of export restrictions on soybeans (Argentina initially banned export, then permitted export with high export tax), and palm oil (by Indonesia) was felt particularly in Bangladesh, India, and Pakistan, as prices rose immediately.

In reference to the geographical concentration of trade affected in Asian countries, heterogeneous effects have been found across regions during different episodes of export restriction (Figure 4.6). In the current Russian invasion of Ukraine, Central Asia and South Asia have been heavily affected by the export blockade for two reasons. First, Central Asia is exposed to trade on the Black Sea, and second, because South Asia has a large population that relies on the import of wheat and vegetable oils from large exporters, any export ban or high export tax makes the region vulnerable. During the 2008 food price crisis, countries in Southeast Asia, South Asia, and West Asia were most affected. Trade, as measured in calories, was less restricted in Central Asia and East Asia.

It is important to mention that these beggar-thy-neighbor policies also hurt producers, who face the lower prices of their artificially suppressed commodities. We have seen this price suppression in the case of the palm oil export ban by Indonesia this year, when farmers and their representative bodies protested against the export ban and urged for the immediate withdrawal of the government's decision.

Figure 4.6: Share of Imported Calories Restricted by Export Restrictions by Asian Regions



Source: Food and Fertilizer Export Restriction Tracker, IFPRI.

4.4 Evolution of Food Trade Over Different Episodes of Export Restrictions

This section analyzes the disruption of global food trade induced by export restrictions on commodities, focusing on several commodities. We aimed to examine the extent of disruption in normal trade of the commodities that frequently come under export restriction. In doing so, we constructed an export index based on the average export volume from 2012 to 2019, a period of normal trade without a major export restriction regime. Figures 4.7–4.14 cover the period from June 2007 to August and September 2022 for wheat, rice, palm oil, and soybean oil.

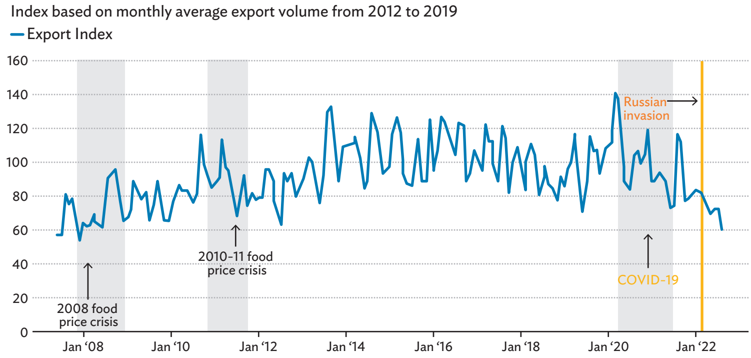
4.4.1 Effect on Wheat Trade

Among recent export restriction episodes, the 2008 food price crisis, when many countries faced soaring prices of staples due to the supply shock, is considered to have had the largest impact on global trade. The period of export restriction started in October 2007 and lasted for more than a year. During this period, the export volume of wheat (Figure 4.7) dipped the most from November 2007 to June 2008, when wheat was traded at half the level of the monthly export volume from 2012 to 2019, a normal period without major episodes of export restriction.

The 2010–2011 (specifically, October 2010 to September 2011) food price crisis is seen as having had a smaller impact on wheat export than the 2008 crisis. Similarly, during the COVID-19 pandemic, export of wheat declined slightly, by 17% in July 2020 and 27% in June 2021. The year 2021 can be described as the year of supply chain disruption. Therefore, export restrictions cannot be blamed much for this drop in the wheat trade.

The Russian invasion of Ukraine also had a large impact on the wheat market, as seen in the sections above that discussed import restriction, measured in kilocalories. Figure 4.7 clearly indicates how disruptive this period of export restriction has been, based on the actual volume of exports. Notably, the Russian Federation and Ukraine are two large exporters of wheat, and the blockade of exports through the Black Sea has had severe consequences. Wheat exports dropped by 31% in May 2022, immediately after the war broke out, and in August 2022, exports declined by 39% from the monthly trade volume in 2012–2019.

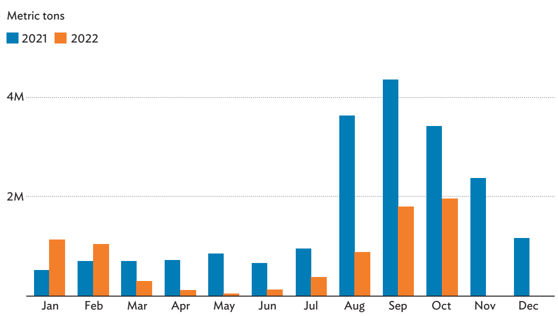
Figure 4.7: Wheat Trade Over Different Export Restriction Episodes



Source: Trade Data Monitor.

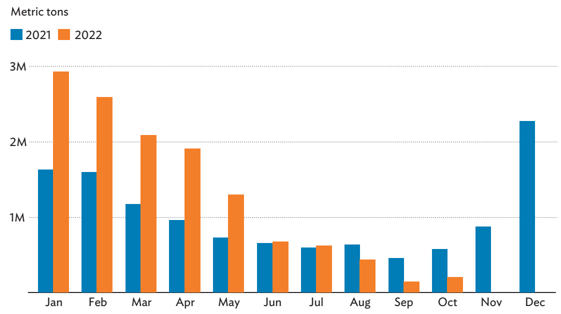
To emphasize the disruption of the export of wheat, Figures 4.9 and 4.10 compare the wheat exports of two countries—Ukraine and Argentina—in 2021 and 2022. Because of the ravages of the invasion, Ukraine could only export very small quantities of wheat between April and July 2022. Following the Black Sea agreement between the Russian Federation and Ukraine, export jumped in August and reached two million metric tons in October 2022. Yet, wheat exports in October 2022 were around only 60% of what was exported at approximately the same time in 2021. We did not have data for November and December 2022.

Figure 4.8: Ukraine Wheat Exports



Source: Trade Data Monitor.

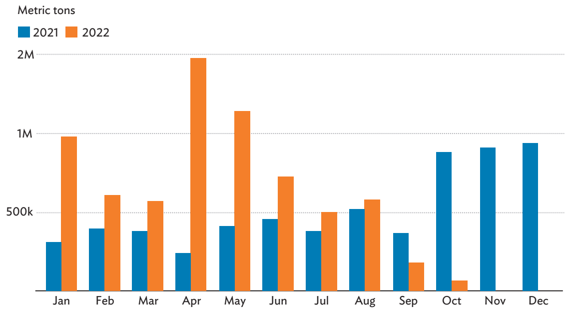
Figure 4.9: Argentina Wheat Exports



Source: Trade Data Monitor.

We analyzed data for Argentina, which did not restrict export and had an export volume of wheat in 2022 that surpassed the levels observed in 2021. Notably, Argentina had a much higher export of wheat from the beginning of 2022 than in the same months in 2021, and the trend continued until May 2022. From January to May 2022, exports were almost double the level in the corresponding months of 2021. June to November is the lean period, when the country has low exports. However, even from August to October 2022, the country had lower exports than those observed in 2021.

Figure 4.10: India Wheat Exports



Source: Trade Data Monitor.

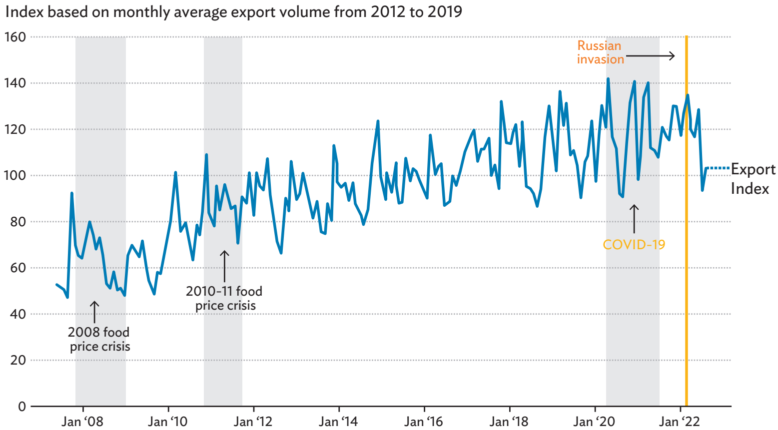
India's wheat export ban is an interesting case that merits broader discussion. The country initially imposed licensing requirements for traders in July 2022 and then imposed a ban on wheat export by the end of August 2022, fearing production shortages due to drought and other climatic conditions. This brought global alarm as the world was looking for alternatives to Russian and Ukrainian wheat. Figure 4.10 shows that the volume of wheat export significantly decreased from September to October 2022, compared with the same period in 2021. In October 2021, the total amount of wheat exported was 877,000 tons; in the same month of 2022, it was only 66,000 tons. Although India placed a complete ban on the export of wheat, the country had to deliver wheat under a previously signed contract order. The effect was felt immediately in neighboring countries, such as Bangladesh, Nepal, and Sri Lanka, which are large trading partners of India. This situation created inflationary pressure on countries that were limited to viable alternative countries to the Russian Federation, Ukraine, and India for wheat import.

4.4.2 Effect on Rice Trade

The PRC, India, the Philippines, Thailand, and Viet Nam are major exporting countries of rice. Figure 4.11 shows a larger drop in the rice trade during the 2008 food price crisis relative to other episodes of export restriction. In 2008, the PRC, India, and Viet Nam imposed either bans or licensing restrictions on rice. Trade volume was low throughout 2008, with the lowest in November of that year, and continued to be low until October 2009. Rice exports only normalized in 2010. The 2010–2011 food price crisis had a negligible effect on rice exports, which declined by 10% to 13% during the period. A similar trend was found during the COVID-19 period. In the current Russian invasion of Ukraine, India, the largest exporter of rice, first levied an export tax and then put a ban on the export of broken rice in September, the effect of which could not be captured in the graph below because of data constraints.

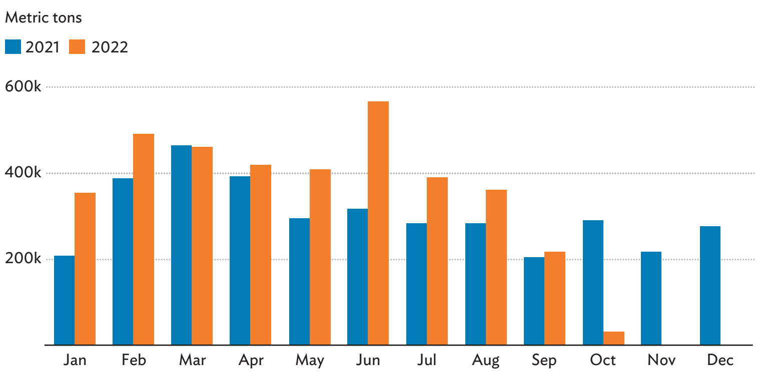
Rice is the staple food in many countries in Asia, and India is the world's largest rice exporter. As mentioned above, the country's exports significantly dropped after it introduced an export ban on broken rice. The country implemented the measure out of fears of escalating food inflation and production shortages due to heatwaves and other weather factors. As is evident from Figure 4.12, throughout 2022, India exported large volumes of broken rice (as high as 571,000 tons in June and as low as 218,000 tons in September) until October, when it exported only around 31,000 tons of rice, which the country had to export in order to maintain a previously signed contract with importing countries.

Figure 4.11: Rice Trade Over Different Export Restriction Episodes



Source: Trade Data Monitor.

Figure 4.12: India Broken Rice Exports



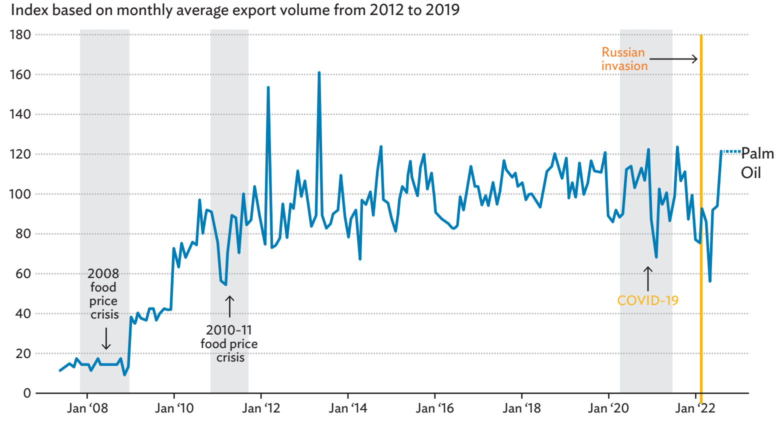
Source: Trade Data Monitor.

4.4.3 Effect on Palm Oil Trade

Palm oil, a popular vegetable oil in many parts of the world, has come under export restriction. With the growing fear of domestic price inflation this year, Indonesia first attempted to restrict export in January 2022 by requiring that 20% of their crude palm oil shipment be sold to local buyers and then by placing a complete ban on exporting the product in April 2022. The latter decision by Indonesia jolted the whole vegetable oil market, because palm oil is cheaper than soybean oil. Figure 4.13 shows the evolution of global palm oil export from 2007 to 2022, and Figure 4.14 shows Indonesia's exports for 2021 and 2022.

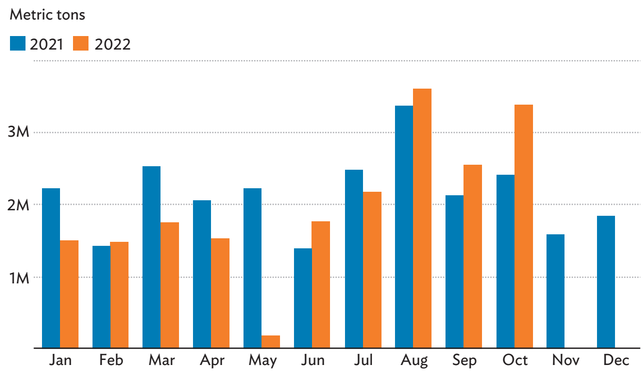
Compared to 2012–2019, the volume of palm oil exports was much lower in 2007–2008, although few countries imposed any sort of export restriction. Interestingly, the countries that put restrictions on export, including the PRC, Bangladesh, India, and Tanzania, are not major exporters of palm oil. It may be the case that palm oil did not get much traction outside world. During the 2010–2011 food price crisis, palm oil export dropped only in March 2011 and then quickly jumped. A similar trend was observed during the COVID-19 pandemic. After the Russian invasion of Ukraine, export of this product dropped sharply in May, the month when Indonesia shut its borders for trading. However, shortly after, exports resumed and returned to a normal trade pattern. Indonesia exported 1.5 million tons of palm oil in April 2022 and only 182,000 tons in May 2022.

Figure 4.13: Palm Oil Trade Over Different Export Restrictions Episodes



Source: Trade Data Monitor.

Figure 4.14: Indonesia Palm Oil Exports



Source: Trade Data Monitor.

Analysis of the evolution of food trade for selected commodities revealed heterogeneous effects of export restriction on trade volume, depending on the type of commodity, the countries that impose trade restrictions (i.e., large vs. small exporters), and the type of restriction (tax, licensing, ban, etc.). Also, it is evident from the data that some effects are short term, such as those observed in the trade of rice or palm oil, and some effects remain for a longer period, such as in the wheat trade. In this section, analysis was limited to export volume only. However, the effect of export restrictions can also be examined from a cost perspective: How do these restrictive measures place additional costs on importing countries? What economic loss or gain do exporting countries incur by postponing trade? These questions are beyond the scope of the study.

4.5 Predicting Export Restriction

Export restrictions of agricultural and food commodities are often seen as a response to rising food prices that many other factors, including supply shocks, extreme weather, and high fuel prices, can trigger. This study mainly focused on price variables and their role in export restrictions. We start with a graphical presentation of the food price index and coverage of export restriction measured in kilocalories. This presentation will reflect any co-movement between food prices and export restrictions. In the next section, we model export restrictions on both domestic food prices (overall) and international commodity prices (individual) by using a probabilistic approach.

4.5.1 Food Price and Export Restriction Coverage

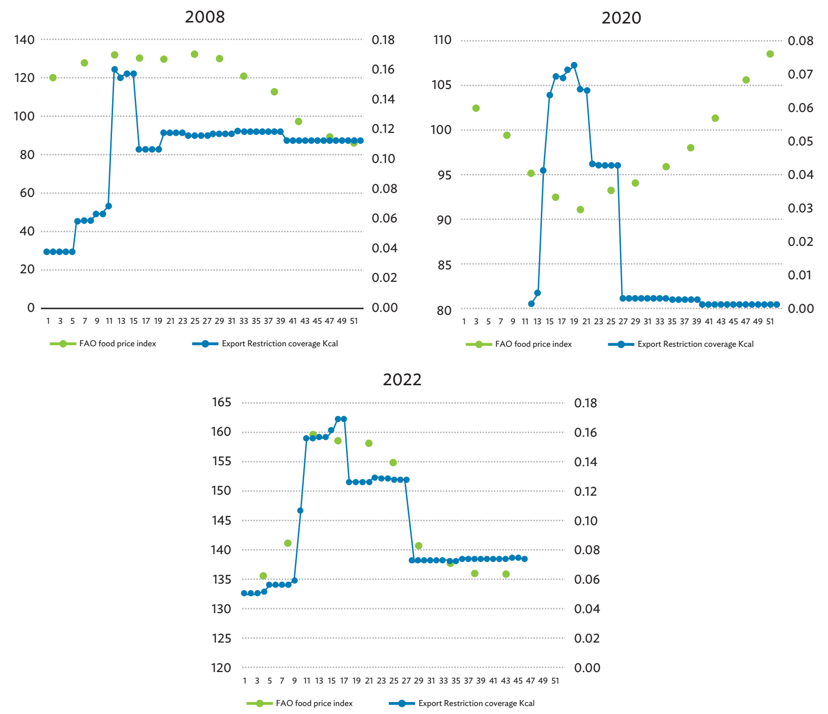
In general, the food price level in a given country is a leading indicator of export restriction, although the latter affects the former when all countries try to insulate their own economy from rising international prices, which exacerbates the situation. Figure 4.15 shows the global food price index (FAO 2022) and export restriction coverage measured in kilocalories (Laborde and Mamun 2022), at a weekly level. Three episodes of food price crisis—the 2008 crisis, the COVID-19 pandemic in 2020, and the Russian invasion of Ukraine in 2022—are depicted separately.

Among these episodes, a clear pattern emerged between food price and export restrictions in 2008 and 2022, but not in 2020. In these two periods, when the food price was high or at its peak, coverage of export restriction was also high, and as the price receded, countries relaxed their borders and opened their market; thus, export restriction coverage dropped quickly. This relationship was more evident in 2022. In 2008, food prices dropped more slowly than export restrictions as time passed. Interestingly, export restriction coverage stayed at almost the same level from weeks 19–20 onward.

COVID-19 presented a unique case, because both supply and demand shocks occurred during the period. Countries responded quickly by shutting borders. Export restriction coverage rose quickly from week 11, reached a peak at week 20, and dropped significantly at week 27. On the other hand, food prices dropped sharply at week 21, when export restriction was at its peak but global demand was collapsing. Prices then rose again until the end of the year. Importantly, the rise in the later period reflected the global supply chain shock.

In the 2008 and 2022 crisis episodes, the food price level had a significant role in the decision to impose export restrictions. Data suggest that some countries responded first and quickly shut their export markets, and other countries followed thereafter (Bouët and Laborde 2010). As food prices declined, trade resumed, and the coverage of export restrictions dropped.

Figure 4.15: Food Price Index and Export Restriction Coverage in Different Episodes of Food Price Crisis



Note: In this graph, the week number is on the x-axis, the food price index is on the left y-axis and the percentage share of export restricted (of total kilocalories) in the right axis.

Source: Authors' calculations based on data from FAOSTAT Consumer Price Index Data (2022) and Food and Fertilizer Export Restriction Tracker (Laborde and Mamun 2022).

4.5.2 Export Restriction in a Probabilistic Model

Two empirical questions that this study aimed to address were: How does price play a role in the decision to impose export restrictions of any type? and Which price has a larger role—the domestic overall food price or the international or world price of the commodities that are being restricted? We explored these questions by using a probit model that used both food price inflation and world price change as explanatory variables. The world price of individual commodities was derived from trade data in COMTRADE. Monthly mean price data for individual commodities (at the HS4 level) have been computed for 2007–2022. In the regression model, we used quarterly price and 12-month price change on the basis of the mean price data derived in the previous step.

Methods

Because we aimed to forecast countries' implementation of export restrictions, this study used an extensive database on export restrictions compiled over various episodes of food price crisis. Additionally, we gathered data from various sources on trade volume, production forecasts, a consumer price index for food, and other macroeconomic indicators. In this section, we describe these data and their sources. The econometric model considered for forecasting the implementation of export restrictions is described below, and the determinants of implementation are identified.

Data

In this study, we used a food and fertilizer export tracker database, which covers all recent episodes of food price crisis, including 2006–2008, COVID-19, and the 2022 Russian invasion of Ukraine (Laborde, Mamun, and Parent 2020; Laborde and Mamun 2022). This database tracked all types of export restrictions imposed by countries (bans, licensing, quotas, taxes, etc.) at the four-digit HS code level and with the start and end dates of the restrictions. We used a combination of systematic and ad hoc data gathering from official and unofficial sources to track food trade policy responses to the 2006–2008 food price spikes, the Russian invasion of Ukraine, and the COVID-19 pandemic. We augmented this information with detailed trade data and data on the caloric value of food trade (Laborde and Deason 2015) to create impact indicators that demonstrate the magnitude of each policy's effect. Table 4.1 provides a summary of the trade restrictions data used for this study.

Table 4.1: Data on Export Restrictions by Episodes of Food Price Crisis

Episode	Number of Countries	Number of Measures	Number of Products	Key Commodities
2008 food price crisis	33	59	194	Rice, wheat, maize, vegetable oils
2010–11 food price crisis	13	54	31	Rice, wheat, maize, soybean oil
COVID-19	25	47	151	Rice, wheat
2022 Russian invasion of Ukraine	32	77	83	Rice, wheat, maize, palm oil, soybean oil

Source: Authors' calculations. Data from Laborde and Mamun (2022).

To obtain world prices for commodities, we assembled monthly trade data sourced from Trade Data Monitor, starting in 2007 and ending in October 2022. We relied on the US Department of Agriculture's Production, Supply, and Distribution database for production forecast data. In the database, we were specifically interested in production forecasts and stock-to-use ratios.

A government's decision to impose export restrictions on a specific product can be influenced by that country's dependence on the product, specifically the share of the product in domestic consumption. Also, it has been empirically observed that when a country's consumer price index for food is very high, there is a high tendency to impose restrictions. We also considered monthly consumer price index food data for 2007–2022 from the Food and Agriculture Organization Corporate Statistical Database. Macroeconomic indicators, such as per capita income and population density, were downloaded from the World Bank's World Development Indicators collection.

Econometric Model

In this study, we proposed to use a simple model to predict the export restriction of a commodity by country. Our objective was to examine how commodity prices play a role in export restriction. We used a dynamic panel data set comprising country, commodity, and time as dimensions.

$$\begin{aligned} er_{ijt} = \alpha_0 + \alpha_1 PCh_{jt} + \alpha_1 FoodInf_{it} \\ + x^{/}_{ijt}\beta + \gamma_i + \mu_j + \theta_t + \epsilon_{ijt}, \end{aligned} \tag{1}$$

where β is a vector of parameters, i is the country dimension, j is the commodity (HS4), and t is time (monthly). The dependent variable, er_{ijt}, is directly observable and takes values of 1 or 0 only. PCh_{jt} denotes the quarterly price change for commodity j at time t. $FoodInf_{it}$ is the food inflation in country i and at time t.

The variable x is the vector of covariates, including population density (log), trade as a share of GDP, and per capita income (constant, PPP). The control variables are selected based on careful examination of their influence on export restriction. For example, it is very important to understand a country's trade exposure because it captures the idea that more open countries are more prone to be exposed to external shocks. Therefore, the higher the trade exposure, the more likely the countries are to impose restrictive measures. Large exporting countries frequently adopt export restrictions. However, countries with high per capita income tend to restrict trade less because of lower immediate concerns about food insecurity and their capacity to rely on nonprice-based policies (e.g., social safety nets). Population density is relevant because the most populous countries tend to be more dependent on imports and could be extremely vulnerable to food insecurity.

Model Results

The model was fitted first with price variables only and then also with control variables, such as trade as a share of GDP, population density, and per capita income. We considered all of these control variables relevant for studying export restrictions. The indicator related to trade indicates an exporting country's trade exposure to the world. Population density is the indicator of how the country perceives its dependency on food consumption and vulnerability. The larger the population, the more likely the country will restrict food trade during a crisis.

Per capita income is the indicator of a country's relative income status in the world. High-income countries tend to practice export restrictions less than those in the developing world. Countries or regions such as the European Union, Japan, and the United States seldom impose export restrictions on food commodities. Therefore, the higher the per capita income, the less likely a country is to restrict trade. Table 4.2 presents descriptive statistics of export restrictions of selected commodities and explanatory variables from data for 57 countries that were used for model fitting. We computed the descriptive statistics on the basis of data from 2021 (except for food inflation, which was computed on the basis of 2022 monthly data, available up to September), mainly because data were available for most variables. Also, note that the price of many commodities had started to climb in 2021, and the Russian invasion of Ukraine compounded the supply constraint.

The probability of export restriction in the sample countries was as high as 46%. For rice and wheat, the probability of any form of restriction ranged from 43% to 46%, and for palm oil it was slightly lower, at 36%. As is evident from the high frequency of export restrictions, protecting consumers from a price rise in grains, particularly in rice and wheat, was a high priority of governments across large exporting countries whenever either supply shocks or high price increases occurred. The average duration of export restrictions (ban here), measured in days, indicated that over different episodes of export restriction, rice export was banned for the longest time—271 days—followed by palm oil and wheat.

Food inflation at the overall level was striking when considering price as the determinant of export restriction. In 2021, food inflation averaged 23.6%, a staggering figure in countries that restricted exports. The highest rate of food inflation was 390%, an exorbitant level that hurt consumers. In regard to the world price of three important commodities, palm oil prices were inflated quite high compared with wheat or rice prices. The median inflation of wheat price was higher than the mean.

Table 4.2: Descriptive Statistics

Variable	Mean	Median	Minimum	Maximum	SD
Duration of export restriction (days over different episodes)					
Rice	271	183	5	1,249	251
Wheat	252	183	1	1,249	248
Palm oil	276	171	14	1,249	352
Food inflation, monthly (%, 2022 as reference year)	23.6	13.9	−4.0	390.3	48.7
Price change at global level (%, 3-month lag)					
Rice	0.2	0.2	−2.7	3.9	2.2
Wheat	0.8	1.7	−25.4	16.2	10.7
Palm oil	7.2	6.1	−3.5	23.9	6.6
Per capita GNI (PPP, constant 2017, international $)	11,792.6	10,291.0	1,208.9	43,051.8	9,100.6
Trade share (% of GDP)	73.1	58.0	24.3	186.5	40.2
Population density	160.0	87.5	7.0	1,301.0	217.5
Probability of export restriction	0.46				0.49
Rice	0.46				0.49
Wheat	0.43				0.49
Palm oil	0.36				0.48

Notes: Descriptive statistics for price change (by commodity), per capita income, trade share, and population density are based on 2021 because of the availability of data. GNI: gross national income. PPP: purchasing power parity. SD: standard deviation.

Source: Authors' calculations.

Note that the world price computed here is a three-month price change. Global prices and overall domestic prices are likely to be drivers of export restriction. The use of three-month price movement in the probit model was based on the idea that countries monitor price movement continuously and take note of short-term price changes when deciding to impose a ban or hike an export tax.

Among the covariates, the most important was the country's trade exposure. Because most countries studied here were large exporters of a specific commodity, the average trade share as a percentage of GDP of 73% reflects this position. The average annual per capita income of

$11,792, measured as gross national income at the purchasing power parity (2017, constant international $) level, indicates that these countries are mostly developing countries. Population density was relatively high, with a mean of 160 people per square kilometer and a maximum of 1,301 people.

Table 4.3 presents the regression results fitted by using the probit model. Two different cases are presented here: one for a three-month price change and the other for a 12-month price change. In each case, we have two models (columns marked as (1) through (4))—one with only price variables and the other with price and control variables. For the results in Table 4.3, we specifically focused on the marginal impacts of the explanatory variables under each model (see marginal impacts columns). Summary statistics of the models have been added.

When the regression equation considered price variables only (Model (1) and Model (3)), we observed that the marginal impacts of

Table 4.3: Probit Model with Price Change of Mean Unit Price of Commodities

	3-month Price Change				12-month Price Change			
Dependent Variable: Export Restriction	(1) Price Vars. Only	Marg. Imp. in (1)	(2) With Control Vars.	Marg. Imp. in (2)	(3) Price Vars. Only	Marg. Imp. in (3)	(4) With Control Vars.	Marg. Imp. in (4)
Food inflation rate (%)	1.083*** (0.055)	0.378***	−0.059 (0.044)	−0.011	1.157*** (0.060)	0.401***	−0.030 (0.047)	−0.005
Price change at global level (%)	0.009 (0.011)	0.003	0.046** (0.015)	0.009**	−0.011 (0.012)	−0.004	0.078*** (0.015)	0.012***
Trade as a share of GDP (%)			0.739*** (0.035)	0.140***			0.852*** (0.042)	0.143***
Population density (log)			−0.407*** (0.010)	−0.077***			−0.377*** (0.012)	−0.063***
Per capita income (log)			−1.469*** (0.016)	−0.279***			−1.555*** (0.019)	−0.262***
N	30,856		26,637		24,240		20,414	
Pseudo R^2	0.013		0.445		0.016		0.502	
Prob>Chi^2 (Wald test for overall effect of coefficients)	0.000		0.000		0.000		0.000	
AIC	37,812		18,488		29,560		12,639	

Marginal impacts, abbreviated as Marg. imp., are given for the explanatory variables on the probability of export restrictions estimated from Equation (1) when independent variables are standardized. Columns (2), (4), (6), and (8) present the marginal impacts at the sample mean corresponding to the estimates in Models 1, 2, 3, and 4. Standard errors based on Z-statistics are reported in parentheses. + $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Source: Authors' estimation.

the price variables were positive and significant on the food inflation rate only. However, when control variables were included in the model, both sign and significance changed; the coefficient of world price appeared positive and statistically significant for both the three-month price change and the 12-month price change scenario. When modeled with the price variables only, the domestic food inflation rate seemed to have a large impact on export restriction; the one standard deviation increase in food price inflation (an increase of food inflation by 5.5 points) increased the probability of export restriction by 37.8% in the three-month price change scenario. The marginal impact was slightly higher for the food inflation rate in the 12-month price change scenario.

However, with the introduction of three control variables, the coefficient of the food inflation rate was negative, meaning the probability of export restriction decreased, although by fewer percentage points (1%). The world price dominated in the full model, and in this case, one standard deviation in the global price change of an individual commodity (1.1 percentage point) increased the probability of export restriction by 0.1% for the three-month price change scenario. For the 12-month price change, the probability of export restriction increased by 1.2%.

Among the control variables, a country's trade exposure influenced export restriction most. If a country has high exposure, it is likely to quickly restrict exports during a global food price crisis. In the model results, a one standard deviation increase in trade (as a share of GDP) increased the probability of export restriction by 14% in both scenarios. The per capita income of a country had the opposite effect on export restriction, as the regression coefficients were found to be negative and statistically significant. The results indicate that the higher a country's per capita income, the lower the probability of export restriction. Surprisingly, population density also appeared to have a negative impact. The higher the population density, the lower the probability. One plausible explanation for this negative impact of population density is that a country with a high population density will likely keep the market open to trade as it relaxes market regulations during a food price crisis.

We attempted to understand the individual country model and presented regression results in the annex (Tables A4.2 and A4.3) for selected large countries in Asia, including the PRC, India, Indonesia, and Kazakhstan. These countries impose trade barriers and implement restrictive measures whenever a supply crisis occurs or prices rise. Findings from the regression models for individual countries reveal that governments in those countries mostly fear overall food inflation as they try to control the export of key food items. In all four models for the PRC, India, Indonesia, and Kazakhstan, regression coefficients of food inflation variables have shown a high positive value and statistical significance, even when controlled for the covariates. These findings are consistent with what has been observed for the model at the global level.

Global price changes for individual commodities seem to have less influence on export restriction. This variable had a positive and significant effect only in India. In the other three countries, world price changes had a negative effect, in contrast to food inflation. The results suggest that the governments of these countries fear domestic food prices and inflation most as they encounter the public. The decision to impose export control comes quicker when governments see the prices of essential food items skyrocket. When other major exporting countries decide to implement an export curb, they trigger a ripple effect across countries.

Overall, from the probit model (without controlling for covariates), we found that price changes at the world level observed at a short interval have less influence in explaining export restriction than does aggregate food inflation. Concern for domestic food prices plays a larger role in the decision to impose food trade restrictions. When food prices become exorbitantly high, restriction on food trade becomes almost inevitable. A country's trade exposure also affects the government's decision to restrict exports.

4.6 Conclusions

During a global food price crisis, trade policy measures are often the first response of many governments across the world as they try to cool the domestic market and protect consumers from anxiety over inflation. These export restrictions seemingly help keep local prices low in the short term but exacerbate the global crisis as the collective actions of major exporting countries heavily distort world prices. Most often, key cereal products, such as wheat, rice, and maize, and vegetable oil products come under different forms of export restriction, while they remain the main staples for many poor people in net food importing countries. Although the export control measures have heterogeneous effects worldwide, in Asia, where countries have very large populations, they have strong negative effects because they raise food prices and hurt consumers. South Asia and Southeast Asia have been affected disproportionately by export curbs on staples and vegetable oils. Notably, several countries in Asia can also be blamed for implementing such trade-distorting measures, most prominently the PRC, India, Indonesia, Kazakhstan, and Viet Nam.

Governments often either try levying high taxes on exports or placing a quota on export volume, leading to moderate and often predictable price responses. When countries ban food and feed exports, the market reacts quickly and severely. In 2022, after the Russian invasion of Ukraine, such reactions from the market were noted when Indonesia banned the export of palm oil and India banned the export of wheat and broken rice. The situation worsened because the Black Sea—a key trading route for wheat, maize, and sunflower oil—was already blocked because of the war. In this study, we provided the most recent inventory of such measures (until December 2022). We have seen how the export ban of wheat and rice by India, Kazakhstan, the Philippines, and Viet Nam, and of palm oil by Indonesia, created a shock wave across countries. During the current Russian invasion of Ukraine, India's overall export volume of wheat and broken rice decreased significantly in the latter months of 2022.

We analyzed the immediate effects of export restrictions during different periods to help identify common features and differences. Then we presented a descriptive analysis of the size of the effects of export restriction over different episodes of food price crisis. This study also attempted to describe the effect in Asia in particular, a region with populations that are highly vulnerable to food insecurity. Finally, using a probabilistic model, we investigated one of the unaddressed questions on why governments impose a restriction, that is: Which price and economic variables have substantial influence on predicting export restriction?

As is evident from the graphical presentation of the price movement of grains, fertilizer, and energy (Figure 4.1) and the recent episodes of export restriction, price fluctuations play a key role in triggering export restriction. The rise in grain prices makes governments nervous, especially in developing countries, as they become concerned about the food security of a large population. When export restrictions of all the major episodes of food price crisis were placed in a time profile, weekly in this case, we observed a quick succession of implementation of new measures over a short period, with too many countries attempting to block export in a cascading effect described by Bouët and Laborde (2010). In Asia, a number of large food exporting countries, such as the PRC, India, Indonesia, Kazakhstan, Uzbekistan, and Viet Nam, often impose restrictions in the form of levying taxes or imposing export bans or licensing. It is, therefore, intriguing to understand how predictive domestic and international food prices are in export restriction decisions. We have addressed this question by using a simple probabilistic model.

In terms of affected countries and regions, we found that net food importing countries, often developing countries, are affected by export restriction, as our analysis showed in the first section of this chapter. In all episodes of food price crisis, the least developed countries are the most affected regions because their imports are heavily restricted by exporting countries. In Asia in particular, regions such as Central Asia, South Asia, and West Asia have borne the effects of export restrictions during the COVID-19 pandemic and the ongoing Russian invasion of Ukraine. However, during the 2008 food price crisis, effects were high in Southeast Asia, South Asia, and West Asia, but not as high in Central Asia.

Although export restrictions destabilize markets and contribute to price fluctuations, they are not just psychological measures. They vary greatly in intensity, and several have led to the collapse of specific trade relations over a few weeks or months. The world has seen how the global food price crisis in 2008 shocked many food-insecure countries as they struggled to find alternatives to importing food. The Russian invasion of Ukraine has placed many countries in Africa and Asia in a much more vulnerable position just as they were starting to recover from COVID-19 and supply chain disruptions. We observed that wheat, rice, and palm oil exports dropped significantly in 2008 and 2022, but not in the 2010–2011 crisis. The COVID-19 crisis brought a mix of supply and demand shock, when many poor people worldwide became jobless and faced severe food insecurity.

The situation observed at the global level is particularly analogous to Asia, which has many countries that are net food importers. This circumstance emphasizes the fact that poor consumers in the poorest countries have to pay a high price for these policies. Although the decision at the WTO ministerial conference of June 2022 to exempt humanitarian shipments from export restrictions is appreciated, the fact that commercial transactions involving the least developed countries could still be disrupted raises a major issue about how the global community addresses the needs of the most vulnerable people. If a global solution cannot be found—recognizing that key WTO members took more than ten years to translate the G20 communiqué of 2011 regarding humanitarian shipment into a trade rule—regional solutions should be promoted. In particular, because Asia includes several countries that are prone to implement restrictions, but also many countries suffering from them, a regional initiative that aims to tackle this issue should be prioritized.

Stakeholders can promote policy dialogue and define new rules that will promote a fair trading system, limiting the consequences of unilateral decisions by larger exporters, but they should also continue to increase understanding of why these countries are using this policy instrument to target the drivers of such policies. Predicting export restriction requires both theoretical and empirical consideration. Price and other economic and demographic indicators play a role in the imposition of export restrictions. Few studies have examined the determinants of export restriction, and we have not found any study that covers all export restriction episodes and addresses the important question of how predictive the price is in export restriction decisions. We have used a simple probit model to explore whether price, along with key control variables, has predictive power on export restriction. We considered the overall food inflation rate and the world price change of commodities and constructed a database covering all major episodes of export restriction.

The regression model has suggested that the domestic food inflation rate has higher predictive power in export restriction than does a commodity's world price change. With a one standard deviation increase in the food inflation rate, the probability of export restriction increases by 37.8% when the model is fitted with short-term price change at the global level and considers only price variables. Food price inflation captures various factors because it reflects not only the sensitivity of consumers to specific food items, but also several structural elements (i.e., institution, stability macroeconomics, level of complexity of the food system) that create an idiosyncratic situation at the country level. The result changes when control variables, such as trade share in GDP, population density, and per capita income, are introduced; in this case, food price inflation as a whole is not a key driver of commodity-level policy responses, but the price changes on global markets of specific commodities are World price change is positively associated with export restriction in both short- (3-month price change) and long-term (12-month price change) price movement: A 1% price rise will increase the probability of a country implementing a restriction on this product by 1%. Models for selected countries in Asia reveal more striking results, with food inflation having large predictive power for export restriction.

Among the control variables, trade share, which indicates a country's trade exposure, has a large influence on the decision to impose a restriction. On the other hand, per capita income was found to be negatively associated with export restriction, meaning that high-income countries have a low probability of export restriction, and low-income countries have a high probability.

Because the current uncertainty over the future supply of commodities looms large, lessons from the past and present food price crisis suggest that developing countries in Asia, both net food importing and exporting countries, should share information about production forecasts and diminishing stocks of staples. Any unilateral withdrawal from the food trade exacerbates the situation and hurts Asia's poor. Both short- and long-term policies are suggested. In the short term, net food importing countries should expand social safety-net programs, subsidize food purchases, and implement other safety-net programs, including allowances for elderly and extremely poor individuals.

Affordability of food will continue to remain a challenge for the governments of most Asian countries. Although the supply of imports looks like staying tight for the near future, these countries should consider effective market monitoring as long as the staple food markets remain tight. This market mechanism can help discourage price manipulators. Governments should also pay attention to the supply of fertilizers, because some key markets, such as the PRC, the Russian Federation, and Ukraine, are closed, which has huge implications for future food security. Unfortunately, few countries export fertilizers in bulk.

Biofuel mandates by many countries also affect food security because the programs rely heavily on food crops and vegetable oils (Hebebrand 2023). The consensus opinion is that countries should implement flexible policies so that biofuel mandates do not harm or negatively affect the food supply. The current crisis of food insecurity is less a problem of availability than an issue of distribution and access. Removing barriers to food trade and reducing food waste and loss can help avoid severe food insecurity (Glauber and Laborde 2022b; Nguyen et al. 2023). In the long term, governments should consider accelerating investment in agricultural research and development. Such investments surged after the food price crisis, and the return to investment in research and development in agriculture has been robust (Alston, Pardey, and Rao 2020).

Most trade literature and empirical studies argue strongly for trade coordination whenever a global food crisis emerges. Export restrictions during different periods, particularly the 2008 food price crisis, have been well studied from the perspective of impact outcomes. Many of these studies focus on the price transmission mechanism and the impact on poverty and food security. This study investigated the factors that trigger export restriction and assessed their forecasting power. With the help of a wealth of data on export restriction coverage, we found that food prices at both domestic and global levels have a large influence on export restriction. This information can help policymakers, and the agencies responsible for implementing restrictions, pay attention to key price variables and coordinate with trading partners.

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Appendix

Table A4.1: Impact of Export Restrictions on Importers in Asia during the Russian Invasion of Ukraine

Economy	Share of Restrictions in Imported Calories (%)	Share of Restrictions in Traded Dollars (%)
Afghanistan	41.2	24.2
Armenia	53.3	19.8
Azerbaijan	71.4	33.3
Bangladesh	41.8	29.3
Bahrain	8.6	4.2
Brunei Darussalam	3.8	2.0
Bhutan	22.1	6.4
Cambodia	1.3	0.4
China, People's Republic of	9.4	4.4
Georgia	58.0	23.5
Hong Kong, China	0.5	0.1
Indonesia	10.6	4.3
India	55.7	36.5
Iran, Islamic Republic	17.8	15.7
Iraq	25.9	23.2
Israel	13.5	7.2
Jordan	17.7	9.0
Japan	2.9	0.7
Kazakhstan	17.3	4.8
Kyrgyz Republic	53.7	17.8
Korea, Democratic People's Republic of	0.5	0.2
Korea, Republic of	11.6	3.5
Kuwait	11.6	7.1
Lao, People's Democratic Republic of	0.3	0.3
Lebanon	47.8	2.9
Macau, China	0.4	0.0

continued on next page

Table A4.1 *continued*

Economy	Share of Restrictions in Imported Calories (%)	Share of Restrictions in Traded Dollars (%)
Maldives	5.3	5.6
Myanmar	16.3	15.8
Mongolia	35.8	9.5
Malaysia	13.1	6.2
Nepal	45.5	30.6
Oman	49.9	9.6
Pakistan	39.3	21.4
Philippines	9.9	3.9
Palestine	10.2	3.5
Qatar	20.7	8.1
Saudi Arabia	13.0	8.2
Singapore	3.9	3.0
Sri Lanka	19.5	11.2
Syrian Arab Republic	31.8	22.3
Thailand	9.4	2.7
Tajikistan	81.2	49.6
Turkmenistan	58.0	27.1
Türkiye	33.7	15.6
United Arab Emirates	17.9	7.5
Uzbekistan	76.2	51.2
Viet Nam	7.6	2.1
Yemen, Republic of	31.5	20.5

Source: Authors' calculations.

Table A4.2: Probit Model for India and the PRC, with Price Change of Mean Unit Price of Commodities

	India				PRC			
Dependent Variable: Export Restriction	**(1) Price Vars. Only**	**Marg. Imp. in (1)**	**(2) With Control Vars.**	**Marg. Imp. in (2)**	**(3) Price Vars. Only**	**Marg. Imp. in (3)**	**(4) With Control Vars.**	**Marg. Imp. in (4)**
Food inflation rate (%)	13.274*** (1.333)	4.728***	*Convergence not achieved*		7.986*** (0.287)	1.913***	0.8662+ (0.504)	0.183+
Price change at global level (%)	0.124* (0.059)	0.045*			−0.0898* (0.044)	−0.022*	−0.047 (0.046)	−0.010***
Trade as share of GDP (%)							7.083*** (0.793	1.507***
Population density (log)							68.285*** (11.530)	14.533***
Per capita income (log)							−6.336*** (0.876)	−1.349***
N	1,163				5,869		5,446	
Pseudo R^2	0.071				0.155		0.273	
Prob>Chi^2 (Wald test for overall effect of coefficients)	0.000				0.000		0.000	
AIC	1,461.4				5,041.6		4,152.2	

Marginal impacts, abbreviated as Marg. imp., are given for the explanatory variables on the probability of export restrictions estimated from Equation (1) when independent variables are standardized. Columns (2), (4), (6), and (8) present the marginal impacts at the sample mean corresponding to the estimates in Models 1, 2, 3, and 4. Standard errors based on Z-statistics are reported in parentheses. + $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Source: Authors' estimation.

Table A4.3: Probit Model for Indonesia and Kazakhstan, with Price Change of Mean Unit Price of Commodities

	Indonesia				Kazakhstan			
Dependent Variable: Export Restriction	**(1) Price Vars. Only**	**Marg. Imp. in (1)**	**(2) With Control Vars.**	**Marg. Imp. in (2)**	**(3) Price Vars. Only**	**Marg. Imp. in (3)**	**(4) With Control Vars.**	**Marg. Imp. in (4)**
Food inflation rate (%)	10.129*** (2.539)	2.129***	Outcome predicts data perfectly		4.494*** (0.517)	1.130***	3.180** (1.113)	0.776**
Price change at global level (%)	−0.161 (0.331)	−0.034			−0.051 (0.074)	−0.013	−0.034 (0.073)	−0.008
Trade as share of GDP (%)							1.013 (1.541)	0.250
Population density (log)							23.475*** (5.452)	5.729***
Per capita income (log)							−12.524*** (3.007)	−3.301***
N	161				1,362		1,234	
Pseudo R^2	0.123				0.058		0.089	
Prob>Chi^2 (Wald test for overall effect of coefficients)	0.000				0.000		0.000	
AIC	127.9				1,240.1		1,095.7	

Marginal impacts, abbreviated as Marg. imp., are given for the explanatory variables on the probability of export restrictions estimated from Equation (1) when independent variables are standardized. Columns (2), (4), (6), and (8) present the marginal impacts at the sample mean corresponding to the estimates in Models 1, 2, 3, and 4. Standard errors based on Z-statistics are reported in parentheses. + p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001.

Source: Authors' estimation.

PART III

Supply Chain Disruptions: Energy Security and Eco-Innovation

5

Navigating the Energy Trilemma During Geopolitical and Environmental Crises

Richard Tol

5.1 Introduction

We want energy to be cheap, reliable, and clean. It is typically easy to meet one of these three criteria, but meeting all three at the same time is difficult. This is known as the *energy trilemma*: You can't have your cake, eat it, and consume it. Trade-offs are real.

The energy trilemma and its components are not new. As the price of fuel wood rose in London, people switched to sea coal, bituminous coal mined on the northeast coast of England. Burning this coal made the air intolerable to breathe, and in 1307 King Edward I of England banned the use of sea coal in lime kilns. The ban was no success and later kings and parliaments issued their own regulations (te Brake 1975). Nonetheless, in December 1952, some 4,000 people were killed by air pollution and maybe 8,000 more in the following months (Bell and Davis 2001). The Clean Air Act of 1956 marks the beginning of the transition away from coal as the prime fuel for heating in the cities of the UK. Elsewhere, indoor and outdoor air pollution, primarily due to energy use, continue to kill millions of people each year.[1]

Energy security focuses on two aspects of the energy trilemma: reliability and affordability (Lefèvre 2010). The two concepts are

1 See WHO.

often mixed together,[2] but they are really separate. Energy reliability is a physical concept. Electric power is unreliable if transmission lines frequently fail, or generation plants suffer many outages. Reliable electric power is available when it is needed, unreliable electricity may or may not be there.

Affordability is an economic concept. Electricity may be available but sold at such a high price that its use is forgone or rationed. From the perspective of the final user, it does not matter whether energy is not there or not affordable. In either case, energy is not used. From an analytical perspective, however, it is important to distinguish the two concepts because technical solutions diff and the two objectives may clash. The reliability of an electricity grid can be improved with more transmission lines that are redundant except in emergencies. The electricity supply can be made more reliable by adding more power plants, used only in times of exceptional outages or very high demand. Such an increase in reliability would come at a cost, and so make electricity less affordable.

Jansen and Seebregts (2010) argue that environmental externalities pose security risks, so that energy security encompasses the whole of the energy trilemma. Bohi and Toman (1993, 1996) agree but restrict attention to those externalities that can be meaningfully influenced by policy, as indicators that are impervious to policy intervention should not be used to advise policy. I disagree, not because clean energy is not important, but because indicators should support policy by clarifying choices and consequences. A single indicator that obscures the reality of the energy trilemma is not helpful. Free after Tinbergen (1952), we should have as many indicators as we have problems.

This chapter continues as follows. Section 5.2 discusses the various indicators of energy security that have been used in the literature and that provide the conceptual framework for the rest of the chapter. Section 5.3 treats policy instruments to increase energy security. Section 5.4 is about the effects of geopolitics on energy reliability and affordability. Section 5.5 treats the impact of climate policy in the short- and long-run. Section 5.6 concludes.

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[2] Some analysts define the energy trilemma to be a three-way trade-off between cleanliness, security, and equity. Besides combining reliability and affordability, equitable access to energy is a matter of the distribution of income—unless there is strong price discrimination. Others replace clean energy with sustainable energy, but why use a long word where a short one will do? Besides, sustainability no longer refers just to the environment but also includes notions of social justice and economic development (Purvis et al. 2019).

5.2 Indicators of Energy Security

If we want to assess the impacts of geopolitics and climate policy on energy security, we need to be able to measure energy security. Much thought has gone into this, but this has not brought much clarity.

Böhringer and Bortolamedi (2015) critically reviews energy security indicators and their use in policy. Energy security indicators tend to suffer from the following limitations. First, indicators are supply-oriented, disregarding the demand side (Jansen and Seebregts 2010; Sovacool 2013; Gracceva and Zeniewski 2014). Second, indicators are proxies only; they do not assess the energy system's responses to shocks (Cherp and Jewell 2011; Gracceva and Zeniewski 2014). Third, energy security indicators have no information on the costs and benefit of different levels of energy security (Gracceva and Zeniewski 2014). Fourth, different energy security indicators cannot meaningfully be added or compared (Böhringer and Jochem 2007; Kruyt et al. 2009; Frondel and Schmidt 2014).

According to Böhringer and Bortolamedi (2015, see also Kruyt et al. (2009); Löschel et al. (2010)), four indicators of energy security are in widespread use:

- **Primary energy intensity** is defined as total primary energy use over Gross Domestic Product (GDP). Primary energy use is a physical measure, so this indicator only proxies reliability, not affordability. However, this indicator makes no distinction between more reliable and less reliable energy supplies. No account is taken of international trade in energy; offshoring energy-intensive industry would seem to increase energy security, even if goods are now imported from countries with a higher energy intensity (Gnansounou 2008). GDP too is problematic. It can be a poor measure of economic output in small open economies. Comparison of prices across international borders is difficult too; economies vary greatly in size between market exchange rates and purchasing power rates (Samuelson 2014; Suehiro 2008).
- **Dependence on foreign primary energy supply** is defined as the sum (over all fuels) of net imports (or zero for net exporters) divided by total primary energy use (Bhattacharyya 2011; Le Coq and Paltseva 2009). As with the previous indicator, there is no distinction between more and less reliable energy supplies. All foreign suppliers are deemed to be equally risky, and all domestic suppliers are supposed to be without risk.
- **Concentration of primary energy supply** is defined as the Herfindahl-Hirschman index—the sum of squared market shares—for fuels (Bhattacharyya 2011). This indicator again

ignores the actual reliability of the energy supply. It also ignores that diff t fuels serve different purposes—liquid fuels for transport, solid and gaseous fuels for power generation—so that diffin demand naturally lead to more or less reliance on particular fuels (Stirling 2010).

- **Concentration of foreign primary energy supply** is defined as the Herfindahl-Hirschman index for net energy imports, where concentration is measured either over the number of foreign suppliers (Kleindorfer and Saad 2005) or over the number of foreign suppliers and fuels (Frondel and Schmidt 2014). Once more, the reliability of imports is omitted from the indicator—oil purchases from Norway are treated the same as oil purchases from Libya—although this can be accommodated by introducing a riskiness parameter per supplier. Fungibility is another critique (Le Coq and Paltseva 2009). A country may depend on a single supplier of coal. An idiosyncratic shock to that supplier would not be a problem if other suppliers can take over. A country may buy oil from many suppliers, but this would not protect it from a system-wide shock. Transport is ignored too. Crossing the territory of a third party may be risky—recall piracy off the Horn of Africa and hijackings in the Strait of Hormuz—and some modes of transport are more flexible than others—contrast gas pipelines and liquified natural gas.

Ang et al. (2015) also review the literature on energy security, finding no fewer than 83 different definitions and a great many indicators. For instance, Sovacool and Mukherjee (2011) use 320 simple indicators and 52 complex ones. None of this makes much sense. Energy security is security from a human perspective, and it should therefore be measured as a reduction of human welfare (Bohi and Toman 1996). There are two reasons why energy might not be secure: An energy source is temporarily or permanently (i) unavailable or (ii) unaffordable and cannot be replaced at short notice.

Ex post, energy security is easy to observe: a power plant tripped, an oil tanker ran aground, energy bills were unpaid, or energy offers were not bought. *Ex ante*, energy reliability is hard to measure because it necessarily involves an assessment of the probability of things not going as expected. Energy affordability is predictable to the extent that incomes and energy prices are.

As argued above, energy reliability is a physical concept: Is the primary energy available, can it be transformed into a useful energy carrier, and can it be transported to the final user? Energy affordability is an economic concept: Is the price acceptable to the final user?

5.2.1 *Ex post* Indicators

The World Bank has a number of indicators that measure the reliability of the electricity supply, including:

- fraction of value lost due to electrical outages;
- percentage of firms experiencing electrical outages; and
- monthly number of power outages in firms.

Electricity is important but there are other energy sources as well. It would be useful to systematically collect information on shortages of transport, heating, and cooking fuels.

The negative impact of power outages is well-documented for both firms[3] and households,[4] as well as for the economy as a whole.[5] The evidence is for all parts of the world, and all levels of development. The negative impact comes in two parts. Unreliable electricity leads to interruption of production and daily life. In addition, firms invest in expensive backup equipment, locking scarce capital into unproductive means.

These studies make it clear that an unreliable energy supply is bad for the economy in the short-run and for economic development in the long-run. Capital diverted to backup power generation could have been used more productively. Learning and human capital accumulation are interrupted too. Although the actual outages happen by chance, the probability of outages can be reduced through better management of power plants and transmission lines, and better regulation of utilities.

The World Bank also publishes data on access to energy:

- Fraction of people (total, rural, urban) that have access to electricity; and
- Fraction of people (total, rural, urban) that have access to clean energy.

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3 Pasha et al. (1989); Beenstock (1991); Tishler (1993); Beenstock et al. (1997); Serra and Fierro (1997); Steinbuks and Foster (2010); Alby et al. (2013); Allcott et al. (2016); Cole et al. (2018); Elliott et al. (2021); Chen et al. (2022).

4 Carlsson and Martinsson (2007, 2008); Carlsson et al. (2011); Amador et al. (2013); Chakravorty et al. (2014); Ozbafli and Jenkins (2016); Poczter (2017); Kennedy et al. (2019); Meles (2020); Bajo-Buenestado (2021); Carlsson et al. (2021); Deutschmann et al. (2021); Meles et al. (2021); Motz (2021); Sedai et al. (2021b); Alberini et al. (2022); Aweke and Navrud (2022); Lawson (2022); Toto (2022).

5 Sanghvi (1982); de Nooij et al. (2007, 2009); Andersen and Dalgaard (2013); Reichl et al. (2013); Carranza and Meeks (2021); Woo et al. (2021).

It would be good to extend this to access to modern energy. Furthermore, while energy access is an important issue in poorer countries, energy poverty is important in richer countries—but there is no systematic data collection on this. Energy poverty is variously defined as energy expenditures above a certain fraction of income or an inability to provide a basic level of energy services. The latter, better definition is difficult to measure consistently over time and space.[6]

The impact of energy access is well-documented too, with mostly positive effects on a range of economic, social, and environmental aspects across the world, for all levels of development, and in the short- and long-term.[7]

These papers show that improving access to energy, by expanding the physical supply and reducing prices, has a direct effect on the economy by reducing costs, freeing up time, and facilitating more production. In addition, it improves health care and education which, in the long term, further accelerate economic development.

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6 Energy poverty is reported in poorer countries as well (Barnes et al. 2011; Khandker et al. 2012; Andadari et al. 2014; Sadath and Acharya 2017; Crentsil et al. 2019; Feeny et al. 2021; Gafa and Egbendewe 2021) but difficult to separate from energy access.

7 Dinkelman (2011); Grogan and Sadanand (2013); Lipscomb et al. (2013); Rao (2013); Khandker et al. (2014); Dasso and Fernandez (2015); Grimm et al. (2015); Kitchens and Fishback (2015); Grogan (2016); Peters and Sievert (2016); Salmon and Tanguy (2016); Abeberese (2017); Akpandjar and Kitchens (2017); Barron and Torero (2017); Da Silveira Bezerra et al. (2017); Grimm et al. (2017); van de Walle et al. (2017); Aklin et al. (2018); Burke et al. (2018); Ding et al. (2018); Fujii et al. (2018); Grogan (2018); Kumar and Rauniyar (2018); Lewis (2018); Rathi and Vermaak (2018); Saing (2018); Thomas and Urpelainen (2018); Dang and La (2019); He (2019); Jahangir Alam and Kaneko (2019); Litzow et al. (2019); Richmond and Urpelainen (2019); Zhang et al. (2019); Burgess et al. (2020); Cravioto et al. (2020); Diallo and Moussa (2020); Emmanuel and Japhet (2020); Fujii and Shonchoy (2020); Irwin et al. (2020); Lee et al. (2020b,a); Lewis and Severnini (2020); Sievert and Steinbuks (2020); Tagliapietra et al. (2020); Thomas et al. (2020); Acheampong et al. (2021b,a); Chhay and Yamazaki (2021); Fried and Lagakos (2021); Gaggl et al. (2021); Gupta and Pelli (2021); Jeuland et al. (2021); Sedai et al. (2021a); Wagner et al. (2021); Wirawan and Gultom (2021); Wu et al. (2021); Acharya and Sadath (2022); Adom and Nsabimana (2022); Ayana and Degaga (2022); Bo et al. (2022); Chaurey and Le (2022); Dendup (2022); Hong et al. (2022); Koirala and Acharya (2022); Ogunro and Afolabi (2022); Sedai et al. (2022); Guo et al. (2023).

Energy poverty too has negative impacts on well-being,[8] physical health,[9] mental health,[10] education,[11] crime,[12] agriculture,[13] and development in general.[14]

5.3 Improving Energy Security

Policymakers have a number of instruments at their disposal to improve energy security in its many guises. This is not the place for an exhaustive discussion.[15]

The reliability of the energy supply is threatened in two ways: There may not be enough energy, or the energy may not reach its destination.

Insufficient capacity is a particular problem in power generation. The technical answer is more capacity. As electricity cannot (yet) be stored at scale and demand varies considerably during the day, week, and year, there is typically a mismatch between peak demand and maximum supply. Peak demand lasts only a few hours, a short period to earn back the investment in peak supply. The best solution is a mixture of setting a level of acceptable blackouts, preparing for blackouts, and a reverse auction to buy spare generating capacity, financed by a levy on electricity use (Creti and Fabra 2007).

Inadequate transport or transmission is the other cause of an unreliable energy supply. The technical solution is to build redundancy in transport and transmission systems. If the market is competitive—e.g., tanker transport of oil—the costs of redundancy will be weighed against the costs of non-delivery, a breach of contract, and loss of reputation. If the market is not competitive—power cables, pipelines—direct regulation is the way forward. Natural monopolies tend to be state-owned and strictly

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8 Sambodo and Novandra (2019); Awaworyi Churchill et al. (2020); Nie et al. (2021).

9 Teller-Elsberg et al. (2016); Ortiz et al. (2019); Bukari et al. (2021); Awaworyi Churchill and Smyth (2021); Nawaz (2021); Prakash and Munyanyi (2021).

10 Zhang et al. (2021).

11 Oum (2019); Rafi et al. (2021); Apergis et al. (2022).

12 Hailemariam et al. (2021); Awaworyi Churchill and Smyth (2022a).

13 Shi et al. (2022).

14 Singh and Inglesi-Lotz (2020); Acheampong et al. (2021b).

15 See, for instance, Anderson (2019); Baumol and Oates (1988); Berck and Helfand (2011); Endres and Radke (2012); Field and Field (2009); Goodstein (2005); Hanley et al. (2007, 2013); Harris and Roach (2018); Hodge (1995); Kahn (2020); Keohane and Olmstead (2016); Kolstad (2011); Lewis and Tietenberg (2019); Pearce and Turner (1990); Perman et al. (2011); Phaneuf and Requate (2017); Tietenberg and Lewis (2018); Turner et al. (1994); Wills (1997).

regulated anyway, so additional regulation is straightforward whereas price signals—taxes or subsidies—are less effective without competition (Jamasb and Marantes 2012; Schmidthaler et al. 2015).

Energy affordability is about energy access in poorer countries and about energy poverty in richer ones. In both cases, poverty is the core problem. Rich people in poor countries have access to modern fuels. Energy companies happily hook up neighbourhoods once enough people can pay for their products. Similarly, energy poverty in rich countries is tightly correlated with income poverty. Stimulating economic growth, and particularly economic growth that disproportionally favours the less well-off, is, therefore, a key strategy to improve energy affordability.

More targeted interventions are also possible. Many countries subsidize energy use. Data are hard to get. The International Monetary Fund (IMF) has probably the best data but does not share, while their aggregate statistics are hard to read as explicit and implicit subsidies are added (Parry et al. 2021). The International Energy Agency (IEA) does share data, but only split by fuel. In 2021 in Azerbaijan, Uzbekistan, Turkmenistan, and Kazakhstan, the retail energy price was less than the wholesale price. These countries, as well as Bangladesh, spent more than 5% of their GDP on fuel subsidies.

Price subsidies are not advised. Price subsidies help those who would otherwise not be able to afford energy, but also and primarily help those who would have bought energy at the unsubsidized price anyway. Price subsidies also encourage waste when energy is, in fact, short. Price vouchers allow targeted price support (Podesta et al. 2021). Income support is another, better alternative to price support—if it is well targeted (Best et al. 2021; García Alvarez and Tol 2021; Bagnoli and Bertoméu-Sánchez 2022).

Furthermore, as lack of energy access and energy poverty hold back development (see above), alleviating this should be part of an overall economic development strategy (Bouzarovski et al. 2012; Karpinska and Śmiech 2021). Unaffordable energy is often caused by a lack of investment, which in turn is caused by a lack of access to capital markets. Investment subsidies are thus justified, in home insulation and efficient heating in richer countries, and in microgeneration, -grids, and -storage in poorer countries. However, energy poverty is not just about financials.[16] Any campaign against energy poverty needs to pay careful

16 Xu and Chen (2019); Awaworyi Churchill and Smyth (2020); Karpinska and Śmiech (2020); Ampofo and Mabefam (2021); Paudel (2021); Awaworyi Churchill and Smyth (2022b); Dogan et al. (2022); Koomson and Awaworyi Churchill (2022); Koomson et al. (2022); Moniche-Bermejo (2022); Barkat et al. (2023); Crago et al. (2023); Elder and Payne (2023); Li et al. (2023b,a); Lin and Okyere (2023); Luan et al. (2023).

attention to age and family structure, as well as to ethnic, racial, and religious discrimination.

5.4 Geopolitics and Energy Security

The exploitation of fossil fuels, and particularly of oil and gas, is heavily concentrated in a small number of places. Although there are oil and gas fields in many countries, most are relatively small. A few large producers dominate production. This has been the case since the start of the large-scale use of oil and gas.

The concentration of production implies that political unrest or violent conflict at the locale of oil and gas fields has a disproportionate impact on the world market for oil and gas. The concentration of production increases the importance of long-distance transport and the bottlenecks of international trade, such as the Panama and Suez Canals, and the Straits of Hormuz and Malacca. Furthermore, aware of the strategic importance of the centres of oil and gas production, outside forces have long sought to control these centres, or to control the strongmen who control them, competing with indigenous people and with other outsiders. In return, the strongmen have sought to influence the politics of other countries, both near their borders and far away. The result is a vicious cycle of political instability, interspersed with periods of stable but brutal and brittle regimes.

The second invasion of Ukraine by the Russian Federation illustrates the short-term issues. The violence has affected key energy infrastructure—damage to substations and thermal generators, threats to nuclear plants and hydropower dams—some accidental, and some apparently deliberate. The violence is concentrated in Ukraine, but occasionally spills into the Russian Federation and there are seemingly related acts of sabotage in Germany and the Baltic Sea. The rulers of the Russian Federation may have hoped that its position as the main supplier of energy to Europe would prevent other countries from coming to Ukraine's aid, but that was a miscalculation. The flow of oil and gas from the Russian Federation to Europe fell sharply. This forced the countries of Europe to seek imports from elsewhere, driving up the price of oil and liquefied natural gas (LNG). This in turn made energy unaffordable elsewhere. Pakistan, for instance, could no longer afford to import LNG and suffered power blackouts as a result. At the same time, Russian oil and gas traded at a discount, benefiting those countries that had the infrastructure to import (e.g., gas pipelines) and even re-export. The details are diff t for other conflicts, but violent conflict involving large energy exporters causes a lot of misery.

For the effects in the long-run, the literature on the natural resource curse offers some empirical support for the hypothesis that economies with weak institutions and an abundance of oil and gas, grow more slowly, as they are susceptible to political corruption[17] and violent conflict[18]—although there are also papers highlighting flows in the research.[19]

Unlike outages caused by the technical failure of energy production and transport, or power generation and transmission, unrest, and conflict are hard to predict. Instead of objective probabilities based on observed frequencies, we have subjective degrees of belief that, as autocratic regimes are rarely transparent, are based on incomplete knowledge and understanding (García-Verdugo and Munoz 2012). Yet, as once again demonstrated by the second Russian invasion of Ukraine in February 2022, geopolitical risks can, when realized, cause great havoc in energy markets as the impacts are system-wide rather than location-specific.

Although some have argued that a shift away from fossil fuels would lead to a reduction in geopolitical energy risks (Kemfert 2019), others point out that geopolitical risks would change rather than disappear (Hache 2018) as discussed below.

5.5 Climate Policy and Transition Risk

The energy trilemma has that we want energy that is reliable, affordable, and clean. Reliability and affordability together constitute energy security. The drive for cleaner energy affects its reliability and affordability. In the current discourse, "clean" energy is seen as carbon-free energy. There are other, perhaps larger environmental problems due to energy use—such as indoor air pollution, outdoor air pollution, and acidification—but these primarily affect poorer countries and are not seen as global priorities.

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17 Ross (1999); Sachs and Warner (2001); Jensen and Wantchekon (2004); Papyrakis and Gerlagh (2004); Bulte et al. (2005); Hodler (2006); Mehlum et al. (2006b,a); Robinson et al. (2006); Boschini et al. (2007); Brunnschweiler (2008); Kolstad and Søreide (2009); van der Ploeg and Poelhekke (2009); Torvik (2009); Aslaksen (2010); Vicente (2010); Cavalcanti et al. (2011); Van Der Ploeg (2011); Williams (2011); Boschini et al. (2013); Brollo et al. (2013); Betz et al. (2015); Havranek et al. (2016); Badeeb et al. (2017).

18 Grossman (1999); Collier and Hoeffler (2005); Dunning (2005); Basedau and Lay (2009); Brunnschweiler and Bulte (2009).

19 Brunnschweiler and Bulte (2008); Alexeev and Conrad (2009); van der Ploeg and Poelhekke (2010); Haber and Menaldo (2011); Smith (2015).

The replacement of fossil fuels by renewable energy will, in the long run, lead to a more reliable energy supply. Whereas thermal power plants are large and therefore few, wind turbines and solar panels are small and therefore many. By the law of large numbers, a large number of small power sources is less vulnerable to outages—be it due to mechanical faults, natural disasters, or terrorist attacks—than a small number of large power sources. Maintenance too is less disruptive.

On the other hand, solar and wind power are not dispatchable; power generation happens when it does, rather than when it needs to happen. This is particularly a problem for wind power. There is no solar power at night, but this is no surprise and can be solved with short-term electricity storage, as demand drops rapidly mid-evening. Lulls in wind can last for weeks, well beyond storage capacity, and may coincide with high demand—in Western Europe, for instance, winter cold and low winds go hand in hand.

Some argue that renewable energy is more secure because it is mostly generated in the home country rather than imported.[20] This argument is false. Foreign suppliers are not necessarily less reliable than domestic ones. The argument rests on either xenophobia or the false belief of being in control of what is happening in your own country.

Others argue that renewable energy is not secure because it relies on rare earths[21] and depends on foreign capital (Nakatani 2010). These arguments affect the speed of expansion of renewables rather than their functioning once installed. Rare earths are essential for both generation and storage. Their spatial concentration is a reason for concern. However, existing solar panels will continue to operate if the supply of rare earths is interrupted—unlike thermal plants which cease to operate if their fuel runs out.

The same argument holds for capital. Renewable energy uses more capital per kilowatt-hour than fossil energy and is, therefore, more exposed to movements of the interest rate and to sanctions in the capital market. This argument holds for the financing of new renewables, and for the refinancing of existing renewables. It does not hold for their operation. Operators run their wind turbines and solar panels regardless of the interest rate. The same cannot be said of thermal plants, which cease operation if the wholesale electricity price does not cover the cost of fuel.

Hache (2018) argues that patents are another bottleneck—a country or company may deny another country or company a license for the

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20 See Wikipedia, UK Government, US Government.

21 See UK Government, US Government.

use of advanced technology. But, as with rare earths and investment, withholding patents would decelerate the expansion of renewables but would not stop existing renewables. And, anyway, legal niceties such as respect for intellectual property rights rapidly go out of the window in case of conflict.

An expansion of nuclear power would also help to reduce climate change, but probably at the expense of affordability and reliability. Taking the costs of accident prevention and waste disposal into account, nuclear fission is not among the cheaper sources of electricity (Ahearne 2011). Nuclear power plants are large;[22] unscheduled outages therefore threaten a reliable power supply. The situation in France in 2022 is a reminder. While small modular reactors are all the rage at the moment, these are in fact only somewhat smaller than a typical gas-fired power plant. Nuclear power poses two unique challenges. An expansion of the nuclear power supply large enough to have a notable effect on greenhouse gas emissions and so climate change would require the building of nuclear power plants in currently unstable countries. The first challenge is that the people who run a nuclear power plant, know how to and have the material to build a dirty bomb. Second, as illustrated by the second Russian invasion of Ukraine, it is a really bad idea to situate a nuclear power plant in a war zone.

However, while climate policy may make energy more reliable in the long run, this is not necessarily the case in the short and medium term. Instability in the fossil-fuel producing regions is one concern, as the old regimes lose their power of patronage—and the restraint to seek conflict with the buyers of their energy.

Another concern is the scale of investment needed, particularly if the ambitious goals set out in the 2015 Paris Agreement and reaffirmed at 27th Conference of the Parties to the United Nations Framework Convention on Climate Change at Sharm el-Sheikh in 2022 are to be met.[23] A rapid expansion of renewable energy by investors with a limited budget may well lead to a lack of redundancy. Reliability would fall as a consequence.

A rapid transition to renewables risks stranding fossil fuel assets Davis et al. (2010); Tong et al. (2019); Ansari and Holz (2020); Semieniuk et al. (2022); Ferentinos et al. (2023). These studies estimate the global size and value of stranded assets, but only Tong et al. (2019) provide substantial regional detail: 41% of the world's committed emissions are in the People's Republic of China, 9% in India, and another 12% in other

22 Nuclear fusion plants would be larger still.

23 See IEA.

members of the Asian Development Bank. Coleman et al. (2021) find that few asset managers in India are aware of the possibility that their fossil fuel assets may be stranded and lose their value.

Asset stranding can be seen as an increase in redundancy, as delays between deactivation and demolition can be long. The current energy crisis in Europe due to the Russian Federation's second invasion of Ukraine is indeed alleviated by previously mothballed power stations being turned back on. However, the greater risk to energy security is the higher probability of bankruptcy as companies have to retire assets before the end of their economic lifetime. This leaves less money to invest within the energy sector and deters money from outside the sector from flowing in. If governments bail out energy companies, the budget for energy support falls—including investment in such things as peak capacity, transmission, interconnection, and storage.

Besides the impact on the reliability of the energy supply, climate policy also affects the affordability of energy.[24] Climate policy necessarily makes energy more expensive, by a little for lenient emission reduction targets and smart policy design, and perhaps by a lot when targets are stringent and policies suboptimal. Energy is a necessary good; the burden of higher energy prices, therefore, falls disproportionally on the poor. However, the substitution away from fossil fuels reduces the return on capital and increases the demand for labour and wages. Climate policy may thus be a relative benefit to the working poor.[25]

Estimates of the costs of climate policy vary widely between studies—predicting the future is hard—but all agree that a uniform carbon tax leading to the complete decarbonization of the economy by 2100 would be cheap, perhaps even too cheap to meter (Clarke et al. 2014; Riahi et al. 2022). The costs can be reduced by the clever use of the revenues from carbon taxes and emission permit auctions (Goulder 1995)—if those policy instruments are indeed used. However, costs rapidly increase if a policy is suboptimal—multiple emission permit markets, overlapping regulations such as a tax on top of tradable permits, unpredictably fluctuating subsidies, or inappropriate technical standards (Boehringer

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24 Chakravarty and Tavoni (2013) note that lifting 3.5 billion people out of energy poverty would raise the global mean surface air temperature by 0.13°C only.

25 Rausch et al. (2011); Cullenward et al. (2016); Rausch and Schwarz (2016); Melnikov et al. (2017); Rosas-Flores et al. (2017); Tovar Reaños and Wölfing (2018); Goulder et al. (2019); Metcalf (2019); Pizer and Sexton (2019); Saelim (2019); Böhringer et al. (2021); Chepeliev et al. (2021); hn and Yonezawa (2021); Garaffa et al. (2021); Landis et al. (2021); Mayer et al. (2021); Vandyck et al. (2021); García-Muros et al. (2022); Wu et al. (2022).

et al. 2009). Costs also increase rapidly if decarbonization needs to be completed well before 2100.

Climate policy affects energy access as well. Under pressure from donor countries and climate activists, development banks and, increasingly, investment banks have stopped the financing of fossil fuel projects in developing countries.[26] In many parts of the world, coal-fired power is the cheapest source of electricity. Restricting investment and driving up the price of electricity reduces access, excluding more people and companies from using electricity and the appliances that use electricity.

5.7 Discussion and Conclusion

Measuring energy security is difficult, mostly because it consists of two conflicting parts—energy reliability and energy affordability—both of which are easy to measure *ex post* but harder to predict *ex ante*.

Providing energy security requires state intervention. Peak capacity is a public good, best purchased in a reverse auction. Redundancy in transport and transmission network monopolies is best achieved by direct regulation. Across Asia and the Pacific, energy price subsidies are large and widespread. Instead, policies on energy access and poverty should focus on well-targeted income support and investment subsidies.

Because the supply of fossil fuels is spatially concentrated, political unrest in the areas of production can have worldwide effects. Outside interference and the resource rents from oil and gas exploitation may increase instability.

In the long run, climate policy and the replacement of fossil fuels with renewable energy should reduce the geopolitical risks to the energy supply. In the medium term, however, climate policy reduces energy affordability and, through asset stranding and bankruptcy, may negatively affect reliability too. Asia holds the majority of potentially stranded assets.

As illustrated by the many references above, there is a vast amount of research on energy security. Further research would be welcome in some areas. Indicators of the reliability of the electricity supply are readily available, but lacking for other energy sources and carriers. Internationally comparable indicators of energy access can be found, but not of energy poverty. Research on policy interventions to increase energy access and reduce energy poverty would proceed most fruitfully

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[26] See World Bank, Asian Development Bank, and HSBC.

via field experiments, in which energy companies, regulators, and academics collaborate to test which policies work well and which not so well. Improved quantification of the probability of the outbreak of violent conflict would be a great boon. We do not understand enough about the impact of asset stranding and second-best climate policies.

Policy implications are implied in the above discussion. The key policy recommendation, however, follows from the reality of the energy trilemma—the impossibility of energy that is clean, reliable, and cheap. If policymakers push too hard on one dimension of the energy trilemma, the other two will suffer. Energy policy, therefore, requires a careful and balanced consideration of all options.

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6

Investment in Innovation: Global Trends, Collaboration, and the Environment

Robert J. R. Elliott, Liza Jabbour, and Yiran Su

6.1 Introduction

The global economy is facing a number of challenges, perhaps the most important of which is climate change, which has immediate but also broader economic and geo-political implications. Whether it is the energy crisis, food security, or migration patterns, one could argue that the changing climate will play an increasingly important role. For example, the latest Intergovernmental Panel on Climate Change (IPCC) report highlights that it is imperative that action is taken to tackle the climate change crisis and argues that international cooperation is essential if we are to find sustainable solutions (Lynn and Peeva, 2021). Environmental concerns are already global concerns that cannot be solved by a single economy acting alone but require cooperation at a global scale (Haščič et al., 2012). For example, some regions, including developing Asia and the Pacific, have put forward plans for a green transition that aim to put their economies on a more sustainable growth path. Central to the transition story is the role played by global value chains (GVCs) and how resilient these GVCs are to external shocks from, for example, war, natural disasters, or pandemics and where firms face generally increased risk and uncertainty.

It is widely understood that a core element of any green transition is technological innovation and the development of climate change mitigation technologies (Aghion et al., 2009; Lee and Min, 2015).[1] Although innovation per se can have environmental benefits (machines that can produce more widgets per hour may also be more energy efficient), within the context of a green transition the emphasis is often on the promotion of eco-innovation and more recently the promotion of collaborative eco-innovation between different economies.[2] If economies are to make a successful green transition, it has been argued that government support for eco-innovation by way of subsides and fiscal policy is required. However, because there is often a lag between R&D expenditures and the actual innovation, governments tend to be reluctant to allocate funds to stimulating green technologies (Yang et al., 2011).

Hence, despite promising a post-COVID green transition, many economies are struggling to meet these goals in the face of the current global energy crisis and geo-political tensions. For example, O'Callaghan and Murdock (2021) analyze the COVID-related fiscal policies of about 50 major economies and shows that only $386 billion of the $46 trillion spent in 2020 was considered green and sustainable, so that only around 18% of the world's major economies' expenditures for economic recovery after the epidemic was for green projects. One possible explanation is linked to the current green jobs debate on how eco-innovation is related to job creation in new green sectors and possible job destruction in traditional heavy industry (Elliott et al., 2021). However, more generally, support for eco-innovation has been shown to bring long-term benefits, and it is argued that it helps economies develop greater domestic R&D capabilities (OECD, 2009; Antal, 2014). However, the current economic and political environment is causing some concern, especially as we move into the winter of 2022 and economies are looking carefully at how they will be able to keep the lights on. Although in the short term we may see renewed investment in coal-fired power stations, this may also spur a longer-term push for more support for renewable energy as a source of power.

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1 Technological innovation refers to the innovation of production technology, including the development of new technologies or a new application of an existing technology (Baden-Fuller and Haefliger, 2013). It is important to distinguish between technological innovation and research and development (R&D); R&D is thought of as the early stages of the innovation process that provide the investment in material and scientific knowledge necessary for later innovation success (Oltra et al., 2010).

2 In the literature, eco-innovation is also called green innovation or environmental innovation and is usually defined as any technological innovation or breakthrough that could reduce environmental pollution or any detrimental effects on the environment of the manufacturing process (Oltra et al., 2010).

An important aspect of the global push for greater investment in eco-innovation, whether through private or public sector investment, is the potential for the rapid diffusion of these new green technologies in the hope that this will lead to significant environmental spillovers and a subsequent reduction in global CO_2 emissions. However, there are considerable barriers to technological diffusion that need to be overcome (Jacobsson and Johnson, 2000; Strupeit and Palm, 2016). These challenges include issues related to intellectual property, patent laws, and the absorptive capacity of economies to be able to incorporate advanced green technologies into their current manufacturing base and overall infrastructure (e.g., transport and power supply sectors). One way in which diffusion can be accelerated is thought to be through international collaboration in the development of green technologies. To understand the role that so-called collaborative eco-innovation may play in future green technological diffusion, it is important to understand recent trends in both innovation and collaborative innovation.

The underlying motivation for this chapter is to get a better understanding of whether a more effective diffusion of green technologies can be achieved through active support for a greater degree of eco-innovation to be initiated through international cooperation between research teams. Our approach is to examine whether the period of rapid globalization between 2000 and 2020 (which includes the People's Republic of China's entry into the World Trade Organization (WTO)) has led to a greater degree of cooperation in the development of green technologies or whether eco-innovation remains the domain of developed economies either acting alone or within groups of economies, such as the Organisation for Economic Co-operation and Development (OECD) (Haščič et al., 2012).

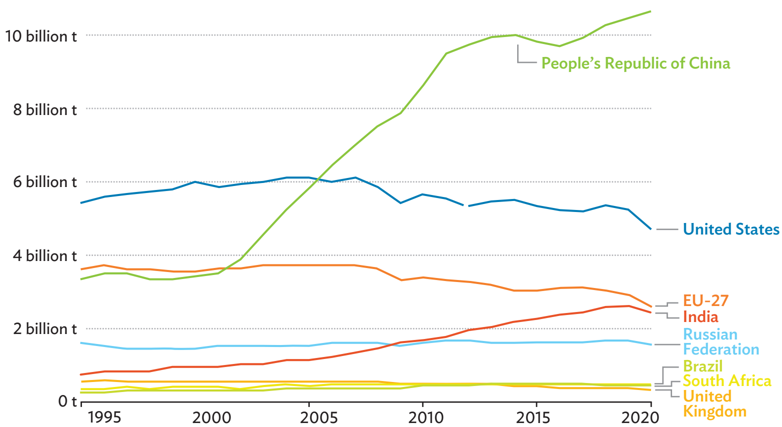
The importance of promoting the effective diffusion of green technologies between developed and developing economies is highlighted by an examination of the recent growth in global emissions, which shows that the growth comes overwhelmingly from developing economies (Copeland et al., 2021). Between 1995 and 2020, annual carbon emissions grew significantly, led by rapid increases from the People's Republic of China and India, while emissions in some developed economies were relatively flat or even, in the case of Sweden, decreased.[3] Figure 6.1 shows, for example, the growing carbon emissions for the People's Republic of China and India, with the former being the world's largest polluter since 2005. Carbon emissions in the United States and European economies have been flat or decreased over this period. However, it is important to remember how emissions can be

3 Annual carbon dioxide emissions are calculated from the burning of fossil fuels for energy and cement production.

contained in imports and exports and are transported along global value chains. A figure of carbon emissions per capita would also show a very different picture, albeit with fairly similar growth paths.

Despite being the primary source of current carbon emissions, not surprisingly, developing economies still lag behind developed economies when it comes to eco-innovation leadership. There are a number of reasons for this relative lack of leadership, including the lack of workers with the appropriate skills, limited R&D capacity, and low investment rates in R&D (Cirera and Maloney, 2017). Policies to strengthen eco-innovation in developing economies could be argued to be a core solution to climate-related challenges. One of the first steps may be the encouragement of collaborative eco-innovation and hence documenting these trends is one of the motivations for this chapter.

Figure 6.1: Change in Annual CO_2 Emissions Over Time



Source: CO_2 emissions data are sourced from the Global Carbon Project and Carbon Dioxide Information Analysis Center (CDIAC) (https://data.ess-dive.lbl.gov/portals/CDIAC/Data [accessed October 2022]).

When we discuss the concept of international cooperation for green technologies, it is important that it is framed in the context of globalized and fragmented value chains. The fragmentation of production value chains generalizes a connection between the production and consumption of emissions, and spreads the emissions along the whole chain. A potentially important causal relationship that needs further investigation is related to understanding whether cooperation between the trade partners helps to stimulate eco-innovation and hence accelerate a global green transition through the more rapid diffusion of green technologies between economies and from developed to developing economies (Duan et al., 2010; Audretsch et al., 2014; Minas, 2018).

There are a number of existing studies on international technological collaboration (De Prato and Nepelski, 2014; Wang et al., 2014; Liu et al., 2018).[4] Some existing studies are based on the case study of a single economy; for example, De Prato and Nepelski (2014) show that economies are more likely to cooperate if they share the same official language, are geographically closer, or are closer in terms of cultural proximity. However, the existing research tends to focus on developed economies and ignores developing economies' participation in collaborative innovation (Truskolaski, 2012; Wang et al., 2014).

There are a number of approaches that policymakers can take to encourage eco-innovation. The most popular can be thought of as the carrot of R&D subsidies (Kemp, 2000) and the stick of environmental regulation (Horbach et al., 2012). However, whether these solutions will also act as a driver of international collaboration in eco-technological innovation is little understood. From a policy perspective, it is also argued that policies need to focus on the number of innovations across different fields, guide the direction that the research should take, and also act as a regulator when needed (Haščič and Migotto, 2015).

The purpose of this chapter is to provide an overview of the global trends in eco-innovation and collaborative eco-innovation. The chapter also includes a mapping exercise in which we illustrate the extent to which trends in international technological collaboration have changed over time. We also provide some practical guidance for policymakers and describe how to formulate policies to encourage collaborative innovation and collaborative eco-innovation. More specifically, we document trends in global innovation across different technology fields or industries and cooperation patterns across economies. Furthermore, we document progress in international collaborative eco-innovation to try to understand why there are different trends in eco-collaborative innovation across different technology fields. We believe that before we design the appropriate policies, it is important to understand existing trends, patterns, and networks of international collaborative eco-

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4 In the majority of studies, international technological collaboration is defined as collaborative innovation when an invention has more than one inventor and the inventors declare different economies of residence (Haščič and Migotto, 2015).

innovation and how this contributes to the resilience of GVCs more generally.

The approach we take in this chapter on international technological innovation is to use patent-based data. Patent data provide rich information about an invention, including the inventor(s), applicant(s), invention time, and a range of other factors. Using the definition of environmentally sound technologies (ESTs) from the United Nations Environmental Programme (UNEP), we are able to use international collaborative innovation patent data to distinguish between eco- and non-eco-innovations.[5] Previous studies have used the classification from the OECD, which classifies ESTs into three types: (1) environmental-related technologies, (2) climate change adaption technologies, and (3) sustainable ocean economy technologies. Expanding on previous studies, we will use UNEP's classification of green technologies, which are classified by production activities and product use rather than the impact on the environment. For example, the technologies of hybrid vehicles are categorized as "transportation" in our research but are classified as "climate change mitigation technologies" based on the OECD classification.

The remainder of the chapter is organized as follows. Section 6.2 describes the source of the data, our methodological approach to measuring innovation, and the strategies used to define and distinguish between innovation and eco-innovation. Sections 6.3 and 6.4 describe the development of technological innovation and international technological collaboration. The development of eco-innovation, international collaborative eco-innovation, and the uneven development issues in different technology fields are also explained. Section 6.5 presents the development of green technologies across the manufacturing sector. Section 6.6 concludes this chapter and discusses a range of policy recommendations that are relevant to developing Asia and the Pacific and contribute to the debate on how to foster more GVCs in the face of increasing risk and uncertainty.

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5 Environmentally sound technologies refer to those technologies that can protect the environment by decreasing waste and reducing pollution and have the potential to improve environmental performance. For details, see https://www.unep.org/regions/asia-and-pacific/regional-initiatives/supporting-resource-efficiency/environmentally-sound (accessed 10 October 2022).

6.2 Data and Methodology

6.2.1 The International Patent Classification

The main source of data used in this chapter is PATSTAT, where patent information is categorized according to the International Patent Classification (IPC) system. The IPC system was created to enable users to identify patents across different technological fields. IPC codes have been applied by over 100 economies to group patents regardless of the language used in the patent application document. An invention can be assigned more than one IPC code depending on its function and the field of application. Hence, the IPC system has been designed to be a combined function-application classification system (OECD, 2009).[6] In addition, an IPC class, when combined with the Statistical classification of economic activities in the European Community (NACE) REV.2 code, can be used to count the number of inventions in different industries or sectors.[7]

One of the main benefits of IPC codes is that they can be used to identify eco-innovations. The "IPC Green List" developed by the IPC Committee of Experts allows users to search for patent information related to environmentally sound technologies (ESTs) that are listed in the United Nations Framework Convention on Climate Change (UNFCCC). There are seven green technical fields, each of which is assigned several green IPC codes. Our research is conducted using the entire green IPC list.[8] It should be noted that a patent may be assigned several IPC codes, which may include green and non-green codes. If the invention information (contribution to the prior art) contained in such a patent filing is classified as "green-related" in the IPC Green Inventory Scheme, this invention is classified as an "eco"-invention, even though there may exist other technical features contained in this invention that are excluded by the Green Inventory Scheme (León et al., 2018).

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6 According to our data, about 23.4% of inventions have at least two 4-digit IPC classes.

7 The IPC-NACE concordance table has been updated by the World Intellectual Property Organization (WIPO). The inventions are categorized based on their manufacturing industry according to the IPC-NACE concordance table. For example, an invention related to agriculture may be classified in the category called the manufacture of food products, beverages, and tobacco products.

8 The complete list of EST classifications categorized by WIPO can be accessed at https://www.wipo.int/classifications/ipc/green-inventory/home (accessed 10 October 2022).

6.2.2 Empirical Measures of Innovation and International Technological Collaboration

The literature on eco-innovation adopts a variety of methods to measure different aspects of innovation. Eco-innovation can be identified from the "effect" perspective, which refers to innovations that can reduce the use of natural resources or achieve environmental sustainability (Kemp and Pearson, 2007; Carrillo-Hermosilla et al., 2010). Measures of eco-innovation include (1) a simple count of environmental patents (Brunnermeier and Cohen, 2003; Carrión-Flores and Innes, 2010), counts of eco-innovations (Haščič et al., 2012), and (3) measures of how effective technologies are in reducing energy use or pollution (De Marchi, 2012). Eco-innovation can also be identified from an "input" perspective. Examples include (1) the green R&D expenditure (Koçak and Ulucak, 2019) and (2) R&D personnel and innovation expenditure (including the intangible investments such as the design expenditure) (Hall and Lerner, 2010). Each measure has its own strengths and weaknesses. For example, the R&D expenditure only reflects investment, such as resources devoted to producing innovation, but does not capture the outcome of the innovation process. Likewise, the ability of an innovation to reduce pollution does not tell us how much pollution has been reduced. On balance, we believe that the number of eco-innovations is a good proxy of the eco-innovation activity, as it captures the result or output of investment in innovation directly (Hall and Lerner, 2010).

The patent data we use come from the PATSTAT database (2022 spring edition) and cover the period 1995 to 2020. PATSTAT contains more than 100 million patent documents collected from more than 90 patent offices internationally (De Rassenfosse et al., 2014). Patent records include information on inventors' addresses, application dates, application IDs, and other information related to patent classification. There is also information on legal events for the more than 40 patent offices that are included in the European Patent Office (EPO) Global Legal Event Data (INPADOC). It is worth providing a short reminder of the advantages of patent data:

- The R&D expenditure and scientific publications only take the input of the inventive process into account. Patent data, on the other hand, are a direct measure of innovation, as these data focus on the outputs of the invention process (Haščič and Migotto, 2015).
- Patent documentation provides a wealth of information related to the innovation process. In our case, where the innovation took place is important to understanding the degree to which innovation is a result of international technological collaboration.

- Patent data can be disaggregated into different technology fields or sectors and classified into various green technology fields. Details concerning green technology fields and their representative technologies are provided in Table A6.1 of the Appendix. The use of technology fields gives us the opportunity to study eco-innovation and collaborative eco-innovation at a disaggregated level and to analyze the patterns and trends of collaborative innovation in the different technological areas.
- However, there are also limitations associated with the use of patent data that are worth recapping briefly:
- Not all inventions are patented (Haščič and Migotto, 2015). Many "inventions," such as copyrighted items, are included in intellectual property right (IPR) regimes but are not patented in the patent office.
- Not all the patented inventions are of "good quality." The quality of a patent is related to the importance of the invention, its commercial value, or the possibility of this invention being maintained after the patent is enforced (Squicciarini et al., 2013). Patent litigation refers to all litigation related to patents and is an expensive process. If an enterprise, or individual, goes to considerable expense to protect a patent, it shows that the patent is expected to have a commercial value that exceeds the litigation cost (Lanjouw and Schankerman, 2001). The patent quality is a good indicator of the link between innovation, technology diffusion, and social and economic development (Squicciarini et al., 2013). The patent records provide information related to quality, including the family size, the number of IPC codes, the lag between the application and granting of the patent, forward citations, and backward citations.[9]
- Unfortunately it is not possible for researchers to exclude inventions whose inventors are located in different places but have the same nationality. Similarly, it is not possible to filter out inventions that have been developed by two laboratories that are located in different places but belong to the same firm (Squicciarini et al., 2013).

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[9] In terms of the Paris Convention (1883), applicants have no more than 12 months from the earliest filing date to file applications and claim the priority date of the first application in patent offices located in other economies for the same invention. The number of patent offices that protect the same invention is the family size. The patent family size may suffer from timeliness issues because different economies have different requirements regarding the time from the filing date to the earliest application needed to claim the priority date for any following application.

After describing some of the benefits and challenges of using patent data, we now describe how we use the patent data to develop our measures of innovation and international collaborative innovation. Our measure of the number of innovations is constructed from simple frequency counts. An invention is considered to be the result of international technological collaboration if it has more than one inventor and its inventors reside in different economies. To avoid any double-counting problem, we calculate the total number of simple patent families instead of the number of patent applications.[10] A simple patent family may have multiple IPC codes because the invention could be categorized into different technology fields. When counting the total number of simple patent families of a specific technology field, each simple patent family is only counted once. For example, an invention related to solar energy may be classified under two sub-classifications: "solar concentrators" and "use of solar heat." However, when calculating the total number of inventions related to solar energy, this invention will be counted only once. Moreover, a distinction can also be drawn between eco-patent families and non-eco-patent families based on the green IPC code listings.

From the PATSTAT database, we rely on the following information:

- Patent family ID: ID number used to identify the patent family;
- Priority date: The earliest filing date, which is used to identify the earliest filing year of an invention;
- Publication date: The earliest publication date;
- Inventors' residence economies: The economies of residence of the inventor(s), which are used to identify international co-invented patents;
- IPC codes: Used to categorize an invention as a eco-innovation and to more generally classify patents into different technology fields and manufacturing sectors.

6.3 Trends in Innovation and Eco-Innovation

We examine trends in innovation between 1995 and 2020. After dropping equivalent inventions, i.e., counting the total number of simple patent families and dropping patent families with the same identification codes, we obtain records on more than 3 billion inventions of which over 4 million are eco-innovations. Figure 6.2 presents the trends in total inventions, eco-innovations, and non-eco-innovations

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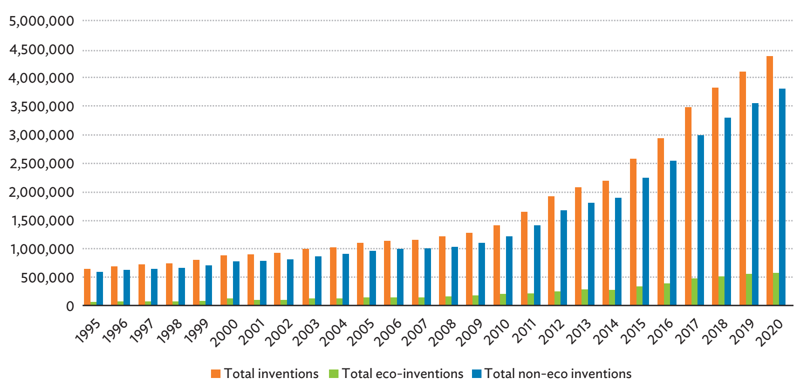
[10] A patent family is a set of patent applications of one specific invention or similar technologies. Members of a simple patent family are all related to the same invention (Park et al., 2009). When calculating the total number of inventions, we try to stay in the patent family realm.

over the last 26 years. Starting in 1995, the general trend is upwards, with no real slowdown during the financial crisis between 2007 and 2009. For example, on 11 February 2009, the United States (US) passed an economic stimulus plan that released 789 billion US dollars to get the economy back on track. As a result, investment in basic research, biomedical research, energy research, and climate change mitigation projects reached record highs (Obama, 2011).

In the same year, Germany (GER), France (FRA), and the United Kingdom (UKG) also attempted to boost their economies by stimulating high-tech research (Andersen, 2009). In terms of eco-innovation, in June 2009, the US passed the "Clean Energy and Security Act" (ACESA), while Germany announced that developing clean energy technologies would be a priority area of research (Lehr et al., 2012). At the same time, several developing economies, such as the People's Republic of China (PRC) and India (IND), also started to pay more attention to eco-technological innovation, especially innovation related to alternative energy (Kumar et al., 2010; Liu et al., 2011). Figure 6.2 shows that the speed of innovation appears to increase after 2009, highlighting the degree to which economies increasingly recognize the importance of innovation both to create economic growth and also, in the case of eco-innovation, to solve environmental issues.

The total number of inventions, eco-innovations, and non-eco-innovations reached 4,375,700, 576,684, and 3,799,016, respectively, in 2020. Even the shock of the COVID pandemic appeared to do little to slow down the pace of innovation.

Figure 6.2: Total Inventions, Eco-innovations, and Non-eco-innovations



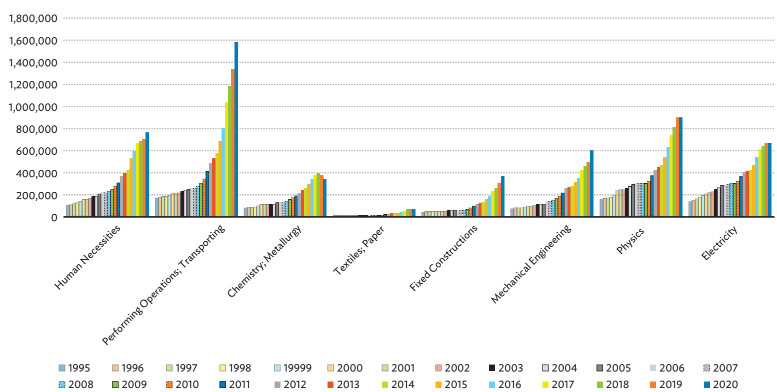
Source: Authors' calculations based on PATSTAT data.

Figure 6.3 presents a count of inventions by technology field between 1995 and 2020. There are eight types of technology fields according to the World Intellectual Property Organization (WIPO):[11]

- Human necessities;
- Performing operations, transporting;
- Chemistry, metallurgy;
- Textiles, paper;
- Fixed construction;
- Mechanical engineering, lighting, heating, weapons, blasting;
- Physics;
- Electricity.

Figure 6.3 shows an increase in innovation across all technology fields. After 2000, the number of new inventions jumps considerably. Specifically, the performing operations and transportation field had the fastest growth rates (17% on average) and the highest number of inventions (1,585,947) in 2020, followed by physics (907,545), human necessities (766,265), and electricity (672,017).

Figure 6.3: Total Inventions in Each Technology Field



Source: Authors' own calculations based on PATSTAT data.

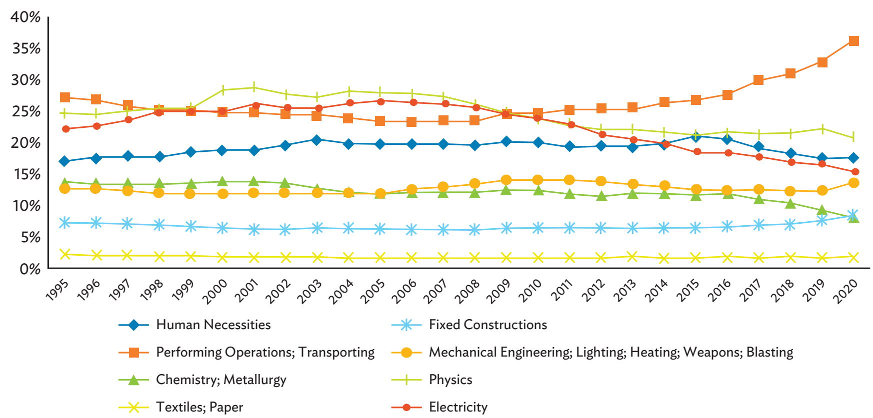
11 WIPO provides a full list of technology fields for invention applications. Each technology field has sub-classifications based on IPC codes.

Although inventions overall have increased, in some technological fields, such as textiles, paper, and fixed construction, the number of inventions is fairly low. These trends reflect natural trends in innovation, with some industries being more likely to rely on existing technologies and to rely more on skilled workers than new technologies (Magee, 1997; Ogunrinde et al., 2020).

Figure 6.4 presents the trend of inventions by technology field as a share of the total inventions. The percentage of inventions in the performing operations and transportation technology field is the largest, accounting for around 27% and 35% of inventions in 1995 and 2020, respectively. However, between 2000 and 2010, inventions related to physics accounted for the largest share, followed by inventions related to electricity, which demonstrates how innovation trends change over time. According to the WIPO classification, the physics category includes inventions related to information storage, computing, and communications. The electricity category includes inventions such as cables, electric communication technologies, and wireless communication technologies. These trends coincide with the move from the third to the fourth industrial revolution.[12] The third technological revolution was marked by the invention and application of atomic energy, electronic computers, space technology, biological engineering, and alternative energy (Prisecaru, 2016). In the late stage of the third technological revolution, the rapid development of microcomputers, wireless communications, and chip applications all marked a rapid increase in innovation related to physics and electricity. However, since 2010, the world has gradually moved towards the era of Industry 4.0, which is more about intelligent manufacturing. As explained by Bloem et al. (2014), Industry 4.0 was driven by new innovations in performing operations and transportation, such as 3D printing technology, autonomous driving technology, and the blockchain.

[12] The third industrial revolution began in the 1960s and is also called the computer or digital revolution (Schwab, 2017). Industry 4.0 was first proposed by Germany at the 2011 Hannover Fair and focuses on using cyber-physical systems, which involves digitizing and intelligentizing the whole production chain, including the upstream supply, manufacturing, and downstream sales. Industry 4.0 aims to achieve increasingly fast and effective supply chains (Prisecaru, 2016; Schwab, 2017).

Figure 6.4: Share of Inventions from Each Technology Field of the Total Number of Inventions



Source: Authors' own calculations based on PATSTAT data.

The next stage is to document where the innovation is taking place. Table 6.1 shows that the leading inventor economies and districts over the last 26 years (summed over 1995–2020) were the US, the Republic of Korea (KOR), the People's Republic of China (PRC), Japan (JPN), and Germany (GER). These economies have become innovation leaders not just due to their rapid economic development but also because of the development of a culture of R&D and strong government support for innovation.[13] Data released by WIPO show that in 2021, Chinese applicants filed 69,500 international patent applications through the Patent Cooperation Treaty (PCT), causing the People's Republic of China to rank first in the number of applications for the third consecutive year.

The US not only ranks first in terms of the GDP per capita but also consistently ranks first in terms of the innovation index. Meanwhile, Japan, the Republic of Korea, and Germany have a strong track record on electricity and transportation research. It is argued that the leading economies have a strong research infrastructure, including research organizations and universities. To encourage innovation, in addition

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13 Many studies have highlighted the role of culture and support in stimulating innovation (Wong et al., 2005; Hall and Lerner, 2010; Edler and Fagerberg, 2017).

to providing financial and policy support, education and enterprise innovation capabilities and a sound patent protection system should all be valued by governments (Maritz et al., 2014; Acemoglu and Akcigit, 2012).

Table 6.1: Top 20 Inventor Economies and Districts Globally in Terms of Technological Innovation

Rank	Economy	% of Total Global Inventions
1	United States	7.39
2	Republic of Korea	5.20
3	People's Republic of China	5.16
4	Japan	3.65
5	Germany	2.97
6	Taipei,China	2.24
7	Russian Federation	0.89
8	France	0.88
9	United Kingdom	0.79
10	Canada	0.55
11	Italy	0.39
12	Netherlands	0.37
13	India	0.32
14	Switzerland	0.32
15	Spain	0.32
16	Ukraine	0.29
17	Sweden	0.25
18	Poland	0.23
19	Israel	0.21
20	Finland	0.19

Source: Authors' own calculations based on PATSTAT data.

Table 6.2 lists the top 20 inventor economies and districts for each technology field, considering the sum of total inventions between 1995 and 2020. The US, the People's Republic of China, Japan, Germany, and the Republic of Korea are also the leading economies in each technology field. The People's Republic of China replaced the US at the top in the paper industry; the People's Republic of China and the Republic of

Korea rank first and second in the fixed construction industry, while the US ranks third. In the People's Republic of China, infrastructure construction and basic manufacturing are considered to have a significant "multiplier effect," which means that investment in infrastructure construction is thought to create substantial social aggregate demand, national income, and jobs (Ansar et al. 2016). The People's Republic of China's continued but slowing investment in construction continues to promote technological upgrading in this field and hence an increasing number of patents. Post-COVID, the Republic of Korea plans to invest $14.7 billion in infrastructure projects to stimulate economic recovery.

Since 2000, the scientific research capabilities of a number of Asian economies have improved significantly. In addition to Japan, the Republic of Korea, and the People's Republic of China, India also appears on the list and performs most strongly in the chemical industry. Taking advantage of the economy's loose patent protection, low costs,

Table 6.2: Top 20 Inventor Economies and Districts Globally in Each Technology Field

Rank	Human Necessities	Transporting	Chemistry	Textiles, Paper	Fixed Construction	Mechanical Engineering	Physics	Electricity
1	USA(US)	USA(US)	USA(US)	PRC	PRC	USA(US)	USA(US)	USA(US)
2	PRC	KOR	JPN	KOR	USA(US)	PRC	JPN	KOR
3	KOR	GER	PRC	US	KOR	GER	KOR	JPN
4	GER	PRC	KOR	GER	GER	KOR	PRC	PRC
5	TAP	JPN	GER	JPN	TAP	JPN	GER	TAP
6	JPN	TAP	RUS	TAP	RUS	TAP	TAP	GER
7	RUS	FRA	FRA	ITA	UKG	FRA	UKG	FRA
8	UKG	UKG	UKG	FRA	JPN	RUS	FRA	UKG
9	FRA	RUS	TAP	FIN	FRA	UKG	CAN	CAN
10	CAN	ITA	CAN	UKG	CAN	ITA	RUS	IND
11	ITA	CAN	CHI	CHI	SPA	CAN	IND	RUS
12	SPA	SPA	NET	TUR	POL	SPA	NET	NET
13	NET	CHI	IND	SWE	ITA	AUT	ISR	SWE
14	CHI	NET	ITA	CAN	NET	POL	CHI	FIN
15	UKR	SWE	BEL	RUS	UKR	NET	ITA	ISR
16	BRA	POL	UKR	NET	AUT	CHI	SWE	ITA
17	ISR	UKR	POL	AUT	FIN	UKR	AUS	CHI
18	SWE	AUT	SPA	BEL	AUS	SWE	UKR	AUT
19	AUS	BRA	SWE	SPA	NOR	TUR	SPA	SPA
20	IND	FIN	AUS	CZE	CHI	DEN	FIN	SIN

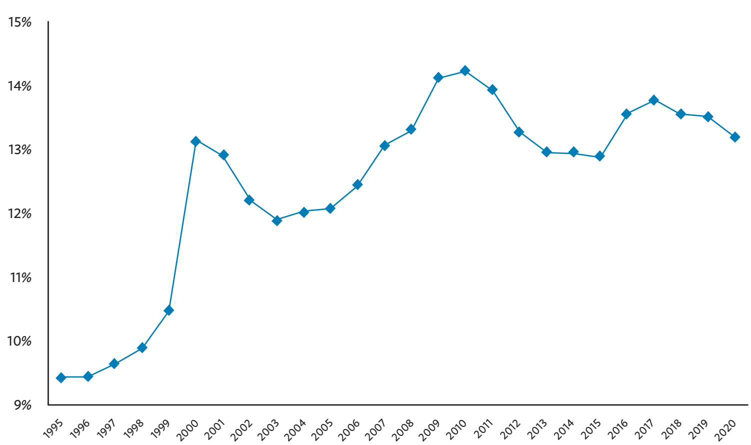
Note: For a list of the abbreviations for economies used in this chapter, see Table 6A.2 of the Appendix.

Source: Authors' own calculations based on PATSTAT data.

and language benefits, Indian pharmaceutical companies actively develop patents, conduct standardized market certification, undertake international API transfer orders, and gradually sell preparations to developed economies (Grace, 2004). As early as 2007, Indian companies spent 30% of their total global investment in the generic drug industry, and R&D investment accounted for more than 10% of sales revenue (Greene, 2007).

Having looked at the total inventions, we now turn to eco-innovation. Figure 6.5 presents the number of eco-innovations as a share of the total inventions between 1995 and 2020. The overall trend is that the number of eco-innovations is increasing, albeit with some peaks and troughs. For example, between 2000 and 2005, the number of total inventions increased significantly (by around 8% on average), while the number of eco-innovations remained relatively flat, leading to a significant drop in the share. However, after 2005 the upward trend resumed, perhaps driven by R&D investment that was initiated after the signing of the Kyoto Protocol, which was officially implemented in 2005. A key element of the Kyoto Protocol was for developed economies to reduce carbon emissions starting in 2005 and for developing economies to start reducing their emissions in 2013. In addition, the Kyoto Protocol recommends that governments adopt green development mechanisms to encourage developed and developing economies to work together to reduce greenhouse gas emissions collaboratively.

Figure 6.5: Share of Eco-innovations of the Total Inventions



Source: Authors' own calculations based on the PATSTAT database.

A number of studies show that implementing the Kyoto Protocol positively stimulated eco-innovation, particularly in the area of renewable energy (Miyamoto and Takeuchi, 2019). It should be noted that 2012 marked the end of the first commitment period of the Kyoto Protocol. In 2015 the Kyoto Protocol was replaced by the Paris Agreement, which was signed by 178 economies (Schreurs, 2016). The Paris Agreement required economies to make an effort to reduce their emissions based on their promises one year later. This matches the uptick in the share of eco-innovations after 2016.

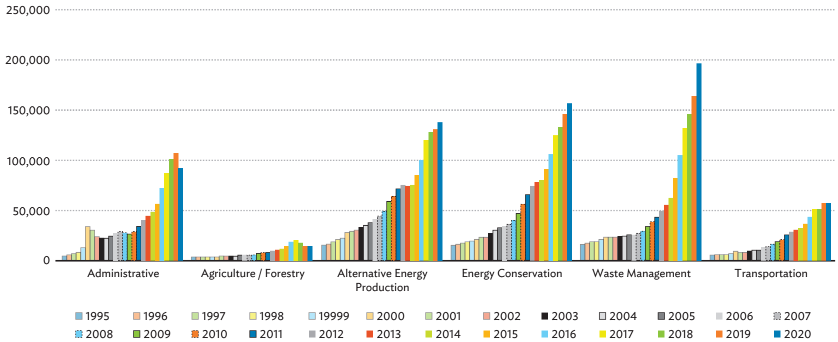
The next step is to present the equivalent of Figure 6.3 for eco-innovation. Hence, Figure 6.6 shows the total number of eco-innovations from 1995 to 2020 according to WIPO's "IPC Green Inventory," which categorizes ESTs into the following six green technology fields[14]:

- Alternative energy production (e.g., technologies related to hydropower);
- Transportation (including inventions related to hybrid electric vehicles);
- Energy conservation (e.g., inventions used to store electrical energy);
- Waste management (e.g., technologies used for pollution control);
- Agriculture/Forestry (including alternative irrigation techniques and organic fertilizers derived from waste);
- Administrative, regulatory, or design aspects (technologies related to carbon/emission trading or teleworking equipment).

Figure 6.6 shows that there has been an increasing trend in eco-innovations in each green technology field. Except for agriculture/forestry, the number of inventions in each green technology field shows fairly rapid growth. For example, the total number of technologies (patent families) related to waste management rose from 17,546 to 196,687 between 1995 and 2020. Total eco-innovations from the waste management, energy conservation, and alternative energy production categories remained in the top three in 1995 and 2020, with little evidence of a slowdown during 2020 when the first lockdowns due to COVID were being implemented. Figure 6.6 also shows an increase, post-Paris Agreement, in investment to stimulate clean energy, renewable energy, and energy conservation research, and this may explain the rapid growth after 2016 in inventions related to waste management, energy conservation, and alternative energy production.

14 Nuclear power generation (such as nuclear reactors or nuclear power plants) is excluded in our research, as it produces uranium waste (although it is zero carbon).

Figure 6.6: Total Number of Eco-innovations by Green Technology Field



Source: Authors' own calculations based on the PATSTAT database.

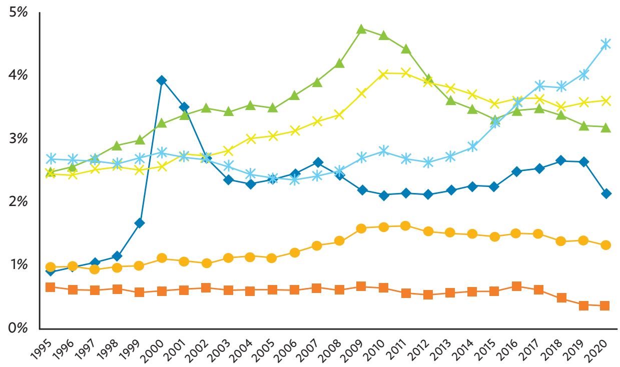
Figure 6.7 shows two different ways to represent the number of eco-innovations: (1) the number of inventions in each green technology field as a share of the total inventions (the total number of patents applied for in a given year), and (2) the number of inventions in each green technology field as a share of the total eco-innovations (the total number of eco-innovation patents applied for in a given year). Figure 6.8(a) shows that the share of eco-innovations of the total inventions is between 0.2% and 4%. The largest shares are in energy conservation, waste management, and alternative energy production.

Comparing sectors, in 2020, eco-innovations related to waste management were ranked first (4.8%), followed by energy conservation (3.6%) and alternative energy production (3.3%). Figure 6.8(b) presents the same information but as a share of the total eco-innovations and shows that eco-innovations related to waste management peaked at around 37% in 2020. Although the number of eco-innovations as a percentage of the total innovations remains limited, waste management, energy conservation, and alternative energy production remain the three most innovative green technology fields.

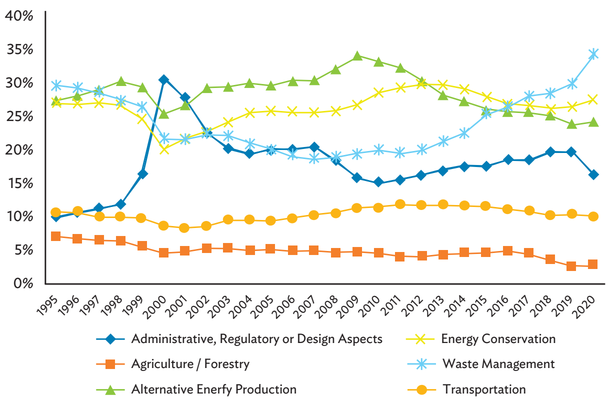
Table 6.3 lists the leading inventor economies and districts engaged in eco-innovation. The results are similar to those shown in Table 6.1, with the US, the Republic of Korea, Japan, the People's Republic of China, and Germany being the top five inventor economies in terms of both total innovation and eco-innovation. The main difference is that the United Kingdom, France, and India are ranked higher for eco-innovation. The

Figure 6.7: Share of Eco-innovations from Each Technology Field of the Total Inventions and Total Eco-innovations

(a) Share of eco-innovations from each technology field of the total inventions



(b) Share of eco-innovations from each technology field of total eco-innovations



Source: Authors' own calculations based on PATSTAT data.

People's Republic of China and India are the only developing economies with substantial CO_2 emissions that appear on the list.

As a developing economy with significant carbon emissions, the People's Republic of China has launched more than 20 critical projects that relate to carbon-neutral technologies such as hydrogen energy and new-energy vehicles (Wang and Liang, 2013). For example, coal consumption using ultra-supercritical power generation technologies has dropped to 266.8 g/kWh, which is 11% lower than the average coal consumption of traditional thermal power units. To support its transport and energy-intensive industrial sectors, India has also introduced several policies to encourage the adoption of green technologies, including the implementation of strict emission standards to regulate air pollutant emissions from compression ignition engines, a battery replacement policy, and appliance energy-efficiency standards (Tibrewal and Venkataraman, 2021). The Indian electric vehicle market is growing steadily, with a compound annual growth rate of 42.8%, and is one example of how environmental policies can stimulate eco-innovation and promote the development of new industries (Brar et al., 2021).

Table 6.3: Top 20 Inventor Economies and Districts Globally in Terms of Eco-technological Innovation

Rank	Economy	% of Total Global Eco-innovations
1	United States	8.96
2	Republic of Korea	6.18
3	Japan	4.22
4	People's Republic of China	3.86
5	Germany	3.34
6	Taipei,China	1.79
7	France	0.98
8	United Kingdom	0.87
9	Russian Federation	0.73
10	Canada	0.72
11	Netherlands	0.47
12	India	0.39
13	Italy	0.31
14	Switzerland	0.31
15	Spain	0.29
16	Poland	0.27
17	Australia	0.24
18	Ukraine	0.24
19	Austria	0.23
20	Sweden	0.22

Source: Authors' own calculations based on PATSTAT data.

As before, we now describe the top 20 inventor economies and districts for each green technology field based on the total number of eco-innovations between 1995 and 2020. Table 6.4 shows that since 2000, the scientific research capabilities of a number of Asian economies have improved significantly. The US, the Republic of Korea, Japan, Germany, and the People's Republic of China are the leading economies in each green technology field. The Republic of Korea has the top position in the waste management category. In addition to Japan, the Republic of Korea, and the People's Republic of China, India and Taipei,China also specialize in a large number of green technology fields.

Table 6.4: Top 20 Inventor Economies and Districts Globally in Each Green Technology Field

Rank	Administrative	Agriculture	Alternative Energy	Energy Conservation	Waste Management	Transportation
1	USA(US)	USA(US)	USA(US)	USA(US)	KOR	USA(US)
2	KOR	PRC	KOR	KOR	USA(US)	JPN
3	JPN	GER	JPN	JPN	PRC	GER
4	PRC	KOR	PRC	PRC	GER	PRC
5	GER	JPN	GER	GER	JPN	KOR
6	TAP	UKG	TAP	TAP	TAP	TAP
7	UKG	FRA	FRA	FRA	RUS	FRA
8	CAN	RUS	UKG	UKG	FRA	RUS
9	IND	CHI	NET	CAN	UKG	UKG
10	FRA	CAN	CAN	RUS	CAN	CAN
11	ISR	IND	RUS	NET	POL	ITA
12	AUS	SPA	DEN	CHI	NET	AUT
13	NET	TAP	SPA	AUT	UKR	CHI
14	CHI	BRA	ITA	ITA	SPA	SWE
15	SWE	ITA	CHI	POL	ITA	POL
16	RUS	UKR	POL	IND	BRA	UKR
17	FIN	POL	IND	SPA	FIN	SPA
18	ITA	AUS	UKR	SWE	SWE	NET
19	SIN	ISR	AUS	FIN	CZE	CZE
20	BRA	BEL	BEL	ISR	CHI	IND

Source: Authors' own calculations based on PATSTAT data.

Tables 6.5 and 6.6 show the performance of the top 20 inventor economies or economies based on different technology classifications. To assess the inventor economies' specialization in a certain technology field, we measure a economy's "relative technological advantage" (RTA) (Haščič and Migotto, 2015). The RTA is calculated as follows:

$$RTA_{ij} = (IN_{ij}/IN_{wj})/(TI_i/TI_w), \qquad (1)$$

where RTA_{ij} is the RTA of economy i in technology field j; IN_{ij} is the total number of inventions of economy i in technology field j; IN_{wj} is the total number of inventions globally in technology field j; TI_i is the total number of inventions of economy i; and TI_w is the total number of inventions globally. An RTA larger than one means that the economy has a prominent position in that technology field. A higher RTA implies that the economy is more specialized in that specific technology field compared to other technology fields.

Table 6.5 shows the RTAs of the top 20 inventor economies or economies based on the total number of inventions (eco-innovations and non-eco-innovations). Based on the WIPO classification, we classify technologies into eight different fields. Table 6.5 shows that the US specializes in inventions related to physics (1.62), electricity (1.36), chemistry (1.32), and human necessities (1.33). Economies such as the Republic of Korea, Japan, the People's Republic of China, and India have a significant specialization in electricity-related technologies. Germany specializes in mechanical engineering and weapons manufacturing, while the United Kingdom is stronger in chemistry.

Turning to eco-innovation, Table 6.6 presents the RTAs for the top 20 inventor economies or economies based on eco-innovations. Recall that the WIPO Green Inventory Scheme classifies green technologies into seven different green technology fields. Table 6 shows that the US and the Republic of Korea have a specialization in administrative, regulatory, or design eco-innovations, and they do not produce as many eco-innovations related to agriculture. Germany and Austria specialize in green transportation technologies, while Japan, France, Spain, the Netherlands, and Sweden all have a relative specialization in alternative energy. The United Kingdom, Spain, Italy, and Poland tend to specialize in eco-innovations related to agriculture and forestry.

The results presented in Tables 6.5 and 6.6 show that India has its most significant relative advantage in the administrative, regulatory, or design category. Switzerland has a high RTA for agriculture-related technologies. Although the Netherlands scores most highly for alternative energy production, Taipei,China has the highest RTA for energy conservation-related innovation.

Table 6.5: RTAs of the Top 20 Inventor Economies and Districts based on the WIPO Classification

Inventor Economy	Human Necessities	Transporting	Chemistry	Textiles, Paper	Fixed Construction	Mechanical Engineering	Physics	Electricity
USA(US)	1.33	0.72	1.32	0.61	0.65	0.76	1.62	1.36
KOR	0.83	0.73	0.91	1.02	0.91	0.86	1.12	1.56
PRC	1.11	0.70	0.94	1.03	0.94	1.03	0.87	1.14
JPN	0.56	0.93	1.50	0.74	0.23	0.90	1.73	2.00
GER	0.84	1.27	1.18	1.36	0.86	1.70	0.98	1.03
TAP	1.02	0.76	0.41	0.64	0.68	0.86	1.11	1.50
RUS	1.58	0.66	1.73	0.36	1.10	0.96	0.79	0.49
FRA	1.19	1.09	1.52	0.85	0.88	1.31	1.08	1.14
UKG	1.42	0.78	1.58	0.78	1.13	0.95	1.31	1.13
CAN	1.31	0.79	1.38	0.58	1.26	0.83	1.43	1.32
ITA	1.43	1.14	1.26	2.27	1.03	1.24	0.72	0.74
NET	1.49	0.77	1.60	0.87	0.93	0.77	1.23	1.19
IND	0.88	0.37	1.70	0.45	0.19	0.47	1.83	1.72
CHI	1.66	0.93	1.87	1.85	0.73	0.85	1.17	0.86
SPA	1.75	1.01	1.11	0.89	1.62	0.94	0.68	0.58
UKR	1.76	0.69	1.38	0.52	0.97	0.92	0.76	0.38
SWE	1.15	0.91	1.15	1.47	0.71	0.99	1.04	1.70
POL	1.09	0.96	1.74	0.77	2.13	1.24	0.67	0.55
ISR	1.52	0.43	1.04	0.30	0.28	0.37	2.07	1.53
FIN	0.79	0.81	0.96	3.62	1.25	0.86	1.05	1.70

Source: Authors' own calculations based on PATSTAT data.

Table 6.6: RTAs of the Top 20 Inventor Economies and Districts based on the WIPO Green Inventory List

Inventor Economy	Administrative	Agriculture	Alternative Energy	Energy Conservation	Waste Management	Transportation
USA(US)	1.91	1.47	1.03	0.76	0.48	0.73
KOR	1.66	0.55	0.92	1.00	0.72	0.79
JPN	0.93	0.71	1.21	1.27	0.47	1.36
PRC	0.61	1.40	1.06	1.01	0.97	1.34
GER	0.70	1.42	1.10	1.07	0.68	1.62
TAP	1.11	0.32	0.94	1.40	0.44	1.37
FRA	0.81	1.77	1.21	0.88	0.76	1.25
UKG	1.29	2.02	1.15	0.81	0.67	0.77
RUS	0.33	2.04	1.06	0.70	1.09	1.23
CAN	1.54	1.31	1.15	0.74	0.72	0.83
NET	0.55	0.88	1.80	0.86	0.63	0.51
IND	2.60	2.11	0.77	0.58	0.41	0.46
ITA	0.65	1.72	1.20	0.82	0.86	1.50
CHI	0.79	3.81	1.08	0.95	0.55	1.04
SPA	0.63	2.07	1.36	0.76	0.94	0.94
POL	0.32	1.86	1.24	0.87	1.33	1.06
AUS	1.73	1.90	1.18	0.59	0.66	0.61
UKR	0.29	2.22	1.20	0.67	1.23	1.20
AUT	0.48	1.17	1.01	1.17	0.73	2.03
SWE	1.10	1.08	0.93	0.92	0.83	1.36

Source: Authors' own calculations based on PATSTAT data.

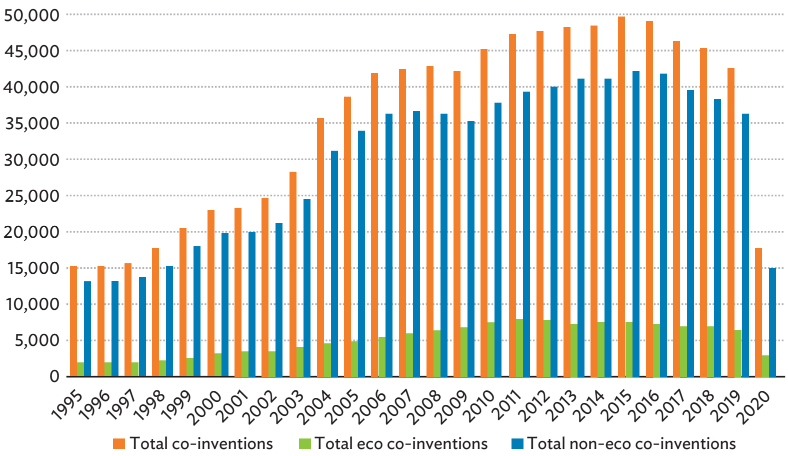
6.4 Trends in International Technological Collaboration

International technological collaboration, also called international collaborative innovation or international collaborative innovation, refers to inventions for which at least two inventors reside in different economies. To count the number of international collaborative innovations, we calculate the total number of simple patent families. Trends in international collaborative innovations, international collaborative eco-innovations, and international collaborative non-eco-innovations from 1995 to 2020 are presented in Figure 6.8.

An immediate observation is that there has been a significant increase in the number of international collaborative innovations and international collaborative non-eco-innovations since 1995. Although there was a dip in the total inventions in 2009 following the global financial crisis, the number of international collaborative eco-innovations continued to rise slightly and peaked at 7,885 in 2011. The total number of collaborative innovations peaked at 49,761 in 2015, when the number of collaborative non-eco-innovations was 42,138. Since 2015 the number of collaborative eco-innovations has remained fairly stable but may have dipped slightly, following the pattern for total collaborative innovations. In these data we see a significant shock to collaborative innovation driven by the COVID pandemic.

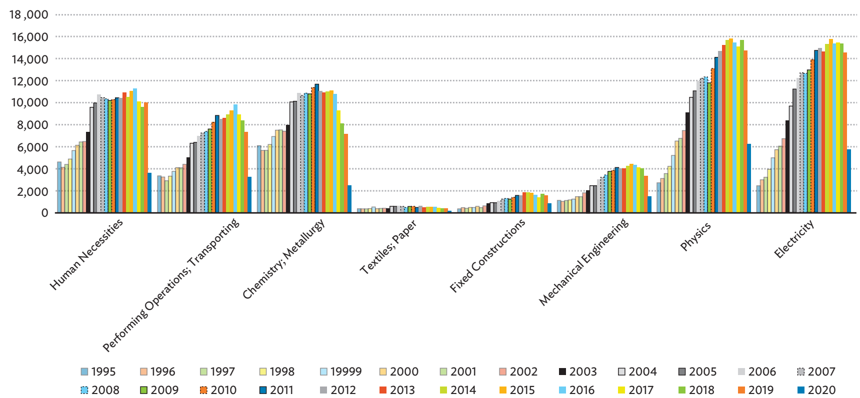
Figure 6.9 shows the development of international collaborative innovations at a more disaggregated level. In all technical fields, the number of cooperative inventions has increased. Moreover, from 1995 to 2019 there has been a significant increase in collaborative innovations related to physics and electricity (which increased from 2,863 to 14,799 and 2,526 to 14,562, respectively). As shown in Figure 6.9, there was a significant drop in 2020 due to COVID.

Figure 6.8: International Collaborative Innovations, Collaborative Eco-innovations, and Collaborative Non-eco-innovations



Source: Authors' own calculations based on PATSTAT data.

Figure 6.9: Total International Collaborative Innovations in Each Technology Field



Source: Authors' own calculations based on PATSTAT data.

During this period more and more economies increased their investment in high-tech R&D. International research collaboration can amplify the effects of domestic research capabilities, increase invention efficiency, and lead to greater technology transfer (Andrade et al., 2009). The main growth areas since 2000 have been technologies related to physics and electricity, which include computers and wireless communications (Yamin, 2019).

Table 6.7: Top 20 Inventor Economy Pairs Globally in Terms of Total International Collaborative Innovations

Rank	Economy	% of Total Global Collaborative Innovations
1	US-PRC	6.43
2	US-CAN	5.65
3	IND-US	5.60
4	GER-US	5.58
5	UKG-US	5.24
6	TAP-PRC	2.99
7	JPN-US	2.80
8	FRA-US	2.71
9	GER-CHI	2.44
10	US-KOR	2.27
11	FRA-GER	2.12
12	US-TAP	1.93
13	US-ISR	1.67
14	AUT-GER	1.66
15	US-CHI	1.44
16	US-NET	1.41
17	UKG-GER	1.39
18	NET-GER	1.26
19	FRA-CHI	1.15
20	PRC-KOR	1.03

Source: Authors' own calculations based on PATSTAT data.

Table 6.7 shows the top 20 inventor economy pairs in terms of international collaborative innovations. The top 20 economy pairs include a wide range of economies, including the US, Germany, Japan, India, Canada, France, the Republic of Korea, and the People's Republic of China. These economies tend to have strong research capabilities and stable economic environments. According to the table, over our time period, cooperation between the People's Republic of China and the US was responsible for the largest number of inventions, with 6.43% of the world's total international collaborative innovations, followed by collaboration between Canada and the US (5.65%), India and the US (5.60%), and Germany and the US (5.58%). Cooperation between economies is influenced by many factors, such as culture, language, geographic location, and politics (Dawes et al., 2012). The United States and Canada are neighboring economies and Canada is also the US's largest trading partner (Wonnacott and Williamson, 1987). Geographical proximity and trade are likely to be significant contributors to a greater

Table 6.8: Top 20 Inventor Economy Pairs Globally in Each Technological Field

Rank	Human Necessities	Transporting	Chemistry	Textiles, Paper	Fixed Construction	Mechanical Engineering	Physics	Electricity
1	UKG-US	US-GER	PRC-US	GER-US	UKG-US	US-GER	US-IND	PRC-US
2	GER-US	US-CAN	GER-US	GER-CHI	US-CAN	GER-FRA	CAN-US	IND-US
3	CAN-US	UKG-US	US-UKG	US-UKG	US-GER	CAN-US	UKG-US	US-CAN
4	US-PRC	PRC-US	CAN-US	AUT-GER	US-FRA	IND-US	US-PRC	TAP-PRC
5	GER-CHI	GER-CHI	US-IND	CAN-US	US-PRC	UKG-US	US-GER	GER-US
6	US-FRA	FRA-GER	US-FRA	US-PRC	AUT-GER	AUT-GER	TAP-PRC	UKG-US
7	US-IND	US-IND	GER-CHI	GER-FRA	IND-US	CHI-GER	JPN-US	US-KOR
8	FRA-GER	JPN-US	US-JPN	FRA-US	US-NET	PRC-TAP	US-ISR	JPN-US
9	JPN-US	AUT-GER	FRA-GER	BEL-US	GER-CHI	US-PRC	US-FRA	US-TAP
10	CHI-US	FRA-US	UKG-GER	GER-UKG	US-NOR	NET-GER	US-KOR	US-FRA
11	FRA-CHI	PRC-TAP	KOR-US	FRA-CHI	GER-FRA	US-FRA	TAP-US	US-ISR
12	UKG-GER	GER-NET	US-NET	IND-US	AUS-US	GER-UKG	GER-CHI	JPN-KOR
13	KOR-US	UKG-GER	FRA-CHI	NET-US	FRA-UKG	US-JPN	CHI-US	JPN-PRC
14	NET-US	KOR-US	CHI-US	NET-GER	PRC-TAP	GER-ITA	NET-US	PRC-KOR
15	US-ISR	US-NET	US-BEL	US-JPN	JPN-US	TAP-US	US-AUS	GER-AUT
16	FRA-UKG	US-TAP	GER-AUT	US-CHI	US-SIN	US-ITA	FRA-GER	IND-PRC
17	US-ITA	GER-BEL	NET-GER	KOR-US	RUS-UKR	GER-BEL	IRL-US	FRA-GER
18	AUS-US	US-BEL	FRA-UKG	US-FIN	RUS-US	US-KOR	GER-AUT	GER-CHI
19	TAP-US	US-CHI	GER-BEL	ITA-GER	GER-UKG	PRC-GER	NET-GER	NET-US
20	GER-NET	CHI-FRA	FRA-BEL	JPN-KOR	NOR-UKG	JPN-KOR	UKG-GER	US-SWE

Source: Authors' own calculations based on PATSTAT data.

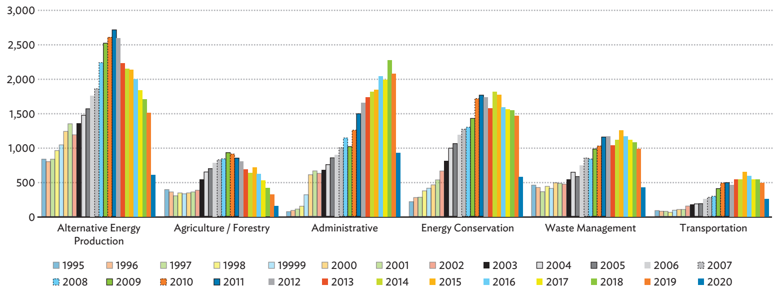
degree of cooperative innovation between the two economies. Aside from Canada, the two most important innovation partners for the US are the People's Republic of China and India. Perhaps unsurprisingly, the US is the most important innovation partner for many economies on the list. In Europe, Germany, the United Kingdom, and France collaborate most with the US, and in Asia, the People's Republic of China, India, Japan, and the Republic of Korea collaborate most with the US.

Table 6.8 shows the most important inventor economy pairs by technology field. The US is consistently one of the top co-inventors across all technology fields. The cooperation between the US and the People's Republic of China in chemistry and electricity ranks first, while the US is the leading innovation partner for Germany in technologies related to transportation, engineering, and paper. The United Kingdom and the US generate the largest number of collaborative innovations in the human necessities and fixed construction fields. For physics, India has the largest number of collaborative innovations with the US.

Figure 6.10 presents the development of international collaborative eco-innovations in each green technology field. There is a significant increase in collaborative eco-innovation in each green technology field. Despite the limited extent of the collaborative innovation in alternative energy, it has proven to be one of the most promising future clean energy sources for humanity. We can also note that collaborative innovation in alternative energy, energy conservation, and waste management is growing rapidly, reflecting the trend of more and more economies investing in green technology-related R&D and seeking solutions to environmental problems through cooperation.

Despite the increases in collaborative eco-innovation, Figure 6.10 also shows how the number of collaborative innovations fell over the last 5 years or so of the sample, with notable declines in alternative energy production and agriculture and forestry. Given that cooperation is seen as an important way that green technologies are diffused globally, these declines are potentially important and warrant further investigation.

Figure 6.10: Total International Collaborative Eco-innovations in Each Technology Field



Source: Authors' own calculations based on PATSTAT data.

Table 6.9: Top 20 Inventor Pairs Globally in Terms of Total Collaborative Eco-innovations

Rank	Economy	% of Total Global Collaborative Eco-innovations
1	CAN-US	6.29
2	GER-US	6.13
3	UKG-US	5.97
4	IND-US	5.50
5	PRC-US	5.05
6	FRA-US	2.66
7	US-JPN	2.50
8	GER-FRA	2.37
9	GER-CHI	2.28
10	KOR-US	2.07
11	PRC-TAP	1.84
12	AUT-GER	1.83
13	UKG-GER	1.61
14	NET-GER	1.53
15	NET-US	1.47
16	ISR-US	1.41
17	TAP-US	1.36
18	US-CHI	1.35
19	US-AUS	1.22
20	KOR-JPN	1.19

Source: Authors' own calculations based on PATSTAT data.

Turning again to collaborative eco-innovations, Table 6.9 presents the most important eco-inventor economy pairs at the economy level. Although the People's Republic of China and the US rank first in collaborative innovation, they only rank fifth when it comes to collaborative eco-innovation, with first place now taken by the US and Canada, whose collaborative eco-innovations account for 6.29% of the total international collaborative eco-innovations. In addition, the US and Germany, as well as the US and the United Kingdom, rank relatively highly for collaborative eco-innovations. The People's Republic of China and India are the only developing economies that make the list.

Table 6.10 shows the most important inventor economy pairs for each green technology field. Again, the US is the most important eco-innovation partner for each green technology field. Cooperation between the US and the People's Republic of China in energy conservation is still at the top of the list. The US is Germany's most important innovation partner in the agriculture field, while the United Kingdom and the US

Table 6.10: Top 20 Inventor Economy Pairs in Each Green Technological Field

Rank	Administrative	Agriculture	Alternative Energy	Energy Conservation	Waste Management	Transportation
1	IND-US	US-GER	GER-US	PRC-US	UKG-US	CAN-US
2	UKG-US	FRA-GER	US-CAN	US-GER	US-CAN	GER-AUT
3	US-CAN	US-UKG	US-PRC	CAN-US	GER-US	US-GER
4	GER-US	GER-UKG	US-UKG	IND-US	US-PRC	PRC-US
5	US-PRC	US-PRC	US-IND	UKG-US	US-IND	GER-CHI
6	US-ISR	GER-CHI	JPN-US	PRC-TAP	US-FRA	US-IND
7	FRA-US	CAN-US	FRA-US	KOR-US	NET-GER	UKG-US
8	US-IRL	FRA-US	KOR-US	JPN-US	CHI-GER	GER-FRA
9	US-AUS	US-IND	CHI-GER	TAP-US	GER-AUT	TAP-US
10	JPN-US	CHI-FRA	NET-US	KOR-JPN	US-NET	PRC-TAP
11	TAP-PRC	US-CHI	TAP-PRC	US-FRA	FRA-GER	US-JPN
12	US-CHI	US-JPN	FRA-GER	AUT-GER	KOR-US	US-KOR
13	KOR-US	GER-JPN	NET-GER	GER-CHI	JPN-US	UKG-GER
14	US-SIN	UKG-CHI	GER-AUT	GER-FRA	BEL-GER	US-FRA
15	US-NET	FRA-UKG	TAP-US	GER-NET	UKG-GER	GER-NET
16	CHI-GER	GER-SPA	UKG-GER	ISR-US	BEL-FRA	CHI-US
17	CAN-UKG	GER-SPA	KOR-JPN	GER-UKG	RUS-US	UKR-RUS
18	UKG-GER	AUT-GER	AUS-US	US-CHI	KOR-JPN	JPN-KOR
19	US-BRA	IND-GER	US-BEL	NET-US	US-AUS	SWE-GER
20	IND-GER	BEL-US	CHI-US	PRC-GER	US-BEL	PRC-GER

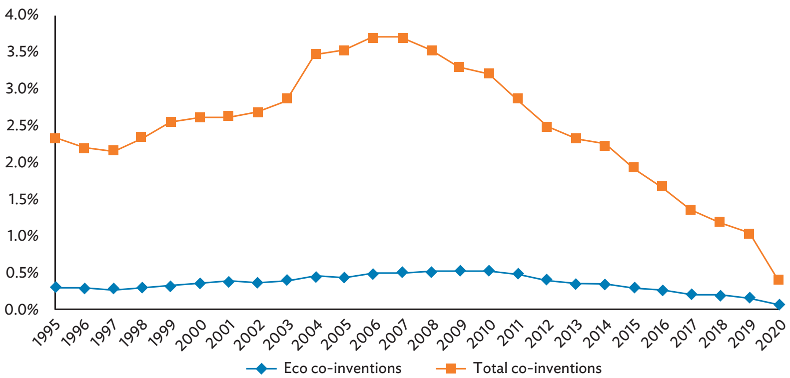
Source: Authors' own calculations based on PATSTAT data.

cooperate in innovation related to waste management. India and the US are ranked first in the administrative or design technology field.

To show the evolution of collaborative innovation and collaborative eco-innovation, Figure 6.11 introduces the share of international collaborative innovations and the share of international collaborative eco-innovations of the total inventions between 1995 and 2020. Although the number of international collaborative innovations has significantly increased since 1995, the share of international collaborative innovations of the total inventions started to fall significantly after a peak of around 3.7% in 2007. The trend is similar for collaborative eco-innovations, but at a lower level; it is the more stable of the two trends.

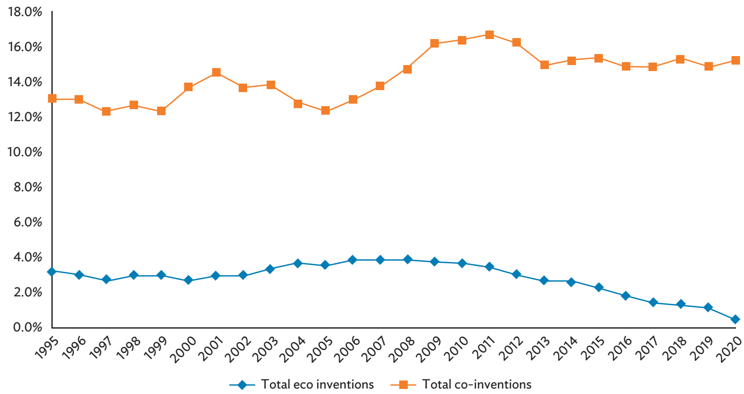
A possible explanation is that since the beginning of the 21st century, economies have continued to build their domestic R&D capacity, which means that economies are increasingly able to support all of the different aspects of the innovation process without the need for help from overseas. It has been argued, as is central to the climate change debate, that eco-innovation is more complex and therefore requires skills and knowledge that are still beyond the capacity of individual economies to provide (Wagner and Llerena, 2011). Again, the final year of our sample shows a significant COVID effect, which not surprisingly impacts collaborative innovation even more heavily than innovation more generally.

Figure 6.11: Share of Collaborative Innovations and Collaborative Eco-innovations of the Total Inventions



Source: Authors' own calculations based on PATSTAT data.

Figure 6.12: Share of Total Collaborative Eco-innovations of the Total Eco-innovations and Total Collaborative Innovations

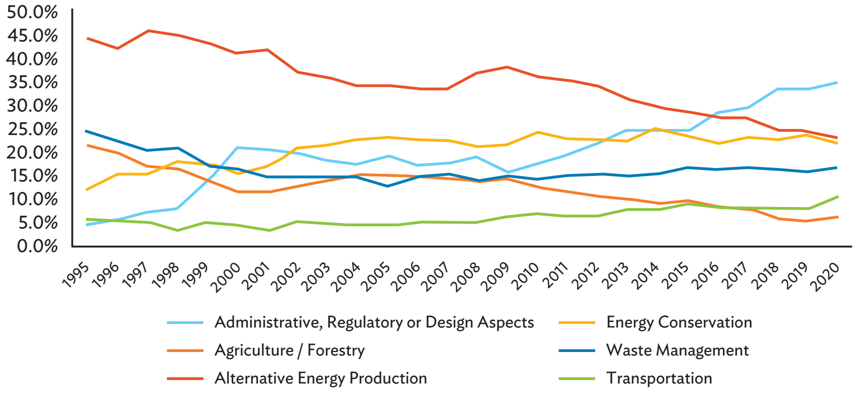


Source: Authors' own calculations based on PATSTAT data.

Figure 6.12 shows the share of total collaborative eco-innovations of the total eco-innovations and total collaborative innovations. The figure shows an upward trend in collaborative innovations but captures the fall in the share of collaborative eco-innovations after 2007 that we saw earlier. Although the total number of eco-innovations continues to increase, the share of collaborative eco-innovations of the total eco-innovations remains low and has fallen since the financial crisis. Understanding the reasons for these trends is an important area for future research.

The next stage is to look at trends in collaborative eco-innovations at a more disaggregated level. Figure 6.13 presents the share of collaborative eco-innovations for each technology field of the total collaborative eco-innovations. Although collaborative eco-innovation shows a fairly continuous decline in the alternative energy production-related green technologies and agriculture-related green technologies, the other trends show a slight increase. Hence, the overall decline we saw in Figures 6.12 and 6.13 appears to be driven by declines in the alternative energy production category.

Figure 6.13: Share of Collaborative Eco-innovations for Each Green Technology Field of the Total International Collaborative Eco-innovations



Source: Authors' own calculations based on PATSTAT data.

Tables 6.11 and 6.12 show the performance of the top 20 economy pairs in terms of collaborative innovations in different technology fields for both total collaborative innovations and total collaborative eco-innovations, respectively. Again, to assess the inventor economy pairs' specialization in a specific technology field, we calculate the "relative technological advantage" (RTA) (Haščič and Migotto, 2015). As a reminder, the RTA is calculated as follows:

$$RTA_{ijk} = (COIN_{ijk}/COIN_{wj})/(TCOIN_{ij}/TCOIN_{w}), \qquad (2)$$

where RTA_{ijk} is the RTA of the economy pair *ij* in the specific technology field *k*; $COIN_{ijk}$ is the total number of collaborative innovations of the economy pair *ij* in the specific technology field *k*; $TCOIN_{wk}$ is the total number of collaborative innovations globally in technology field *k*; $TCOIN_{ij}$ is the total number of collaborative innovations of the economy pair *ij*; and $TCOIN_{w}$ is the total collaborative innovations globally. Again, an RTA larger than one means that the economy pair is more specialized in that technology field. A higher RTA implies that the economy pair is more specialized in that specific technology field compared to other technology fields.

According to Table 6.11, Canada and the US tend to specialize in collaborative innovation related to fixed construction and physics technologies. The US and the People's Republic of China have an RTA in electricity and chemistry-related technologies. According to Table 6.12, the US and Japan have an RTA in inventions related to alternative energy. It is also interesting to note that Germany and Switzerland have a strong collaborative eco-innovation RTA in agriculture-related technologies, while Germany and the Netherlands have an advantage in alternative energy collaborative innovation.

Table 6.11: Specialization in Each Technology Field (Based on the WIPO Classification) of the top 20 Inventor Pairs (The RTA is Constructed Based on the Total Collaborative Innovations)

Inventor-pairs	Human Necessities	Transporting	Chemistry	Textiles, Paper	Fixed Construction	Mechanical Engineering	Physics	Electricity
US-PRC	0.87	0.62	1.09	0.48	0.37	0.49	0.95	1.53
US-CAN	1.01	0.89	0.92	0.72	1.26	0.81	1.26	1.07
US-IND	0.54	0.49	0.68	0.32	0.35	0.72	1.47	1.47
GER-US	1.13	1.15	1.19	1.21	0.63	1.08	1.06	0.85
US-UKG	1.21	0.78	1.13	0.89	1.43	0.76	1.26	0.88
PRC-TAP	0.24	0.58	0.25	0.17	0.42	1.09	1.38	1.69
US-JPN	0.88	0.97	1.17	0.53	0.45	0.63	1.21	1.26
US-FRA	1.23	0.91	1.29	0.95	1.29	0.74	1.04	0.91
GER-CHI	1.43	1.31	1.41	2.09	0.74	1.44	0.75	0.51
KOR-US	0.69	0.66	0.88	0.59	0.31	0.43	0.97	1.66
FRA-GER	1.21	1.35	1.40	1.27	0.70	2.22	0.64	0.63
US-TAP	0.66	0.66	0.54	0.30	0.37	0.58	1.09	1.79
US-ISR	0.85	0.38	0.41	0.26	0.14	0.18	1.88	1.31
GER-AUT	0.73	1.49	0.91	2.51	1.21	2.23	0.66	0.98
CHI-US	1.63	0.78	1.31	1.02	0.34	0.48	1.14	0.74
US-NET	1.10	1.05	1.40	1.27	1.31	0.60	1.03	0.86
UKG-GER	1.50	1.10	1.50	1.57	0.62	1.28	0.75	0.67
NET-GER	0.98	1.23	1.19	1.36	0.67	1.91	0.84	0.83
FRA-CHI	1.97	0.89	1.68	1.82	0.34	0.61	0.89	0.48
KOR-PRC	0.72	0.51	0.86	0.56	0.21	0.29	0.85	1.62

Source: Authors' own calculations based on PATSTAT data.

Table 6.12: Specialization in Each Green Technology Field (Based on the WIPO Green Inventory List) of the top 20 Inventor Pairs (The RTA is Constructed Based on the Total Collaborative Eco-innovations)

Inventor-pairs	Administrative	Agriculture	Alternative Energy	Energy Conservation	Waste Management	Transportation
US-CAN	0.96	0.72	1.46	0.89	0.84	0.95
GER-US	0.53	1.64	1.50	1.04	0.81	0.89
UKG-US	1.12	1.01	1.27	0.67	0.98	0.47
IND-US	1.42	0.60	1.05	0.88	0.58	0.56
US-PRC	0.54	0.92	1.60	1.46	0.69	0.89
FRA-US	0.61	1.35	1.55	0.94	0.99	0.45
US-JPN	0.53	0.95	1.79	1.20	0.64	0.92
GER-FRA	0.20	3.50	1.10	0.90	0.69	1.10
CHI-GER	0.25	2.02	1.53	1.04	0.81	1.49
KOR-US	0.52	0.45	1.75	1.49	0.78	1.08
TAP-PRC	0.65	0.11	1.49	1.99	0.29	1.26
AUT-GER	0.25	0.91	1.25	1.35	0.99	3.10
GER-UKG	0.31	3.04	1.31	0.83	0.75	0.79
GER-NET	0.23	0.80	1.60	1.27	1.45	0.77
NET-US	0.46	0.66	2.18	0.85	1.17	0.36
US-ISR	1.52	0.57	1.03	0.96	0.36	0.55
US-TAP	0.35	0.46	1.60	2.12	0.37	1.72
US-CHI	0.80	1.84	1.29	0.95	0.43	0.84
AUS-US	1.15	0.83	1.46	0.66	0.76	0.59
JPN-KOR	0.16	0.17	1.62	2.27	0.85	0.75

Source: Authors' own calculations based on PATSTAT data.

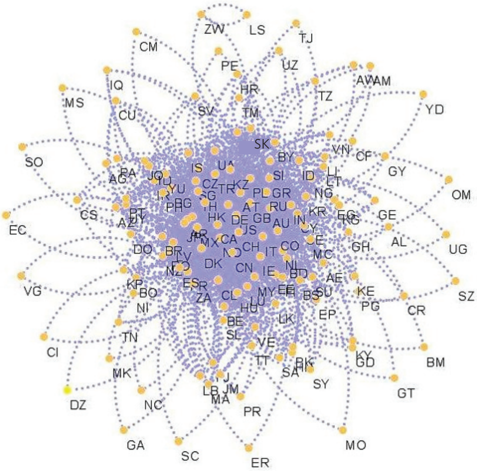
In the final stage of our descriptive analysis, we present the global technological collaboration network in visual form for the years 1995 and 2019.[15] Figure 6.14 shows that, compared with 2019, collaborative innovations in 1995 reveal that the world was less strongly connected. At the center of Figure 6.15(a) are the US, Japan, the United Kingdom, Germany, the People's Republic of China, Canada, and a number of other developed European economies. Those economies located at the center of the figure can be considered the leaders in technological collaborative innovation in 1995. Figure 6.15(b) shows the network for 2019 and reveals that many more economies participate in collaboration and that the world is more closely connected. There is also a notable increase is the number of less developed economies participating in global technological cooperation. However, although the linkages between economies have increased, the leaders remain those economies that were leaders in 1995.

Figure 6.15 shows an equivalent visual representation for the network of collaborative eco-innovation and displays how it has evolved over time. Again, the number of economies and collaborative innovations increased substantially between 1995 and 2019 and again, collaborative eco-innovations are still led by developed economies such as the US, the United Kingdom, Germany, Canada, Japan, and the Republic of Korea. However, by 2019, India and the People's Republic of China had moved towards the center of the network, demonstrating their growing importance as partners in the development of green technologies.

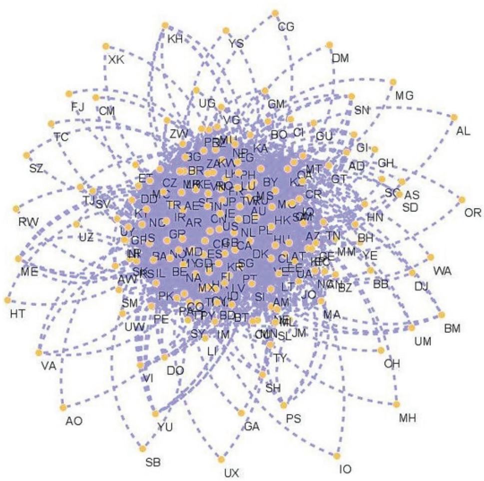
15 Since 2020 was impacted by COVID in ways we do not yet fully understand, we look at 1995 and 2019.

Figure 6.14: The Global Collaboration Network

(a) 1995



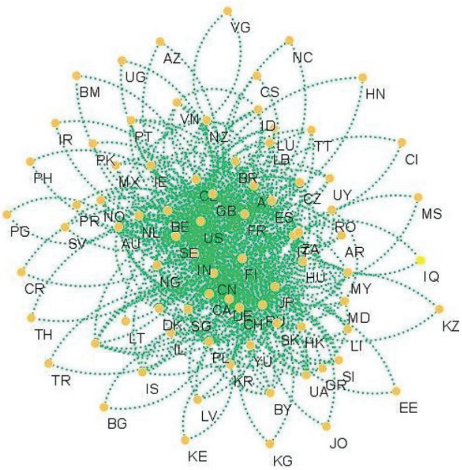
(b) 2019



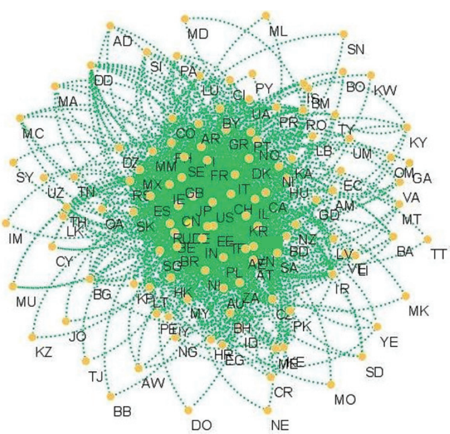
Source: Authors' own calculations based on PATSTAT data.

Figure 6.15: The Global Eco-collaboration Network

(a) 1995



(b) 2019



Source: Authors' own calculations based on PATSTAT data.

6.5 Innovation and the Manufacturing Industry

In this section, we describe the development of inventions and collaborative innovations considering just the manufacturing sector. The main finding is that there are significant differences in inventions and collaborative innovations across sectors. Our industry-level analysis is based on a concordance table linking the IPC codes and NACE codes.[16] Using the correspondence table linking NACE codes with IPC codes enables us to map inventions to different sectors in the manufacturing industry.[17]

6.5.1 Trends in Manufacturing Innovation

The first step is to look at how patent families are distributed across different industries. Figures 6.16 and 6.17 show that the computer and electrical equipment sector has the most inventions and eco-innovations by a considerable margin. The smallest number of inventions and eco-innovations is in the wood and textiles sector. The chemical and non-metallic mineral products sector ranks second in terms of the total eco-innovations over our time period.[18] In summary, the computer, electronic, and electrical equipment sector, machinery and equipment sector, and chemical sector are the top three sectors whether we look at total inventions or eco-innovations. Individual production processes require a substantial level of energy consumption. Given that manufacturing is traditionally one of the highest-polluting sectors, it is reassuring to see how much research activity has taken place in this area of the economy.

Figure 6.18 presents the number and growth of total inventions and eco-innovations in each industry. Each industry shows a significant increase, with inventions related to electrical products having the fastest growth, followed by the machinery and chemical industries. Figure 6.19(b) shows that eco-innovations are growing across all industries, although the increase is most rapid for computer technologies. It is worth noting that the chemical and machinery industries also experienced rapid growth. The relatively slow pace of eco-innovation in wood and paper and basic metals is reassuring and reflects the maturity and relatively simple structure of these industries.

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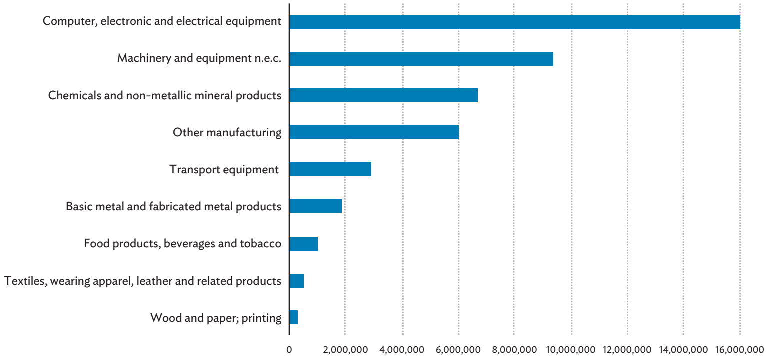
16 NACE is the standard European nomenclature.

17 IPC codes are only linked to the manufacturing industry.

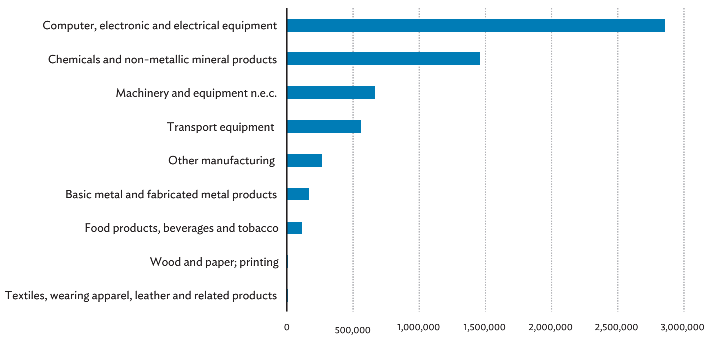
18 Non-metallic mineral products include the production of cement, ceramics, glass, and lime. The conversion of natural minerals through energy-intensive processes characterizes the manufacturing industry related to non-metallic minerals.

Figure 6.16: Inventions in Selected Manufacturing Industries



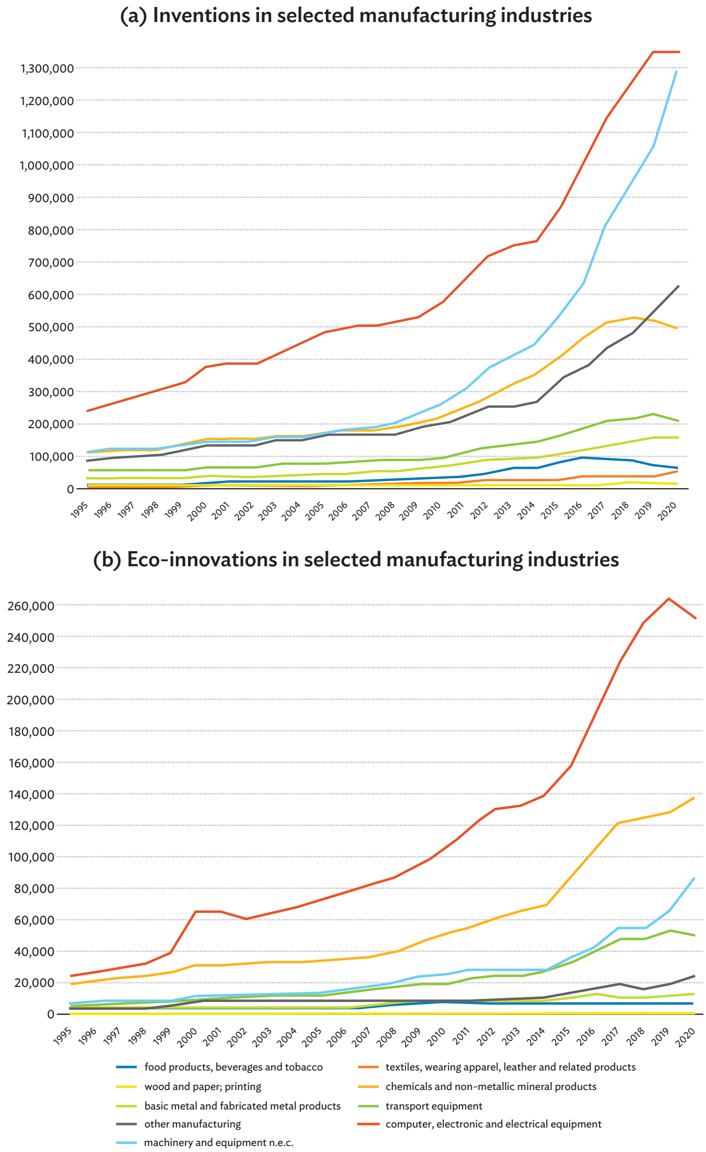
Source: Authors' own calculations based on PATSTAT data.

Figure 6.17: Eco-innovations in Selected Manufacturing Industries



Source: Authors' own calculations based on PATSTAT data.

Figure 6.18: Number of Inventions in Selected Manufacturing Industries

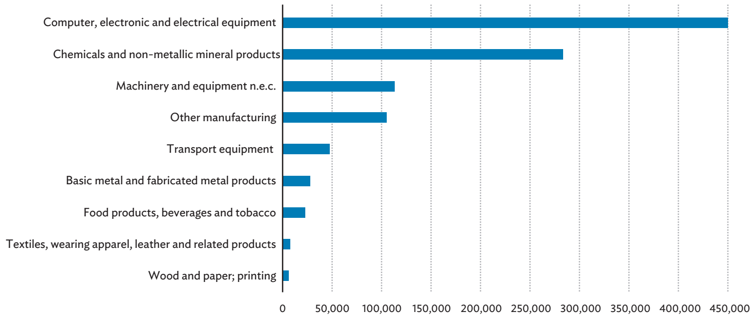


Source: Authors' own calculations based on PATSTAT data.

6.5.2 Trends in Manufacturing Collaborative Innovation

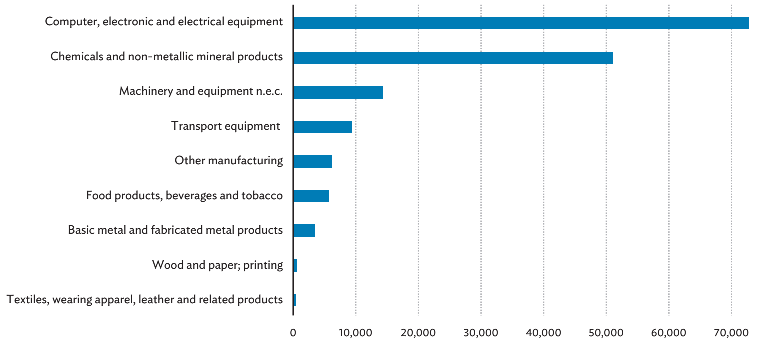
Figures 6.19 and 6.20 present equivalent evidence for collaborative innovations and collaborative eco-innovations for selected manufacturing industries. Compared with other industries, the number of collaborative innovations in the computer and electronics industry and the chemical and non-metallic mineral products industry are significantly higher that those in the other industries. The machinery and equipment industry and the transport industry also have a significant number of collaborative eco-innovations, as might be expected due to the development of the electric vehicle industry.

Figure 6.19: Collaborative Innovations in Selected Manufacturing Industries



Source: Authors' own calculations based on PATSTAT data.

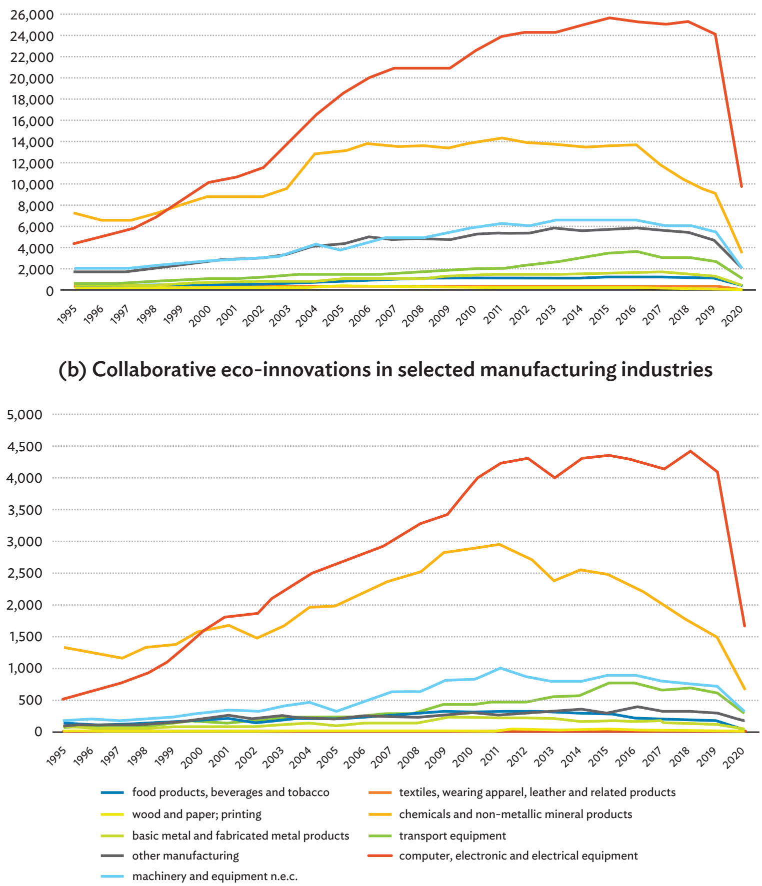
Figure 6.20: Collaborative Eco-Innovations in Selected Manufacturing Industries



Source: Authors' own calculations based on PATSTAT data.

Figure 6.21: The Number of Collaborative Innovations in Selected Manufacturing Industries

(a) Collaborative innovations in selected manufacturing industries



Source: Authors' own calculations based on PATSTAT data.

Finally, Figure 6.21 shows how the number of collaborative innovations has changed over time. The fastest-growing sector is the computer, electronic, and electrical equipment industry, which also has the largest increase in the number of collaborative eco-innovations. As we have previously shown, there was a significant drop in the total number of collaborative innovations in each manufacturing sector as a result of the COVID pandemic.

6.6 Conclusions and Policy Recommendations

To better understand global technological innovation, this chapter examines the global trends in innovation, collaborative innovation, eco-innovation, and collaborative eco-innovation. The analysis is based on data collected from the PATSTAT database, which provides detailed information on patent families between 1995 and 2020 for each technology field. The purpose of this chapter is to understand how innovation and collaborative innovation have changed over time and how these concepts may help mitigate the impact of climate change and allow economies to meet their Paris Agreement obligations. Understanding the role of collaborative innovation is also linked to the debate on how best to foster more resilient GVCs; collaboration and deeper links between economies are likely to play an important role.

This chapter presents broad trends but also breaks innovation down by technology fields for both general innovation and eco-innovation. Overall, we find that there was a very significant increase in innovation between 1995 and 2020 as more and more economies developed the internal capabilities that allowed them to undertake the level of R&D that eventually leads to a patent. Although innovation remains strong in the US, Germany, and Japan, it is notable that developing economies have considerably strengthened their innovative capabilities. This trend is reflected in the changing patterns of collaborative innovation, as shown in our visual representation of innovation networks. The People's Republic of China and India saw very considerable increases in innovation and to a lesser extent eco-innovation.

The growth in eco-innovation offers hope that human ingenuity will be able to offset some of the most damaging effects of climate change. However, eco-innovation can only really be beneficial if those technologies are quickly and efficiently diffused across the world's economies. When it comes to collaborative eco-innovation, the story is similar but there is some cause for concern. Although the general trend is upward there has been a noticeable decline in the number of collaborative eco-innovations in certain technology fields. This is important for two reasons. First, eco-innovation is often thought of as highly complex, requiring inputs from more than one economy given the enormity of some of the technical problems that need to be overcome. Second, collaboration is more likely to lead to a greater diffusion of these green technologies and hence makes them more likely to have larger global environmental benefits.

To encourage eco-innovation governments may need to pay more attention to subsidies, environmental regulations and policies, R&D

investment, and developing their economies' research capacity more generally (Duan et al., 2010). There is also the possibility of learning-by-doing effects, whereby economies learn from collaboration and go on to develop larger domestic research capabilities, leading to a broader level of technological upgrading. It is important therefore to look carefully at the reasons for the fall in collaborative eco-innovation in recent years and determine whether this is a result of economies developing stronger domestic capabilities or whether it is part of a broader pattern of de-globalization, protection of IP, geopolitical tensions more generally (e.g., the US-People's Republic of China trade war), and the perception that firms and governments are facing an increasingly uncertain outlook after the dual shocks of COVID-19.

Greater collaboration between economies at both the intensive and extensive margins should also build in greater resilience. If a economy develops collaborative research with a larger number of economies, this portfolio approach to research should leave the economy in a stronger position if any one partner is subject to an external shock (economic or political). However, this assumes a larger number of short supply chains. When supply chains become longer, this inevitably creates weak points. This is why GVC resilience is best created by having complex networks in which any one point of failure can be quickly filled by another equally competent supplier or research team.

Although policymakers have different solutions to stimulate eco-innovation, it is less clear whether these same methods also encourage collaborative eco-innovation. Governments should consider which green technology field they have an innovation advantage in and which economies are their most important collaborative innovation partners. In the case of developing Asia and the Pacific, it is important to identify core strengths and weaknesses so certain sectors or individual firms can be encouraged to seek international partnerships and in some cases helped financially and helped to identify possible partners, regardless of where they are located geographically. To build more resilience into the research system, governments may wish to encourage collaboration across a range of developed and developing economies at different stages of the research process.

Developing Asia and the Pacific may also consider gathering information on the eco-innovation performance of member economies based on a series of indicators (similar in nature to the European Commission, which publishes an EU eco-innovation index based on 18 different indicators). The Asian Development Bank (ADB) already sets clear climate targets and has project-level disclosure for all of its climate-related projects. Other policies that may have direct and indirect impacts on future eco-innovation and collaborative eco-innovation include its energy transition mechanism (ETM) in Indonesia and the Philippines and the ASEAN Green Recovery Platform, which matches ADB funding with pledges from the EU, the United Kingdom, and others to de-risk private investment in green infrastructure. Similarly, the ADB Ventures climate technology funds aim to promote venture-stage innovation in the hope that this triggers innovation and future global cooperation. The ADB Southeast Asia innovation hub was also set up to provide innovative financing solutions to help attract greater levels of green and sustainable investment in Southeast Asia. The ADB's Faces of Innovation report in 2020 provides a good summary of the innovation powers in Asia and the Pacific and the role of sustainability (ADB, 2020).

One of the most pressing issues, following a rapid increase in global energy prices, is to promote and help fund innovation in green energy-related projects. For example, the ADB invested $8.5 billion in clean energy and energy efficiency projects between 2016 and 2020, with a considerable investment going into wind and solar power. The broader 2009 Energy Policy of the ADB has also spent over $42 billion on energy-related projects, although this includes fossil fuel-related projects. The ADB Strategy 2030 has a focus on low-carbon technologies; this should support existing cooperative agreements.

Policymakers can also help firms overcome some of the legal and IP concerns that other economies may have by having a strong rule of law and IP protection, including through the PATENT system. Policymakers can also help if mediation is required when there are disagreements on time frames, ownership, pricing, and how to deal with litigation if initiatives break down. If these challenges can be overcome, there are plenty of growth opportunities for companies, especially in the area of eco-innovation and clean tech development. The need for cooperation is also exacerbated by rapidly changing technologies such that it is difficult for any one economy to have complete expertise (in, for example, AI, large language models such as ChatGPT, and cloud computing). The rapidly changing technological frontier also has implications for supply chain resilience and again supports the argument for working with a range of different partners to shorten supply chains and get exposure to different advanced technologies.

Finally, the world is facing a period of great uncertainty and risk. This backdrop may act as a brake on future collaborative research between firms based in different economies. To pull back from collaborative innovation, especially in environmental-related research, could lead to greater risks. Fostering more resilient supply chains goes hand in hand with building stronger collaborative research links, and the two can be considered to be complementary. Policies that strengthen GVCs are likely to have a similar impact on patterns of collaborative innovation. Given the close links between trade and innovation, supply chain disruptions due to the COVID-19 will have had a cooling effect on collaborative innovation. There is some hope that recent policies from the US, such as the CHIPS Act, the EU's Green Deal Industrial Plan, and China's recent "Green Development in a New Era" plan for the industrial sector will mean considerable investment in eco-innovation. It is yet to be seen whether this will result in more or less collaborative eco-innovation and how these policies will impact overall trade patterns and the structure of existing supply chains.

This chapter presents overall trends in innovation and collaborative innovation, with an emphasis on the environment. However, there is more research to be done to address the limitations related to data quality and the use of patent data to capture innovation. Research looking at the determinants of innovation and eco-innovation and an examination of policy effectiveness in encouraging innovation would be particularly welcome. If we are to understand how we can green global value chains and improve GVC resilience, it is important to understand the impact of collaborative innovation on the carbon content of trade. These remain topics for future research.

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Appendix

Table A6.1: Examples of Green Technologies in Each Green Technology Field

ALTERNATIVE ENERGY PRODUCTION	
Bio-fuels	Vegetable oils, biogas, etc.
Fuel cells	Inert electrodes with catalytic activity, etc.
Harnessing energy from manmade waste	Fuel from crop residue, etc.
Hydro-energy	
Wind energy	
Solar energy	Photovoltaics (PVs), etc.
Geothermal energy	Geothermal heat, etc.
Other products or use of heat not derived from combustion	Heat pumps, etc.
Using waste heat	Using waste heat to produce mechanical energy, etc.
TRANSPORTATION	
Vehicles in general	Hybrid electric vehicles, etc.
Vehicles other than rail vehicles	Human-powered vehicles, etc.
Rail vehicles	
Marine vessel propulsion	
ENERGY CONSERVATION	
Storage of electrical energy	
Power supply circulatory	Storage of thermal energy, etc.
Low-energy lighting	
Thermal building insulation, in general	
Recovering mechanical energy	
WASTE MANAGEMENT	
Waste disposal	
Treatment of waste	Disinfection, sterilization, etc.
Reuse of waste materials	
Pollution control	Air quality management, water pollution management, etc.
AGRICULTURE/FORESTRY	
Forestry techniques	
Alternative irrigation techniques	
Pesticide alternatives	
Soil improvement	
ADMINISTRATIVE, REGULATORY, OR DESIGN ASPECTS	
Commuting	HOV, teleworking, etc.
Carbon/emission trading	Pollution credits, etc.
Static structure design	

Source: Authors' own collection based on the work by WIPO.

Table A6.2: Abbreviations of Economies Included in the Report

Abbreviations (Two-letter Codes)	Abbreviations (Three-letter Codes)	Economy Names
AR	AGR	Argentina
AT	AUT	Austria
AU	AUS	Australia
BE	BEL	Belgium
BG	BGR	Bulgaria
BR	BRA	Brazil
BY	BLR	Belarus
CA	CAN	Canada
CH	CHI	Switzerland
CL	CHL	Chile
CN	PRC	People's Republic of China (PRC)
CO	COL	Colombia
CZ	CZE	Czechia
DE	GER	Germany
DK	DEN	Denmark
ES	SPA	Spain
FI	FIN	Finland
FR	FRA	France
GB	UKG	United Kingdom
GR	GRC	Greece
HK	HKG	Hong Kong, China
HR	HRV	Croatia
HU	HUN	Hungary
IE	IRE	Ireland
IL	ISR	Israel
IN	IND	India
IT	ITA	Italy
JP	JPN	Japan
KR	KOR	Republic of Korea
MD	MDA	Republic of Moldova
MX	MEX	Mexico
MY	MAL	Malaysia
MX	MEX	Mexico
NL	NET	Netherlands
NO	NOR	Norway
NZ	NZL	New Zealand
PH	PHI	Philippines
PL	POL	Poland
PT	PRT	Portugal
RO	ROU	Romania
RU	RUS	Russian Federation
SA	SAU	Saudi Arabia
SE	SWE	Sweden
SG	SIN	Singapore
SI	SVN	Slovenia
SK	SVK	Slovakia
TH	THA	Thailand
TR	TUR	Türkiye
TA	TAP	Taipei,China
UA	UKR	Ukraine
US	USA	United States
ZA	ZAF	South Africa

Source: Authors' own collection based on the work by the International Organization for Standardization (ISO) and Asian Development Bank (ADB).

PART IV

Global Supply Chain Transformation

7

Global Supply Chain Resilience: Facts and Implications

Alicia Garcia Herrero

7.1 Introduction

What we thought was an unstoppable trend, namely, globalization, has been centered on the rapid increase in trade flows across the globe; it has now halted and, worse still, may reverse. Rapid globalization has been possible thanks to rapid innovation in information technology, logistics, and transportation, which has reduced costs, accelerated the speed of communication, and cheapened the transportation of air and sea freight. Other causes are the formation of massive trade blocs such as the European Union and the liberalization of trade and investment policy. In the 1990s and 2000s, the reduction of barriers to global trade and investment created rapid de-localization and specialization of the production of parts and components, arbitraging the costs of inputs and regulation and giving rise to the complex supply chains we have today.

That process of the fragmentation of production, and of input goods traveling across global supply chains before a final good is finalized and sold to the consumer, is known as the global value chain, and it has been one of the most important revolutions in recent economic history. The ability of developing economies to tap into their comparative advantage of cheap labor markets through the liberalization of trade and investment policy, not to mention their laxer environmental and labor regulation, has allowed them to gain more productive jobs and sticky capital investment, and, most importantly, to tap into the global value chain to raise productivity and generate wealth. From Eastern Europe to the People's Republic of China (PRC), and, more recently, Viet Nam, the process has lifted millions out of poverty and generated significant wealth.

Moreover, global value chains have shaped the world beyond trade, from the increasing importance of efficiency as a key objective of the production process—and the development of new business models to accommodate this—to the surge in foreign direct investment (FDI) to set up production plants overseas to produce parts and components for the supply chain. Thus, there are a number of reasons why global value chains are important for trade.

First and foremost, they shape the role that countries may play in moving up the ladder of adding value in production. A growing role in the supply of parts and components, especially if this is accompanied by supportive innovation policies, should help countries increase the value embedded in production. This is clearly the case in the PRC. In the same way, the labor force involved in the production of such parts and components will need to accompany this move up the ladder by scaling up their capabilities. Related improvements in innovation and human capital are important positive consequences of a country's role in the global value chain.

That said, in recent years, globalization has increasingly become more contentious and it cannot be taken for granted that it will continue to prosper, as the dark side of rampant globalization and the liberalization of trade and investment has emerged. Beyond the obvious divergence in environmental and labor policies and the consequence of the asymmetric liberalization of trade and investment policy, the unevenness among the losers and winners of over-fast globalization has given rise to criticism of globalization and more protectionism and pushback against some of its shadows.

Clearly, at the center of that debate is the rise of the PRC in the global value chain (GVC). The way it has achieved this feat is increasingly contentious. Since 1978, the PRC's reform and opening up process has very much relied on trade as a key tool for economic development. The PRC's trade liberalization started well before the PRC's accession to the World Trade Organization (WTO) in 2001, but clearly accelerated thereafter. In fact, the most immediate impact of the accession to the WTO was the reduction of the PRC's import tariffs (import tariffs for PRC products to the rest of the world were already quite low because of the preferential tariffs for developing countries). This also implied a huge surge in the imports of capital goods to the PRC to increase its production capacity. The reduction in import tariffs attracted foreign investors and made it cheaper for them to produce in the PRC as the cost of importing the necessary capital goods became much lower.

The PRC's huge original comparative advantage—a close to infinite pool of cheap labor coupled with massive savings which could be deployed to invest in state-championed sectors at a relatively low cost—has made the PRC what it is today, the center of the global value chains. Both the infinite pool of cheap labor and, to a lesser extent, the savings ratio are no longer as key in the PRC's comparative advantage, but increasingly innovation and the value-added embedded in the production of goods and services play a key role. Within this process, the PRC has harnessed the power of FDI to tap into the global supply chains while keeping control of its own market. This strategy has clearly been a success in terms of the jobs and wealth created in the PRC during all these years, with the PRC expanding its global market share of manufacturing to an impressive 19% of the global total. However, the fact that foreign investors do not enjoy real market access in the PRC's domestic markets creates asymmetries, not only for the provision of final goods in the PRC but also for the functioning of supply chains.

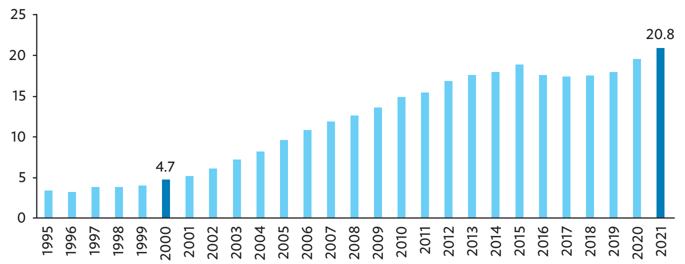
Against this backdrop, a very important shock, namely the COVID-19 pandemic, hit the global economy in 2020. The pandemic was not only a major global health issue but also put to the test global value chains across the world, creating huge bottlenecks and a scarcity of essential goods, including medical and sanitary ones, when they were most needed. Since then, the resilience of value chains has become a key topic in economics, as well as interdisciplinary research, and this chapter aims to contribute to this research. The reality is that preoccupations with supply chain resilience did not start with the pandemic but were already high on the agenda of policymakers as a result of the disruptions that had already occurred because of natural shocks and policies, in particular the United States (US)–PRC trade war. In fact, the US trade war was a catalyst in the development of the idea of excessive dependence on the PRC for the sourcing of goods, which only accelerated during the pandemic. At this juncture, we find ourselves in the midst of a reshuffling of the global value chain. The aim of some of that reshuffling is to find alternative manufacturing ecosystems to the PRC, but other important considerations exist. Beyond the geopolitical reasons for political leaders pushing in this direction, this chapter points to economic reasons behind the push away from a PRC-centric global value chain as a way to increase resilience and, therefore, ensure the provision of critical goods when they are most needed.

To achieve this goal, this chapter first, in section 7.2, reviews the PRC's accession to the WTO as a key driver of global value chains. Secondly, in section 7.3, it explains the consequences for the rest of the world, especially as far as resilience is concerned. section 7.4 deals with the actions taken by some of the key governments to increase the resilience of their participation in supply chains. Finally, section 7.5 looks at the actions taken by companies so far in terms of supply chain reshuffling. Section 7.6 concludes.

7.2 The PRC's Movement from the Periphery to the Center of the Global Value Chain

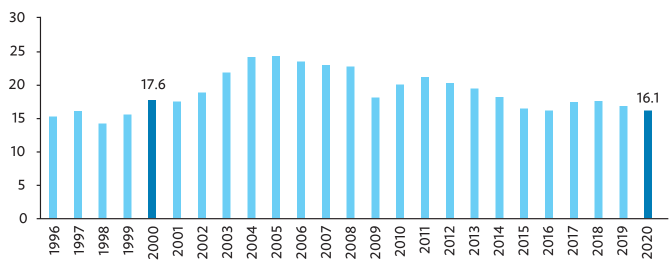
The PRC's rise began four decades ago, but its accession to the WTO punctuated its emergence. In 2000, two decades ago, the PRC's GDP per capita was only $959, versus that of the United States, which was $36,334. Despite being the most populous country in the world, with 1.26 billion people, the PRC's share of global output was only 4%, and manufacturing was at a meagre 4.7% (Figure 7.1). Moreover, it was considered a backwater for manufacturing, and its exports were mostly goods requiring low-skilled manufacturing. Labor-intensive manufactured goods made up the largest share of the export items. Despite having a low share of global exports and low value-added, the PRC's dependence on foreign intermediates for production was 17.6% (Figure 7.2).

Figure 7.1: PRC's Global Market Share of Manufactured Exports (%)



Source: Natixis, UNCTAD.

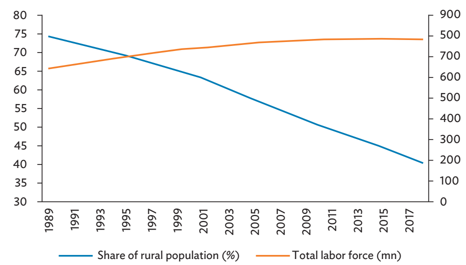
Figure 7.2: Share of Foreign Value-Added in the PRC's Gross Exports (%)



Source: Natixis, TiVA OECD.

Moving forward to 2021, the PRC's share of global manufactured output rose to 20.8%, and its dependence on foreign intermediates lowered to 16.1% in 2020. Even more impressive was its ability to lift 1 billion people out of poverty, with an average annual growth rate of 14.8% from 1978 to 2019 and an increase in GDP per capita in this period from $156 to $9,770. For the PRC, the opening to the world via trade, investment, and technology was necessary, as its main comparative advantage was its excess rural labor population (Figure 7.3) while its capital and technology levels were poor.

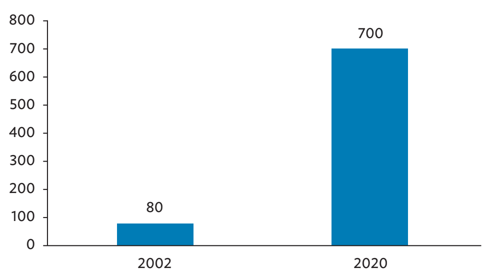
Figure 7.3: PRC's Total Labor Force
(million)



Source: Natixis, World Bank.

It is the process of opening its economy in the past four decades that has allowed the PRC to raise its human capital and increase its technological capability, so much so that it now has 700 million middle-income people (Figure 7.4). Of the Fortune 500 companies, a staggering 145 are Chinese-owned as of 2022.

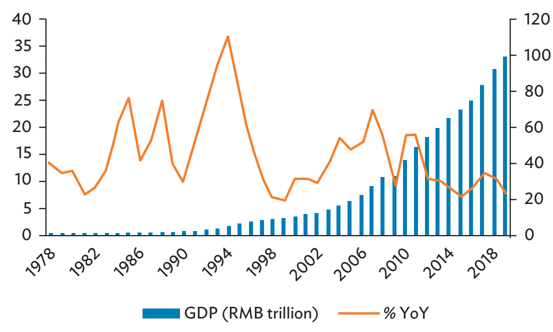
Figure 7.4: Middle Class Population in the PRC
(million)



Source: Statista, Natixis.

The growth of the PRC's role in the global value chain depended on the critical decision to open up and reform the economy in 1978 (Figure 7.5), after the unsuccessful experiment with a centrally planned economic policy. This significantly enhanced its integration with the international markets via trade, investment flows, and technology exchange. The opening-up has been progressive and has been carried out in stages. Significant efforts have also been made to liberalize FDI policies and attract FDI inflows, including gradually opening areas to FDI, promulgating regulations for foreign investment, and offering special tax incentives for foreign investors. However, the sectors opened up for investment remain limited and are concentrated in processing and manufacturing. In the second stage of opening up between 1992 and 2000, the PRC reduced its import tariffs and restrictions following a memorandum signed between the US and the PRC. Also, in a limited and experimental fashion, more regions were opened to foreign investors and service industries—such as aviation, telecommunications, banking and retail trade. A more liberalized and consistent FDI regime was established, but most sectors remained under the control of the state.

Figure 7.5: PRC's GDP Growth Since 1978

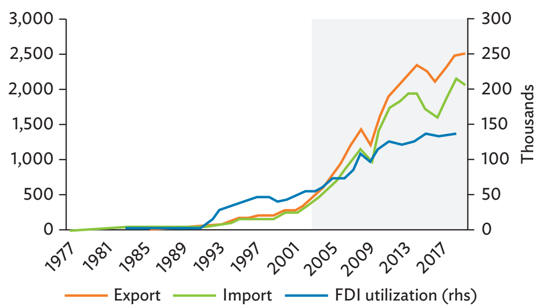


Source: CEIC, Natixis.

The PRC's accession to the WTO in 2001 marked the third stage of the reform and opening up. To comply with the WTO's national treatment, the PRC amended and reviewed a large number of its laws and regulations. Both tariff and non-tariff barriers were greatly reduced, and minimum law enforcement standards for the protection of intellectual property were set. In terms of FDI, the PRC made greater efforts to conform to international FDI requirements and issued its "Provisions on Guiding the Orientation of Foreign Investment" which assigned FDI into "encouraged," "permitted," "restricted," and "prohibited" categories to encourage FDI inflows into more industries. In effect, the PRC's opening up was rolled out in stages with increasing speed and coverage.

Such reforms led to the PRC's rapid integration into the international trade and capital markets. In terms of trade liberalization, the accession to the WTO in 2001 was a key milestone in the PRC's trade integration, with reduced tariffs and favorable international policies, and it marked the beginning of the transformation of the PRC's value chain into a more integral part of global trade. Since then, the PRC's export and import value has taken off, with an annual growth rate of 13.8% and 12.7% for exports and imports, reaching, respectively, $2.5 and $2.1 trillion in 2019 (Figure 7.6). Additionally, FDI into the PRC also surged to $138 billion from $0.9 billion, representing a 19% annual growth in foreign capital attracted to the country (Figure 7.6).

Figure 7.6: PRC's Trade and FDI Utilization Since 1978
($ billion)



Source: CEIC, Natixis.

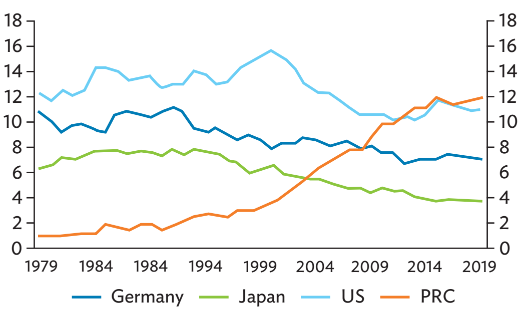
However, a closer look at the progress shows that the opening up is strongly biased towards trade liberalization, with a much more limited and gradual opening up in FDI. In fact, the PRC's actions have been to open trade to global competition, and the domestic economy to foreign investment inflows, without losing control of its strategic sectors. Despite its efforts to open sectors to foreign investors, numerous sectors remain, especially strategic sectors in which the PRC seeks to protect, nurture and develop domestic companies into globally competitive cooperation, and sectors that have traditionally benefited state monopolies. Also, foreign investors in most key sectors are required to form joint ventures with local companies that maintain control, giving rise to the risk of forced tech transfer. Thus, although the PRC's opening has been successful in bringing economic development, its progress is largely biased towards trade, and the nature of competition in the PRC market has not been fully changed.

Under its targeted liberalization policy, the PRC's foreign trade had 42 years of rapid development. The total value of imports and exports increased from $21 billion in 1978 to $4.6 trillion in 2019. Exports increased from $10 billion to $2.5 trillion, while imports increased from $11 billion to $2.1 trillion. From 1978 to 2019, the average annual growth rate of the PRC's total foreign trade was 15.4%, far higher than the global average.

Figure 7.7 shows the PRC's market share in total exports in comparison to US, Germany, and Japan from 1978 to 2019. The proportion of the PRC's exports in total global trade increased from less than 1% in 1978 to 12% in 2019. Meanwhile, the US, Japan, and Germany saw a decline in their market share and were surpassed by the PRC in terms of their global export contribution. In other words, the PRC has, at an astonishing rate, succeeded in becoming an integral part of international trade, and the world has been much more dependent on the PRC ever since the PRC's reform and opening in 1978.

No longer at the periphery, the PRC has become the center of the global value chain, especially in terms of intermediate goods. In 2003, 8% of global exports in manufacturing came from the PRC, and by 2021

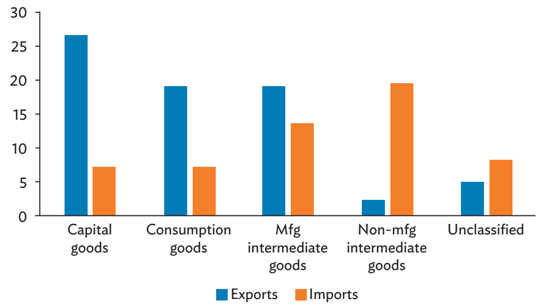
Figure 7.7: Share in Global Trade
(%)



Source: Natixis, UNCTAD.

this had grown to a staggering 21%. Moreover, the PRC's dominance in sectors like office machines, furniture, and apparel parts is even higher, at 50%, 60%, and 40% of the global market share, respectively. On top of gaining market share at the gross export level, at the value chain level more Chinese intermediates are used in the global value chain than in the past. What is key is that the PRC's exports of intermediates used by the rest of the world for export inputs have risen significantly, from 24% in 2003 to 43% of the PRC's gross exports in 2021. Figure 7.8 decomposes the PRC's exports and imports, by stage of production, as a share of global trade. The PRC's global export share is much bigger than its import share for all categories except for non-manufactured intermediates, mostly commodities (Figure 7.8). As a result, the PRC has captured an increasing and, by now, dominant market share in the global export of manufactured intermediates.

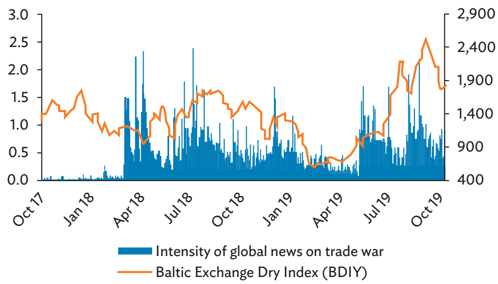
Figure 7.8: PRC's Share in Global Trade by Stage of Production (%)



Source: Natixis, UNCTAD. Data as of 2021. Products classified under the Broad Economic Categories.

After an amazingly rapid rise, the PRC is today central to the global value chain, so that when the PRC shuts its factories, as happened since January 2020 during the COVID-19 outbreak, there may be global shortages of key ingredients for production, from India's pharmaceutical products to the Republic of Korea's automobiles and Viet Nam's textiles. What is also increasingly clear is that the PRC's role in the GVC is asymmetric, as the PRC continues to export more and more intermediate goods that are used for other countries' production of exports, while it imports fewer and fewer of such products. The key question is how reliant the world is on the PRC and how much of this large share in global manufacturing is created by the PRC, in value-added terms. This consideration is especially key as the PRC has long striven not only to move up the ladder by raising the value-added of its exports but also to become more self-sufficient when serving the needs of its own market.

Figure 7.9: Trade Flows and Intensity of Global News on Trade War



Source: Natixis, GDELT, Bloomberg.

The PRC has made this very clear with its Manufacturing 2025 plan, which identifies key manufacturing sectors that the PRC plans to develop. One key objective is to become less dependent on the rest of the world (Garcia-Herrero and Xu 2020). The plan prompted a strong negative reaction from developed economies due to its implications for exports of intermediate goods into the PRC. The PRC's half-hearted opening (for trade but increasingly less for goods with high added value) and the many sectors in the PRC closed for FDI have certainly not helped its relations with the US or the EU. The first major blow came from the Trump administration, which in 2018 embarked on a trade war, with retaliatory trade measures that included, but were not limited to, higher tariffs on Chinese goods (Figure 7.9). By contrast, Europe used the WTO toolkit while developing its own autonomous measures to respond to an increasingly asymmetric economic relationship with the PRC.[1] Within these instruments, there has been some focus on the resilience of the

1 For a review of the EU's autonomous measures, please see Storey (2022). u4W78NC667K3FLC0nYpkhJ6VSBazOca8bX8D51RomqfK0QawczirU3R59FAuz9NjgeQMrMKT78iqn4OIlIsaW-ETUjDqKJEpToiLr8gWbk&utm_content=221526961&utm_source=hs_email.

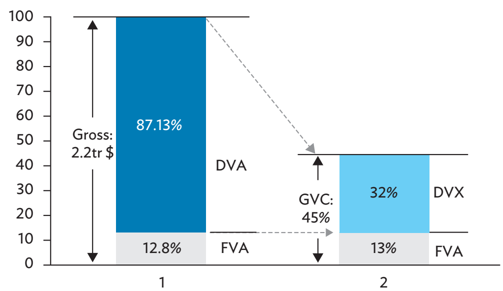
supply chain, as will be discussed later. While the PRC has since toned down its Manufacturing 2025 ambitions, the issue of the PRC becoming more self-reliant and less dependent on the sourcing of intermediate goods for the rest of the world, especially intermediate goods in key sectors, is important, not just for the PRC but also for the rest of the world. If the PRC were to become self-sufficient, this would imply that the rest of the world would benefit much less from the PRC's increased exports of goods. The next section discusses the PRC's increasingly central—but asymmetric—role in global supply chains, and how this situation may lie behind their reshuffling.

There are two questions regarding trade and globalization in this age of escalated tensions and nationalistic rhetoric that we would like to address in this report: a) Is globalization on the decline in terms of the integration of the supply chain in key economies? and b) What is the PRC's role in this transformation?

Before addressing these questions, the concept of the global supply chain needs to be defined more narrowly so as to create a workable measure that is comparable across countries and is easy to understand in terms of macroeconomic consequences. To that end, we will use the global value chain (GVC) concept developed by Haltmaier (2015), Koopman et al. (2010), and Hummels, Ishii, and Yi (2001). This measure allows us to gauge the international integration of a country's exports with a value-added dimension. For this, a distinction needs to be made between domestic value added (DVA) and foreign value added (FVA) (Aslam, Novta and Rodrigues Bastos 2017). A third concept is also key, namely, the domestic value added of exports (DVX), which analyzes how much of the domestic value-added export is then used by the third country as inputs for its exports. The nominal value of exports, although meaningful in showing the growth and intensity of trade activities, does not address a number of key issues for countries in terms of their global trade integration and the relative value of their export structure, or their economy, more generally. Indeed, key issues that are not addressed with gross export data are: a) the extent to which a country is capturing the gains of its exports through the domestic value added of its trade; b) how much of the domestic value added of a country's gross exports is used by other countries as inputs; and c) the share of FVA and DVA used by other countries as inputs (DVX) to determine how globally integrated the country's exports are into the production networks. The GVC, by decomposing the value added of gross exports, allows us to measure the participation of a certain economy or sector in the GVC and its determinants. We will be using 2018 input–output data, the latest available. Figure 7.10 shows the PRC's gross export value of $2.2 trillion in 2018. Of this total, 13% or $290 billion was derived from foreign value added (imports such as semiconductors would fall into this category), while the remaining 87% or $1,900 billion was domestic value added (domestic inputs such as domestic assembling). Within domestic value added, $700 billion, or 32% of the $2.2 trillion, were intermediate products of the country of interest, being exported to another country which used them for its own exports.

To measure the degree of global value chain participation, we add together the percentage of foreign value-added exports or FVA (13%) and the domestic value-added intermediates that are used by third countries for exports (32%) (the DVX) to get a GVC ratio of 45% for the PRC. This basically means that 45% of the PRC's gross exports participate in the global value chain (Figure 7.10). This is obviously a huge proportion and points to the PRC's centrality in global supply chains.

Figure 7.10: Breakdown of the PRC's Value Added of Gross Exports (2018, %)



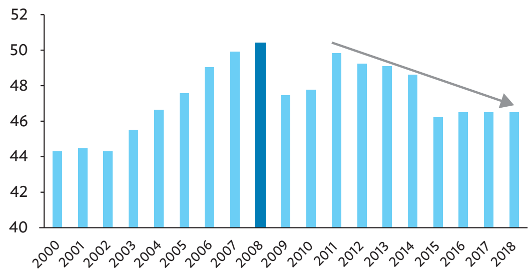
Note: The UNCTAD-EORA Global Value Chain (GVC) database offers global coverage (189 countries and a "Rest of World" region) and a timeseries from 1990 to 2018 of the key GVC indicators: foreign value added (FVA), domestic value added (DVA) and indirect value added (DVX). Results from 1990 to 2015 are generated from EORA Multi-Region Input-Output tables [MRIOs]. The results for 2016–2018 are nowcasted based on the IMF World Economic Outlook.

Source: UNCTAD-Eora database forecast, Natixis.

Regarding the first question above, namely whether the world is continuing to integrate in terms of the global supply chain, the chart below points to a clear reduction since 2008 (Figure 7.11). As for the second question, the PRC's global market share in terms of gross exports rose quite positively until 2015, then fell and stood at about 12.9% of global exports for two years before strongly rebounding during the COVID-19 pandemic and reaching an all-time high of 15.2% as of 2021

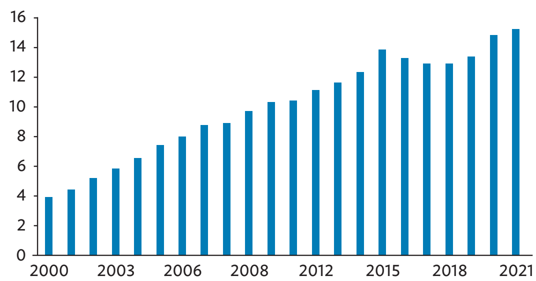
(Figure 7.12). The rise of global GVC coincided with the PRC's joining the WTO in 2001. That said, curiously, since 2008, the PRC's rise in global market share is running alongside lower GVC participation. These two developments seem somewhat contradictory, so it is worth digging into them more deeply.

Figure 7.11: World GVC Participation (%)



Source: UNCTAD-Eora database, Natixis. N.B. Results for 2016–2018 are forecasted by UNCTAD-Eora.

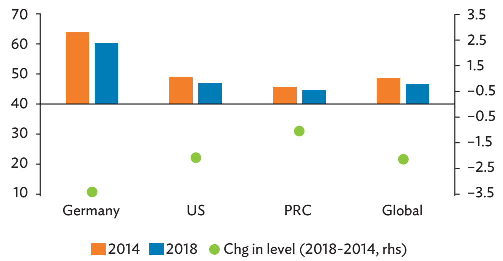
Figure 7.12: PRC's Market Share in Global Gross Export (%)



Source: UNCTAD, Natixis.

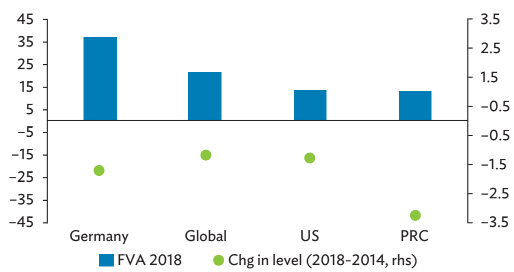
It is important to note that the PRC is not the most integrated country in the world in terms of its participation in the global supply chain. EU countries are much more integrated than the PRC, but the key question is the direction of change (Figure 7.13). On that front, we can see that Germany's integration is shrinking fast, while this is much less true for the PRC. Furthermore, as shown in Figure 7.14, the rather small—but still negative—growth in the PRC's participation in the GVC is explained by the smaller share of foreign inputs into the production of goods for export markets (FVA) or, conversely, a rise in the domestic value-added of exports (Figure 7.15). This is not the case for Germany, since the reduction in FVA is less than the overall reduction in DVA. In other words, the reduction in Germany's participation in the GVC cannot be explained by additional vertical integration within Germany, but most of the small reduction in the PRC can. As a result, one can argue that the PRC's vertical integration is happening much faster.

Figure 7.13: GVC Participation
(%)



Source: UNCTAD-Eora database, Natixis. N.B. Results for 2016–2018 are forecasted by UNCTAD-Eora.

Figure 7.14: Foreign Value Added in Export
(%)

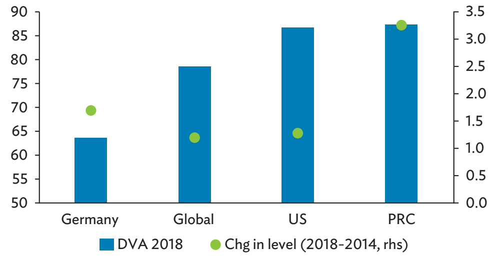


Source: UNCTAD-Eora database, Natixis. N.B. Results for 2016–2018 are forecasted by UNCTAD-Eora.

In the same vein, Germany's decreasing integration in the global value chain is mainly driven by a sharp reduction in its domestic value added in the third country's exports (or a very negative change in DVX in Figure 7.16). In other words, Germany's exports of intermediates used by other countries for their own exports have been coming down rapidly as a share of gross German exports. This is also true for the US, although to a lesser degree. The mirror opposite has occurred in the PRC, since its contribution to other countries' exports has increased very substantially.

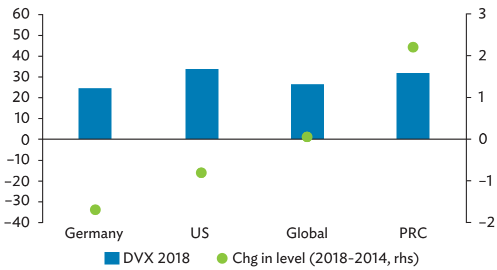
In a nutshell, not only is the PRC's integration in the global value chain coming down much more slowly than that of key economies globally but, more importantly, the reduction is mostly explained by a reduction in the foreign composition of its exports. Conversely, the PRC is pushing more and more domestic content in goods that recipient countries export themselves. One could say that the PRC is becoming more vertically integrated while also becoming an increasingly relevant provider of intermediate goods for third countries. Considering the asymmetry of the importance of backward and forward participation in determining GVC interdependence, the surge in the PRC's forward participation may result in higher costs for other countries to diversify their production away from the PRC, as they rely on the PRC for imports of intermediate goods more than the PRC relies on them.

Figure 7.15: Domestic Value Added in Export
(%)



Source: UNCTAD-Eora database, Natixis. N.B. Results for 2016–2018 are forecasted by UNCTAD-Eora.

Figure 7.16: Domestic Value Added in Third Country's Export or DVX (%)



Source: UNCTAD-Eora database, Natixis. N.B. Results for 2016–2018 are forecasted by UNCTAD-Eora.

7.3 Evolving Resilience of Global Value Chains

The PRC's rapid development in the past two decades has played an important role in global growth, but it has also created asymmetries in the way the global value chain works. More specifically, the world's dependence on the PRC's exports has only increased over time, particularly since the COVID-19 pandemic started in 2020. One of the consequences of this situation was the massive bottlenecks generated in the supply chain as Chinese factories closed during COVID-19.

The case of the European Union (EU) has been analyzed in detail. Between 2000 and 2019, the EU's imports from the PRC increased tenfold thanks to the PRC's competitive prices, which helped to raise European households' disposable income. However, this positive wealth for households did not come free. The PRC's rise as a manufacturing superpower also implies that the production of intermediate and final goods shifted to the PRC from the early 2000s onwards. Twenty years later, the PRC dominates many EU imports. A recent study by MERICS (Zenglein 2020) defines strategic dependence on the PRC for a product on the basis of two conditions: first, that at least 50% of imports of the specific product come from the PRC, and second that the PRC holds more than a 30% share in the global market for that specific product. Based on this definition, the report concludes that in 2019 the EU was strategically dependent on the PRC for 659 products, which accounted for 43% of the total value of all imports from the PRC. Among the top ten categories, six are consumer products (textiles, furniture, and toys) and consumer electronics (mobile phones, personal computers, household appliances), which are vital for retail consumption. The positive aspect, though, is that these products are not key intermediate goods, which makes this dependence less strategic than it seems. In any event, the study also finds 103 other product categories, concentrated in electronics, chemicals, minerals/metals, and pharmaceutical/medical products. Although the vast majority of these products require less sophisticated technology for their production, the EU's critical strategic dependence on the PRC may be important, since building up an alternative supply chain would be complex and expensive. In the same vein, a review by the European Commission on the EU's strategic dependence reviewed more than 2000 products and found that about a quarter of them were highly vulnerable because of the low potential for their diversification and substitution by EU-produced products, while more than half of the products on the list were from the PRC (European Commission 2021, 2022). Viet Nam was ranked second, with 11% of the products. The report also included six in-depth reviews of supply chains in strategic areas, such as pharmaceutical ingredients, batteries for electric vehicles, hydrogen, raw materials, semiconductors, and cloud and edge technologies. The Commission estimated that, in sensitive ecosystems, the EU is less dependent on the US than vice versa, but that both have important common dependencies vis-à-vis the PRC.

Table 7.1: World's Most Dependent Goods on the PRC, With Import Value Exceeding $100 billion

Items	**ROW Imports from the PRC** ($ billion)	**ROW All Imports** ($ bn)	**ROW Dependency on the PRC** (PRC % share of all imports)
Office machines and automatic data processing machines	363	687	52.9
Telecommunication and sound recording apparatus	357	684	52.2
Textile yarn and related products	104	267	38.8
Articles of apparel and clothing accessories	148	457	32.3
Electrical machinery, apparatus, and appliances, n.e.s.	468	1,533	30.5
Miscellaneous manufactured articles, n.e.s.	185	645	28.8
Manufactures of metal, n.e.s.	110	404	27.2

Source: Natixis, UNCTAD. The notion of "n.e.s." means "not elsewhere specified". "ROW" means "rest of the world."

The situation for the rest of the world is not too different from that of Europe, as the PRC dominates some export markets, such as office machines, telecommunication equipment, textile products, and electrical machinery, by more than 50%, according to an UNCTAD report based on SITC 2-digit product items (Table 7.1).[2]

In the same vein, multiple reports from the US government have pointed to the nation's heavy reliance on the PRC's supply chains, from agriculture and food to critical materials for energy transition and national defense (Zhang, Parry and Aldin 2022). Focusing on agriculture, the PRC provides more than 70% of US imports of pesticide ingredients (U.S. Department of Agriculture 2022). Besides, the PRC is a predominant supplier of processed food. US farmers and farm machinery producers also rely on the PRC for low-tech machinery parts. Another key critical dependence—as is the case for Europe—are products related to the energy transition from fossil fuels, whether that is batteries for electric vehicles, solar panels or wind turbines. According to the International Energy Agency, the PRC has invested over $50 billion in new capacity to produce solar panels, which is ten times more than Europe's investment (International Energy Agency 2022). As a result, the PRC has the majority share in all manufacturing stages of solar panels, including wafers (96.8% of global capacity), cells (85.1%), polysilicon (79.4%), and modules (74.7%). In addition to solar, the PRC is a pioneer in the lithium battery industry, an industry that the US Department of Defense deems critical for the security of the US supply chain. The PRC's market share is massive, not only for the final product, but also across the supply chain: 94% for lithium hydroxide, 76% for cells, 76% for electrolyte, 70% for lithium carbonate, 65% for anodes, and 53% for cathodes. Finally, the PRC also controls the supply and, especially, the refining of critical materials for lithium batteries, with a 72% share for cobalt, a key input material for lithium-ion batteries. The same is true for the rare earth metals needed to produce wind turbines (which are 80% controlled by the PRC); the PRC has a 61% market share of global lithium refining, which is key for electric vehicle batteries, and an astonishing 100% share of the processing of natural graphite used for battery anodes (U.S. Department of Defense 2022).

Beyond the general trend of an increasing centrality of the PRC in the global value chain, the global pandemic was a major test for the resilience of such a concentrated production. The test clearly did not work well. Most countries in the world—except for the PRC—experienced bottlenecks in deliveries, shortages of inputs to production

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2 Data from https://unctadstat.unctad.org/wds/ReportFolders/reportFolders.aspx?sCS_ChosenLang=en.

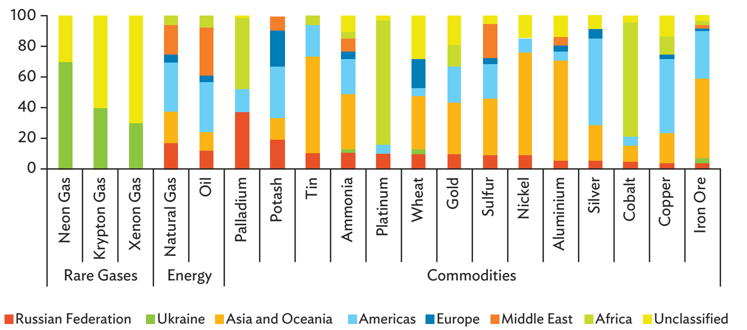
and final goods, and inflation. As a result, senior policymakers in many of the world's leading economies, and not just those from governments associated with populist policies and economic nationalism, have drawn negative conclusions about the way in which global value chains are designed, including the PRC's centrality. In some cases, legislation has been introduced to encourage the repatriation of production or to stimulate domestic production to displace imports. One of the best-known cases, for the specific medical/sanitary sector, is Japan, but more general ones have followed and will be reviewed later (Evenett 2020).

Some might dismiss these statements by policymakers as shifting the blame. Given that it was often the same policymakers who, once the coronavirus had spread, disrupted supply chains in the medical goods and medicines sector by resorting to over 200 export controls, there may be something to this. The flaw in this argument is that the Japanese government, which did not impose any export bans, has joined those criticizing cross-border supply chains and is financially supporting Japanese firms that move production facilities out of the PRC.

While the COVID-19 pandemic certainly caused a huge negative shock to policymakers' perception of the functioning of the global value chain, the Russian invasion of Ukraine brought confidence even lower. The focus, this time round, is not so much on manufactured goods but on critical components of production. On the surface, the Russian Federation and Ukraine are not very important players in trade, with 1.6% and 0.3% of the global export share, respectively. Still, they have significant market shares of global exports in specific products, such as neon gas as well as other rare gases in the case of Ukraine (70%) (Figure 7.17), and palladium in the case of the Russian Federation (37%). For other commodities, the concentration is less but there are important socio-economic consequences, as is the case for natural gas and oil in the case of the Russian Federation (17% and 12%, respectively), wheat, mainly for the Russian Federation (13%), and nickel, with 9% of market share concentrated in the Russian Federation. Most of these commodities play a relevant role in upstream sectors and, thus, in global value chains, or are, like wheat, basic staples affecting food prices (Table 7.2). More specifically, rare gases, palladium, and nickel from the Russian Federation and Ukraine are key for the production of semiconductors and electric vehicle batteries. Neon gas is a rare gas that is used in the lithography process for chips (Garcia Herrero and Ng 2021a), palladium is important for memory chips and sensors (Garcia Herrero and Ng 2021c), And nickel is at the core of ternary lithium batteries (Garcia Herrero and Ng 2021b), so a price surge may accelerate the shift towards lithium iron phosphate (LFP) batteries, which is a cheaper option that does not require nickel.

The sanctions imposed on the Russian Federation, as well as the Russian Federation's own retaliation, have disrupted supplies of these critical components, with negative consequences, once again, for the functioning of the global supply chain.

Figure 7.17: Key Commodities: Production by Country (% of Global Market Share)



Source: Natixis, United States Geological Survey, United States Department of Agriculture, British Petroleum, TrendForce, Techcet, Bloomberg.

Table 7.2: Impact of the Russian Invasion of Ukraine on Asia

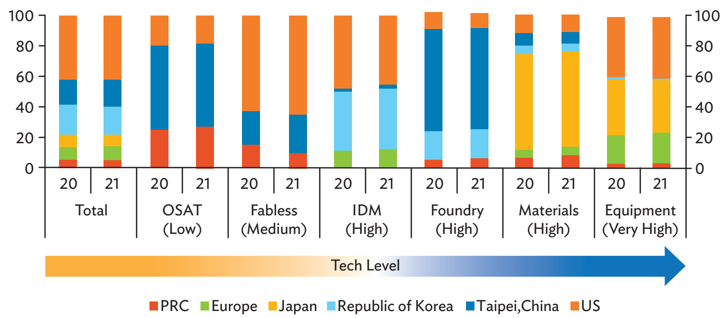
Sector	Sub-sector	Key Implications for Asia
Energy	Oil	Oil and gas prices will surge because of the concern for future supplies
	Natural Gas	
Technology	Palladium	Palladium is used in making memory chips (DRAM, NAND Flash) and sensors
	Nickel	Nickel is used in ternary lithium batteries for electric vehicles
	Rare Gases	Neon gas, krypton gas and xenon gas are used in lithography processes for semiconductors
Agriculture	Wheat	Food prices may surge
Shipping	–	Sea and air routes affected

Source: Natixis.

Finally, another huge shock to the functioning of global supply chains could come as Taipei,China accumulates the bulk of the production of advanced semiconductors (Figure 7.18 and Figure 7.19). It is interesting to note that a natural disaster could also create havoc; this is not impossible, given both climate change and the high frequency of earthquakes on the island.

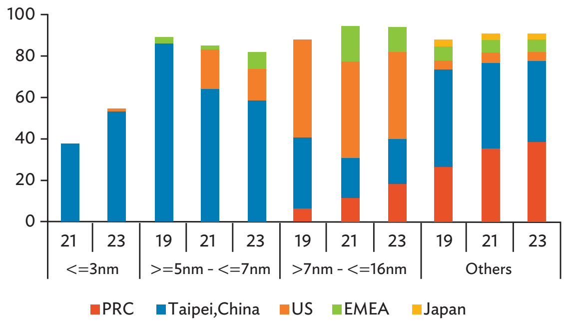
All in all, one could argue that full supply chain resilience is more of an aspiration than an achievable objective, as over-dependence on a specific geography is not uncommon and is related to many different factors, and building supply chain resilience usually implies high costs. However, such reliance is becoming increasingly risky and the economic trade-off between resilience and efficiency is being altered as geopolitical tensions and unanticipated public events (such as the COVID-19 pandemic) can magnify the vulnerabilities of GVC participants (global supply chain disruptions). The PRC's centrality in the global value chain has been very important and has triggered actions from other countries to reduce their dependence on the PRC. In particular, the emergence of an increasingly harsh rivalry between the US and the PRC has pushed companies towards diversification. The Russian invasion of Ukraine, and the related sanctions on the Russian Federation, have also been instrumental in influencing companies' views of the merits of diversification, given the high concentration of advanced semiconductors in Taipei,China, which remains a key risk.

Figure 7.18: Semiconductor Supply: Global Market Share by Sub-sector (%)



Source: Natixis, Financial Statements, TrendForce, IC Insights, Gartner, Bloomberg. N.B. Including foundries.

Figure 7.19: Global: Share of Fabrication Capacity of Foundries by Location and Node Process
(%)



Source: Natixis, SEMI, Bloomberg.

7.4 What Are the Options to Increase Supply Chain Resilience?

In this section, we summarize the major strategies to enhance supply chain resilience that could be (or are being) adopted by companies. In response to an increasingly complex global economic environment, global corporations are taking certain measures to reduce supply chain risk. A number of strategies are being considered and, in some cases, executed. These include reshoring, near-shoring, friend-shoring, and diversification, with policies such as the so-called PRC+1 policy (Suzuki 2021). It should be noted that such strategies are usually more costly than the scenario in which no action is taken, at least ceteris paribus. However, one important variable we must account for in the decision-making process is the higher risk of future supply chain disruptions, given the US–PRC strategic competition, which does not bode well for supply chain resilience. We limit this discussion to what companies can do, and ignore the question of what they should do, as this is beyond the scope of this chapter.

Starting with reshoring, this basically consists of redirecting manufacturing operations back to the home market. This trend has been evident since 2019, particularly in the United States, because of tariff increases in the wake of the US–PRC trade conflict that has caused the US manufacturing import ratio (imports as a percentage of total domestic manufacturing output) to fall for the first time in almost a decade. However, policymakers are fully aware that reshoring entire supply chains is not practical because of the additional labor and overhead costs, so reshoring is only meant to be applied to strategic sectors for national security reasons. Near-shoring is a strategy to restructure supply chains in the same region as a major consumer market, such as Mexico and Central American countries for the US market and Central and Eastern European and North African countries for the European market. Regionalization is expected to facilitate communication by reducing the distance between markets and the risk of being drawn into trade wars and protectionist policies through strengthening political, social, and cultural ties among regional neighbors. This brings us to the concept of friend-shoring, which means focusing on like-minded countries when deciding where to offshore the production of intermediate or final goods within the supply chain but also where to source the necessary raw materials and critical components.

Secondly, the PRC+1 strategy aims to increase trading with other countries in addition to the PRC, to dilute the now very high concentration of production in the PRC. In other words, it is a diversification strategy to reduce the risk of overdependence on the PRC. This trend was also evident before the COVID-19 pandemic because of the growing trade friction between the United States and the PRC. In fact, in 2019 imports of electronics from the PRC to the United States declined, while imports from suppliers in Viet Nam, Malaysia, and Taipei,China increased. Other countries, such as the Republic of Korea, have also embarked on PRC +1 policies. It goes without saying that diversification cannot happen fast even if governments introduce incentives, and the reason for this goes back to the very high concentration of production in the PRC. In the industries related to green technology, where the concentration is very high, and even in more mature, lower-end sectors where one could imagine that diversification would be easier, the PRC dominance in production is astounding. For example, the PRC share of global exports in the machinery and electrical equipment sector is over 20%, and the PRC's share in the garment sector is over 40%—larger than the combined export shares of the next five countries (Bangladesh, Viet Nam, India, Germany, and Italy).

Beyond reshoring and diversification, one should not forget that there are smaller scale policies that can increase supply chain resilience. In fact, we can focus on the more technical aspect embedded in the concept of supply chain resilience, which is the ability of a given supply chain to prepare for and adapt to unexpected events; to quickly adjust to sudden disruptive changes that negatively affect supply chain performance; to continue functioning during disruption; and to recover quickly to its pre-disruption state. To enhance this, certain measures can be taken, such as rapid detection, response, and recovery. To do this, end-to-end and data-driven supply chain control is key. Being able to view raw materials, semi-finished goods, and finished products, starting from your "suppliers' suppliers" and ending with your "customers' customers" is more important than ever. In other words, it is key to develop the data analytics that will give information about potential supply chain disruptions before they occur. This is clearly happening in many industries, which will result in an important improvement compared to the situation prior to the COVID-19 pandemic. In the same vein, another important action is stockpiling to ensure business continuity in the event of a shock. Huge stockpiling has been another feature in the aftermath of the COVID-19 pandemic, and it is only now starting to unwind, especially in the ICT and semiconductor sectors (Lakovou and White III 2020).

Except for supply chain insurance, the above mentioned options are not only available for companies but also may form part of governments' actions to enhance the resilience of their supply chains. Some governments have used window guidance to guide their companies away from the risks of excessive concentration in their supply chains, while others have preferred fully-fledged legislation.

The below section goes through the actions taken by the Japanese and the Republic of Korea's governments, as well as the actions by the European Union (EU) and the United States (US).

Japan

Japanese businesses, even before those of the EU and the US, significantly expanded their supply chains in the PRC from the 1980s onwards, but the US–PRC trade war and, most importantly, the COVID-19 pandemic have had profound consequences for the way in which Japanese businesses think about their participation in supply chains and also for government actions. The Japanese government acted very quickly to address supply chain bottlenecks during the COVID-19 pandemic, especially in the medical/sanitary sector. As early as April 2020, the program for Promoting Investment in Japan was announced to strengthen supply chains. This program consists of a generous JP¥108.2 trillion ($700 billion) stimulus package, covering 300 firms. The intention is to support companies to move their supply chains back to Japan or to countries within the Association of Southeast Asian Nations (ASEAN), reinforcing a trend which started before the pandemic. The key sector for reshoring is the medical and sanitary one, given the consequences arising from the COVID-19 experience. These funds are meant to be used to cover costs for feasibility studies, the introduction of equipment, or the construction of new facilities. Apart from reshoring/near-shoring, the second edition of the program aims to enhance the viability of industries by subsidizing equipment and companies' facility costs. The impact of these measures has been limited so far, since only 8% of Japanese companies operating in the PRC have declared their intention to leave or to limit their activity there in the future.

Finally, in October 2021, Japan hit the headlines by establishing the world's first economic security ministry. This ministry aims to develop strategies and a legal framework to enable Japan to boost its economic security. The framework will encompass supply chains, resources, innovative technologies, and relevant infrastructure. Finally, the semiconductor sector has been identified by this ministry as key for such initiatives.

Republic of Korea

The Republic of Korea was the first country outside the PRC to experience a factory shutdown due to the coronavirus. The supply bottlenecks that the PRC experienced were important not only in the medical and sanitary sector, but also for manufacturing. Given the Republic of Korea's key role in the fabrication of semiconductors, geopolitical considerations became essential in this equation. It should also be noted that the Republic of Korea has had a reshoring strategy since 2014. Companies looking to relocate are eligible to have their corporate taxes waived for the first five years, with an additional 50% cut offered for two consecutive years thereafter. The results of this strategy have not been very promising so far. According to the Ministry of Trade, Industry, and Energy, only around ten companies, on average, reshored part of their production to the Republic of Korea each year between 2014 and 2018. In fact, the Republic of Korea's reliance on external supply chains has only deepened since 2013, especially with the PRC.

Apart from this long-standing strategy, the COVID-19 pandemic was a wake-up call for the Republic of Korea, as it was for other countries. In July 2020, the Ministry of Trade, Industry, and Energy issued its Materials, Parts, Equipment 2.0 Strategy. Under the strategy, the government of the Republic of Korea will allocate ₩1.5 trillion ($1.3 billion) over five years to develop new materials, parts and equipment technologies. As under Japan's strategy, the government offers ₩20 billion ($16.8 million) to cover relocation and facility costs for firms relocating to regions outside Seoul, and up to ₩15 billion ($4.2 million) to high-tech firms relocating to the Seoul region. For smart factories and the deployment of industrial robots, the amounts are higher (from ₩300 million to 500 million). The aims of the initiative are to pre-emptively address the shift in global supply chains in the post-coronavirus world and to deal with the fall-out from the export restrictions introduced by Japan, whose trade and economy is closely linked with the Republic of Korea's while diplomatic relations remain characterized by persisting difficulties.

European Union

The notion of the resilience of supply chains had already been widely discussed before the pandemic, in the context of ensuring the availability of the resources necessary for the twin—green and digital—transition. The 2020 Trade Policy Review stated that strengthening the resilience and sustainability of the EU economy and its supply chains was a pillar of the European Union's drive towards the key strategic concept that the Commission had published, namely open strategic autonomy (Szczepański 2021). The strategic framework that has been developed by the European Commission to increase the resilience of value chains has several tools. The first one is to move away from the absence of an industrial policy to the introduction of a policy for key strategic sectors. A good example is the EU Chips Act, which pulls together over €40 billion to enhance the EU's role in this key sector. More generally, the European Union sets up projects, called Important Projects of Common European Interest (IPCEIs), which are aimed at ensuring the good functioning of certain key sectors of European industry. A good example of an industrial alliance is the European Raw Materials Alliance (ERMA), which was launched in October 2020 to specifically address the numerous challenges faced by raw materials value chains. The March 2020 Industrial Strategy called for the creation of such industrial alliances and complete industrial ecosystems to achieve the EU's green and digital transition. In the same vein, sectoral policies developed by the EU Commission now also have dedicated chapters on enhancing supply chain resilience, as is the case for the Pharmaceutical Strategy for Europe published in 2020.[3] Furthermore, the Commission sees potential in using public procurement to increase resilience. Finally, the EU is moving towards a mandatory system of due diligence for supply chains, to curb human rights and environmental abuses.[4] According to the OECD, such due diligence would be expected to build up more long-term value and resilience.[5]

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3 See details at https://health.ec.europa.eu/medicinal-products/pharmaceutical-strategy-europe_en.

4 See details at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0071.

5 See details at https://www.oecd.org/coronavirus/policy-responses/covid-19-and-global-value-chains-policy-options-to-build-more-resilient-production-networks-04934ef4/.

The second channel is to diversify external trade to cushion possible shocks and disruption. On that front, the EU has accelerated its negotiations on free trade agreements with other areas of the world, including Australia and New Zealand, and is also in negotiations with India. Beyond its own legislation, the EU Commission is pursuing multilateral cooperation and coordination mechanisms at the G20, WTO and other relevant venues.

United States

As early as March 2020, the US administration brought in a series of measures to protect supply chains. Under the $2.2 trillion stimulus package, the Coronavirus Aid, Relief, and Economic Security (CARES) Act, special funding was provided for medical supply chains and air cargo. The government also reverted to applying the Defense Production Act—which gives the president sweeping authority over the private sector in times of emergency—to increase domestic capacity and significantly boost the production of necessary medical goods and vaccines. A series of important executive orders on US medical supply chains followed, with subjects ranging from direct funding to reducing dependence on foreign sourcing.[6] A major step taken by President Biden in his first week in office was to launch a comprehensive review of critical supply chains, cutting across all branches of the administration and the relevant stakeholders. The goal was to identify risks, address vulnerabilities and develop a strategy to promote resilience. The result was a review of supply chains in four key areas: semiconductors; large capacity batteries; critical minerals and materials; and pharmaceutical ingredients (The White House 2021). As is the case for the EU, the PRC is the main source of dependencies for the US in these four areas. Shortly after this evaluation, in February 2022, the White House issued its summary reports on domestic supply chains, with proposals to increase resilience. The report also offers some solutions to the over-dependence on the PRC. One is to build strong relationships with allies and partners who share US values, which has been dubbed "friend-shoring." So far, the US has started supply chain partnerships with Japan, the Republic of Korea, and the EU.

Beyond these actions, the administration has established that it is a policy priority to reduce US dependence on the PRC, especially in these critical industries. Legislation like the America COMPETES Act and the US Innovation and Competition Act are already increasing investment in some of these sectors. The semiconductor industry is a case in point.

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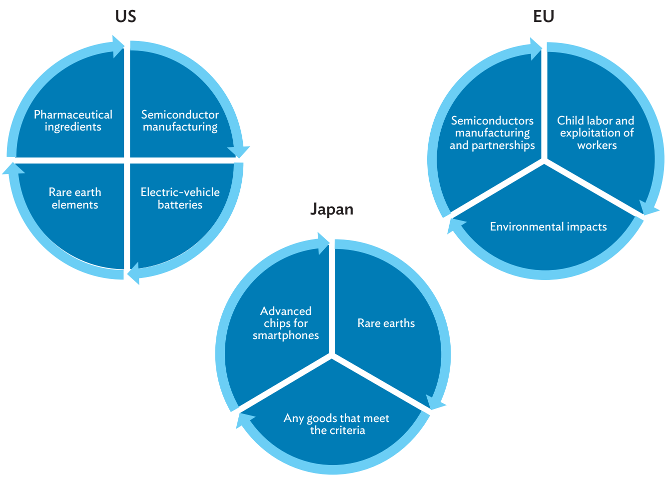
[6] See details at https://www.whitehouse.gov/briefing-room/presidential-actions/2021/02/24/executive-order-on-americas-supply-chains/.

Table 7.3 below shows a summary of the key legislation passed and in the pipeline by the countries under discussion, as well as an infographic with the key issues covered in this legislation for the US, the EU, and Japan.

Table 7.3: Key Legislation in the US, the EU, Japan, and the Republic of Korea

Country	Name	Last Update	Status
US	Executive Order on America's Supply Chains	24 Feb 2021	Signed
	Bipartisan Infrastructure Law	15 Nov 2021	Passed
	United States Innovation and Competition Act of 2021	28 Mar 2022	Passed
EU	Directive on corporate sustainability due diligence	23 Feb 2022	Passed
	European Chips Act	12 May 2022	In progress
Japan	Act for the Promotion of Economic Security by Integrated Implementation of Economic Measures	11 May 2022	Passed
The Republic of Korea	Act on Supporting the Return of Overseas Korean Enterprises	27 Jun 2013	Passed

Source: White House, European Commission, Cabinet of Japan, Korean National Assembly. Compiled by the authors.



Source: White House, European Commission, Cabinet of Japan. Compiled by the authors.

7.5 What Has Happened So Far in Terms of Supply Chain Reshuffling?

It is clearly still too early to measure the degree to which supply chains are being reshuffled. Information is scant and fragmented, but a general assessment of the different surveys produced by consultancy companies and chambers of commerce operating in the PRC can be summarized as follows. Reshuffling of supply chains away from the PRC has clearly started, but it is slow. In addition, the PRC is still attracting new investments from companies, although in smaller amounts than before. The bulk of the investment consists of retained earnings, which means that it is mainly companies that already operate in the PRC that are staying, while new ones are looking for other venues in which to operate. Among the existing ones, the more recently established companies may find it easier to set up operations elsewhere.

To be more specific, the results of a survey run by EY in September 2020 shown in Table 7.4 were that 53% of respondents had already near- or re-shored part of their operations in the previous 24 months, and 44% were planning new or additional near-shoring activities in the next 24 months (Knizek, Jenner, and Dharmani 2022). The percentages were even higher for US companies, which are more concerned about US–PRC strategic competition. On the new investment front, 57% of the respondents had established new operations in one or more additional countries in the previous 24 months and 53% were planning to do so in the next 24 months. The survey responses from companies based in Germany, France, Spain, Italy, and the UK show similar trends to those from companies based in the US, with 55% saying they had engaged in near- or re-shoring in the previous 24 months. The European respondents were also likely to have made supplier base changes, with 61% saying they had done so in the last 24 months. These results may understate the degree of reshoring, as the survey was conducted before the Russian invasion of Ukraine. Given the extensive challenges related to everything from component availability (e.g., lack of automotive wire harnesses from Ukrainian suppliers) to logistics (e.g., Asia–Europe cargo routes disrupted by the Russian airspace closure), European companies have probably moved even faster than planned with their reshuffling, whether this is reshoring or near-shoring.

The other important actors in reshoring are Chinese companies themselves. In addition to cost reasons, the US trade war has resulted in a huge surge of Chinese companies moving to Viet Nam, Cambodia, and other destinations, in order to avoid the US import tariffs. In fact, as many as 65% of the Chinese respondents to the EY survey said they had near- or re-shored their operations in the previous 24 months. In the same vein, 75% said they had made significant supplier base changes over the same period.

All in all, companies appear to be seeking diversification of their plant locations to increase the resilience of their supply chains, but changes are also observed at a more granular level, with 62% of the respondents having made significant changes in their supplier base in the previous 24 months, and 55% planning significant changes in the next 24 months. For the respondents, a key incentive was to increase the proximity to their customers from the perspective of consequentialism, as 47% of the respondents had reported such outcomes. It should also be mentioned that not every company considered these actions to be very costly. In fact, only 22% of the companies expected costs to increase because of these actions in the short term, while the percentage increases to 37% in the medium term.

Sectoral aspects of supply chain reshuffling are also important. Given the sensitive nature of defense technologies, aerospace and defense companies are somewhat ahead of the curve, with shorter, domestically oriented supply chains. However, they continue to shift production closer to demand hubs to improve resilience, while employing technologies like additive manufacturing and automation to preserve margins. In the same vein, automotive companies are shortening their supply chains by sourcing from local suppliers and building battery plants closer to US and European markets. Many automotive manufacturers have also shifted some production and raw material sourcing out of the PRC in favor of North America, Europe, and other parts of Asia to keep production lines moving, despite higher costs. Chemical companies are diversifying supplier bases and expanding capacities closer to demand hubs. This means that they are investing heavily in the PRC via joint ventures, partnerships, and capacity expansions to ensure country-wide positioning, as the PRC constitutes 50% of the global market, but, at the same time, are adding capacity in the US, India and other countries in Asia to reduce risk.

Moving to the surveys from chambers of commerce in the PRC, the most recent one, published by the American Chamber of Commerce in Shanghai, shows a sharp increase in the number of companies planning to redirect their investments to other countries (The American Chamber of Commerce in Shanghai 2022). In fact, as many as a third of the 307 companies surveyed were planning to do so. In addition to geopolitical reasons, it is important to note that more than 50% of the companies did not expect any growth in revenue, compared to only 18% in the previous year. The European Union Chamber of Commerce Business Confidence Survey in 2022 clearly points to the growing challenges of doing business in the PRC, and pays special attention to the mobility restrictions which severely constrain the ability to attract talent into the PRC (European Union Chamber of Commerce in China 2022). In addition, the respondents expressed severe concern about growing geopolitical tensions and the increasing risks of decoupling, which had forced many companies to develop two separate supply chain, information technology (IT) system and data storage infrastructures—one for the PRC and one for the rest of the world—to buffer potential disruptions in the future, leading to much higher costs. Even in the September 2020 report by the European Chamber in Beijing, nine different layers of decoupling were considered. As many as 85% of the companies and experts interviewed were negative about the increasing risk of decoupling for the digital and telecom industries, and a smaller percentage about the risk for data governance. Even for standards, 68% of the respondents were worried about decoupling (European Union Chamber of Commerce in China 2021).

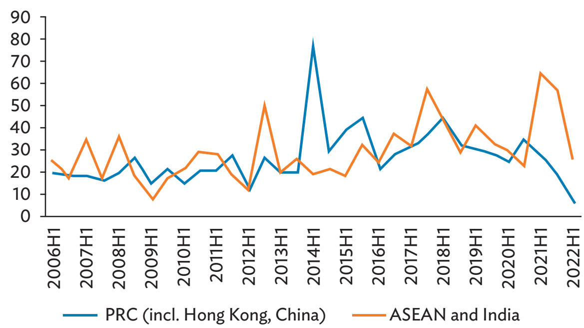
Table 7.4: European Chamber Survey on Decoupling (%)

	All Negative (Significant Negative) in %	No Impact in %	All Positive in %
Digital/telecoms	85 (34)	12	0
Data Governance	76 (24)	16	4
Financial	70 (23)	23	1
Supply Chains	68 (23)	23	6
Standards	68 (15)	22	5
Self-sufficiency	64 (15)	26	6
Political	59 (12)	34	0
Critical Inputs	49 (15)	42	3

Source: Natixis, European Chamber survey on decoupling conducted in September 2020.

Beyond surveys, it is important to look at the latest trends in cross-border mergers and acquisitions (M&A) into the PRC, and compare them with those into the rest of Emerging Asia, including India. Based on a detailed analysis of M&A deals, a significant drop in cross-border M&A deals into the PRC can be found, especially in 2021 and 2022 (Figure 7.20). This development does not seem surprising against the backdrop of zero-COVID-19 policies, regulatory restrictions, and the real estate demise. Meanwhile, although the figures were still down, the ASEAN countries, India, and Australia have attracted significantly more capital since 2020. Flows were reshuffled to reflect the rising need for the diversification of supply chains, changes in demand and energy source security. The ASEAN countries and India attracted 56% of total inbound flows, giving them the largest share in Asia, with Indonesia punching above its weight and receiving twice as much as the PRC in completed deals (Garcia Herrero, Nguyen, and Xu 2022).

Figure 7.20: Completed M&A Deals by Recipient (USDbn)



Source: Natixis, Mergermarket.

7.6 Conclusions

Over the decades of the growth and reshaping of global supply chains, the PRC has acquired an increasingly central role, but some adverse signs are also emerging. The US–PRC trade war and, especially, the COVID-19 pandemic, followed by the Russian invasion of Ukraine have been crucial shocks to the good functioning of supply chains and have resulted in higher food and fuel inflation which have wounded households and hurt the profitability of businesses. In reaction, many companies are, so surveys suggest, now focusing on the resilience rather than efficiency of supply chains, as the higher risks of production disruption are tilting the balance in favor of a reshuffling of their supply chains. Meanwhile, government action, including legislation, has been introduced in several countries including Japan and the Republic of Korea, but also the

European Union and the US; this legislation is all aimed at improving the resilience of global value chains, and promotes relevant business plans in the private sector. That said, the decision by many companies to reshuffle production away from the PRC may still be incentivized by the stronger needs of diversification amidst growing geopolitical turbulence but also by the PRC's worsening medium-term economic prospects. In other words, companies diversifying their production away from the PRC—as shown in the recent slow-down in mergers and acquisitions into the PRC accompanied by an increase into India and the ASEAN countries—might be a rather rational decision based on an economic rationale and also, in some cases, government action.

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8

How Have Recent Global Events Accentuated the Need for Transformation in the Global Supply Chain?

Mona Ashok

8.1 Impact of Global Events on Global Supply Chains in Recent Years

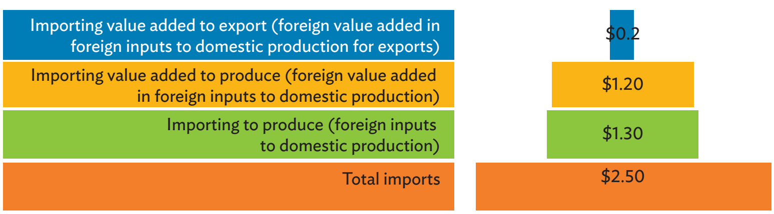
8.1.1 Context

Why are we interested in global supply chains? Worldwide, economies are more interconnected than ever before, while goods and services produced and delivered include domestic and foreign value-added, all using global supply chains. The foreign value-added contributes between one-fifth and one-half of the total value-added across nations and industries (Blanchard et al. 2016). Supply chains are defined as a set of functions and processes that link several tiers of producers and suppliers with the distributors and consumers (Branch 2009). The focus for supply chains is to optimize the flow of products, services, and information. Research shows that industrialization, globalization, trade agreement policies, digitalization, and cost differentiation have facilitated the rise in global supply chains for decades (Kano et al. 2020). Exports of goods peaked at 25.5% of global gross domestic product (GDP) in 2008 (KKR 2020; 7). Global exports of goods and services stood at 29% of global GDP in 2021 as per World Bank (WB) data (n.d. b).

Another phrase used synonymously with global supply chains is global value chains. United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP) (2015) define global value chains as a sequence of activities that require value creation involving more than one country. Thus, global value chains break down production and service processes across nations, where organizations focus on a few tasks but do not produce the whole product or service. It is important to note that value creation could come in the form of labor, raw material, or intermediary goods and services that country boundaries, often several times. The Organisation for Economic Co-operation and Development (OECD) (n.d.) estimates that 70% of total trade in goods and services includes global value chains.[1] Baldwin and Freeman (2022) illustrate global supply chain exposure, sourcing 2015 United States (US) data from the OECD database.[2] Figure 8.1 highlights the complexities of global supply chains, which may use foreign value-add or foreign inputs both directly and indirectly, and for domestic consumption or exports.

The World Bank (2020) highlights that all countries participate in global value chains but in different ways. The Asia and the Pacific region covers the full spectrum of value chains from low participation to innovative activities.

Figure 8.1: Types of Sourcing-Side Global Supply Chain Exposure, United States, 2015
($ trillion)



Source: Baldwin and Freeman (2022: 162); author.

Rodrigue (2020) summarizes the risks of global supply chains as demand, supply, and operational risks, which in turn are determined by four factors. each having sub-factors with varying probability and potential mitigation strategies. The factors are: geopolitical (political instability, trade barriers, terrorism, etc.), environmental (natural

[1] As the heart of global value chains is intermediary goods that may cross country borders several times. McKinsey Global Institute (2020) showed that since 2000, the worldwide trade of intermediary goods has increased three times to more than $10 trillion annually.

[2] https://stats.oecd.org/Index.aspx?DataSetCode=TIVA_2018_C1

disasters, extreme weather, etc.), economic (demand fragility, price instability, etc.) and technological (information communication technology [ICT] disruptions, etc.).

In summary, supply chains are increasingly dynamic, complex and globalized; thus, supply chain functions are becoming strategic tools to achieve competitive advantage (McKinsey Global Institute 2020). Regional and international trade agreements have adjusted tariffs and trade barriers (World Bank 2020). In an IDC (2020) study, 55% of organizations agree that a competitor with resilient supply chains and better supply chain capabilities has already disrupted or is very highly likely to disrupt organizational operations.

Despite the importance of global supply and value chains, several research gaps remain (Blanchard et al. 2016; Kano et al. 2020; Marslev et al. 2022). There is a lag in understanding innovation development (in global value chains) in emerging nations; this could be primarily due to an imbalance in (often technological) capabilities, absorptive capacity, and knowledge (De Marchi et al. 2018). In theory, global value chains enable developing nations to improve their position worldwide; however, organizations in emerging countries find it hard to meet the standards/requirements/expectations of advanced markets (Gereffi et al. 2005).

8.1.2 Supply Chain Trends from the Past Decades

"Efficiency-seeking" has triggered massive expansion of global supply and value chains in recent decades (United Nations 2017). Two factors, i.e., globalization and digitalization, have enabled growth in value chains, which accelerated worldwide trade.

Globalization enabled intricate supply chain networks, bringing together several tiers of upstream suppliers with downstream distributors, retailers, and consumers. Supply chains have evolved with the changes in the competitive landscape; for example, coopetition (collaboration with competitors), servitization (bundling services with products sold), and industry-wide consolidation are making supply chains key differentiators (Mangan and McKinnon 2019). As a result, developed economies depend on developing countries to compete on cost (Chick et al. 2014). We can study the impact of globalization using People's Republic of China (PRC) as a case example. PRC container shipping connectivity improved by 54% between 2004 and 2012; this, in turn, improved logistics performance between 2007 and 2012, resulting in a 19% decrease in trade costs, a 27% increase in PRC exports, and, as of 2017, imports and exports contributed 25% of the PRC's GDP (Maersk 2017).

However, Constantinescu et al. (2015) noted that global trade and supply chains underwent structural changes in the late 2000s. This was caused by numerous factors, including the financial crisis of 2008, domestic sourcing, the substitution of inputs from local or regionally produced goods, trade wars, regional tensions, changing wage structures, and geo-economic restructuring. Reshoring, i.e., the decision to move supply chain operations close to the focal company's home location, was becoming an important trend before the coronavirus disease (COVID-19) pandemic (Gray et al. 2017; Butollo and Staritz 2022). However, globalization is not dead. Dicken (2015: 37) argues, "the interconnections within the global economy are now much deeper – and faster – than in the past."

Digitalization has enabled supply chains to become strategic and create differentiation for competitive advantage (Schrauf and Berttram 2016). The fourth industrial revolution (Industry 4.0) enabled organizations to transform their operations digitally. Digitalization has influenced the global economy because it enabled innovation and radically changed organizational practices. Digitalization transforms an organization's interface with its external partners, through digitally enabled systems, services, business processes and tools/applications (Ashok 2018).

While organizational capabilities, technology and processes had enabled the adoption of digital advances (Ashok et al. 2022), the true benefit of value co-creation with ecosystem partners had been made possible through digital supply chains. Analytics, logistics visibility, integrated planning, efficient inventory management, and procurement processes enabled digital supply chains to take a center stage in organizational transformation (Schrauf and Berttram 2016). The use of technology has enabled organizations to track vital statistics on trade flows and to take mitigation strategies against potential threats (Chick et al. 2014). The push factors (technologies) along with pull factors (from external stakeholders like global policies and regulations, cost pressures, demand pressures, digital penetration, increasing complexities and interdependencies in supply chain networks) have accentuated digital supply chains (Schrauf and Berttram 2016).

Digitalization, however, has also introduced new risks to supply chains, for example: McKinsey Global Institute (2020) shows that cyberattacks expose vulnerabilities in demand and supply value chains. A large-scale cyberattack can lead to a catastrophic disruption to global value chains costing trillions of dollars of losses. Cyberattacks have also increased in frequency; for example, while a business was stricken with ransomware every 40 seconds in 2017, in 2021, the rate stood at every 11 seconds (BCI 2022).

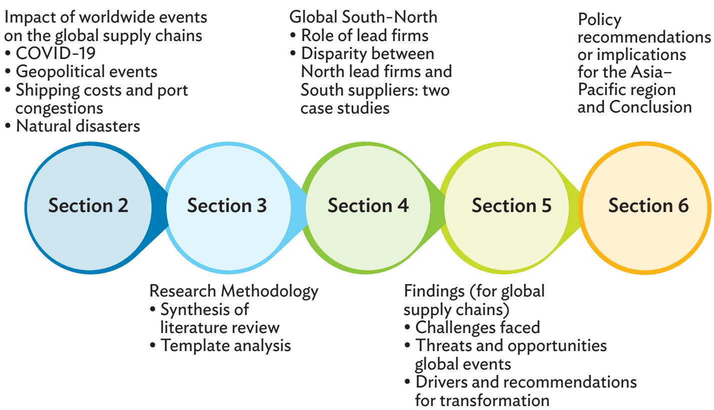
8.1.3 Research Questions and Structure of the Chapter

The research questions underlying this chapter are,

> *RQ1 "How have recent events accentuated the need for transformation in the global supply chain?"*
>
> *RQ2 "What is the role of Asia and the Pacific in addressing global supply chain emergencies and how does the region develop its supply chain capabilities?"*

The remainder of the chapter has been structured as follows (Figure 8.2).

Figure 8.2: Structure of the Chapter



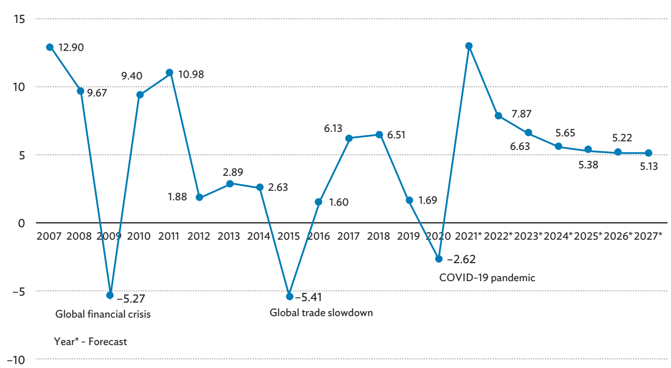
Source: Author.

8.2 Impact of Worldwide Events on Global Supply Chains

To understand the impact of recent events on the world economy and supply chains, it is important to evaluate some global statistics. For example, Statista (2022a), based on International Monetary Fund's (IMF) April 2022 data, shows the annual growth of GDP between 2007 and 2020, with projections until 2027. Except for two blips (2008–09 financial crisis, and 2015 global trade slowdown), the global GDP mostly experienced growth between 2007 and 2020. However, the COVID-19 pandemic led to a big decline in global and regional GDPs (Figure 8.3). The World Bank Data showed that South Asia was the best-performing region as it bounced back faster than other regions.[3]

The last 3–4 years of global and local events have exposed supply chain fragility, leading to a long-term impact with a potentially longer recovery period. For example, 94% of Fortune 1000 organizations reported COVID-19 supply chain disruptions (Fortune 2020). The Business Continuity Institute (BCI 2021) highlighted an increase in organizations reporting more than 20 supply chain disruptions in a year (Elliott et al. 2021). COVID-19 disruptions highlighted the need for organizations to understand their wider supply chain ecosystem. For example, 40.2% of respondents reported that supply chain shocks came from Tier 2 and beyond suppliers (Elliott et al. 2021); however, only 6% of organizations have end-to-end visibility of their supply chain (Wolters Kluwer 2022). Similarly, Resilinc (2022) showed that year-on-year the supply chain upheavals in 2021 were up 88%; of these, supply shortages (for example of raw material, semiconductor chips, etc.) recorded a 452% increase, labor disruptions, 156%, cyberattacks, 143%, extreme weather 130%, and factory fires, 129%.

Figure 8.3: Growth of Global Annual Gross Domestic Product at Current Prices (Compared to the Previous Year as a %), 2007–2027



Source: Statista (2022a); author.

[3] https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG?contextual=min&end =2021&locations=Z4-1W-8S&start=2008&view=chart

EIU (2021a: 3) showed that global supply chains are susceptible to worldwide events and phenomena. Similarly, Gartner (2022) emphasized that supply chain disruptions were widespread and expected to last. Supply chains have been at breaking point due to the COVID-19 pandemic, cyberattacks, wildfires, hurricanes, earthquakes, flooding, trade wars, gas and energy crisis, conflicts, elections, mass protests, Brexit, etc. Four key factors disrupting supply chains are further explored in this section.

8.2.1 Impact of the COVID-19 Pandemic on Global Supply Chains, Especially Asia and the Pacific

Recent global events have put significant pressure on supply chains as accentuated by behavioral changes (Santacreu and LaBelle 2022). In particular, the global nature of the COVID-19 pandemic, resultant lockdowns, unemployment, recession, and quick recovery across major economies challenged long-established systems and operations that depended upon intricate global value chains (Panwar et al. 2022; OECD 2020a). In the immediate aftermath of the pandemic, demand for some goods and services increased dramatically (stockpiling, panic buying), while, in some instances, the demand patterns shifted as governments, businesses and individuals were forced to adapt (Sajjad 2021). The supply ecosystem was equally challenged by labor shortages (for example, as a result of quarantine requirements), raw material shortages, strict cross-boundary scrutiny, different rates of vaccine rollout, and logistical and infrastructural issues (Santacreu and LaBelle 2022). Simpson (2020) detailed the significant impact of the pandemic on global supply chain. For example, March 2020 saw a 66% drop in annual exports of PRC electronics and machinery, an approximately £2,000 increase in haulier cost per truck travelling between the United Kingdom (UK) and France, a 30% drop in shipping capacity used at Felixstowe and Southampton ports in the UK, a 45% drop in US imports from the PRC, and a 20% drop in Canadian container volumes.

Although global supply chains had shown a high degree of robustness over the previous decades, they have been strained by the COVID-19 disruptions (Xu et al. 2020). It is important to differentiate between supply chain resilience and robustness. Resilience is defined as the ability of the business and its supply chain network to plan, respond and pull through from supply chain disruptions in a “timely and cost-effective manner”. In comparison, the robustness of supply chains is their capability to continue operations throughout a crisis (Baldwin and Freeman 2022). Global supply and value chains experienced significant risks and instability due to the pandemic and resultant demand and supply shocks (OECD 2021; Sajjad 2021). This is because supply and value chains were built to benefit from global demand by harnessing efficiencies and cost leadership through the worldwide diffusion of production and service phases.

OECD (2022) reported that the magnitude of the impact of the pandemic on trade and supply chains in 1 year was similar to changes usually seen over 4 or 5 years. Although international trade quickly recovered in 2021, significant imbalances remained; for example, OECD countries experienced a higher contraction in the export of services (–16.7% as compared to the export of goods, –8.2%). Similarly, by August 2021, the export of services by G7 countries remained below the 2019 levels, while the export of goods was higher than 2019 levels (OECD 2022). Part of the growth in the export of goods was to clear off the backlog from 2020.

8.2.2 Impact of Recent Geopolitical Events on Global Supply Chains

Countries were just coming out of the pandemic turbulence when the Russia-Ukraine conflict began in February 2022, which further aggravated global supply chain disruptions. The conflict has led to sanctions on Russia, reduced the supply of gas to Europe, impacted OPEC decision-making, caused energy prices to soar, cut off key shipping routes, increased air freight rates, and negatively impacted electronic chip-making (Ukraine is a key supplier of key products like Neon gas and krypton gas) (Ngoc 2022). Despite the expectation that exports of its fertilizers would collapse, the Russian Federation saw a 70% increase in the first 10 months of 2022, primarily due to global demand leading to price rises (*Financial Times* 2023).

As per the International Chamber of Shipping, the Russian Federation and Ukraine account for 14.5% of global shipping crew, whose unavailability has pushed shipping costs upward. As per the Centre for Economic Policy Research (CEPR 2022), the Russian invasion of Ukraine and the lack of gas and oil supplies from the Russian Federation led to a nine-fold increase in prices across Europe (baseline of €20/MWh in 2021 to €180 by mid-2022). CEPR argues that removing Ukrainian and Russian Federation businesses from global value chains will have a long-term impact; the world is already seeing a huge shortage of grains, cereals, vegetable oils, chemicals, fertilizers, metals, mechanical goods, and vehicles. The shortage of metals and chemicals from the Russian Federation and Ukraine is significantly impacting the supply chains for automotive, aircraft manufacturing, smartphones, and dental fillings sectors (Mbah and Wasum 2022). The National Institute of Economic and Social Research (NIESR 2022:1) reports that the Russian invasion of Ukraine is likely to contract the world GDP by 1% in 2023 alone (roughly $1 trillion); this is in addition to about a 3% increase in inflation in 2022.

The pandemic and geopolitical conflicts have amplified vulnerabilities in the semiconductor industry. Despite microchips being perceived to have a relatively small value-add to final goods, semiconductor shortages have exposed supply chain fragility across 169 sectors and consumer lines (J.P. Morgan 2022; Mohammad et al. 2022). Semiconductor chip supply is inelastic, capital-intensive, inflexible, lead-time-intensive, and highly concentrated, which impacts supply chains' resiliency and agility (Annex – FTI Consulting 2022). Very few organizations have the competency to design and fabricate chips, with each production stage depending on its own intricate supply chain; most of the chip manufacturing, assembling, testing and packaging clusters are in the Asia and the Pacific region (Mohammad et al. 2022). The industry faces a demand-supply mismatch.[4] Countries are taking a nationalist view and funding the development of local semiconductor capabilities to reduce reliance on global supply chains (SIA 2021).

To summarize, the Russian invasion of Ukraine has put the global supply chain crisis in the spotlight. With no end in sight for the invasion, governments and businesses must develop a risk and resilience plan to mitigate its long-term impact. KPMG (2022) reports that 81% of chief executive officers are adjusting their risk management outlook in response to supply chain interruptions, especially due to geopolitical issues.

8.2.3 Impact of Shipping Costs and Port Congestions on Global Supply Chains

More than 80% of the world's goods trade happens by sea (IMF 2022). The global supply chains have been impacted by a significant increase in maritime transport costs, limited container capacity, port congestions, driver shortages and logistics constraints (CBRE 2022). In specific, the supply chain of vehicles and parts, minerals, machinery and appliances were affected the most by sea transport issues and costs (OECD 2022). In 2021, the global sea transport costs were about 4.75 times the pre-pandemic levels, attributing 30%–40% of global inflation; the worst impact was on the Asia and the Pacific region, where global shipping issues and costs accounted for 50% of inflation (Brown 2022). Economic

4 The World Semiconductor Trade Statistics (WSTS 2022) reported that the industry had a market size of $580 billion in 2022, having grown 4.4% annually.

recovery will continue to be strained by the impact of the COVID-19 pandemic and shipping costs (FTI Consulting 2022).

The global supply chain pressure index[5] (Statista 2022b) is scaled by its standard deviation; a zero indicates that the index is at its average value; a positive value signifies how many standard deviations the index is above the average value; a negative value denotes the opposite. The index scores continue to be higher than in the pre-COVID-19 pandemic period. The average index value between January 2000 to December 2019 was −0.26. The index peaked in December 2021 at 4.2, gradually falling until early 2022, when the index rose again due to lockdown measures in the PRC and the Russian invasion of Ukraine. As of Autumn 2022, the global supply chain pressure index remained high at 1.05, thus showing supply chain-related cost pressures.

Rising global container freight prices, along with port bottlenecks like the Suez Canal blockage, and port congestions and closures across the world put significant stress on the global supply chain. As per the Financial Times (2021), until October 2021, there was a 7- to 10-day waiting time at Los Angeles/Long Beach, 6 to 7 days at Savannah, up to 6 days at Rotterdam, 1 to 3 days at Shanghai/Ningbo, and 1 to 2 days at the Shenzhen area.

IMF's (2022) study of 30 years of data from 143 countries showed that, as global container freight price doubled, there was a 0.7 percentage point increase in inflation. This inflation peaked after a year at about 1.5 percentage points and the effect lasted up to 18 months.

8.2.4 Impact of Natural Disasters on Global Supply Chains

Research shows that natural disasters have increased in intensity and frequency between 1970 and 2010 (ADB 2013: 2). The World Economic Forum (2018) shows that, despite a similar number of natural disasters in 2009 and 2017, the cost of natural disasters had gone up astronomically in recent decades. The cost of natural disasters increased from about $47 billion in 2009 to $340 billion in 2017. Global crises like natural disasters and extreme weather led to $81 billion in losses worldwide in 2018.

Statista's (2022d) 2021 data on regions with the highest disaster risk worldwide show that some regions of the world are more impacted than others. The Asia and the Pacific region (Oceania and Asia regions)

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5 The global container freight rate rocketed from $1,525 in March 2020 to $10,361 in September 2021; gradually decreasing to $2,404 in November 2022 (Statista 2022f).

accounts for about 40% of all natural disasters (ADB 2021). This is important since UNESCAP (2015) shows that the Asia and the Pacific region accounted for about 44% of exports and 26% of imports of global value chains for finished goods in 2013. Similarly, the Asia and the Pacific region accounted for 43.2% of exports and 38.3% of imports of global value chains for intermediary goods. Thus, supply chain disruptions in this region have a significant impact on goods flow and trade.

Ye and Abe (2012) and Gunessee et al. (2018) detail the vulnerabilities of supply chains to natural disasters using several examples from Asia. Global supply chains are especially exposed to risks due to distributed supply networks, and extensive reliance on outsourced and offshored processes (to achieve cost efficiencies). Lean adoption and just-in-time practices, where organizations maintain a minimal inventory and depend on a sophisticated supply chain network, have further hampered organizations' flexibility and agility to negate the impact of natural disasters on supply chains (McKinsey Global Institute 2020).

8.3 Research Methodology

An extensive literature review was undertaken. A search was conducted on EBSCO Host and Google Scholar, using keywords "supply chain", "global supply chain", "global value chain", "COVID-19", "pandemic", "Russia-Ukraine conflict", "shipping cost", "natural disaster", "supply chain disruption", and "value chain disruption". Identified relevant academic papers, books, and conference proceedings by reading the abstracts and keywords. Duplicates were removed. Further literature review involved searching international organizations' research and policy documents, like Asian Devlopment Bank, World Economic Forum, World Bank, OECD, Centre for Economic Policy Research (CEPR), National Institute of Economic and Social Research, International Labour Organization (ILO), IMF, UNCTAD, etc. In addition, searches for consulting reports and the latest research on supply and value chain disruptions were undertaken. Since this paper is evaluating recent events, it was important to access portals for up-to-date market data, like Gartner, Statista, and World Bank Data.

The synthesis of qualitative data was done using template analysis. This approach allowed the development of conceptual themes and sub-themes which would help with the presentation and interpretation of the results (Pathak et al. 2022; Madan and Ashok 2022a). The objective of this paper is to provide valuable insights to academics, practitioners, and policymakers. A three-step template analysis process was undertaken; in step one, a priori themes were identified from the literature; In step two, each source document was coded, while in step three the final template was created (Ashok et al. 2022; Madan and Ashok 2022b). The final template focused on four elements of the global supply chain, as highlighted in the research aims, covering challenges, threats and opportunities, drivers for change, and policy recommendations (especially for the Asia and the Pacific region).

8.4 Global South–North

The resurgence of Global South[6] economies has been significant: they grew four-fold between 2000–16 as compared to a two-fold increase in the world economy (Mohanty et al. 2019). South-South trade is increasing, with 75% of this within developing Asian countries (Horner and Nadvi 2018); these nations contribute to regional and global supply networks by defining new governance types and power structures (Barrientos et al. 2016). North-South and South-South trade has been increasing, especially in medium- and high-technology-intensive industries. South-South trade shows that organizations are engaged in 41% more tasks than South-North trade[7] (Mohanty et al. 2019). However, organizations in the Southern block show limited compliance with international quality standards (41% in North-South and 26% in South-South value chains).

Supply and value chains have provided new employment opportunities to countries in the Global South; however, it has experienced widespread labor, financial and environmental vulnerability (Marslev et al. 2022). Dünhaupt and Herr (2021) argue that Global South organizations do not automatically benefit by participating in value chains, nor do these countries necessarily catch up with the Global North in terms of development; this is because the Global South usually participates in vertical value chains that are driven by cost efficiencies and resource exploitation.

6 Developing "economies in Latin America, the Caribbean, Africa and developing Asia, including the PRC" (Horner and Nadvi 2018: 207)

7 More tasks indicate diversification, which increases negotiating and bargaining power.

8.4.1 Role of Lead Firms in Global Value Chains

Lead firms in developing economies use global value chains to boost resources driven by home nation endowment deficits to a) grow abroad to accrue value-added segments,[8] b) meet mature/refined demands, and c) internalize to wield domination. In comparison, lead firms in advanced economies focus on the dissemination of activities, disengagement of simplified segments to reduce cost, and externalisation (offshore outsourcing) (Cuervo-Cazurra and Pananond 2023).

Lead firms use varying governance structures based on three factors – *capabilities* available to suppliers and required to meet demand, the extent of knowledge *codification* possible, and the *complexity* of knowledge, technology, and information transfer (Gereffi et al. 2005). However, more research is needed to understand how lead firms and their strategic partners (key suppliers and customers) organize themselves to achieve network collaboration, and how firm-specific activities are governed to enhance value chain performance (Kano et al. 2020). Lead firms and their suppliers are governed by both external (host country policies, buyer market expectations) and internal factors (firm-level strategies) (Kano et al. 2020).

Lead firms and their key suppliers can play a vital role in reducing environmental impact by adopting green and sustainable policies (Marchi et al. 2013). Decisions to decentralize sourcing and manufacture regionally enable lead firms to be closer to their markets (as a result reduce emissions and costs); however, these may not be feasible for all industries due to setup costs, country politics, competencies and trade policies (Butollo and Staritz 2022).

Economic and labor vulnerabilities in value chains are driven not only by national policies and trade agreements but also by lead firms' strategies (Marslev et al. 2022). Lead firms can take advantage of slack policies in Global South countries to distribute activities unfairly across the supply chain and to exploit local labor and resources. Lead firms in Global North have incentives to enhance economic upgrading; in comparison, South-South trade is less likely to engage in specialization (Mohanty et al. 2019).

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8 Organisations that trade internationally accrue up to 14% more value than organisations that don't (Mohanty et al. 2019).

8.4.2 Disparity between North Lead Firms and South Suppliers: Case Studies

Electronics Supply Chain: Case of Apple Incorporation

Apple's value chain has been extensively researched, as it operates in the computers and electronics sector,[9] which is knowledge-intensive[10] (Xing et al. 2021: 60). Seric and Tong (2019) report that, although the PRC exported iPhones to the US at $179 per unit, the PRC's value-add accounted for only $6.5 per unit, while Apple accrued 58.5% of the value-add in 2010 (Kraemer et al. 2011, Figure 8.4). Interestingly, Apple continues to accrue a similar percentage of value-add a decade later (Xing et al. 2021: xxiii). Apple's value-add is enhanced by intangible assets; for example, the Apple logo, iOS operating system, and marketing contribute 59% of the retail price of iPhone X (Xing et al. 2021). However, the value-add accrued by Apple through its intellectual property and services bundled in its products sold internationally are not accounted for in the US trade data; if these data were included (for 2015), US exports to Japan and the PRC would have increased by 8.7% and 16.6%, respectively, and reduced the US trade deficit with these countries by 7.8% and 5.2%, respectively (Xing 2020).

Apple does not own any manufacturing facility; rather, it outsources manufacturing to its suppliers in emerging economies, while maintaining core competencies like new product development and accruing huge profits (Xing et al. 2021). Further, Apple has been lax about the ethical, human rights, and environmental considerations within its supply chain. After damaging evidence of working conditions at Foxconn, Apple's principal supplier in the PRC, Apple introduced its Supplier Responsibility Programme but real changes are limited (Clarke and Boersma 2017). Thus, there is clear evidence of uneven distribution of value-add between large Global North lead firms (Apple) with their Asian suppliers. Further, the reporting of intangibles-based exports for bilateral trade data continues to be a cause for concern. Apple also has a dismal tax record worldwide (Fortune 2018; Reuters 2022).

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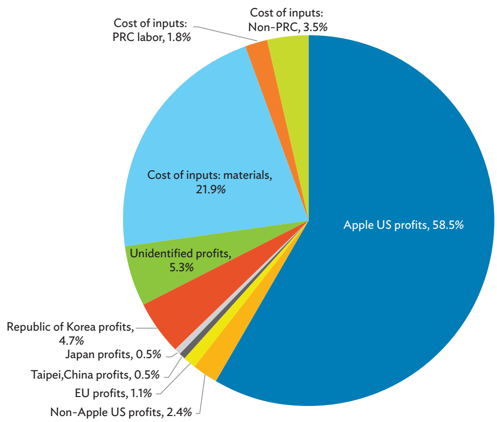
9 United Nations Conference on Trade and Development (UNCTAD 2022a) estimates that global events like Russian invasion of Ukraine, and shipping cost increases will lead to 11.4% consumer price increase in this sector. Between 2010 and 2020, this sector experienced 39% net present value losses due to supply chain disruptions (Statista 2023d).

10 Computers and electronics sector has shown an 8.1% increase in spending on intangibles as a proportion of revenue: 2000–16 (Xing et al., 2021).

Figure 8.4: Uneven Distribution of Value of Apple iPhone, 2010



Source: Kraemer et al. (2011).

Apparel Supply Chain: Case of the PRC

Apparel value chains are labor-intensive, with the sector showing an 8.2% increase in spending on intangibles as a proportion of revenue between 2000 and 2016 (Xing et al. 2021: 60).[11] Historically, lead firms in apparel value chains yield great bargaining power and create barriers for suppliers to upgrade to higher value-add activities like branding, designing, retailing, and marketing; further, these value chains can be easily relocated (Li et al. 2019). In 2021, the PRC was the lead clothing exporter with a share of 32.8% (followed by European Union with 28.1% and other Asian countries), but the US accounted for the largest revenue share of the apparel market with $317.6 billion (followed by the PRC with$303.3 billion); textiles and clothing contributed about 10% of the PRC's manufacturing value-add between 2000–20 (Statista 2023a). All of Asia plays a key role in the apparel supply chain, with Asian garment employment constituting 75% of the worldwide total in 2019 (Statista 2023b). However, there is evidence of uneven distribution of value-add across Global North lead firms and Global South suppliers.

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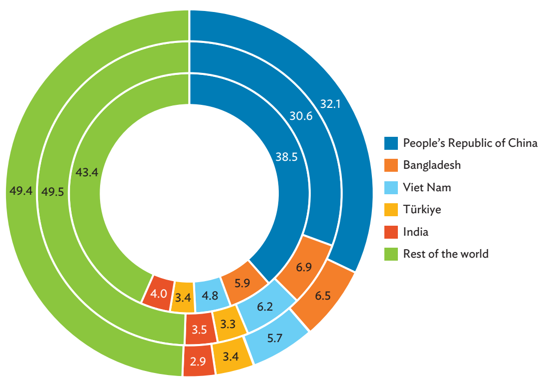
11 UNCTAD (2022a) estimates that global events like Russia's invasion of Ukraine and shipping cost increase will lead to 10.2% consumer price increase in this sector. Between 2010 and 2020, this sector experienced 38.9% net present value losses due to supply chain disruptions (Statista 2023d).

The PRC's business-to-business apparel electronic commerce (e-commerce) trade has increased over the past decade (Statista 2023c). In fact, the PRC accounts for almost half of the world's e-commerce market (ITA 2021). This is because the PRC has played a key role in setting up an ecosystem that supports e-commerce, allowing organizations to upgrade (product, process, functional, end-market, and chain upgrading) across value chains (Li et al. 2019). However, the PRC and other major Asian apparel exporters, e.g., Bangladesh, Viet Nam, Türkiye, and India, have experienced a downward trend in production volume, revenue, and profits from clothing manufacturing in recent years (Statista 2023a; Figure 8.5).

Figure 8.5: Clothing Exporters' Market Share (by value)



Source: Lu (2022); author.

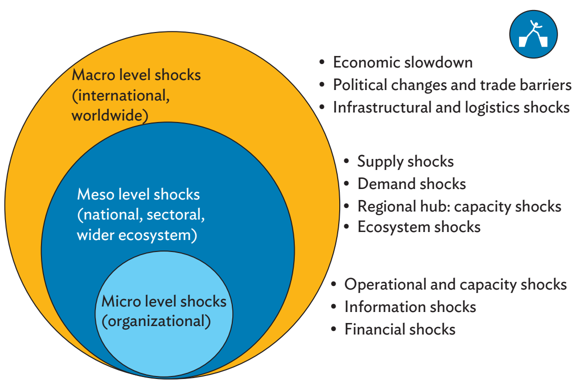
Global North lead apparel firms like Nike manufacture predominantly outside the US (mostly in the Global South), but their sales to the PRC do not show up in US export data (similar to the Apple case study above) (Xing et al. 2021).

8.5 Findings for Global Supply Chains

8.5.1 Challenges Faced

The challenges faced by global supply chains are summarized (Figure 8.6) at macro (international, worldwide), meso (national, sectoral, wider ecosystem), and micro (organizational) levels as discussed in business literature (Molthan-Hill et al. 2020). At each level, sub-themes have been identified based on the analysis conducted in this paper.

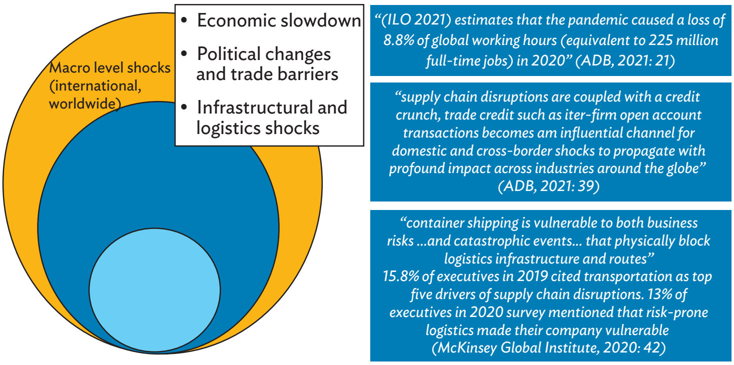
Figure 8.6: Challenges Faced by Global Supply Chains



Source: Author.

Macro-level challenges are summarized in Figure 8.7. The global economy saw a loss of 8.8% of working hours, i.e., about 225 million full-time jobs, in 2020 due to the pandemic; further, trade fragility and credit crunch impacted all sectors (ADB 2021). Infrastructure, logistics, and transportation shocks have been key source of risk. For example, McKinsey Global Institute (2020) showed that transportation was one of the top five determinants of supply chain disruptions (15.8% of executives surveyed in 2019), and risk-prone logistics continue to be a challenge as they make companies vulnerable (13% of executives surveyed in 2019).

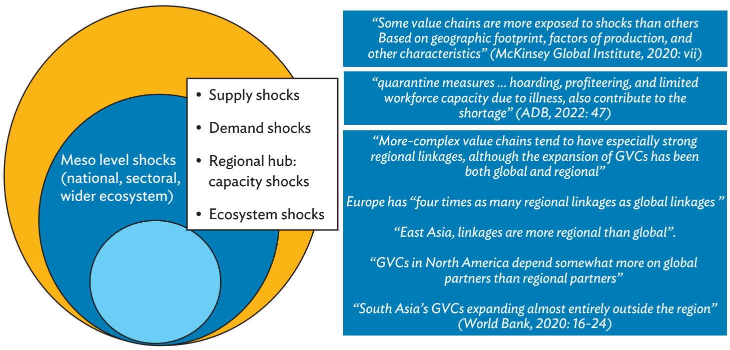
Figure 8.7: Macro-level Challenges Faced by Global Supply Chains



Source: Author.

At the meso level, the challenges vary (Figure 8.8); for example, McKinsey Global Institute (2020) reports that production characteristics, geographical footprint, and other factors make some value chains more susceptible to shocks. The World Bank (2020) shows that complex value chains tend to have stronger regional ties: Europe and East Asia have more regional than global partners; however, South Asia and North America depend more on global linkages. Some of the key factors leading to meso level shocks included: reduced workforce capacity, exploiting/profiteering, and stockpiling (ADBI 2022). Lack of access to regional manufacturing hubs and regional development funds, and less competitive regional trade agreements are other challenges (UNCTAD 2022b).

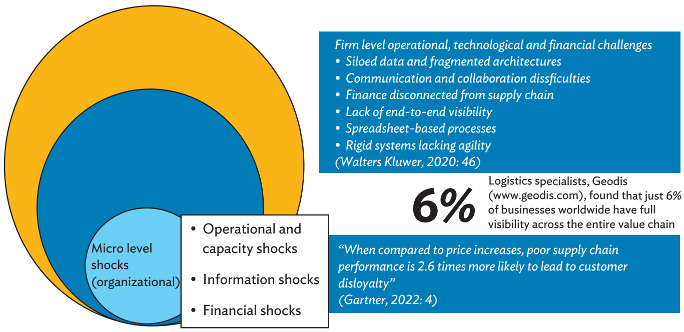
Figure 8.8: Meso-Level Challenges Faced by Global Supply Chains



Source: Author.

At the micro level, challenges include siloed data, lack of effective communication and collaboration, lack of end-to-end visibility, and rigid systems (Figure 8.9). Gartner (2022) highlighted that poor supply chain performance leads to customer disloyalty 2.6 times more than price rises.

Figure 8.9: Micro-level Challenges Faced by Global Supply Chains



Source: Author.

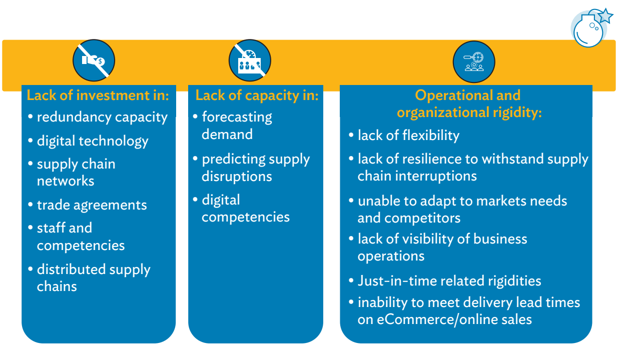
8.5.2 Threats and Opportunities of Global Events

The impact of the global events and phenomena on supply chains is presented as threats and opportunities it presents to organizations, governments, and international and regional bodies.

Threats of global events on supply chains can be summarized as lack of investment, lack of capacity, and operational and organizational rigidity (Figure 8.10).

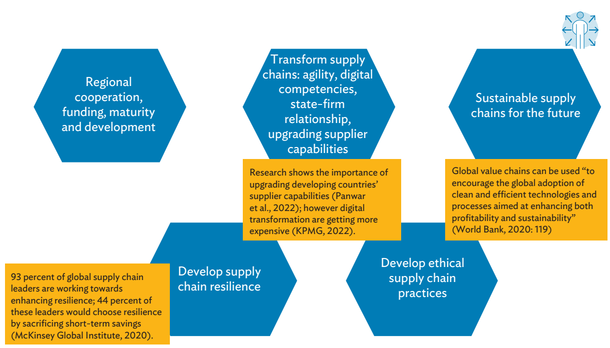
Supply chain opportunities arising from global events and phenomena are summarized under five themes below (Figure 8.11).

Figure 8.10: Threats Due to Global Supply Chain Disruptions



Source: Author.

Figure 8.11: Opportunities to Respond to Global Supply Chain Disruptions



Source: Author.

(1) *Regional cooperation, funding, maturity, and development.*
There is a lack of consensus in the literature regarding globalization versus localization of supply chains. However, McKinsey Global Institute (2020) anticipates that 16%–26% of global trade could relocate to different countries due to several factors. Several sources agree that regional collaboration and funding would develop supply chain maturity and resilience in the long run. Organizations must consider a mix of supply chain strategies that include:

- relocation
- shifting to different onshore and/or offshore locations
- reshoring / nearshoring / domestic production versus offshoring
- localization versus globalization
- vertical integration versus outsourcing

Regional collaboration could be enhanced by the relaxation of professional licensing. Three regions have high regional integration based on 2018 data (World Bank 2020). First, Europe and Central Asia report 65%, East Asia and the Pacific shows 55%, and the North American Free Trade Agreement countries show 39% regional integration. Pla-Barber et al. (2021) argue that organizations may choose to regionalize value chains in the medium to long term by reducing the number of linkages and trading off efficiency for security, thereby reducing risks. However, relocation of supply chains is not straightforward:

- relocation of value chains is time-consuming and costly;
- relocation is not attractive for all sectors: for example, capital- and knowledge-intensive sectors, and industries that depend on location-bound material;
- regionalization of value chains needs a different governance approach and power structure; and
- reshoring could face barriers like lack of access to specialized skills, infrastructure, and capabilities at the right cost (Kano et al. 2022).

EIU (2021a) reports that 31% of organizations are simplifying their supply chains by adopting regionalization or localization.

(2) *Develop supply chain resilience.*
Global events and supply chain issues have led 73.5% of executives to reconsider resilience and business continuity (BCI 2022). Supply chain managers can consider several

factors to improve resilience (KPMG 2022; McKinsey Global Institute 2020):

- diversify supply chains
- dual sourcing
- inventory management of critical goods
- increasing supplier base and nearshoring
- regionalization
- reducing product lines or simplifying product portfolio
- higher inventory across the supply chain
- back-up production sites
- nearshoring
- increase distribution centers
- innovation

(3) *Transform supply chains.*
Businesses focus on agility, digital competencies, state-firm relationships, and upgrading supplier capabilities. Investment in digitalization and automation will improve supply chain agility. Digitalization will enable organizations to maximize the value from collaboration and new supply chain models. Digital supply chains will allow organizations to take an operational, tactical, and strategic view of supply chain partners and entire value chains, maturing from siloes to an integrated (internal and external) strategy.

(4) *Sustainable supply chains for the future.*
Combating climate change should be the top priority. Global supply chains in eight industries attribute 50% of total CO_2 emissions (Zurich Insurance Group 2021);[12] these industries must adopt and monitor sustainable practices. Organizations should adopt the triple bottom line theory to focus on sustainability. Supply chains must adopt socially and environmentally responsible practices (KKR 2020). ADBI (2022) shows that some industries like food can reduce greenhouse gas emissions by 80% by managing demand and supply factors.

(5) *Develop ethical supply chain practices.*
The use of clean, efficient technology and processes in global value chains will help organizations achieve their ethical

12 These industries include automotive, construction, electronics, food, fashion, fast-moving consumer goods, freight, and professional services.

standards, improve sustainability, and enhance profitability (World Bank 2020). Supply chains must focus on:

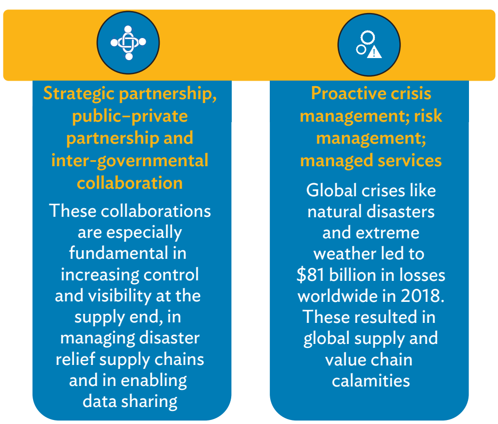
- ethical sourcing;
- building goodwill with local communities;
- ethical trade partnerships;
- adoption of ethical practices; and
- taking proactive steps regarding ethical practices in the digital environment (Buergi et al. 2022).

8.5.3 Drivers and Recommendations for Transformation

Drivers for supply chain transformation include factors that help mitigate supply chain interruptions. Drivers include diversifying sources, improving visibility, enhancing agility, moving supply chains to different countries, improving the capability to fulfil demand, developing flexible production processes, and complying with regulations and policies, with 97% of manufacturers prioritizing end-to-end visibility across supply chains (IDC 2020).

Two key recommendations (Figure 8.12) to transform global supply and value chains are listed below. These must be applied in conjunction with the opportunities to respond to supply chain disruptions listed above.

Figure 8.12: Recommendations for Global Supply Chain Transformation



Source: Author.

(1) *Strategic partnership, public-private partnership and inter-governmental collaboration.*
Strategic partnerships within the supply chain will increase control and visibility at the supply end, and may lead to restructuring (integration). Public-private partnerships help managing disaster relief supply chains and enable data sharing. An example is Deutsche Post DHL Group's Get Airports Ready for Disaster (GARD)13 partnership with the United Nations Development Programme, although the pandemic tested the GARD programme, as workshops and training had to evolve due to travel restrictions. Partnerships like GARD allow the collaboration of capabilities, provision of logistics support to areas affected, development of skills, sharing of best practices, and prioritization, all of which reduce response times and risks.

It is imperative to set up inter-governmental cooperation to enable disaster response and alleviate supply chain woes. Some examples: Association of Southeast Asian Nations (ASEAN) Agreement on Disaster Management and Emergency Response, Hyogo Framework for Action, Asian Regional Seismographic Network. 2022 saw a renewed focus on supply chain collaboration: The US and 18 partner economies issued a joint statement on cooperation on global supply chains,14 while the UK is developing supply chain resilience initiatives with partners, and the World Trade Organization held its global supply chains forum.

(2) *Proactive crisis management; risk management; managed services.*
Global crises and phenomena in the last few years resulted in global supply and value chain calamities (EIU 2021b); thus, proactive management of risks has become imperative. Risk management strategy (Figure 8.13) may include mobilizing a risk response team, sense-taking (prioritizing risks and identifying implications for the entire supply chain), analyzing data and scenarios (maximizing the use of digital and analytical tools), and configuring an approach to track strategies (Accenture, n.d.).

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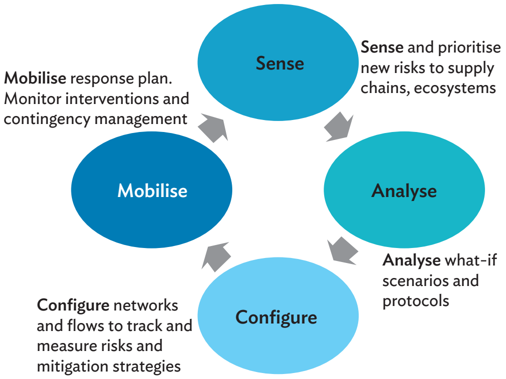
[13] https://www.dpdhl.com/en/sustainability/society-and-engagement/disaster-management/disaster-preparedness.html

[14] https://www.state.gov/supply-chain-ministerial-joint-statement/

Other strategies to enhance resilience include:

- multiple/alternate sourcing (just-in-time delivery approaches are prone to supply chain disruptions as experienced by the automotive industry);
- rapid recovery or transfer to secondary production system;
- supplier selection based on risks (rather than costs);
- reducing logistics risks by outsourcing;
- strong institutional logics;
- maintaining buffer to shorten disruption;
- using risk-exposure index;
- identifying country-level risks and monitoring;
- increasing visibility and monitoring; and
- redesigning sources of vulnerability (substitute, hedging with insurance, flexibility, using data for decision making) (Kwok 2018).

Figure 8.13: Risk Mitigation Strategies

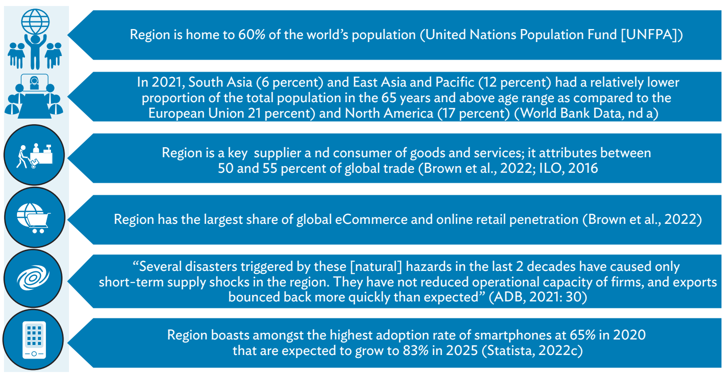


Source: Author, adapted from Accenture (n.d).

8.6 Policy Recommendations and Implications for the Asia and the Pacific Region and Conclusion

The policy implications for the development of the Asia and the Pacific supply chain is critical not just for the region but also globally. This is because of the region's growing influence on all elements of supply chains including value generation, sustainability, inter-connectedness of economies, and more (ILO 2016; Figure 8.14). For example, Seric and Tong (2019) shows that Asia is the largest importer of intermediary goods (for further processing, assembly) at 59.6% in 2020 (as compared to global imports at 51.4%), however, it underperforms as an exporter of intermediary goods at 52.3% (as compared to leading region Africa at 70.9%).

Figure 8.14: Factors in Favor of the Asia and the Pacific Region



Source: Author.

Asia, led by the PRC, benefited the most from supply chain adjustments due to the pandemic. Demand patterns and supply disruptions due to the pandemic and resultant lockdowns, cross-boundary restrictions and checks, and transport issues enabled Asian countries to fill supply gaps arising in Europe, the Middle East, North Africa, and North America (OECD 2022; EIU 2021b).

UNESCAP (2015) shows that exports from Asia and the Pacific economies vary by income levels of those economies and sectors. In general, the electronics sector from upper-middle-income economies in Asia and the Pacific is most prominent in global value chains (with reference to exports). Not all manufacturing happens in the PRC; different economies specialize in different goods. For example, Bangladesh and Cambodia are lead exporters of footwear and apparel, Malaysia is a key exporter of intermediary goods for the agriculture and electronics sector, and Thailand is a major exporter of automotive and agricultural goods. Further, EIU (2021b) shows that Viet Nam is a key supplier in the food, beverages, and manufacturing industries. This is because Viet Nam benefits from proximity to the PRC (which allows PRC organizations to get around US sanctions), low cost, and progressive regional and international trade agreements.

Brown et al. (2022) further predict that the Southeast Asia region and India will be rising economies due to their competencies in technology-based products. Similarly, the World Bank (2020) also shows that global value chains are expanding quickly in the services sector, with India and the Philippines rising in the information and communications technology and business services sectors. Thus, it is not a surprise that EIU (2021b) shows that one-fifth of global executives have either invested or are interested in investing in the Philippines and India in the coming year.

At its core, there are significant opportunities for policy interventions to minimize supply chain disruption and its impact, and further accelerate value-added in global value chains.

8.6.1 Policy Recommendations for the Asia and the Pacific Region

(1) *Boost domestic consumption and regional trade to relieve supply chain disruptions in international trade.*
Enhance national and regional trade agreements and collaboration, and reduce trade barriers. For example, use regional cooperation platforms like ASEAN to integrate supply chains and develop regional networks. The Republic of Korea has introduced the New Southern Policy to enhance ties with India and Southeast Asian countries, while lessening historical trade dependencies on the PRC, the US, Russian Federation, and Japan. The PRC has introduced an internal circulation (domestic consumption) initiative. The clothing and textiles industry shows a higher proportion of regional supply chains; Asia-Asia trade for this sector was greater than 80% in 2022, and thus a good sector for regional trade (Lu 2022).

(2) *Enhance diversification and reduce concentration within supply chains as part of supply chain resilience strategy.*
Incentivize supply chains redefinition and resilience building. Additional sourcing, nearshoring (close to manufacturing base or biggest market), increased capacity (warehousing, distribution, production), and relocating supply chains need capital-, resource- and knowledge-intensive strategies. For example, supply chain restructuring to reduce over-reliance on a region needs agility, support from trade and customs

authorities, and investment. EIU (2021b) shows that Asia and the Pacific managers report the following strategies for value chain interruptions: 29.7% adopt diversification, 22.3% regionalization, 20.6% prefer localization, 14.9% consider reshoring, and 12.6% have the PRC plus one policy (most strategy adoptions are significantly lower than their North American and European counterparts). Some successful examples are from the electric vehicles industry, capabilities of which have historically concentrated around South Korea, Japan, and the PRC. During COVID-19, a Vietnamese manufacturer developed the capability to launch new electric vehicles globally, while Indonesia is investing in becoming the region's principal electric vehicle manufacturer and seller, and Thailand is expanding its capabilities in this sector (KPMG 2021).

(3) *Undertake economic and social upgradation within global value chains.*
Focus on capability development to attract multinationals and foreign direct investment, especially in technology and innovation, and to provide investment for the development of facilities and networks to upgrade value chain positioning. The Asia and the Pacific region will benefit by increasing their exports of goods and services as a percentage of GDP (World Bank Data, n.d. b). Higher maturity, knowledge retention, and capabilities will strengthen the positioning and reduce the risk of replacement of Asia and the Pacific companies in global value chains. There is a positive correlation between the liberalization of FDI and value-added factors (productivity, domestic value-added gains, global integration, and upgrading). ASEAN+3 countries15 have been very strong in upgrading the electrical and optical equipment sector's global value chains (Crescenzi and Harmon 2022). The Asia and the Pacific region should focus on moving toward high-value-added activities within and across sectors. The extent of supply chain digitalization and digital capabilities enable value generation in supply chains (Fu 2022). The use of digital technologies (online platforms), online dissemination of knowledge, support for technical issue resolution and training will help upgrading; for example, the PRC's fresh fruits export

[15] ASEAN countries plus the PRC, Japan and South Korea. See Crescenzi and Harmon (2022) for types of upgrading.

network has cut out intermediaries by using online platforms (Butollo et al. 2022).

(4) *Improve ease of doing business.*
Continued intervention on strategies to enhance macroeconomic variables like investment in infrastructure, logistics, business-friendly tax policies, supportive business services, conformance to international standards, and increased transparency. For example, India launched the Atmanirbhar Bharat initiative to promote ease of domestic manufacturing in industries like automobiles, pharmaceuticals, and electronics. Business-friendly countries benefit more from research and development (national and international spillovers) and human capital development (Xing et al. 2021). Some Asia and the Pacific economies have made strides in ease of doing business,16 with New Zealand; Singapore; Hong Kong, China; and Republic of Korea featuring in the top five. As an example, 80% of Singapore's value-added exports can be attributed to foreign origin; Singapore is predominantly a service-economy; Japan and Singapore signed an economic partnership agreement in 2002, which allows Japanese companies to enjoy tariff-free exports (ASEAN-Japan Centre 2018). Thus, trade partnerships and bodies simplify doing business (EIU 2021b; KPMG 2021).

(5) *Strengthen supply chain response to natural disasters.*
Recovery strategies to be formulated to enhance supply chain partner collaboration and investment in natural disaster response. Statista (2022e) highlights that over 207 million people were displaced by natural disasters in the Asia and the Pacific region between 2010 and 2021.17 Investment in infrastructure and support for vulnerable (often low-income, rural, and small) value chains through financial resources and insurance will ensure that local businesses are able to stay afloat (Breiling 2021). Investment in digital technologies will enable better monitoring of real-time data, and surveillance of supply chain disruptions. Collaboration between stakeholders (government, businesses, non-government organizations,

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16 https://data.worldbank.org/indicator/IC.BUS.EASE.XQ?most_recent_value_desc=false&locations=HK

17 Lower-middle- and low-income countries accrue two-thirds of global deaths due to natural disasters (Breiling 2021).

charities, health care providers and others) will be critical in developing contingency plans and coordinating crisis response. Cross-country and pan-regional cooperation will enable quick response and lessen supply chain disruptions. Support to sectors that need to switch supply chains from risker regions will be essential to build long-term resilience (Freund et al. 2022). By focusing on digital and service-driven value-added activities, the region can combat high CO_2 emissions in the manufacturing sector (ADB 2023).

(6) *Enhance value-added activities through services.*
Services exports in the Asia and the Pacific region showed an annual growth of 18.8% in 2021 and are expected to grow by 8.9% in 2022; transport, other business services and ICT are the main contributors to service exports (UNESCAP 2023). Viet Nam, Cambodia, and Singapore have shown the highest increase in business services. Services are also used to create value, directly or indirectly, in the manufacturing, distribution, and marketing of goods (defined as servicification by UNESCAP [2015:xix]). The region would benefit from building stronger regional value chain ties in high technology and high value-added sectors, especially because digital services trade accounted for 55% of total services trade in Asia and the Pacific in 2020 (ADB 2023).

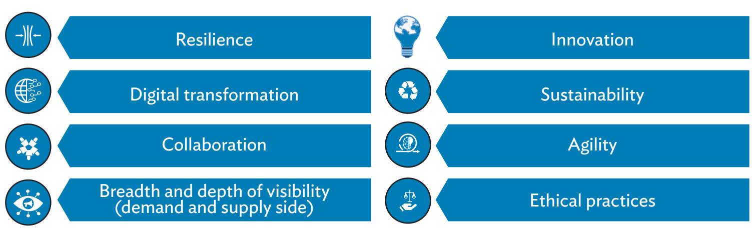
8.6.2 Conclusion and Future Research Opportunities

Recent events have challenged stability and reliability, leading to an unstable world affected by geopolitical conflict, economic and financial crises, natural disasters, and technological and societal change; volatility is here to stay. Global value chain disruptions have widespread implications like contraction in GDP, inflationary pressures, recessions, currency fluctuations, financial crises, and trade conflicts. The COVID-19 pandemic, macroeconomic shocks, Brexit, geopolitical unrest, nationalistic directions (countries pulling out of global treaties; see Rockwell 2023), increasing logistical and infrastructural challenges (shipping costs, port congestions), climate change and natural disasters, and technological risks (cyberattacks) have put astronomical stress on globally spread value chains. Supply chain disturbances are becoming more acute and common (McKinsey Global Institute 2020). Failing to mitigate supply chain disruptions leads to capabilities gaps like lack of resilience, limited digital competencies, lack of collaboration, lack of customer insight, and lack of breadth of new products or services offering pipeline (IDC 2020). Thus, recent events and phenomena have indeed accentuated the need for transformation in the global supply chain.

Changing trade dynamics, complexities of value chains and increasing global trade barriers have made regional and global trade within Asia and the Pacific more attractive. The region is an important exporter and importer of goods and services. Further, economies in the region have differing geopolitical directions, capabilities, resources and drivers for development; thus, cooperation will strengthen national and regional ties. However, as recent research shows (Martins et al. 2022), it will be a mammoth task for organizations and nations to overcome self-serving behavior to enable supply chain partnerships and collaboration.

Supply chains are increasingly dynamic, complex, and globalized. The ability to respond to future supply chain disruptions will thus depend on a complex set of capabilities like resilience, digital transformation, collaboration, visibility of upstream and downstream supply chain, innovation, sustainability, agility, and ethical practices (Figure 8.15). Investment in supply chain digital capabilities will help organizations tackle human resource shortages/constraints, support new business models (product and sales offerings), strengthen resilience and agility, improve speed and accuracy of decision-making, and enhance productivity (Klappich et al. 2022).

Figure 8.15: Key Takeaways for Future Global Supply Chains



Source: Author.

This chapter synthesizes the literature on the impact of worldwide events and phenomena on global supply and value chains. Future studies could build on this and explore the challenges, threats, opportunities, and recommendations in further detail. Researchers could explore the findings of this chapter in the context of individual countries or regions. The development of hypotheses and testing with empirical data will add tremendous value to academicians, policymakers, and practitioners. A debate on how organizations, countries, regions, and international bodies could collaborate to create policies and practices that would elevate the challenges of global supply chains will be necessary for future generations.

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PART V

Digitalization for Resilient Supply Chains

9

Building Supply Chain Resilience with Digitalization

Kim Hua Tan

9.1 Introduction

Today's supply chains are overly global and complex with multiple interdependent echelons and hidden pain points. Yet even without a full spectrum understanding of a firm's supply chain, managers are still capable of "firefighting" and fixing most of the small-scale, unpredictable supply chain issues. But the scale of the COVID-19 pandemic, the ongoing United States–People's Republic of China trade decoupling, and the Russian invasion of Ukraine have disrupted global trade relations and supply chains. Many studies (Ambulkar, Blackhurst, and Grawe 2015; Ali and Golgeci 2019; Carissimi et al. 2022) have pointed out that firms need to enhance the resilience of their supply chains (SCs) to quickly recover from disruptions. This increased supply chain flexibility will better equip firms to withstand unanticipated disruptions, such as a global pandemic, as well as predictable events, such as adverse weather or logistics delays.

Thus, supply chain resilience is at the top of the agenda for firms as well as for supply chain researchers. But what is supply chain resilience? In the literature, there is no clear agreement on a definition of supply chain resilience. Holling's (1996) seminal work on the engineering versus ecological perspectives of resilience laid the foundation for the current supply chain resilience debates. Some of the leading researchers that are taking the engineering perspective in defining resilience are: Rice and Caniato (2003); Christopher and Peck (2004); and Sheffi (2005). Table 9.1 summarizes the definitions of supply chain resilience from various authors. The core notion of the engineering perspective of resilience is recovering speed and costs. In contrast to this rather 'static' engineering perspective, the evolutionary school of thought argues that firms' supply chains are capable of learning from disruptive events and developing new capabilities to withstand future uncertainties (Hamel and Valikangas 2003; Seville, 2008; Tukamuhabwa et al. 2015). The foundation of this school is adaptive capabilities to accommodate future uncertainties and to emerge stronger after the disturbance (see Table 9.1).

Table 9.1: Summary of the Supply Chain Resilience Definitions

	Authors	Supply Chain Resilience Definitions
Engineering	Rice and Caniato (2003)	The ability to build a secure supply chain to bounce back from any disruptions. Luck plays no part in the equation.
	Christopher and Peck (2004)	The ability of a system to return to its original state or move to a new or more desirable state after being disturbed.
	Sheffi (2005)	The ability of the supply chain to return to a normal performance level (i.e., production, services, and fill rate) and the speed at which it can do so–after a disruption.
Evolutionary	Hamel and Valikangas (2003)	The ability to anticipate and adapt to change as well as dynamically reinvent supply chain business models as circumstances change. Having the capacity to change even before the cause for change becomes obvious.
	Seville (2008)	The ability to develop the capacity to seize the opportunities that arise from a crisis to build a supply chain that is stronger and better than before.
	Tukamuhabwa et al. (2015)	The ability to develop the adaptive capabilities to make a timely and cost-effective recovery and, therefore, progress to a post-disruption state of operations—a better state than prior to the disruption.

Source: Kim Hua Tan.

The supply chain resilience effort is a complex and challenging journey that will continue through the years. A high level of supply chain resilience can help firms to more effectively prepare for, respond to, and recover from disruptions (Tukamuhabwa et al. 2015; Scholten, Stevenson, and Van Donk 2019; Zhang, Liu, and Godsell 2021). Most of the existing studies argue that supply chain resilience covers pre-disruption, disruption, and post-disruption (Kochan and Nowicki 2018; Zouari, Ruel, and Viale 2021). The three most widely acknowledged supply chain resilience dimensions are Readiness, Responsiveness, and

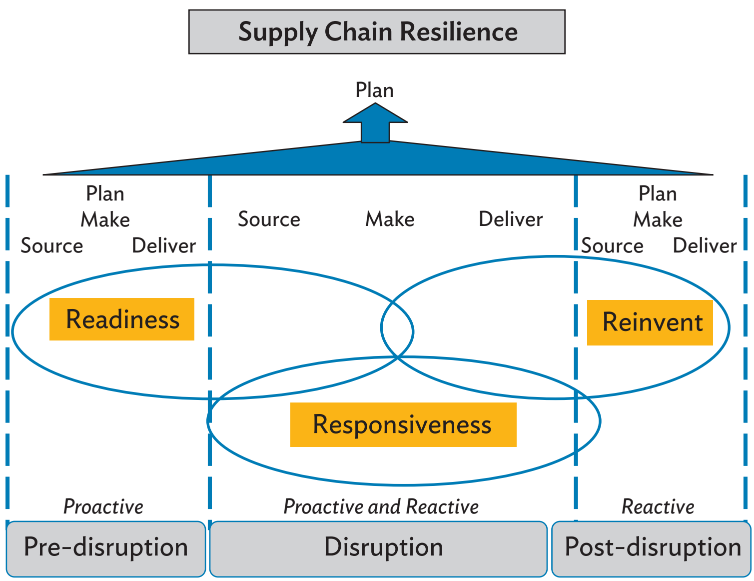
Recovery. These dimensions are also widely acknowledged as the 3Rs of supply chain resilience (see Figure 9.1). The Readiness dimension refers to the proactive preparation in anticipation of possible disruptions. Examples include planning for alternative suppliers and creating and testing possible disruption scenarios to mitigate labor, manufacturing, and delivery disruptions. The Responsiveness dimension refers to a range and volume of adaptation in order to mitigate the magnitude of disruptions. Examples include intervention in scheduling and temporary workforce arrangements to ramp production up or down during or immediately after disruptions. The focus will be to ensure the continuity of supply chain operations. In the aftermath of disruption. The Recovery dimension refers to how firms could rapidly recover from disruption and achieve new growth. Examples include how firms coordinate the processes of source, make, and delivery operations and restore them to pre-disruption performance levels.

However, given the current competitive business climate, regaining pre-disruption performance may no longer be enough. Incremental adjustments to existing supply chain operations may not deliver a revitalization that is fit to cope with any future unforeseen disruptions or to achieve the advantage needed to effectively compete in the new normal. Firms should also capitalize on the disruption to make a fundamental change in strategy and assets to improve supply chain operational resilience and capabilities. This would help firms to gain new competitive advantages. Supply chain resilience should not only provide consistency for short-term recovery action but also identify new opportunities for repurposing supply chain configurations. In the literature, “Reinvention” implies a significant stretch for a firm’s current capabilities and resources. Building on the disruption lessons, firms should learn how to be more creative while making use of existing resources to systematically build new post-disruption advantages, for example, the capabilities to repurpose supply chains and respond quickly and accurately to fast-changing customer demands and market needs. For instance, during the COVID-19 lockdown in early 2020, the Digipas group of Indonesia was able to repurpose its supply chains and production facilities to rapidly ramp up a new product, namely an intelligent face mask to meet new market demand. As such, “Reinvention” is a more appropriate dimension of supply chain resilience than “Recovery.”

Two broad sets of strategies are available to firms for the development of resilience across the three phases: pre-disruption (proactive); disruption (proactive and reactive); and post-disruption (reactive). However, the boundaries between proactive and reactive strategies are not clearly defined in the literature. Broadly speaking, proactive strategies involve the pre-disruption and disruption phases in which pre-planning is carried out so that a minimum level of adaptation in supply chain operations is required. The main part of a proactive strategy is to monitor component availability. Key practices include demand forecasting and emergency planning; using real-time data to gain better supply chain visibility; and establishing multiple sourcing and buffer management. Reactive strategies normally involve the disruption and post-disruption phases in which flexibility is vital for firms to adapt themselves to fast-changing supply chain environments. For example, to quickly find alternative components or suppliers to substitute for component shortages; or to rapidly repurpose operations to ramp up the production volume of new products to meet new market needs. Figure 9.1 illustrates the 3Rs, that is, three phases, and the two supply chain resilience strategies.

Regarding metrics for supply chain resilience, the two most common measures are time to survive and time to recover. Time to survive normally refers to the amount of time required for firms to regain

Figure 9.1: 3Rs, Three Phases and Strategies of Supply Chain Resilience



Source: Kim Hua Tan.

supply chain operations after a disruption. For example, the time taken to secure approval from authorities and to restart factory operations after a lockdown. The time to recover metric is mainly composed of the time to recover all unfulfilled orders and incomplete work and to resume normal operational capacity. Recently, Jabil Caltabiano (2022) introduced a third metric, that is, time to thrive, which measures the states of the firm pre-and post-disruption.

This chapter investigates how firms could build supply chain resilience with digitalization. It addresses three important research questions: a) What does it take to become more resilient?; b) How can digital technologies play a part in providing greater certainty and flexibility to improve supply chain resilience?; and c) How should firms go about implementing digital transformation? These issues have considerable significance for supply chain management and policymakers in developed and developing countries. To address the research questions, a neo-systematic literature review of digitalization and supply chain resilience literature in the last 15 years (2007–2022) was conducted. The systematic literature review (SLR) is a robust evidence-based review approach in supply chain management research (Tranfield et al. 2003). Through systematic identification, analysis, and interpretation of relevant publications, the SLR allows researchers to map out and have a critical overview of the existing territory of knowledge and the existence of any gaps.

The review started with identifying and selecting the most relevant "resilience," "visibility," "transparency," "COVID-19 resilience," and "digitalization" keywords in titles, abstracts, and full texts from journal articles in four leading business management databases, namely ScienceDirect, ABI/Inform, Business Source Premier, and Emerald. After screening more than 560 relevant abstracts, 34 articles were deemed to be suitable. These outputs were screened for relevance to ensure that only publications that specifically discussed supply chain resilience, visibility, and digitalization were analyzed. Not surprisingly, most of these articles were from 2020 onwards in response to the COVID-19 disruptions. The process was then repeated in the Google search engine to find relevant articles, books, blogs, and news. Although the review process does not guarantee that all the related supply chain resilience articles are covered, the author believes this method has collected a critical mass of representative supply chain resilience materials that serve as inputs for this research.

The chapter begins with a discussion of supply chain resilience dimensions, phases, and strategies. Next, the chokepoints and vulnerabilities in the supply chain are reviewed, and the advancement of technology and digitalization in enhancing operations visibility is examined. Section 9.4 discusses the key building blocks of digitalization capabilities. The chapter concludes with recommendations for practitioners and policymakers on how best to help firms realize their digital potential to boost supply chain resilience.

9.2 Understanding Supply Chain Chokepoints and Vulnerabilities

How can you achieve supply chain resilience or where should you begin? In the art of war, one of the famous Sun Tzu quotes is "if you know the enemy and know yourself, you can fight a hundred battles without disaster." Accordingly, understanding a firm's existing supply chain chokepoints and vulnerabilities are the key step in the supply chain resilience journey. At times of unforeseen events, the weakest links in the supply chain will be at their most vulnerable and at risk of sending ripples along the whole supply chain. Thus, firms should evaluate their supply chains to identify critical raw materials or components at risk from shortages or price fluctuations. Firms should also identify which processes, transportation, or facilities could be the tipping point that causes failure in the supply chains.

Although there is no clear definition in the literature, the term chokepoint or pain point generally refers to a process point in an operation that can jeopardize the entire supply chain operation if it fails (Alicke and Kwan 2021). In normal times, today's global supply chains are designed to function with high dependability and reliability at the lowest cost. Nonetheless, many international aspects are uncontrollable, such as trade wars, changing tariffs, and shipping, and add to firms' supply chains risk exposure. Therefore, an unanticipated, sudden disturbance may deviate from many interconnected planned operations and turn a lean and well-managed supply chain upside down. For example, the lack of delivery drivers during the COVID-19 pandemic as a result of restrictions and lockdowns was a chokepoint for many logistics firms. Chokepoints are thus vulnerabilities in the supply chain, and they should be identified, managed, and eliminated over time. Given the complexity and globalized nature of today's supply chain operations, there are some inherent chokepoints that are inevitable. For example, long delivery lead times, a single source or dependency on commodities from a single region. Consequently, firms need to be aware of where the vulnerabilities exist and how those chokepoints can fail in the supply chains.

The three main sources of uncertainty in supply chains are suppliers, production, and customers. It is essential to carefully examine each source to understand the supply chain-wide impact of the uncertainties and the likely impact on customer service. Supply chain vulnerabilities tend to manifest in four key areas: a) raw materials and supply networks; b) transportation and logistics systems; c) production planning and operations; and d) customer fulfillment.

Unforeseen disruptions will affect all echelons in the supply chains, including overseas suppliers. Without raw materials or components, firms may have to stop production and will be unable to meet customer deadlines. Shortages of materials will also trigger more holdups and unpredictability and amplify the bullwhip effects – meaning that a small variation in downstream customer demand will be amplified as orders move further up the supply chain (Lee, Padmanabhan, and Whang 2015). Single-source components or suppliers concentrated in a single region are another obvious vulnerability. For example, in early 2020, one firm in Indonesia classified as a small- and medium-sized enterprise (SME) realized that all the tier one and tier two key component suppliers were in the same country and facing serious COVID-19 lockdown measures. Hence, firms should consider multi-sourcing and, if possible, use various suppliers from different regions. If multi-sourcing is not possible, then firms should build relationships with suppliers to share information and receive early warning of potential shortages, which can improve supply chain visibility.

Today's supply chains depend on the tight integration of networks of operators and service providers in the delivery of goods and services, from the raw materials stage to the final products to customers (Chowdhury, Quaddus, and Agarwal 2019). Supply chains involve intricately linked transportation, warehousing, and last-mile delivery logistics systems (Davis 1993). Often, materials movements cross borders and cut across various regions and are always vulnerable to uncertainties and extreme weather events. For example, in the electronics industry, the manufacture of a smartphone will involve multiple supplier shipments with differing regularity to manufacturing sites in various regions of the world. At these sites, components, subassemblies, and final assembly operations of the final products are undertaken with complicated production lines and uncertain processes. The products are then shipped to distributors, wholesalers, or final customers. The logistics are further complicated by the various options available for transportation: ships, planes, trucks, delivery drones, or trains. The uncertainties and vulnerabilities existing in such complex supply chain networks can easily be imagined. Higher fuel prices along with shortages of shipping containers, truck drivers, or warehouse pick-and-pack operators are the lingering infrastructure pain points. Some researchers have pointed out that logistic clusters, that is, co-location of value-added logistics services at scale, could mitigate some of the transportation and logistics vulnerabilities.

Information sharing is vital for supply chain coordination (Park, Hong, and Roh 2015; Scholten and Schilder 2015; Sa et al. 2019). In this way, real-time information on delivery can provide better visibility and buffer time for firms to explore alternative delivery.

To improve efficiency and to minimize the supply and demand mismatch, firms typically spend significant amounts of effort on medium- to long-term production planning and resource allocation. However, a supply shortage, power failure, machine breakdown or worker unavailability can cause a deviation from the initial production plan and cause disruption throughout the whole supply chain. Though some of these factors are external, such as a power failure, pandemic worker restriction, or changes in demand, firms should nonetheless seek to have better end–end supply chain visibility to prepare for the unexpected. This is to ensure that the recovery plan can cope with the changed environment brought about by the disruptions as well as meet the initially promised customer delivery. In brief, the level of a firm's resilience is also crucially affected by the capabilities of its customers and suppliers to anticipate and respond to disruption.

The COVID-19 pandemic has changed consumer purchasing behavior. The sudden increase of online shopping has made many firms' conventional warehousing and fulfillment strategies irrelevant and unable to meet customer delivery expectations. Fulfillment disruptions are not new, but today's supply chains are being stressed in multiple ways all at once. No firms can accurately predict the future, but they can take actions to address the fulfillment vulnerability and meet customer expectations. Firms could improve fulfillment networks by diversifying logistics service providers and with better inventory management; that is, the right inventory at the right location at the right time. Moreover, better management of customer expectations is crucial. Unfulfilled orders and delays are not good ways to impress customers. Thus, providing real-time updates on changes and delays to customers is a must. Tukamuhabwa et al. (2015) argued that the adoption of relevant digital and information technologies can boost the flexibility, visibility, collaboration, and velocity of operations, which are all critical for supply chain resilience.

9.3 Leveraging Digitalization for Supply Chain Resilience

In the aftermath of the COVID-19 pandemic, firms learned that they should reduce complexities by shortening and strengthening their supply chains to face future uncertainties. Increased end-to-end visibility of the supply chains is vital for firms to pick up early signals of uncertainties, allowing themselves sufficient time to orchestrate operations and resources to withstand disruptions. Today's advanced technology and digitalization are ready to make supply chains more transparent, thereby providing firms with many capabilities to cope and even emerge stronger after disruptions (Pu et al. 2021; Cui et al. 2022; Gandhi 2022). Savvy managers are quick to tap the values provided by advanced technologies to make their end-to-end supply chain more resilient and cost efficient. Advanced technologies (such as artificial intelligence, robots, virtual realities, cloud computing, blockchains, and 3D printers) are making it possible for firms to monitor operations in real-time, adjust inventory and supply sources, as well as make early interventions. In addition, they are helping firms to streamline complex supply chain operations and reduce the time needed to train workers to be ready for repurposing supply chain operations. Firms are riding on the wave of digital transformation to gain many benefits in the supply chains, including:

Transparency and Predictability. Firms need time to align resources and capabilities to better deal with uncertainties (Ferdows and De Meyer 1990). To do so, firms need real-time data, not just on the internal operations but also on the upstream and downstream of the supply chains. Technologies such as artificial intelligence (AI), blockchain, and the Internet of Things (IoT) allow firms to digitalize their supply chain operations so that data can be shared in real time, more frequently, and captured for further modeling and analysis in order to identify trends and network dependencies. With better visibility, firms have a complete real-time view of the supply chain inventory and status and can take proactive risk mitigation measures as needed. For example, firms can adjust inventory decisions in anticipation of potential disruptions or changes in market needs. Gap, a leading fashion retailer, is using AI and machine-learning tools to better allocate its inventory; that is, to predict demand for styles, colors, and sizes as well as forecasting ahead of and during seasons, considering factors such as the weather to anticipate market needs (Broughton 2021). In addition, firms could use advanced algorithms and simulations to develop a "digital twin" of their supply chain operations in a virtual world. A supply chain digital twin is a digital replica of the physical supply chains (including management processes). Firms could use the supply chain digital twin to test scenarios, model different flows, identify the chokepoints, identify optimal worker–machinery interactions, and understand how disruptions could spread through the supply chains. In addition, data collected from the digitalized operations could be used to train predictive models to obtain more accurate forecasting.

Repurpose Production and Ramp Up of Volume. During the COVID-19 crisis, many firms experienced either a sudden drop or increase in market demand. For some firms, almost overnight, their main products were no longer in demand in the market. For example, a digital luggage lock manufacturer experienced almost zero sales during the two years of the global lockdown, whereas a personal protection equipment (PPE) firm saw a sudden, big surge in demand overnight. In addition, governments around the world strongly encouraged firms to repurpose their supply chains to address the shortages of critical items, such as PPEs and ventilators. Hence, firms must develop the capability to repurpose their manufacturing to keep supply chains working during disruptions. Modeling tools, cloud computing, and digital twins make it possible for firms to repurpose manufacturing operations for those goods that are in high demand. Digital technologies, such as 3D printing (or additive manufacturing), enable rapid prototyping and make it possible for firms to affordably produce a broad range of components and products in a short period of time (see Table 9.2). Many firms are not able to respond quickly to any disruptions or sudden changes in demand because of long lead times (days or weeks) to order and transform raw materials into finished goods. Digitalization of supply chain operations will make it possible for firms to quickly respond to: a) pivot to manufacture different products to meet market needs; and b) to ramp up production volume to meet high demand.

Remote Working and Training Flexibility. An obvious downside of social distancing for firms was the shutdown of factory operations. Today, advances in 5G technologies, virtual meetings, and digitalization of working processes allow hybrid/remote working as well as flexibility in where and when people work. Remote working also helped firms to comply with the COVID-19 social distancing guidelines. Virtual reality and augmented reality are powerful virtual training tools that provide workers with immersive learning experiences that allow them to grow knowledge and develop new operational know-how skills. Digital training tools provide flexibility, allowing firms to remotely train their workers in combination with the ability to test the workers' newly gained skills and knowledge at any time. Table 9.2 summarizes some of the key digital technologies and how they could be used to support supply chain resilience.

Table 9.2: Key Digital Technologies and Their Possible Use to Support SC Resilience

Digital Technologies	Applications	Supply Chain Resilience: Transparency and Predictability	Supply Chain Resilience: Repurpose Production and Ramp Up Volume	Supply Chain Resilience: Remote Working and Training Flexibility
Artificial intelligent (AI)	Advanced algorithms and machine learning can process large volumes of data and solve problems at higher levels of speed and accuracy. AI can support accurate demand prediction and facilitate smart decision making in supply chains.	✓	✓	
Internet of Thinks (IoT)	A system of connected, smart sensors that could collect, share, and analyze real-time data. Widely used in inventory management, maintenance, transportation, and production.	✓	✓	
Blockchain	A digital ledger that provides digital evidence of what is occurring in the supply chain. The shared ledger facilitated “trust” among network members and cut down lead times and paperwork.	✓	✓	
Digital twin	Living replica of supply chain processes and systems. Based on real-time data, firms can gain end-to-end supply chain visibility and test various supply chain disruption scenarios.	✓	✓	✓
3D printing	3D printing (additive manufacturing) makes it possible for firms to manufacture components in factories, hence shortening manufacturing lead times and reducing reliance on` overseas suppliers.		✓	
Robotics	New advancement in Cobots (robots that directly interact with workers) that boost productivity and support rapid production ramp up. Robots and automation allow firms to operate longer hours without health and safety constraints.		✓	✓
Virtual reality/ Augmented reality	Virtual reality (VR) and augmented reality (AR) allow firms to rapidly develop digital training packages and simulate supply chain operations to train or reskill workers. Self-isolated workers also have the flexibility to train and learn new skills remotely.		✓	✓

Source: Kim Hua Tan.

9.4 Building Digitalization Capabilities for Supply Chain Resilience

COVID-19 has shown that firms with poor end-to-end visibility supply chains are vulnerable to disruptions. Many studies have indicated that digitalization of supply chains using advanced technologies can improve supply chain visibility and resilience (Zouari, Ruel, and Viale 2020; Kittipanya-Ngam and Tan 2020; Iftikhar et al. 2022). But how can firms build supply chain resilience with digitalization, and where should they start? There are many general-purpose frameworks available in the literature to provide firms with an overview of digital technologies and challenges in the supply chain digitalization process. Some of these frameworks allow firms to assess their digital maturity, but they are general purpose and not cut out for the supply chain resilience task. To develop a sustainable digitalization capability for supply chain resilience, a robust digital backbone, a digital twin, and an enhanced digital workforce are some of the key value levers that firms must pull. Figure 9.2 illustrates the proposed building blocks of supply chain digitalization capabilities for supply chain resilience. The triangle constitutes the boundary of the supply chain digitalization, enclosing the capabilities on which it relies. The arrows on the triangle boundary stipulate the coordination being applied. The triangular shape is convenient for representing hierarchic structures and has no other significance.

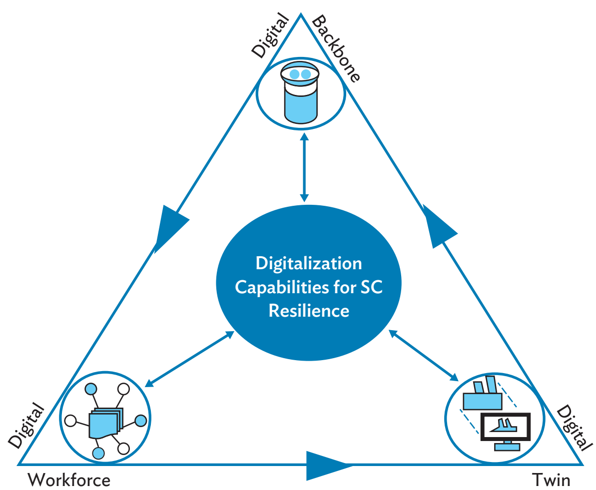
9.4.1 Digital Backbone

In order to achieve end-to-end supply chain visibility, firms need to capture vast amounts of real-time data (inventory, delivery, weather, production, worker availability, sales, etc.) all along their supply chains (Zhan and Tan 2017). This includes data collected from different sources, such as: radio frequency identification (RFID) tags; global positioning systems (GPS); loyalty cards and Point of Sale (POS) transactions; and data emitted by social media feeds and equipment sensors. From the collected data, firms could utilize artificial intelligence, machine learning, and other game-changing data analytics to gain better insight into supply chain operations and provide better value-added services to customers (Tan et al. 2015; Tan et al. 2017). For example, data collected on suppliers' on-time deliveries, average lateness, and degree of inconsistency are valuable to firms in making inventory decisions, such as how much extra stock needs to be held, where it should be held, and when to hold it to keep the supply chain running reliably.

Hence, a supply chain "digital backbone" is needed to coordinate the seamless collection, sharing, and integration of data along the supply chains. Firms need to establish the key digital technologies that underpin the entire supply chain ecosystem so that sensors in different domains and platforms can connect to/communicate with each other and so that firms can have access to data in real time. The digital backbone is a secure, firm-specific digital architecture that is comprised of smart platforms, cloud-based applications, automation, and lean processes. Firms need the digital backbone to deliver real-time supply chain visibility to mitigate uncertainties. Apart from linking the technologies and data collection sensors, a digital backbone should also drive real-time interoperability across domains and platforms of the supply chain stakeholders (suppliers, partners, logistic providers, and customers).

Developing one's own cloud and platform systems may be costly and time consuming. Therefore, firms could leverage and take advantage of existing innovative Platform-as-a-Service (PaaS) and Software-as-a-Service (SaaS) solutions available in the market. When evaluating the option, firms need to assess the cost and speed of deployment as well as the pros and cons of public and private cloud and data centers.

Figure 9.2: Building Blocks of Digitalization Capabilities for Supply Chain Resilience



Source: Kim Hua Tan.

9.4.2 Digital Twin

Considering the fast-changing business landscape and frequency of disruptions, the old way of theoretical modeling and simulation to enhance supply chain resilience is no longer adequate. When complex, interrelated events interact with one another, the existing model-based systems lack closed-loop information control capabilities to cater to the uncertainty during disruption. To strengthen the supply chain resilience in a proactive manner, a digital supply chain twin, which refers to a digital replica of the physical supply chain, is required (Ivanov and Dolgui 2020). The information that physical supply chains provide, such as transportation status, production level, customer demand, and inventory level, can be collected in real time for firms to monitor and make decisions. A digital twin enables the simulation of a supply chain to evaluate the disruption propagation and its impact. Via the digital twin, firms can model and predict the relative impact of different sources of uncertainties in the supply chains as well as measure the indirect effect of uncertainty on downstream or upstream echelons in the supply chain. As a result, the recovery policy, remedy measures, and contingency plans to address the identified disruptive events can be proactively formulated. Firms could also examine and understand the possible impact of adjusting inventory parameters across supply chains and the implication on costs and customer service.

The data sources enabled by the digital backbone need to be seamlessly integrated and updated to the supply chain digital twin in real time. In addition to supply chains, there are digital twins for products and infrastructure. For example, a product digital twin can help firms reduce development time and, hence, time to market as well as to improve product quality. Firms can do many rapid iterations and optimizations of product designs and manufacturing processes using the product digital twin to eliminate potential design flaws.

The full value of the supply chain digital twin relies heavily on the amount of high-quality data from multiple sources that the twin would require. In addition, it will often require a highly skilled workforce with strong simulation and analytics capabilities.

9.4.3 Digital Workforce

Cloud platforms and collections of Software-as-a-Service-based team productivity applications are the backbone and foundation for supply chain digital transformation. Needless to say, the knowledge and skills of a firms' workers in the areas of intelligence, machine learning, data analytics, and process automation will be critical in continuing their supply chain digital transformation. Therefore, the upskilling of workers' digital capabilities for a digital age is essential to supply chain resilience. Digital technologies and workers' dexterity and behaviors toward them are key for successful digital transformation. Moreover, as the digital technologies landscape is rapidly changing, firms need to constantly develop reskill strategies to have the right capability, size, and shape of the worker digital dexterity.

There is no one-size-fits-all approach to upskill workers' digital dexterity. Firms can grow talent internally or via an external pipeline using apprenticeships and graduate schemes. Firms can rely on external talent to fill immediate digital capability gaps, but they also need to establish a roadmap for how to best upskill the existing workforce. One thing is clear: high workers' digital dexterity will increase the firms' digital transformation. Accordingly, sound talent management and incentive schemes would be required.

9.5 Recommendations for Practitioners

Recent COVID-19 pandemic disruptions, the United States–People's Republic of China trade war, and the Russian invasion of Ukraine have all clearly shown the world that lean and agile operations are not enough to help firms withstand uncertainties. A resilient supply chain demands a short and quick response time, time to recover, and time to thrive in all three stages of the disruption. Firms need to develop capabilities to repurpose existing supply chains and invest in technologies. It is necessary for firms to be able to digitally model the propagation of uncertainty up and down the supply chains and to use the outputs of the model to support strategic decision making about supply chain operations. Fortunately, firms could tap into advanced technologies, such as AI, IoT, Blockchain, robotics, VR/AR, and simulation models to transform and gain better end-to-end visibility to achieve supply chain resilience. Supply chain digitalization enables firms to connect and integrate complex operations at multiple levels and to grasp dynamic operations in real time. The time required to detect potential disruption, its scale, the duration of disruption, and the recovery time is key for supply chain resilience and to maintain satisfactory service levels to customers.

The study highlights for supply chain practitioners and policymakers how to develop digital technologies capabilities to strengthen the supply chain resilience to withstand future uncertainties. A framework for digitalization capability development will provide clarity and help firms to identify the coordination needed to achieve resilient growth. Supply chain digitalization enables firms to proactively identify and manage risks, particularly since many of the conventional supply chain risks stem from a lack of collaboration and visibility (Alicke and Swan 2021). Digitalization offers accuracy and transparency to enhance the overall resilience across all members of the supply chain networks, from raw material suppliers, logistics providers, warehouse operations, and retailers to customers. Good supply chain visibility and assessment enables firms to understand current pain points and vulnerabilities at the supplier level and assess the level of exposure to uncertainties. Supply chain digitalization transformation is key to support the 3Rs of resilience. "Readiness" refers to a firm's ability to ensure continuity of supply chain operations and quickly recover from external disruptions. "Responsiveness" refers to a firm's ability to restart the supply chain after complete stops and redesign/reconfigure the supply chain to meet new demands under/after external disasters. "Reinvention" refers to a firm's ability to quickly and accurately respond to the fast-changing customer demands and market needs. Practitioners could also capitalize on the new digital capabilities to realign supply chain capabilities and develop competitive advantages for the next normal.

Before embarking on the digitization journey, firms need to be aware of the resource requirements and consider existing digital maturity. Several questions should be considered. What cloud-based systems and platforms are required to collect, share, and analyze data seamlessly? How can a firm tap into the real-time data feed to enhance decision making? What degree of upskilling is required to build a digital-enhanced workforce? This study points out the building blocks of capabilities required for building supply chain resilience with digitalization. If developed, these capabilities can provide strong support for firms seeking to efficiently deploy digital solutions to enhance supply chain resilience. Implicit in the architecture is the assumption that firms have the means and resources to build the capabilities.

A sound and robust supply chain transformation draws heavily on a clear, prioritized set of cloud-based digital platforms and solution requirements in terms of the criticality of the supply chain operations issues that need to be addressed. Firms need to ensure that the bolt-on systems have high connectivity with existing operating systems and that both the firm internal and external supply chain members have instant, secure, and private access to this data. To gain a better competitive advantage, firms need a digital architecture that serves as the backbone connecting their core assets and operations that enable an integrated and seamless way of working. Firms should envision the connected, digitalized supply chain operations as a living organism that could respond to uncertainties and disruptions in real time, without sacrificing high quality products and innovative services for customers.

With seamless interoperability of the connected platforms and systems, firms can tap into the data to develop a model of each specific supply chain process and system to monitor performance in real time. In other words, the digital twin is a living model of the supply chain physical asset and system. Through the up to date and analytical insights gained from the digital twin, firms could make timely decisions and interventions to maximize performance in terms of product quality, cost, responsiveness, and service delivery. Nonetheless, investing in digitalization is not enough; firms also need to enhance workers' digital capabilities as part of building a digitalized supply chain. An enhanced digital workforce is the fuel for digital transformation. To do this, firms need to keep pace with the rapidly evolving digital technologies and to anticipate the skills that will be needed in the future.

The proposed digital backbone, twin, and workforce triangle do not comprise a supply chain resilience solution but rather a navigation towards a proposed digitalization end-to-end operation for better visibility. The building block architecture of capabilities is general and should be applicable to practitioners keen to develop digital supply chain solutions. The architecture enables practitioners to decompose firm-level capabilities to be as detailed or focused as required. For example, the digital backbone that underpins a production line, the digital twin that populates it, and the workforce that manages it feeds and modifies it and so on. But bear in mind that each of the building blocks can trigger a paradigm shift for supply chains. Hence, practitioners may consider a fundamental change to the supply chain configuration and order a penetration/decoupling point to best exploit the potential of integrated digital technologies. In addition, introducing resilience metrics into KPIs helps firms ensure supply chain decisions are made to balance cost, efficiency, and performance. Given that supply chain disruptions are fast changing, firms should conduct regular stress tests and reviews to ensure the resilience KPIs remain appropriate. Lastly, firms will also need a flexible, robust management control system and an agile organizational structure with a dedicated team to proactively respond to challenges faced in the fast-changing digitalization journey.

9.5.1 Recommendations for Policy Makers

The digital transformation is driving swift changes in the global supply chain at an unprecedented scale. At a time of rapid change and high uncertainty, policymakers in developing Asia and the Pacific need to provide the best support and resources to allow firms to ride the wave of digitalization. This is to build up supply chain resilience to gain competitive advantages. Firms need support and guidance on what digital technologies are being adopted and how and where to acquire them. They also need conviction that their supply chain security is robust and protected before data is shared with members of the supply chain.

The following recommendations on digital backbone and digital talent are to help policymakers better identify vulnerability, anticipate disruptive changes, develop a digital workforce, promote digital security, and develop innovative policies to support firms' digitalization.

Digital Backbone

Excellent telecommunications and digital infrastructures are the backbone of any successful digital transformation and are fundamental to a thriving digital economy. The government's digital strategy and masterplan should ensure that fundamental telecommunications and digital infrastructures are sound with good broadband coverage both in urban and rural areas. Every corner of the country needs to meet the international standard, a secure digital infrastructure so that firms and consumers can access the connectivity they need – at home, office, or transport. Policymakers need to make significant progress in rolling out wireless connectivity and improving coverage.

Digital data security policy should not only narrowly concentrate on national security but also direct more attention to the economic and social dimensions of digital security. Outstanding connectivity should be coupled with sound data protection laws. Policymakers in developing Asia and the Pacific should ensure local data protection laws are compatible with the regional and international standards of data protection. To do this, policymakers should promote the digital security strategy via relevant ministries at the government level.

Policymakers should bring forward or reform legislation to safeguard the responsible use of personal data – which is key for global competition – to provide firms with the clarity and confidence they need in the supply chain digitalization journey. Another key point is that policymakers in developing Asia and the Pacific should seek international compliance and agreements to facilitate the free flow of data with trust and avoid data localization if possible. In other words, a strong and trusted digital economy is the engine for thriving economic growth. This is the reason legislation and laws should keep pace with digital technology development, continuing to provide firms with the latest tools, knowledge, products, and services to operate safely Other crucial steps in delivering the secure digital backbone foundation are the inclusion of more publicity and materials to raise awareness as well as instilling a positive digital data security culture among users.

In addition to speeding up digitalization, solid telecommunications and a digital backbone with safe digital data could also add value in the following areas:

- **Promote electronic commerce** – Although electronic commerce exploded during the COVID-19 disruption, policymakers should do more to promote the growth of electronic commerce and to increase national capacity for firms to implement it.
- **Ensure service delivery quality** – An integrated digitalization can enable essential government services to be delivered in a responsive and people-centered manner and better accommodate the needs and expectations of firms.
- **Protect firms from fraud and data theft** – A robust digital data security strategy will ensure sensitive customer and worker data is protected at its source. Firms are able to provide a world-class trusted digital experience that earns workers' trust and customers' loyalty.

Digital Talent

Policymakers in Asia and the Pacific should be aware that the digital backbone is as much about digital talent as it is about data and security. The rapidly changing world of work practices will require our workers to upskill and learn new digital skills to remain relevant. Hence, successful exploitation of the digital backbone will require firms to transform and embed their workforce with digital skills. As the pace of digitalization is globally gaining momentum, the demand for digital talent is high. Thus, policymakers need to invest in developing and nurturing a digital workforce, offering accessible training opportunities, and a full commitment to equip the workforce with digital competence so that there is a sufficient supply of digitally- and technology-enabled workers at all levels. To unlock the full potential of digitalization and to improve the availability of digital talents, the following recommendations are suggested for the policymakers in Asia and the Pacific:

- **Enlarging the digital education channel and occupation pathways.** More resources should be invested to strengthen the pipeline of knowledgeable and digitally savvy teachers. This ensures that digital and technology courses are well taught in schools and universities. With the right teaching and training infrastructure, it is possible to improve digital education in schools and increase the number of undergraduates and the digital skills of the next generations to enter the workforce. Policymakers should also ensure that young people are aware of the breadth of digital careers and opportunities. Government websites should be available for them to learn about various digital career information and demonstrate how various pathways of skills, qualifications, and apprenticeships align to an occupation.

- **Supporting lifelong learning and continuous improvement.** The policymakers should provide various channels (digital bootcamps, skill retraining programs, etc.) for workers to reskill for digital roles in the dynamic job market. Scholarships and bursaries should be made available for workers from underrepresented groups to develop the talent required to support the cutting-edge digital job market. To enhance the learning experience and knowledge acquisition, it is vital for learners to understand and be aware of their digital skills level. Hence, policymakers should work with teachers and practitioners to develop a digital skill framework to effectively identify workers' digital talent levels so that they could be referred to the appropriate level of advanced, intermediate, or foundation digital courses. Policymakers should also explore whether the existing tax mechanism is adequate to incentivize firms to invest in high quality training and continuous improvement. The idea is to bring in firms and universities so that they, too, have vital roles in developing workers' digital skills capabilities.
- **Competing for global talent.** It is well understood that global talent can improve firms' digital intellectual capital and complement the domestic digital workforce pipeline. Policymakers should streamline processes to enable firms to quickly, easily, and globally attract the best digital talent. For example, the UK government is launching various initiatives, such as the Global Talent Visa and Global Business Mobility, to reform and expand several existing pathways to allow firms greater flexibility in transferring digital skills workers from overseas to the UK via a fast-track pathway (UK Government 2022).
- **Cultivating an innovative digital culture.** Practitioners can easily explain to policymakers that acquiring digital talent won't be enough. To realize **the full potential** of supply chain digitalization, firms need to foster an agile and innovative culture in which workers could confidently find new ways to capitalize on the digitalization across the supply chain operation and business domains. Hence, policymakers should collaborate with firms to develop initiatives to cultivate an innovative digital culture that encourages creativity and risk taking and disintegrates the barriers to innovation and exploitation.

- **Boosting leadership and management capability.** A fish rots from the head down. Acute leadership and management capability in the digital era is key for successful digital transformation. Digital talent is not enough without the right leadership to innovate the business model and consider how to adopt and invest in new digital technologies to fuel growth and success. Firms often experience lengthy and difficult processes to integrate new technologies, select the right software or technology platforms, and obtain financing. It is important to note that to maximize the operation's effectiveness, a digitalization process will often lead to organizational restructuring as well. Likewise, policymakers should ensure there are dedicated online support services available to offer free and impartial advice to managers: a) on what technology platforms are best for digitalization; b) guidance on early preparation before placing the order; and c) the type of organizational structure that is suitable for the digital era, control systems, and decision-making processes. A supply chain digitalization mentor scheme will be a good start on addressing the leadership and management challenge in Asia and the Pacific. The UK Help to Grow Management scheme (Help to Grow 2023) is a good example of how to support leadership development with expertise linked to industrial digitalization and resource efficiency.

The process of digitalization of supply chain operations can be costly and time intensive. Hence, the policymakers in Asia and the Pacific should be aware that firms need a steady stream of capital to invest and grow. Enabling the availability of funding and improving access to capital across all stages of the digitalization lifecycle is an essential prerequisite of digitalization. The policymakers in Asia and the Pacific should ensure the availability of capital and a funding ecosystem to support firms in the digitalization journey. The majority of the firms in Asia and the Pacific are small- and medium-sized firms (SMEs). Therefore, these SMEs need access to government business support schemes to expand and invest in digital technologies in order to join the global digital bandwagon. Digitalization is a continuous process, and more scale-up investments will be needed in its later stages. Policymakers should remove obstacles for SMEs to seek overseas investors for investment in digitalization if needed. Moreover, an SME advisory service for supply chain digital adoption should be established to provide much-needed impartial advice on technical, process, and change management expertise.

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10

The Surprising Developments of Digital Supply Chains to Raise Resilience in the Face of Disruptions

Carlos Cordon

10.1 Introduction

In recent years, supply chains have been facing constant disruptions of a magnitude unparalleled in history, from COVID-19 to the Russian invasion of Ukraine, that have exposed the great fragility of our supply chains. Consumers have been facing a series of stockouts in the last few years, from the panic buying of toilet paper at the beginning of the COVID-19 pandemic, to delays in getting new cars from manufacturers, to recently finding out that sunflower oil was not widely available due to the Russian invasion of Ukraine.

Consequently, there is a big emphasis on how to increase the resilience of supply chains, both from governments and companies. Scholars and executives (Buatois and Cordon 2020) have even suggested that company boards should stress-test the resilience of their supply chains similarly to the stress test of financial institutions in the aftermath of the financial crisis of 2008. Very recently, governments around the world (from the Biden administration to the European Union) have passed legislation aimed at increasing the resilience of the supply chains in different "strategic" sectors like food, pharmaceuticals, and micro-electronics. Thus, there is widespread effort to make our supply chains more resilient in the face of "waves" of disruptions.

In a parallel way, during the last few years, the digitalization of supply chains has been praised as a solution to many of the challenges facing different industries. In the early 2010s, many executives, consultants, academics, and governments expected the digitalization of supply chains to deliver billions in savings and to increase the value they created. A prime example was the initiative by the German government regarding Industry 4.0, whose objective was to help German companies to implement digital technologies to attain the benefits derived from those advanced tools.

During the 2010s, initiatives to push the digitalization of both factories and the complete supply chain proliferated, like the example of lighthouses where companies would use one factory as an example of how digitalization might help to increase value and productivity. Some of these initiatives delivered on the promise of savings and more value created. Quite a few created acceptable returns and many others failed to provide almost any benefit (Büyüközkan and Göçer 2018). Interestingly enough, many research papers and consultants claimed that around 70% of those "digital transformations" failed to deliver the expected results.

While many of these digital initiatives were originally driven towards lowering the costs or "creating a competitive advantage by transforming" the industry, the recent wave of disruptions has changed dramatically the context and even the purpose of supply chains. In a stable context, the main objective of supply chain executives was to minimize cost for a given level of service and a given quality level. In a context of very high instability, the objective is not to minimize cost but to maximize availability and fast service, to profit from the scarcity of products.

Such a fundamental change in the objective of supply chains has pushed the emergence of some digital solutions that provide unexpected benefits for resilience, while the initiatives focusing on lower costs in a stable environment have lost momentum. For example, relatively straightforward digital communication tools have proven to be very useful in managing disruptions, while sophisticated tools like the IOT for digital twins of machines are not being pursued strongly because many of their benefits are not so relevant in a very unstable environment.

Additionally, the recent drive towards sustainability has made the situation more complex, leading to many companies looking for digital solutions to manage such complexity. For example, because of the huge demands for reporting, many global companies are developing and adopting digital solutions because it is simply impossible to fulfill the reporting requirements in a nondigital way. In a recent case study about the global company Henkel (Wellian and Cordon 2022), it is described how challenging it is to obtain the required information about the consumption of energy by its customers using their detergents, as they have millions of consumers. The only accurate way of tracking the consumption patterns of millions of consumers is by using digital technologies.

In this chapter we explore how digital developments in supply chains are having a positive effect on resilience and why some digital initiatives have failed to deliver any benefit. Specifically: (1) we explore how management for resilience is fundamentally different from managing for low cost; (2) we explore the development of a framework to try to understand the logic behind the impact of digital tools on resilience; and (3) we conduct a discussion on what could be the future evolution of digitalization of supply chains and its impact on resilience.

Spieske and Birkel (2021) have performed an extensive literature research on papers examining the effect of digital technologies on resilience, but logically their data are based on papers published mainly before 2021, so most of them do not consider the events of COVID-19 and the Ukrainian war. They conclude that only big data analytics seem to help to increase the reliability of supply chains. Given the recent events of such an unprecedented magnitude, we base our research on very recently published cases and on conversations in forums with practitioners. Thus, in the paper some hypotheses are proposed, but there are not yet enough data and experience to build a database and test propositions. Our objective is to provide a taxonomy that could be the basis for future empirical research.

10.2 The Objective of a Supply Chain: Resilience vs. Cost Minimization

10.2.1 Focus on Cost Minimization

During the last few decades companies and researchers have focused most of their objectives and research on how to reduce cost. The objective function of supply chains was minimizing cost while providing a given service level (often in the high 90s) within a given quality level (often close to 100%).

Executives pursued strategies of factory focus and low-cost country sourcing to minimize costs. Focusing factories on the production of the biggest possible quantity of the same or similar products makes it possible to obtain economies of scale and follow the learning curve as fast as possible. We have seen over the last few decades a constant reorganization of supply chains by closing factories to focus on the biggest ones and rationalizing warehousing and transportation to reach economies of scope. In the same vein, companies have followed a very strong policy of offshoring, looking for locations with lower costs, availability of labor, and regulations whose fulfillment requires lower costs.

Researchers have developed models and frameworks to understand how to minimize costs and how to make decisions about sourcing locations (Daehy et al. 2019), outsourcing (Heikkila and Cordon 2002), and offshoring. In the field of operations, there are many academic papers on improving algorithms to minimize costs in different production settings. There are also quite a lot of models and empirical research about outsourcing and offshoring, ranging from competencies in outsourcing to how to develop a partnership with offshoring partners.

This drive to minimize costs is reflected in how the different digital initiatives in supply chains were focused and evaluated by companies before 2020. As an illustration, in the case of Faurecia (Kumar et al. 2019), the company evaluated the different technologies used in the digital transformation almost exclusively on cost savings.

While it could be argued that there are some notable examples of both executives and academics developing initiatives to increase agility and, therefore, resilience, they remain exactly that, notable exceptions: for example, the case of Philip Morris International (PMI) receiving a prize from the Gartner organization because of the development of their Digichain, a very agile digital supply chain that provides the flexibility needed to support their changing business model from cigarettes to electronic heating devices (Wellian and Cordon 2020). In that case, they reduced the time to volume from four months to seven days.

Similarly, academics have developed models and theoretical research about the potential benefits in terms of flexibility of using digital supply chains, but still most of the efforts have been about cost minimization. It should be noted that given the tradition in academic research about the effects of flexibility and time-based competition, there are quite a few models that could prove very useful in helping practitioners to understand the flexibility of trade-offs with respect to cost minimization.

10.2.2 The Emergence of Resilience

Because of the disruptions faced over the last few years due to COVID-19, a lack of availability of truck drivers, the Suez Canal blockage, the Russian invasion of Ukraine, and so on, consumers have experienced shortages and companies have not been able to deliver the levels of service they have been used to. These dramatic changes have made visible the fragility of supply chains in such a very uncertain environment.

Being able to cope with these disruptions in a supply chain is what many people would define as resilience. An accepted definition of supply chain resilience would be "the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function" (Ponomarov and Holcomb 2009). Another definition is provided by Ponis et al. (2012) through a systematic review of the literature, in which they define supply chain resilience as "the ability to proactively plan and design the supply chain network for anticipating unexpected disruptive (negative) events, respond adaptively to disruptions while maintaining control over structure and function and transcending to a post-event robust state of operations, if possible, more favorable than the one prior to the event, thus gaining competitive advantage." These definitions do not distinguish between the type or severity of unexpected events or disruptions.

The level of disruptions since the COVID-19 surge has been of a much higher level than before and, we argue, we need to understand how those disruptions have affected our supply chains and what would be an appropriate definition of resilience under those circumstances. We are going to review a few of the different types of disruption and infer what would be an appropriate definition of resilience for those circumstances.

Temporary Disruptions

The first substantial type of shortage globally happened in the spring of 2020 with the surge of COVID-19 infections and the consequences of the containment measures. News of shortages of toilet paper was controversial because consumers were buying large quantities of the product in anticipation. The news was particularly noticeable because arguably the consumption of toilet paper is a very stable one, and the surge of COVID-19 shouldn't have any impact on its consumption.

This first wave created an initial dilemma in the management of the supply chain: should toilet paper manufacturers expect a long-term increase in the consumption of toilet paper or is it just a temporary increase in demand. It was obvious that it was a temporary increase, so manufacturers raised the production volumes in the short term as much as they could, but they didn't plan for any additional long-term capacity. This happened with quite a few consumer products in different continents (e.g., soap, canned ravioli). In this case, many experts would qualify resilience as the capacity of the supply chain to adapt to that temporary surge of demand and maintain the level of service as it was before the disruption.

Huge Demand Increase

The second type of shortage was the lack of many of the healthcare materials needed for personal protection and for taking care of COVID-19 patients. The challenge here was that the demand increased manyfold for products like masks for personal protection and ventilator machines to help patients to breathe. The logical reaction was to multiply capacity in manufacturing and throughout the supply chain to be able to cover the needs.

In this case, the definition of resilience becomes more problematic. Some experts would suggest that being able to deliver under such an increase in demand goes way beyond resilience; some estimates indicate that the demand for masks was 12 times the capacity of the main producer, the People's Republic of China (PRC) (OECD 2020).

By contrast, the increase in the demand for ventilators was around 300% and the demand had returned to normal by the end of 2020 (GlobalData Healthcare 2021). In the case of ventilators, it could be argued that a resilient supply chain should have been able to cope with the increase in demand to later resume its normal operation. Nevertheless, the dramatic situation of patients not being taken care of led to many different types of companies in different industries trying to produce those ventilator machines.

While it could be argued that no supply chain could ever manage this kind of huge increase in demand, some proponents of digital technologies like 3D print claim that in the future technology could be able to cope with such situations.

Structural Supply Chain Fragility

A surprising third type of shortage has been the lack of capacity of car companies to cover the demand. Different estimates indicate that car production was reduced by around 11.3 million in 2021 (Statista 2022) because of a shortage of semiconductors. The situation of the car industry deserves further elaboration to create an appropriate understanding of what resilience would mean in this supply chain.

Before the pandemic, quite a few experts in the automotive industry expected car sales to stabilize and peak around 2020 due to consumer trends (sustainability, new generation, uberization, etc.). Many car companies reacted accordingly, planning for a reduction in capacity over the years. Thus, the supply chain of the car industry was designed for a stable or slowly declining demand.

When the coronavirus outbreak started to have a global impact, many car companies were forced to close their factories and they also planned for a very substantial reduction in consumer demand. On 17 March 2020, Volkswagen, the world's biggest car maker, suspended production at factories across Europe (Reuters, 17 March 2020). The expectation was that consumers would stop buying cars, the world would enter an economic recession and that, consequently, demand in the long term was going to be way below the plans before the pandemic.

Car companies warned their suppliers that they would not accept further deliveries because production had been stopped, and that the expectation was a much lower demand going forward. In turn, the suppliers to the car companies went to their own suppliers, the semiconductor manufacturers, and canceled their orders. The reaction of the semiconductor manufacturers was to reduce the production of microchips for the automotive industry and, when possible, to move their production capacity to consumer electronics (which by that time was seeing an increase in demand as consumers were buying a lot of products for the home). Also, semiconductor manufacturers traditionally had a much higher profitability in consumer electronics than in automotive semiconductors.

While this was very much the case through the spring and summer of 2020, the demand for cars surprisingly started to increase in the autumn of 2020. GM (General Motors) reported a 4.8% increase in US sales in the fourth quarter of 2020, Toyota reported a 9.4% increase, and Volkswagen a 10.8% increase (Reuters, 5 January 2021). Some experts indicated that some consumers were reluctant to take public transport because of the risks of contagion and that the economic measures by governments providing subsidies for consumers helped to avoid a recession. When car companies went back to their suppliers, who in turn went to the semiconductor manufacturers with an increase in demand after having almost stooped the whole supply chain, the capacity was not there. On top of that, the industry is undergoing a massive change to electric vehicles, which require many more semiconductors.

Some experts argue that the automotive supply chain executives created their own fragility by (1) having a supply chain in which semiconductor manufacturers captured a very low part of the total value created, (2) reacting brutally when the disruption started, basically turning their back on suppliers, and (3) completely mispredicting the evolution of the market (both in terms of demand volumes and types of cars) (McKinsey 2021).

In these types of cases where the industry developments by its different organizations have created a structural fragility, resilience could be the capacity of the supply chain to adapt to disruption and changes in demand. However, it is not clear whether recovery means going back to the previous situation, because in the case of the automotive industry, the demand going forward from 2022 is very different from the one before. The obvious example is the huge demand for electric cars, as this is very different from the one experienced before the pandemic.

Finally, in the case of the car industry, it is also fair to question whether the lack of resilience has been detrimental for the industry or just for the consumer. An anecdotal illustration is presented in Table 10.1, which shows the quantity of cars sold by three leading companies in 2021 in comparison to those sold in 2019. (We chose GM, FORD, and VW (Volkswagen) because they are leading companies, and the period is the same.)

Table 10.1: Comparison of Global Sales of Cars in 2021 Vs. 2019 by Three Leading Companies (car figures in millions; revenue and profit figures in $ billion)

Company	Cars Sold 2021	Cars Sold 2019	Revenue 2021	Revenue 2019	Profits 2021	Profits 2019
GM	6.29 M	7.72 M	127 B	137 B	10 B	6.7 B
FORD	3.90 M	5.50 M	136 B	156 B	18 B	6.4 B
VW	8.90 M	11 M	250 B	253 B	20 B	19.3 B

Source: Created by the author.

As can be seen in Table 10.1, in 2021, these three leading companies sold 21% (5.1 million) fewer cars than in 2019 and had 48% higher profits in 2021 than in 2019. Thus, even though their supply chain was not resilient enough to adapt to the increase in demand and the shortage of semiconductors, their business had record profits.

Disruption of Transport Services and Basic Infrastructure

A fourth type of disruption is the disruption of transport and basic infrastructure. In 2020, it had already become very difficult to ship products around the world. The closure of borders and the confinement imposed to stop the pandemic meant that many transport and basic infrastructure services were no longer available.

Governments were very conscious of the consequences of confinement restrictions and allowed strictly necessary transport and basic infrastructure to continue working. However, while companies believed that once those restrictions had been relaxed those services would go back to normal, that didn't happen. Prices of containers skyrocketed, as well as transport costs, and there were bottlenecks in global supply lines. On 5 July 2021, the *Wall Street Journal* reported that the average price worldwide to ship a 40-foot container had more than quadrupled in one year to $8,399 on 1 July 2021 (WSJ, 5 July 2021).

Over the last two years, the Suez Canal became blocked, and shipping ports experienced huge traffic jams, strikes, and even paralysis at times because there were not enough truck drivers to transport all the unloaded containers. Finally, the zero-tolerance policy for COVID-19 in the PRC meant that some of the busiest ports in the world would be stopped for several days or weeks because just one coronavirus case had occurred.

In the case of disruptions, many supply chains simply became blocked and the challenge was to find alternatives, i.e., air transport or suppliers in different continents. Resilience in this case would be being able to adapt and find a response that would allow the supply of the product or the service to continue.

Disruption of Local or Nearby Services or Infrastructure

The fifth type of disruption is the one that we have used for decades when defining resilience, that of a specific service or infrastructure being disrupted – for example, when there are strikes or local disruptions that affect a part of the supply chain. An anecdotal example is the lack of truck drivers in the UK (United Kingdom) to transport gas from the depo to the gas stations.

These types of disruptions happen relatively often, are considered at a global level to be of low impact, and are the ones for which companies have business continuity plans and risk plans. The typical way of managing and preparing for these disruptions is a risk management framework that traditionally includes steps like: identifying the risk, analyzing, prioritizing, minimizing, and monitoring.

Many organizations have well-elaborated plans based on those methodologies that have proven effective with this type of disruption. The challenge is that the disruptions listed above were way beyond the risks these organizations considered. For example, almost no organization included in their business continuity plans the possibility of a global pandemic. Thus, when COVID-19 happened at a global level, those business continuity plans were of very limited use.

For this type of disruption, a localized disruption, the traditional definition of resilience is very appropriate: “the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function.”

Global Shortage of Products and Materials

The last type of disruption is the global shortage of products and materials, as has happened with the Russian invasion of Ukraine, with the world experiencing shortages of sunflower oil, cereals, and many other items. While this kind of disruption was eventually considered by military organizations, it should be said that most businesses didn’t even have in their risk plans the possibility that such an event might happen.

It should be noted that many experts consider the Russian invasion of Ukraine to be the event triggering a lot of the resilience supply chain plans by governments and companies. For example, at the start of the war, governments in countries like Egypt were very concerned that basic food would not be available in sufficient quantities for their population (Barnes 2022).

Also, for many European companies, it meant that the country risk in the east of Europe was not zero, as many have considered for years, and their supply chains were heavily affected. As an anecdotal illustration, Skoda car production was heavily affected by the war and was forced to move its sourcing of cable harnesses to the Czech Republic. This would be a typical example of managing a disruption and increasing the resilience of the supply chain, finding and developing a new supplier in a short time.

Another type of reaction by suppliers, particularly in the food industry, reacting to the shortage of sunflower oil, has been to change the composition of their products (what they call "flexible recipe") to adapt to available ingredients. It should be said that this goes against the traditional way of working for many global companies who try to "standardize" products to obtain economies of scale.

Using the stated definition of resilience, we could say that the reaction of a company like Skoda, as explained above, can be classified neatly into that definition of a more resilient supply chain that could adapt to disruptions. Similarly, the idea of a flexible recipe for food companies would fit very well into that definition.

On the other hand, it could be said that no supply chain would ever be able to support a disruption of that magnitude. The amount of sunflower oil in the global market taken out by the Russian invasion of Ukraine was more than 50% (Strubenhoff 2022). Thus, a company consuming a lot of sunflower oil can't cope with this magnitude of disruption.

10.2.3 The Dilemma of Lost Revenues Vs. Cost Savings

The main reason for organizations to focus on increasing the resilience of their supply chains is that the disruptions create losses of potential revenues because of the lack of product. It also creates potential long-term losses of market share, as customers might be forced to try competitors' products and they might keep buying them after the disruption has finished. Finally, some companies are very concerned about the damage to the brand and reputation of their companies because of the failure in servicing customers.

There were plenty of examples during the pandemic of companies losing sales because they had chosen in the past to source products from low-cost locations that couldn't deliver due to the restrictions in manufacturing and trade. Some governments' organizations, like the Danish Ministry of Industry, even conducted studies about how to help companies to find nearshoring alternatives to avoid losing production and sales.[1]

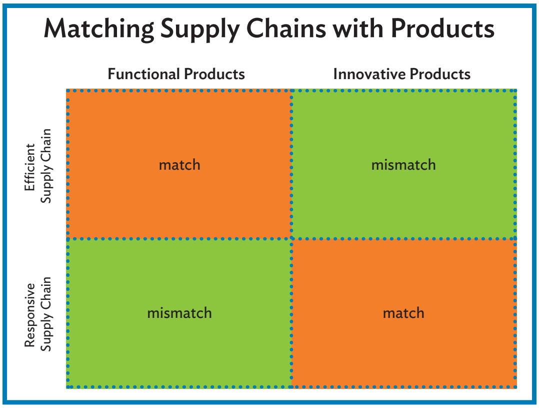
The main challenge of potential lost revenues vs. cost savings is clearly expressed in the agility vs. efficiency matrix developed by Fisher (Fisher 1997) in the 1990s and presented in Figure 10.1. In that classification the author proposes that a more efficient supply chain for a differentiated product is not the right choice because the potential lost profit due to the lack of availability would be higher than the savings obtained by reducing the production cost. Logically, the ideal would be to be the most cost-efficient producer of a highly differentiated product, but the logic is that the more efficient a supply chain is, the less capacity to change volume it has and, therefore, the less capability to react and the higher the probability of lacking supply if the demand increases.

In practice, it is not at all obvious how to make those trade-offs, because cost savings are very precise while potential sales lost are perceived as very hypothetical. The calculation of how much a company is going to save by going to a low-cost location is often relatively easy to calculate and it appears in the accounting books as a positive deviation with extreme accuracy (it might be wrong, but it is very accurate). On the other hand, the sales lost because of a lack of capability to supply are very inaccurate because companies usually do not know how much more sales they would have got if they had the supply. For example, a retailer might not know how many sales were lost because the shelf was empty; it can only calculate the out-of-stock incidences at the retail level. (It might be different for digital retailers because they might calculate how many customers were looking for the product but couldn't buy it because of the lack of availability.)

Because of this situation, many companies have found themselves in a supply chain situation over the last few decades where they had focused so much on efficiency that they had the wrong supply chain for an appropriate balance of loss revenues vs. cost savings. Finally, the instability of global supply chains has made many supply chains much less agile than before. For example, while sourcing from the PRC was, for

1 This author was asked by a Danish Ministry of Trade department to help with the development of a framework to make nearshoring decisions.

Figure 10.1: Matching Supply Chains with Products



Source: Fisher (1997).

many companies, quite flexible thanks to the responsiveness of Chinese suppliers, the reality of the transport situation has made those supply chains lose much of their agility.

In short, global supply chains have lost a lot of agility, capability to adapt, and, therefore, resilience. Thus, companies and governments are looking very strongly (some experts would even say desperately) to increase the reliability of global supply chains.

10.3 Digitalization: A Taxonomy of Success and Failures

Given that our objective is to look at the developments in supply chain digitalization to improve resilience, we are going to use standard and convenient definitions of digitalization. We are not going to try to clarify the debate on defining what digitalization is in supply chains as there is a considerable amount of debate among scholars and executives about what is part of digitalization and what is not part of it.

A widely accepted definition is that of Industry 4.0, which includes the following technologies:

- Augmented reality
- System integration
- Cloud computing

- Big data and analytics
- IIOT (Industrial Internet of Things)
- Additive manufacturing (3D printing)
- Cybersecurity
- Autonomous robots
- Simulation

Since that taxonomy was proposed more than 10 years ago, several other technologies have emerged that could be added to that list. The two that we propose to include are artificial intelligence and blockchains, the first because of its wide use and the second because of the number of proposals concerning its potential utilization. We group artificial intelligence (AI) with big data and analytics, because AI requires big data and it could be argued that it is a further development of analytics from a practical point of view.

As we discussed previously, there have been successes and failures in the use of these digital initiatives in supply chains. We review below the successes and failures of those initiatives from the perspective of the supply chain resilience against the disruptions that have occurred in the last few years.

Given that the phenomenon is very recent, it is not yet possible to conduct empirical research about the usefulness of the technologies discussed; we just provide anecdotal examples based on how companies have used them. In some cases, there are very recent case studies that provide support for those claims, but it is obvious that future research should be conducted to test empirically to what extent the proposed effects on resilience are widely applicable in different industries and to different types of disruptions.

10.3.1 Augmented Reality

Augmented reality in the industrial setting has been a surprisingly useful digital initiative for very specific tasks like maintenance and training. At the same time, it has been a dismal failure, for the moment, for the consumer market, and its usefulness in increasing resilience is, for the moment, limited.

A widely publicized introduction of augmented reality was the Google Glass product introduced in a beta stage by Google. It was developed by Google with the ambition of becoming a widely adopted consumer product. However, it never became a mass production success, and the company basically discontinued the product and abandoned the market.

A very similar development has been happening very recently with the apparent popularity of the metaverse, which often includes the use of augmented reality together with blockchain technology. The company that used to be called Facebook changed its name to Meta to symbolize its commitment to that development with its augmented reality product, Oculus. It could be said that the jury is still out in assessing whether those developments would revolutionize the Internet or if it would experience limited adoption.

On the industrial side, augmented reality has been relatively widely adopted for training and maintenance. It could be said that while the adoption has been positive and with profitable business cases, it can't be claimed that it has created a revolution.

Companies are finding it very useful to conduct training for operators on how to operate machines. The main advantage is that operators find it easier and quicker to learn. They are also finding that it makes maintenance tasks easier because of the way the maintenance operators are guided on how to proceed and the easy access and view of a representation of the machine being maintained.

With respect to its usefulness for resilience, it should be said that its impact has been relatively limited. Some companies explain that they can do maintenance remotely, and therefore the disruptions caused by machine failures are solved in a shorter time frame.

10.3.2 System Integration

By system integration is typically understood the automated linkage between different systems and the ability to share data transparently across different systems. Using this definition, applications like control tower would be part of the system integration class.

These applications allow companies to understand where products are produced, where materials are sourced and stored, where components are in the supply chain, and how the product reaches the distribution and the customer. There are different scopes and definitions of control tower, but at its root most of them allow parts of that visibility.

In one anecdotal example, a medical device company used a digital technology called "process mining" to extract the data from the ERP (Enterprise Resource Planning) system and to be able to follow in real time the procurement situation and foresee potential supply problems during the pandemic. Specifically, it was able to extract in real time all the purchase orders from the ERP, visualize their manufacturing orders, and identify which products were potentially affected by potential delays in deliveries of those purchase orders. It should be noted that process mining is not designed for that purpose but that the company used the ability to integrate systems to visualize the information.

There are many examples of companies using control towers or similar applications based on system integration to be able to visualize the supply chain end to end and to improve its performance significantly. On top of those systems, many companies use other digital technologies like AI and simulation to improve even further the performance of the supply chain.

In another significant example, in November 2021, at a Summit at IMD, a group of chief supply chain officers from big multinational companies selected three initiatives that they considered worth working on together to improve their supply chains. The most selected initiative was "Connected Planning," which was defined as the ability to integrate planning systems with other systems, specifically to deal with disruptions.

While it could be argued that system integration in itself doesn't solve any problem created by disruption, it was clear for many companies that the capability to visualize the situation and understand the whole picture was key to being able to take decisions to adapt the supply chain and to make it more resilient. In our opinion, this seems to be the most useful digital initiative to increase the resilience of the supply chain. While it doesn't create resilience in itself, executives explain that it allows faster and much more informed action.

10.3.3 Cloud Computing

This digital technology was thought to be one that big companies would develop and profit from. For example, GE (General Electric) developed a full suite of tools based on their protocol Predix that included a cloud computing solution.

After years of evolution, it has become a widely adopted solution provided externally by big companies (Google, Amazon, Microsoft, and Oracle) that other companies use as a service. It could be compared to a utility like electricity. Thus, it is widely adopted because it has provided clear benefits of scalability, ease of use, reliability, and good cost/price trade-offs. However, it could be argued that except for the providers of cloud computing services, it has not provided any competitive advantage to any company using it.

In terms of reliability, one of the advantages of moving to cloud computing is the increase in the reliability of digital services. However, no significant impact on the reliability of the supply chain itself was anecdotally reported by any company.

10.3.4 Big Data, Analytics, and Artificial Intelligence

These technologies have been widely adopted by companies in their supply chains in many different applications and in combination with other digital technologies. They have provided substantial benefits and some companies claim that they have provided clear advantages over their competitors (Bag et al. 2021; Papadopoulos et al. 2017).

Of particular relevance is the area of forecasting and predictive analytics. In the area of forecasting, many companies have found that by using big data and AI to create better forecasts of demand, significant improvements in accuracy and, consequently, in the overall performance of the supply chain have been achieved.

It was very interesting that at the outbreak of the pandemic, many experts doubted the use of AI for forecasting given that the situation was so different, and that the historical data reflected past trends but certainly not the dynamics created by the pandemic. Quite a few companies followed closely the comparison of the accuracy of AI systems vs. the forecast done by human experts to assess their efficacy and when to reconnect them. The conclusion was that AI didn't do worse than the human experts (Henkel IMD-7-2420 2022) in the first weeks of the pandemic and that after a few weeks the AI system was already providing superior predictions to the human experts.

A similar example is the use of big data and AI for predictive maintenance. By accumulating and analyzing a lot of data it is possible to predict when would be the best time to carry out the maintenance of machines and how to minimize the downtime due to interruptions. Many manufacturers are applying these tools to minimize maintenance operations, maximize availability, and reduce stoppages due to machine failure. Some companies have even been able to increase production when confronted with external disruptions by assessing the probability of failure vs. the opportunity cost of keeping production running.

We could claim that there is ample anecdotal evidence that big data, analytics, and artificial intelligence have proven very useful in increasing the resilience of the supply chain and, in some case, even provided a competitive advantage to the companies using them.

10.3.5 Industrial Internet of Things (IIOT)

The IIOT is relatively rarely used in isolation, but rather to capture data and to take actions at the local level. Many uses of this technology are a way of providing data to AI, real-time updates to control towers, and to apply changes in machine control systems based on the analysis of predictive maintenance, for example (Al-Talib et al. 2020; Chen et al. 2022).

A typical example of the IIOT is using this technology to control the energy consumption in different parts of the supply chain and taking action to minimize the waste and excess consumption. It could be thought of as an industrial application and version of the popular Nest device sold by Google to create an intelligent house with respect to heating and cooling.

Thus, despite having been adopted relatively widely, very few organizations would claim that it provides a competitive advantage or that it helps significantly to increase supply chain resilience. However, as mentioned before, it could be claimed that without its utilization, the benefits of other technologies like system integration or AI could, in some specific cases, be severely diminished.

10.3.6 Additive Manufacturing (3D Printing)

Additive manufacturing or 3D printing is a technology that has existed for decades but that was thought to reach maturity with the other technologies of Industry 4.0, and it was expected to deliver substantial benefits. At the beginning of the early 2010s, there were even expectations that it would replace mass manufacturing and enable mass customization of products. Even today, many experts would claim that in the near future 3D printing will replace mass production in quite a few industries.

The fact is that additive manufacturing today has found several markets where it provides substantial advantages (Naghshineh and Carvalho 2022). It is a clear winning proposition in several healthcare applications like hearing aids and prostheses for knees where the value of creating a product customized for the anatomy of a specific person is very high. The technology has also been very useful in the massive creation of art products (printed in plastic) and of toys.

In the industrial setting it is has found a clear application in the development of prototypes for products, in the production of temporary spare parts, and in the creation of tools to help to increase productivity in line set-ups (Henkel IMD-7-2420, 2022). Attempts were made during the early breakout of the pandemic to manufacture ventilator machines for breathing to help to increase production volumes, but the results were quite disappointing.

With respect to supply chain resilience, we can conclude that so far it has not proven to provide any increase in resilience. However, many proponents would claim that with the improvement in material technologies for printing we could see a much more positive impact on resilience.

10.3.7 Cybersecurity

It is not obvious how to classify cybersecurity with respect to supply chain resilience. It could be easily claimed that cybersecurity is a fundamental part of resilience because it prevents major disruptions due to cyberattacks. It could also be reasoned that apart from cyberattacks, which are a very specific kind of disruption, cybersecurity has no impact on the resilience of the supply chain.

The occurrence of a cyberattack is certainly a potential major disruption in a supply chain (Roege et al. 2017). It is not only a potential threat but a reality of increasing proportions as many cybersecurity company reports continuously remind us. An unfortunate memorable example was the attack on the shipping company Maersk that forced several of their ports to stop operations for several days. It was without doubt a major disruption. Since then, the company has increased very substantially its level of cybersecurity to enhance the resilience of the supply chain.

It is also the case that in the current Ukrainian conflict, cyberattacks have been used as a weapon with the objective of disrupting the supply chains of the opposing forces. It is even the case that hacker groups have tried independently to harm the communications and supply chains of the opposing forces.

It could also be argued that these are very specific attacks that focus not only on supply chains but also on disrupting whole organizations, and that, therefore, they are not specific to supply chains. While there is merit in this argument, we believe that it should be included in the supply chain resilience considerations.

The challenge with cybersecurity is that it is difficult to estimate its benefits, since it is more a prevention tool for a specific risk than a way to help the response of the supply chain.

10.3.8 Autonomous Robots

Autonomous robots have existed for many decades and have been used in supply chains for many years. The main, relatively recent development in this area was the creation of cobots, or collaborative robots. In contrast to the previous generation of robots that could be dangerous machines and as such were typically kept in cages, cobots will stop to make sure that they do not damage any human or animal and work alongside humans. There has also been a lot of expectation about the development of autonomous vehicles, like self-driving trucks, that were going to alleviate substantially the problem of the lack of truck drivers.

The adoption of robots continues to increase in the supply chain because of the ease of implementation and the decreased costs, and to alleviate the struggle to find operators willing to work in certain environments. A clear example of that is Amazon Robotics using its Kiva robots to reduce cost, to be able to deliver packages in a reduced time, to facilitate the work of its warehouse workers, and to reduce the cost of picking through very sophisticated use of AI, the IIOT, and systems integration. It is a clear example of those technologies combining to provide a competitive advantage to a company.

On the not-so-positive side, cobots and autonomous vehicles have not delivered at all on the expectations created. Relatively few cobots have been implemented in supply chains, and engineering experts claim that we are still many years away from self-driving vehicles (although this is not an opinion shared by leading companies like Tesla).

The fact is that autonomous robots have not, for the moment, provided any major help to increase the resilience of supply chains. Certainly, the potential of autonomous driving is high with respect to resilience, but it is not yet a reality.

10.3.9 Simulation

Digital simulations have been used for decades in supply chain management to design its footprint, to optimize its performance, and to respond to disruptions. The developments in recent years have mostly been about the level of granularity and realism of the simulation, the ability to run many scenarios in a very short time, and the ability to use more sophisticated algorithms to find better solutions using many more variables.

The benefits have been the ability to minimize costs, the development of business continuity plans based on different scenarios, and the ability to react in the case of disruptions by evaluating different possibilities. It is the last of these that has seen the biggest improvements with the capability of central teams to gather information in real time and to even use artificial intelligence to evaluate many options digitally and present to management the ones worth considering.

As an illustration, one of the global leaders in packaging has a center in South America where they continuously monitor and simulate different scenarios to enable them to make fast decisions in reacting to unexpected events. The benefits in the words of the chief supply chain officer of that company are “a much better and faster reaction to disruptions.”

Thus, simulation is certainly a digital initiative that provides resilience to supply chains by allowing much better and faster decisions to be made in adapting to disruptions. Also, it is worth noting that the combination of simulation and other digital technologies like artificial intelligence and system integration has provided even better results.

10.3.10 Blockchain for Supply Chain

The last digital initiative that we consider in this chapter is blockchain for supply chains (Taqui et al. 2022; Dubey et al. 2020; Min 2019). We include it in this analysis because of the amount of news about it both from providers of solutions (i.e., companies like IBM and Accenture) and from companies promoting its use (e.g., Maersk was promoting its use for shipping e-commerce), and because of the increasing number of doctoral dissertations about its use in supply chains (this author has been asked by several doctoral students from other universities in the last year to provide input as a scholar in supply chains).

The fact is that while there are many claims about the expected use of blockchain for supply chains, its use at scale is very rare. Many companies, particularly FMCGs (Fast-Moving Consumer Goods companies), have done proofs of concept successfully, so the technology works. However, it seems that no company has scaled the solution up, mainly because they find that there are no important benefits associated with the use of the technology.

There are many debates about how in the future the technology will prove very useful for supply chains in many situations, but the fact today is that there are very few examples of successful and beneficial deployments at scale. Accordingly, today blockchain is not a digital technology that increases the resilience of a supply chain.

Finally, we summarize the effect of these technologies on supply chain resilience in Table 10.2. In this table, a +++ sign means that the technology strongly supports supply chain resilience while a + sign indicates a minor supporting effect. It should be mentioned that some technologies, like robots and blockchain, might take time to redeem their potential, so this assessment is based on the current status of the achievements of those technologies as of today (2023).

Table 10.2: Effect of Digital Technologies on Supply Chain Resilience

Digital Technology Used in Supply Chain	Effect on Supply Chain Resilience
Augmented Reality	+
System Integration	+++
Cloud Computing	+
Big Data, Analytics, and Artificial Intelligence	+++
Industrial Internet of Things (IIOT)	+
Additive Manufacturing (3D Printing)	+
Cybersecurity	++
Autonomous Robots	+
Simulation	+++
Blockchain	+

10.4 Discussion

To assess whether a digital solution has a positive impact on resilience, we can review for which kinds of disruption the digital technologies examined are able to increase resiliency or provide help to increase resiliency. In Figure 10.2, we list the different types of disruption that we identified in Section 10.4 and which digital technologies have proved to increase resilience against those types of disruption.

It is very important to emphasize that this assessment is based on the experience provided by executives and on some cases documented by scholars about the use of those digital solutions when facing disruptions over the last 2 years. We propose this classification with the objective of promoting further research to empirically validate these propositions.

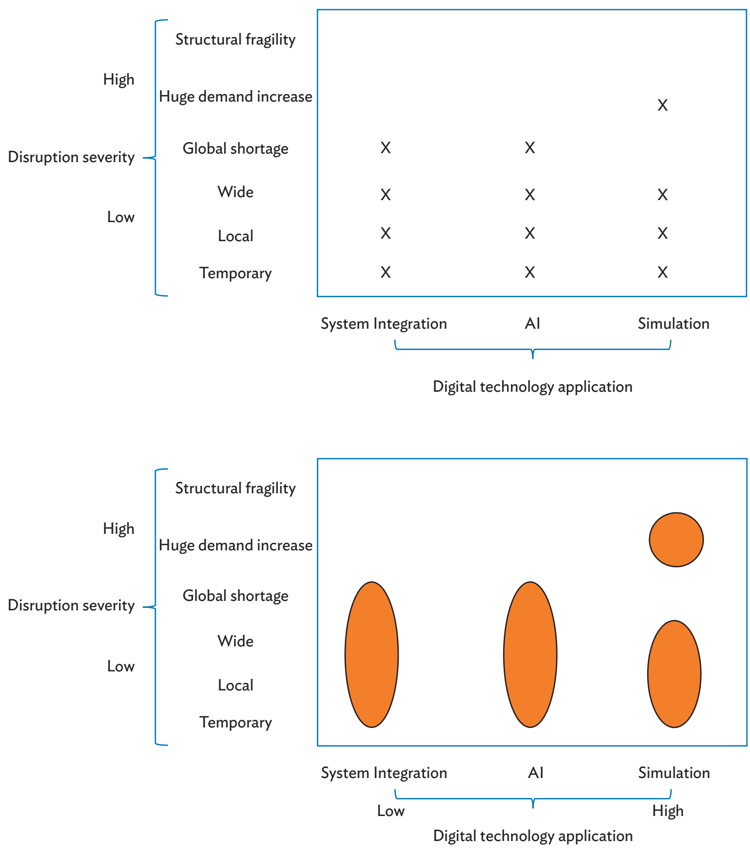
We should also note that the effect of the analysis realized leads to the conclusion that different digital solutions alone might not be the best way to proceed. In Figure 10.2, we present the different types of disruption identified on the vertical axis, and the digital solutions that seem effective in increasing the resilience of the supply chain when faced with those disruptions on the horizontal axis. The way to read the figure is that systems integration (x axis) increases resilience in the case of disruptions that are temporary, local, widespread, and for global shortages, while not increasing resilience significantly in the case of a huge demand increase and structural fragility.

Thus, our framework leads to the conclusion that a potential hypothesis to test is that the combination of digital solutions could be superior to their individual use.

The analysis of the different types of disruption and how digital supply chains help to increase the resilience against those disruptions leads to some expected and some surprising results.

As could be expected, for major disruptions and structural challenges in supply chains, a digital supply chain is not going to have a much better resilience than a nondigital savvy one. Digital solutions might help marginally, but the disruption is so brutal that it could be argued that there are very few ways of increasing resilience.

Figure 10.2: Framework for Disruptions and Digital Solutions: Which Digital Solution Increases the Resilience of the Supply Chain with Respect to the Types of Disruption



Source: Created by the author.

For some substantial disruptions concerning services, infrastructure, and global shortages, companies have found that system integration, AI, and simulation help in making decisions that increase the resilience of the supply chain. The surprising factor seems to be the cumulative effect of those digital solutions. It would be a very interesting hypothesis to test that these solutions reinforce each other. It would also be very interesting to test whether there is a specific order that maximizes the value they provide.

It is also surprising that many digital solutions have very few effects on resilience. Technologies like robots, the IIOT, and augmented reality seem to have no impact on resilience. Others like 3D printing and blockchain seem to have a potential role in the future but today that potential is not realized.

Future research should test empirically whether the propositions made in this chapter are validated across different industries and continents. Our suggestion is that such research should clearly identify resilience against the type of disruption, because, as we propose in our framework, different solutions apply to different aspects of resilience.

The challenge for such future research is that to measure scientifically how resilient a supply chain is against specific disruptions, it would be necessary to have multiple disruptions of that type. Hopefully, we are not going to have repeated pandemics or wars, so the research should be based on the answers from executives. Nevertheless, such research would be valid since many executives have gone over such situations in recent years.

10.5 Conclusion

The supply chains of the last two years have experienced unprecedented disruptions that have made the world try to increase its resilience fundamentally. The reality is that many supply chains have shown their fragility against disruptions, prompting companies and governments to try to act to improve the situation.

Digital supply chains have proved to be more resilient than nondigital ones, but not in all cases against all sorts of disruptions. This chapter has proposed a framework to enable an understanding of which digital solutions are effective against which types of disruption based on documented examples and experiences from executives in conversation with the author.

The framework key learning is that the most effective digital tools for raising the resilience of supply chains are systems integration, AI, and simulation. Furthermore, when combined, they are even more effective.

The somewhat challenging finding is that other digital technologies seem to have, at best, a marginal effect on resilience.

From the policy point of view, the fact that systems integration is one of the effective digital technologies for increasing supply chain resilience raises the hypothesis that regulators could take into consideration the need to foster the development of standards for systems to be able to integrate.

As mentioned in the introduction, governments and companies are adopting policies to increase the resilience of supply chains, particularly in the Americas and Europe. As a consequence, disruptions in global supply chains are driving global companies to find alternatives to Asia and the Pacific as the main source of manufacturing goods. Thus, digital tools that increase resilience will eventually reduce the extent to which companies are going to move manufacturing away from Asia and the Pacific. The recommendation based on this research is that Asia and the Pacific should promote the use of systems integration, AI, and simulation among companies in the region to increase the resilience of their supply chains. That would lead to global companies continuing to source from Asia and the Pacific.

This research is limited in that it is based on anecdotal evidence from practitioners and from documented academic cases. More research is needed to validate the proposed framework; in particular, the use of empirical research could validate the positive findings about technologies impacting in a positive way the resiliency of supply chains.

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11

Bespoke Supply Chain Resilience Facilitated by Dedicated and Shared Resources

Florian Lücker

11.1 Introduction

The production of chips needed for the assembly of automobiles ground to a halt in December 2020 due to COVID-19-related disruptions in the People's Republic of China (PRC). As a result of these supply shortages, chip manufacturers raised chip prices and also invested in expanding capacity. Automotive companies experienced production shortages, which resulted in declining sales. Supply chain disruptions such as these were reported continually across various industries in the years after the coronavirus was first identified at the end of 2019.

Practitioners and academics alike have looked into ways of building resilience in supply chains. A variety of levers have been identified to increase the resilience of supply chains, including keeping buffers (such as additional inventory) and building flexibility in supply chain networks. The total cost of operating a supply chain is often much higher when disruptions are included than when they are ignored. Anecdotal evidence, however, suggests that firms are often reluctant to implement resilience-enhancing measures. Many firms are not willing to make financial commitments (for example, in the form of sourcing from an expensive reliable supplier instead of sourcing from a cheaper unreliable) that pay off only in the unlikely event of a disruption. Firms' resistance to adopting these resilience levers is further exacerbated by the fact that firms are often unable to estimate the likelihood of a rare event, making it difficult for them to quantify the benefits of resilience investment. In addition, firms often focus on a short time horizon for creating shareholder value, whereas resilience investments often only pay off in the long term. Consequently, many firms are reluctant to make significant investments to build resilience in their supply chains.

One might expect that firms are not well prepared to deal with disruptions. However, this is not necessarily always true. The pandemic illustrated how some firms managed to flourish during the crisis, whereas others lost significant revenues and market share. True, some of these differences can be explained by the different markets firms serve (e.g., many grocery retailers had only a few demand or supply disruptions); however, some firms managed to create genuine resilience in their supply chain without sacrificing supply chain efficiency. Here are some examples:

- **Zara and H&M.** While Zara experienced only a small decline in sales and profit, H&M was badly hit by the lockdowns that prevented customers from shopping in its brick-and-mortar stores. Zara's success relative to H&M has been attributed to its omnichannel solution. An omnichannel solution refers to selling goods (in this case, clothes) through the online and brick-and-mortar stores. Essentially, both sales channels merge in an omnichannel solution. That way, for example, customers might decide to order online and pick up the good from a store. Having a sophisticated omnichannel solution in place has allowed Zara to generate and meet customer demand in spite of lockdowns (Orihuela and Hipwell 2020). Interestingly, Zara originally set up an omnichannel solution to increase supply chain efficiency. It came as a surprise that this omnichannel solution would also be helpful in dealing with the disruption caused by the pandemic.
- **Walmart, Amazon, and Target.** Many large retailers, such as Walmart, Amazon, and Target, capitalized on their internal flexibility to manage supply or demand disruptions during COVID-19. Besides being capable of switching sales from brick-and-mortar stores to online stores, they are also increasingly capable of dealing with supply disruptions. They have the flexible internal capacity to transship goods between different stores and warehouses whenever product shortages occur at a single location.

These examples illustrate that some resilience levers – often related to some sort of flexibility – not only provide some resilience but also increase supply chain efficiency, i.e., they allow the supply chain to run at low cost even in normal times in the absence of any disruption.

In this chapter, we offer a characterization of resilience-enhancing measures. We argue that resilience-enhancing measures are either based on using dedicated resources (referred to as "dedicated resilience levers") or on using shared resources (referred to as "shared resilience levers"). By a dedicated resource, we mean a resource that is provided only for the purpose of building resilience. An example would be to source components from an expensive reliable supplier rather than a cheaper unreliable one. In contrast, shared resilience levers are based on using shared resources. By shared resources, we mean resources that are not only used for risk mitigation but also serve another purpose, such as better meeting customer demand (through a higher service level, for example). Typically, shared resources not only help build resilience but also help meet customer demand in the absence of disruptions. An example would be increasing the safety inventory, which helps improve the service level and the supply chain's resilience. We argue that shared resilience levers are particularly helpful for supply chains that focus on cost-efficiency and produce basic functional products, such as consumer goods (where price competition exists). In contrast, dedicated resilience levers are particularly helpful for supply chains that are less exposed to cost pressure and that produce innovative products, such as patented medical drugs. The chapter aims to highlight the importance of matching the right resilience lever with the right supply chain. That way, firms can achieve a suitable level of resilience while considering the associated costs. Another objective is to call for more research in the area of shared resilience levers.

In this chapter, we explore the topic of shared resilience levers for building resilience and efficiency using a field research study approach. Field research is a particularly useful methodology when exploring a new topic (Eisenhardt 1989; Yin 2003). Voss, Tsikritsis, and Frohlich (2002) and Seuring (2005) argue that field research is helpful when new topics are explored that are not yet well understood or even defined. The observations developed in this chapter are based on qualitative analysis where different sources of input are used. (i) Interviews were conducted with about 10 executives in different industries such as pharmaceutical, consumer goods, and finance. Open questions were asked with regard to how their firms build resilience while considering the pressure to operate a supply chain at low cost. The output of these interviews was used to form initial hypotheses about how firms manage risks while considering cost-efficiency. (ii) These initial hypotheses were then further validated through a detailed literature review. The literature review is based on searching articles in the Web of Science over the past 20 years using the keywords supply AND (chain OR chains) AND (disruption OR resilience). The literature review has helped in finding additional support for the initial findings. Such a methodology is common in the literature, where a two-step framework is often proposed (Voss et al. 2002). First, direct observations are conducted (in our case, the interviews). Second, the initial findings are further validated to make initial findings more concrete (in our case, the literature review). Applying this methodology has helped us develop a characterization of resilience levers and a description of how they match the supply chain characteristic.

Our chapter is structured as follows. Section 11.2 introduces a categorization of resilience-enhancing levers and argues how they match with different supply chain topologies. Section 11.3 provides a detailed example of the reverse factoring of the supply chain finance solution. We explain how reverse factoring works and argue why it helps improve supply chain efficiency and resilience. As such, reverse factoring can be considered a shared resilience lever. Finally, in Section 11.4, we call for more research to enhance understanding of the trade-off between resilience and efficiency in supply chains. Although the traditional supply chain disruption risk management literature indicates that resilience is typically achieved by sacrificing efficiency (Yildiz et al. 2016; Lücker and Seifert 2017; Lücker et al. 2019), the discussion around shared resilience levers shows that supply chain resilience and efficiency can be achieved at the same time. Further, most previous research emphasizes how managing disruption risk is different from managing demand uncertainty. However, we believe that more research is needed to identify the joint benefits of resilience-enhancing levers for mitigating disruptions and serving customer demand in the absence of disruptions.

11.2 Tailored Risk Management Approach

Identifying the right levers to build resilience in the supply chain is critical for succeeding in a versatile business environment. In this section, we aim to categorize resilience-enhancing levers (shared versus dedicated resilience levers) and argue how they match with different supply chain archetypes (just-in-time versus just-in-case supply chains).

In the following, we argue that resilience levers (i.e., a measure that enhances a supply chain's resilience) can be shared or dedicated. In order to explain the difference between the two levers, let us distinguish two situations: a) Normal times where no disruption occurs. During normal times, firms are primarily concerned with serving customer demand using the available supply while keeping costs low. b) Disruption times. During disruption times, firms are primarily concerned with recovering from the disruption and still serving customer demand using all available (not disrupted) resources.

The insights discussed in this section are primarily based on the interviews conducted. As only open questions were posed, the output of the interviews was further backed up with findings from the literature search.

11.2.1 Dedicated Resilience Levers

In this section, we give examples of dedicated resilience levers. Recall that these levers are defined as levers that use dedicated resources. By a dedicated resource, we mean a resource provided only for building resilience (and that is not of help in normal times when no disruptions occur). Here are some examples:

(a) **Sourcing from a reliable supplier.** Firms often have a choice to source raw materials from more reliable or less reliable suppliers. Less reliable suppliers are often cheaper than more reliable ones. Thus, sourcing from a more reliable supplier typically comes at an additional cost, and thus requires resources or funds (Tomlin 2006). The key observation is that these additional resources are provided only for the purpose of building resilience. There is no other benefit of sourcing from a more reliable supplier than enhancing resilience (as long as all the other characteristics of the supplier remain unchanged). Thus, sourcing from a reliable supplier is a dedicated resilience lever, as the resource provided is dedicated only to building resilience.

(b) **Protecting manufacturing plants from external threats/hazards.** Some firms might be exposed to the risk of external threats/hazards such as floods or earthquakes. It is known that there is an increased likelihood of floods in some areas (for example, manufacturing plants close to a river). In such cases, firms might decide to invest in protecting manufacturing plants against flooding (by setting up barriers). This additional protection would only be helpful to ensure the continuation of production even if there is flooding (up to a certain degree). The payoff occurs only in the event of disruption, and not in normal times. Thus, protecting manufacturing plants from external threats/hazards is a dedicated resilience lever.

(c) **Better estimating disruption probabilities.** Firms sometimes make an effort to better estimate the probability of disruption at specific production sites (Lim, Bassamboo, and Chopra 2013). Pharmaceutical company Roche, for example, purchases data from insurance companies to better estimate the likelihood of natural hazards at their production sites in California, US. Clearly, improving the estimation of disruption probabilities requires a dedicated resource of funds that help build resilience but do not offer any other benefit in the absence of disruptions.

(d) **Incentivizing suppliers to increase reliability.** Firms may make an effort to increase the reliability of a supplier (Wang, Gilland, and Tomlin 2010). This helps to stabilize the supply chain. Increasing reliability can be achieved through closer collaboration, financial incentives, or penalty contracts that stipulate a penalty fee for not delivering goods (Tang, Gurnani, and Gupta 2014). Such measures typically help to make a supply chain more resilient but are less helpful for other purposes.

11.2.2 Shared Resilience Levers

Shared resilience levers are based on using shared resources. By shared resources, we mean resources that are not only used for risk mitigation but also serve another purpose, such as better meeting customer demand in normal times (through a higher service level, for example). Typically, shared resources not only help build resilience but also assist in meeting customer demand in the absence of disruptions. Here are some examples:

(a) **Using safety inventory.** Firms hold a safety inventory to protect them from stockouts when demand is higher than anticipated. Holding a safety inventory allows a firm to achieve a high service level. Because carrying an inventory is costly, firms often hold only some safety inventory and accept the risk of some stockouts. The key observation is that a safety inventory not only helps to deal with jumps in demand, but it is also a stockout protection when supply disruptions occur (Liu, Song, and Tong 2016). Thus, we may argue that a safety inventory is a shared resource as it serves the purpose of building resilience and of increasing service levels.

(b) **Using excess capacity.** Firms typically do not operate at 100% capacity utilization because of demand swings. If demand turns out to be higher, additional goods can be produced to serve customer demand. Having too much excess capacity, however, is expensive. As a result, companies have to carefully assess the amount of excess capacity they need, which is often in the range of 5%–20%, depending on the industry. It turns out that excess capacity not only helps in dealing with demand swings but also builds some resilience in the supply chain network (Lücker, Chopra, and Seifert 2021). If one manufacturing plant is disrupted, some production might be scheduled at a nondisrupted plant where there is some excess capacity. Obviously, this works only if the manufacturing plants are flexible and qualified to allow this capacity scheduling change. Here again, excess capacity is a shared resource that helps both build resilience and increase customer service levels without disruption.

c) **Reducing lead time.** Roughly speaking, lead time is the time it takes to produce a good. It is the time that elapses between starting and finishing the production. Lead time reduction provides significant operational benefits and is generally seen as a tool for better matching supply with demand (De Treville et al. 2014). It helps significantly in reducing inventory levels, thereby making supply chains more cost-efficient. At the same time, lead time reduction might make supply chains more resilient. A short lead time might allow a firm to recover more quickly (because the production lead time after recovery is shorter), but it also provides more flexibility in the supply chain.

d) **Using component commonality.** Using the same components for different products (referred to as "component commonality") also increases supply chain efficiency (Thonemann and Brandeau 2000). Although there might be an initial increase in cost (due to having more expensive components even though a cheaper one would also work for some products), it provides the benefit that these components can be shared if some products experience more demand than others. Likewise, it provides resilience because these components can be shared across products if there is some supply issue for some products.

e) **Using pricing flexibility.** Dell uses pricing flexibility to manage demand. If there is more demand than anticipated for one product, a similar product might be offered at a lower price to shift demand from the popular product to the less popular one. The same argument can be made when there is a supply chain disruption (Tang and Yin 2007). Demand for a product with limited supply can simply be shifted to similar products through changing prices.

f) **Using multi-sourcing.** Multi-sourcing might reduce the impact of a disruption and increase the resilience of the supply chain (Babich, Burnetas, and Ritchken 2007). In some cases, it might also help the buyer to negotiate lower wholesale prices with the suppliers as the buyer can let the two suppliers compete against each other to lower the wholesale price.

g) **Emergency purchases.** Emergency purchases might be possible for some commodity products where there is a spot market for such products. Purchasing on the spot market is typically considered to be more expensive than regular purchases through long-term contracts (Gümüs, Ray, and Gurnani 2012).

However, having access to such a spot market enables a company to serve demand when a disruption occurs or when demand is higher than anticipated. As such, access to a spot market might help both objectives, i.e., to build resilience and increase the efficiency of the supply chain.

h) **Flexible transportation.** Flexible transportation may mean that the speed of transportation can be accelerated (Fan, Schwartz, and Voss 2017). Goods may use a faster means of transportation that also comes at a high price. Being able to accelerate transportation helps with resilience and efficiency. Flexible transportation may also mean that there are more transportation paths. For example, transshipment may allow a firm to move goods from one warehouse (serving a specific market) to another (serving another market). This additional transportation link – transshipment – gives the firm more flexibility, which helps build resilience and efficiency.

i) **Reverse factoring.** The supply chain finance solution of reverse factoring might increase resilience and efficiency simultaneously (Banerjee, Lücker, and Ries 2021). We explain reverse factoring in a separate section, Section 11.3, and highlight how it helps build resilience and efficiency in the supply chain.

The list of dedicated and shared resilience levers is by no means exhaustive. The suitability of resilience levers always depends on the industry and product characteristics. Some levers are not suitable in some industries due to the characteristics of the supply chains or products.

We conclude this section with a key observation: Dedicated resources are always available for risk mitigation, whereas shared resources might not be available when needed.

Let us consider the dedicated resilience lever of sourcing from a reliable supplier. A reliable supplier will always provide some level of guaranteed resilience. In contrast, shared resources are used for two purposes and might not be available during a disruption. Thus, shared resources may fail to provide resilience. Consider the shared resource of a safety inventory. It might happen that just before a disruption occurs, there is increased customer demand, resulting in the depletion of the safety inventory. Thus, this safety inventory cannot be used for risk mitigation anymore. Also, the opposite could happen. Demand could be much lower than anticipated, and the entire safety inventory could be available during a disruption. Thus, shared resilience levers only provide some resilience in expectation and cannot guarantee a minimum level of resilience.

We may conclude that dedicated resilience levers provide the benefit of some guaranteed resilience. However, this comes at a higher cost than having shared resilience levers. Shared resilience levers, in contrast, might fail to provide resilience when needed.

11.2.3 Matching the Right Resilience Lever with the Right Supply Chain

In the previous two sections, we classified resilience levers as dedicated or shared. A summary is provided in Table 11.1. In this section, we want to address which lever to use for which supply chain.

We consider two supply chain archetypes that are often discussed in the literature: just-in-time supply chains (Sugimori et al. 1977) and just-in-case supply chains (see Table 11.2 and Jiang, Rigobon, and Rigobon 2022).

Table 11.1: Dedicated and Shared Resilience Levers

Dedicated Resilience Lever	Shared Resilience Lever
Sourcing from a reliable supplier	Using safety inventory
Protecting manufacturing plants from external threats/hazards	Using excess capacity
Better estimating disruption probabilities	Reducing leadtime
Incentivizing suppliers to increase the reliability	Using component commonality
	Using pricing flexibility
	Using multi-sourcing
	Emergency purchases
	Flexible transportation
	Reverse factoring

Source: Author.

Just-in-time supply chains (sometimes also referred to as "cost-efficient supply chains") focus on using lean principles to reduce costs where possible. These supply chains are useful for producing functional products with low product margins. Functional products tend to be exposed to stable market environments with predictable demand patterns. Cost reduction adds value because the products often compete on price, not quality.

Just-in case supply chains (sometimes also referred to as "responsive supply chains") focus on reducing the likelihood of supply chain breakdown. These supply chains are useful for producing innovative products with high margins. Innovative products tend to be exposed to more volatile market environments where precise demand forecasts are often difficult. For such supply chains, flexibility is valuable as it helps to cope with a volatile market environment. Supply chain managers add value by ensuring a reliable supply of goods to customers using buffers such as inventory, capacity, or multi-sourcing.

Table 11.2: Just-in-Time and Just-in-Case Supply Chains

Just-in-time Supply Chain	Just-in-case Supply Chain
Focus on cost-reduction to create supply chain value	Focus on reducing the likelihood of supply chain breakdown
Used primarily for functional products such as consumer goods (where firms compete on price)	Used primarily for innovative products where there is less competition on price
Supply chain managers aim to increase the efficiency of supply chains	Supply chain managers aim to build resilience by using buffers such as inventory, capacity, multiple-sourcing, near-shoring

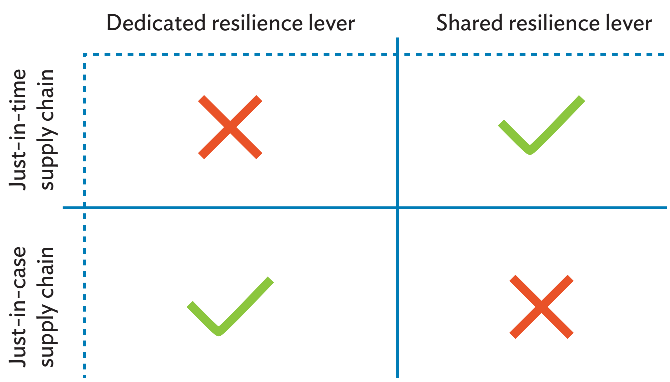
Source: Author.

We argue that it is often economical for just-in-time supply chains to use shared resources rather than dedicated resources when building resilience. The argument is that supply chains that need to operate cost-efficiently simply do not have the financial resources to use dedicated resources. While using shared resources has the drawback that a certain level of resilience cannot be guaranteed, it provides an expectation of some reasonable level of resilience while significantly reducing costs. Arguably, these supply chains can't afford to provide a guaranteed level of resilience as dedicated resources are often considered to be too expensive.

We further argue that it is often economical for just-in-case supply chains to use dedicated resources rather than shared resources when building resilience. Dedicated resources are typically very expensive but provide a guaranteed level of resilience. Dedicated resources might be helpful for companies that are less exposed to cost pressure and where some guaranteed level of resilience is needed. As an example, consider the pharmaceutical industry, which produces patented life-saving drugs. Given the patents, the operating margins are often very high. Thus, increasing operating costs a little might not be a game-changer for pharmaceutical companies such as Roche. Having guaranteed resilience in the supply chain is strategically important to pharmaceutical companies for three reasons: 1) Patient safety. As the drugs are frequently life-saving and patented, often only one pharma company can produce these drugs. Patients often can't find alternative drugs to get treatment. 2) Regulatory requirements. Pharmaceutical companies are under pressure to be on good terms with regulators such as the FDA. Regulators want to ensure that pharmaceutical companies can reliably supply drugs to patients, even when major disruptions such as COVID-19 occur. 3) Given that the margin is so high, financial leeway exists to provide resources for building resilience.

We can say, in summary, that firms producing basic products using just-in-time supply chains find more value in using shared resilience levers than dedicated resilience levers. Firms producing innovative products using just-in-case supply chains might find more value in using dedicated resources for building resilience in the supply chain. We illustrate this observation in Figure 11.1.

Figure 11.1: Just-in-Case Supply Chains Match with Dedicated Resilience Levers Whereas Just-in-Time Supply Chains Match with Shared Resilience Levers



Source: Author.

11.3 Example of Supply Chain Finance

This section aims to provide an example of how the use of supply chain finance solutions, such as reverse factoring or dynamic discounting (Gelsomino et al. 2016), can be seen as a shared resource that helps increase supply chain resilience and efficiency. Supply chain finance solutions aim to help optimize the flow of money or funds in the supply chain. This section considers a supply chain consisting of a buyer and a supplier. We are interested in learning what factors affect the time when the buyer pays the supplier and the amount of money the buyer pays the supplier.

Besides the flow of goods in the supply chain, the flow of money or funds is critical when managing risks in the supply chain. It is not unusual for suppliers to default because of a lack of liquidity (i.e., no access to cash). For example, a buyer might pay a supplier very late, even after the agreed payment date, and as a result, the supplier might struggle to have enough cash on hand to pay back some loans or pay the salaries of the employees. A supplier default can result in a significant supply chain disruption, particularly when the supplier provides a critical component needed for the production of a finished good. Thus, when building resilient supply chains, it is important to ensure that critical suppliers have access to sufficient liquidity (money) in order to ensure a reliable supply.

Managing liquidity can be a challenge for a supplier, particularly when the supplier is a small company. Small companies may struggle with accessing capital as they might not have a sufficient trading history that convinces a banker about the viability of their business model. Thus, smaller suppliers are particularly exposed to the risk of default due to a lack of liquidity. The common practice of delayed payments exacerbates this problem. Delayed payments refer to the practice that buyers buy goods now but pay suppliers later, often 30, 60, or 90 days after the delivery of the good. Thus, a small supplier has to find a source of money to cover the 30, 60, or 90 days of late payment. Late payment is often considered a reason for supplier default.

One could argue that a buyer might be interested in paying a supplier more quickly. However, there is a drawback of paying the supplier early. The buyer would rather keep the money for themselves in order to invest in internal growth projects such as the development of a new product or the exploration of a new market. The buyer might also decide to invest the money better in new production technology, such as 3D printing, which might help the buyer to reduce production costs in the long run. Thus, paying the supplier early might enhance supply chain resilience, but it comes at the cost of sacrificing supply chain efficiency (as long as the purchase price remains unchanged).

To overcome these problems, the financial service industry has developed so-called “supply chain finance solutions” aimed at helping the supplier access capital (while providing benefits to the buyer). While many supply chain finance solutions are available, such as reverse factoring, dynamic discounting, in-transit financing, purchase order financing, and deep tier financing, we focus in this chapter only on the two most popular ones: reverse factoring and dynamic discounting

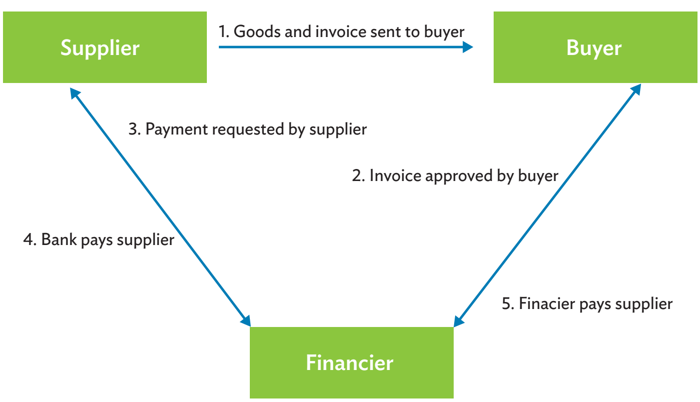
(PwC 2017). However, the insights developed from analyzing reverse factoring and dynamic discounting continue to hold for many other financing solutions as well.

11.3.1 Reverse Factoring

One solution that helps suppliers access capital is called "reverse factoring." The goal of this section is to convince the reader that the use of reverse factoring may enhance the supply chain's resilience while also increasing the cost-efficiency of the supply chain. We will argue that reverse factoring can be considered a shared resilience lever as it serves two objectives: building resilience and improving the flow of funds in the supply chain, resulting in enhanced efficiency.

The aim of reverse factoring is to provide money to the supplier immediately after shipping goods to the buyer while allowing the buyer to stretch payment terms even further (see Figure 11.2). The buyer borrows from a financier – a fintech or a bank – who pays the supplier early (minus the financing costs) and receives the money from the buyer later. Reverse factoring reduces the supplier's working capital needs and allows the buyer to pay at an even later point in time than they would have done under trade credit to the suppliers (Banerjee, Lücker, and Ries 2021; Kouvelis and Xu 2021). Essentially, the process is as follows (see Figure 11.1): (1) The supplier sends goods and an invoice to the buyer. (2) The buyer sends an approved invoice to the financier.

Figure 11.2: The Process of Reverse Factoring



Source: Author.

(3) The supplier sends a payment request to the financier. (4) The financier pays the supplier the invoiced amount less the total discount based on the payment period for the buyer, the financier's cut. (5) The buyer pays the full amount to the financier upon maturity. There are variants to this process: The discount could be deducted later if only 75%–90% of the invoiced amount is paid upfront in Step 2 and the remainder upon maturity. If the buyer cannot pay, the supplier may be liable or not, depending on the recourse arrangements.

While initially, the implementation of reverse factoring turned out to be cumbersome given the huge number of suppliers that large buyers have, nowadays, reverse factoring is being applied across entire supplier bases for large buyers. This is possible due to innovative technology solutions offered by providers such as Taulia and C2FO. A recent celebrated example is Airbus, which offers reverse factoring across their entire supplier base, resulting in improved supply chain resilience and better access to working capital for the suppliers and buyers. Deploying reverse factoring enhances supply chain efficiency as the supplier has improved access to financing, resulting in lower costs for the supplier. Likewise, the use of reverse factoring enhances supply chain resilience as the supplier is arguably less likely to default due to the improved access to capital through reverse factoring. Empirical evidence suggests that using reverse factoring enhances supply chain resilience. Thus, deploying reverse factoring allows a firm to increase resilience and efficiency at the same time.

Reverse factoring is a financing solution that is offered by international and domestic banks. An increasing number of fintechs (financial technology companies) offer reverse factoring through a digital platform. Suppliers and buyers can join such platforms and access the reverse factoring scheme there. The benefit of using a digital platform is that the process of participating in a reverse factoring scheme becomes simpler and more cost-efficient, especially for suppliers. The availability of these platforms has resulted in a significant increase in the use of reverse factoring for suppliers and buyers in recent years.

11.3.2 Dynamic Discounting

Dynamic discounting is another supply chain finance solution that helps to stabilize the supply chain by improving access to cash for suppliers (while also increasing the efficiency by optimizing the allocation of cash between supplier and buyer). The basic idea behind dynamic discounting is that a supplier and buyer agree on a discount on the wholesale price in exchange for an early payment. For example, instead of paying the supplier 30 days after shipping the goods, the buyer might receive a discount for paying the supplier immediately after the buyer has received the goods. There are different variations of dynamic discounting on the market. They are differentiated by how the discount rate and payment time are determined. Let us discuss the two most common variations: (i) the sliding scale approach and (ii) the market-based approach.

The sliding scale approach is based on the buyer offering a discount rate to the supplier that depends on the time when payment is executed. Generally, the earlier the buyer pays the supplier, the higher the discount for the buyer. That way, the buyer is incentivized to pay early. The early payment is helpful for the supplier because it helps to reduce the cash conversion cycle (or working capital need) of the supplier.

The market-based approach is based on creating a market/digital platform where suppliers can upload discount offers for their invoices. The buyer can then choose to pay those invoices early that offer a sufficiently large discount rate. That way, the buyer benefits from receiving a high discount on the wholesale price. Also, suppliers might benefit because those suppliers that are most in need of cash would offer the highest discounts, which in turn results in providing the available cash from the buyer to those suppliers that most need it. This illustrates that dynamic discounting is often a cash management tool as well. Any excess cash that a buyer has can be used to pay the supplier early in return for a profit (rather than depositing the money in a current account where the interest rate is typically low).

From a supplier perspective, it is not evident which dynamic discounting variation is more beneficial. The buyer may ask for a smaller discount in the sliding scale approach than in the market-based approach. In contrast, the market-based approach might be helpful for those suppliers that are most desperate for cash. However, under the market-based approach, the discount rate might be higher because the buyer might reject the discount offered by the supplier if the discount offered is too low. In either case, dynamic discounting is always offered as a voluntary source of financing, meaning that suppliers are not forced to participate in dynamic discounting programs. Dynamic discounting is simply an offer from the buyer to the supplier and provides an alternative way to access the supplier's capital. Arguably, this additional source of financing may help smaller suppliers overcome times when suppliers struggle with liquidity, and as such, it may help stabilize the supply chain.

Fundamentally, the gain in efficiency arises from overcoming trade credit inefficiencies. A trade credit agreement might be inefficient if the supplier has to pay a high interest rate to raise funds and provide them to the buyer in the form of trade credit. Under dynamic discounting, this inefficiency is reduced or even completely eliminated. Thus, dynamic discounting releases supply chain surplus and makes the supply chain more efficient.

Other supply chain finance solutions, such as purchase order financing and deep tier financing, also aim to smoothen the flow of funds in the supply chain and increase supply chain efficiency and resilience.

11.4 Past Research and Future Research Directions

In this section, we continue our review of the academic literature. Specifically, (i) we identify similarities between the literature on shared resources and flexibility in the supply chain, (ii) we identify further examples of how sharing resources helps build resilience in the supply chain, and (iii) we identify gaps in the existing literature and provide avenues for future research.

The concept of using shared resources for building resilience is closely related to the more general concept of flexibility in supply chains. While flexibility does not specifically refer to supply chain resilience, it often refers to resources that can be shared for different purposes in supply chains. As such, it is not surprising that there is some overlap with the flexibility literature. Indeed, flexibility has been acknowledged in the disruption risk literature as a valuable risk mitigation strategy. The literature review by Snyder et al. (2016) specifically looks at the risk mitigation strategies of *sourcing flexibility* and *demand flexibility*. The use of both types of flexibility results in increased resilience, but not necessarily increased supply chain efficiency (in the absence of disruptions). At the same time, the supply chain literature that ignores disruption risk highlights the value of flexibility in dealing with demand uncertainty (Sethi and Sethi 1990). Further, Jordan and Graves (1995) introduce the concept of *chaining*, whereby capacity at each production node is flexible enough to serve a couple of markets, creating a chain. A chain requires a small amount of manufacturing flexibility while maximizing the benefit of this flexibility. Although chaining is designed primarily to deal with normal variations efficiently, it naturally provides some resilience against disruption without requiring any additional investments. As such, chaining can be seen as a shared resilience lever.

Avci (2019) studies the value of (i) transshipment (i.e., having an additional transportation path between different markets) and (ii) expedited shipping in a distribution network subject to disruptions. A feature of the paper is that the author considers the effect of these two levers on building resilience (measured in terms of conditional value at risk) and improving supply chain performance in the absence of disruptions (measured in terms of service level). The author finds that particularly expedited shipping helps to build resilience and to achieve a high service level in the absence of disruptions (despite the higher costs). In contrast, transshipment helps build resilience but is less effective in maintaining a high service level without disruptions. Similarly, Fan, Schwartz, and Voss (2017) study the value of flexible transportation modes (with different speeds) in a multi-product supply chain subject to the risk of disruptions. Disruptions can be mitigated by changing the transportation mode of some products; that is, the delivery of some products can be accelerated to reduce potential stockouts due to disruptions, thus increasing resilience. Interestingly, providing flexibility in the transportation mode also helps to deal with day-to-day glitches such as transportation delays, thereby increasing supply chain efficiency.

Similarly to this discussion, Chopra, Sodhi, and Lücker (2021) propose that supply chain resilience and efficiency can be achieved by creating multiple channels for the flows of information, product, and funds in a supply chain. These multiple channels are often facilitated by means of supply chain commons – a set of pooled resources for the flows of information, product, and funds. The authors argue that firms often create multiple channels for the three flows to improve efficiency. Yet, it turns out that these multiple channels also create some resilience *for free*. Further, the authors argue that the availability of supply chain commons further reduces the costs of established risk mitigation strategies, such as using flexibility in the supply chain.

Chopra, Glinsky, and Lücker (2023) study a sourcing problem where a buyer sources from an unreliable supplier, and the demand for the good the buyer sells follows a finite life cycle curve where future customer demand depends on present sales. The authors show that in such a setting, moving part of the order quantity from a later period to an earlier period – referred to as "placing anticipatory orders" – is optimal. Anticipatory orders are placed at optimality only when future demand depends on present sales (e.g., a supply disruption would result in fewer sales and thus dampen demand in the future). While placing anticipatory orders is optimal even when ignoring demand uncertainty, it turns out that anticipatory orders are placed at even lower disruption probabilities when there is demand uncertainty relative to the case where there is no demand uncertainty. The reason is that ordering a large order quantity in an earlier period of the product life cycle not only helps to protect against disruption risk, but it may also help to serve higher demand than anticipated and thus increase the service level. In other words, because there is a dual benefit (building resilience and increasing supply chain efficiency), anticipatory orders are placed at even lower disruption probabilities (relative to settings with constant demand).

We believe that more research is needed that analyzes strategies that are helpful for creating resilience and improving supply chain efficiency (or do not reduce efficiency significantly).

While our literature review highlights that there may be synergies in sharing resources for risk mitigation and for normal times, we acknowledge that some resources cannot be shared for such dual/multiple purposes. Here, firms have to make a trade-off and decide what is best. Consider the well-known pooling effect (Eppen 1979). Firms often pool production at a single location and serve demand in various countries from this single location. The supply chain efficiency gains of achieving economies of scale and reducing demand uncertainty (through aggregating demand) have been widely studied in the literature. Nevertheless, such pooling at a single location also increases the vulnerability of the supply chain and may make it less resilient. During the COVID-19 pandemic, many companies, including Apple, faced supply disruptions because they relied heavily on one location to produce the bulk of their products (which is the PRC in the case of Apple). Here, a firm faces a trade-off between gaining efficiency and gaining resilience. We call for more research to better understand this trade-off. The gains of pooling have diminishing returns for each unit added. Recall that the benefit of reducing demand uncertainty due to pooling increases with the square root of the number of markets served. Thus, when a firm already produces a significant amount at one location, the additional benefits of further pooling resources at that one location might be small, and instead it might be economical to source from other locations. While sourcing from several different locations might result in a loss of some supply chain efficiency, significantly more resilience can be achieved. Sourcing from just a few different locations might be sufficient to build significant resilience. Saghafian and Van Oyen (2016) show that even a little bit of flexibility here can significantly help a firm deal with disruptions: A little backup flexibility can go a long way (p. 403).

11.5 Anecdotal Evidence from Industry and Impact on Asia and the Pacific

The struggle of companies to build resilient and cost-efficient supply chains is illustrated in a recent survey by Gartner (Wilson 2021). The survey reveals that “almost half of the respondents see lean methodologies, just-in-time systems, and low-cost country sourcing" as relevant to future strategies. Further, 30% of Gartner's survey respondents report that they are shifting from a "global to a more regional supply chain model" even though expensive local suppliers stay beyond consideration for many companies. Further, in the Allianz survey (see Azouz 2020), the respondents comprise 1,181 executives in risk-averse sectors such as IT, machinery and equipment, chemicals, energy and utilities, automotive, and agrifood, and it appears that less than 15% of companies consider reshoring. This highlights the fact that many firms are unable to take the costly decision of sourcing from more reliable suppliers even though they aim to build resilience.

This discussion has some implications for developing Asia and the Pacific. While many global companies are considering moving production closer to the main markets (which for some companies are in North America and Europe), our analysis indicates that there might be value in companies continuing to use less reliable but cheaper suppliers in developing Asia and the Pacific. The cost of using expensive local suppliers might be excessive for many companies. Instead, they might find value in implementing shared resilience levers such as increased flexibility or the placement of anticipatory orders. These measures might be more cost-efficient while providing a higher level of resilience.

11.6 Conclusion and Future Research

In this chapter, we offer a characterization of resilience-enhancing measures. We argue that resilience-enhancing measures are either based on using dedicated resources (referred to as "dedicated resilience levers") or on using shared resources (referred to as "shared resilience levers"). By dedicated resources, we mean resources that are provided only for the purpose of building resilience. In contrast, shared resilience levers are based on using shared resources. By shared resources, we mean resources that are not only used for risk mitigation but also serve another purpose, such as better meeting customer demand without disruption. Typically, shared resources not only help build resilience, but they also help meet customer demand in the absence of disruptions. We argue that shared resilience levers are particularly helpful for supply chains that focus on cost-efficiency and that produce basic/functional products. In contrast, dedicated resilience levers are particularly helpful for supply chains that are less exposed to cost pressure and produce innovative products. Further, we discuss how the supply chain finance solution reverse factoring can be considered a shared resource that helps build resilience and efficiency simultaneously.

This discussion requires more rigorous research to support the observations presented. Specifically, we call for more research that helps in better understanding the value of shared resilience levers for organizations. More rigorous research might be carried out through in-depth case study research and/or expert interviews, as well as modeling work that may help quantify the benefits of shared resilience levers for building resilience in the supply chain.

In the academic literature, supply chain resilience and supply chain efficiency have mostly been discussed as separate topics (with some exceptions, such as Chopra, Sodhi, and Lücker (2021)). For many companies, dedicated resilience levers are simply too expensive, and we need to better understand what value shared resilience levers offer to companies.

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Fostering Resilient Global Supply Chains Amid Risk and Uncertainty

Well-functioning supply chains are central to economic growth outcomes for maximizing the productive capacities of economies at both the regional and global levels. Economic progress through trade and financial channels over the past decades in Asia and the Pacific has been closely linked to the region's effective participation in global supply chains. In recent years, however, the coronavirus (COVID-19) pandemic and geopolitical tensions have exposed vulnerabilities in these supply chains, with notable concentration risks in energy and food supply networks. Supply chain disruptions triggered elevated global inflation due to surging energy and food prices, thereby exacerbating barriers to development in low-income countries in areas such as poverty, inequality, hunger, and malnutrition.

With a focus on Asia and Pacific, *Fostering Resilient Global Supply Chains Amid Risk and Uncertainty* provides evidence-based policy recommendations and implications for economies to navigate their participation in supply chains toward a more sustainable and resilient future. The book examines strategies for the effective diversification of global supply chains across key sectors, as well as the implications for progress toward global goals on climate and sustainable development. It offers timely insights for policy makers and scholars seeking to better understand the current trends in the global supply chain transformation, policy approaches for building resilient supply chains, the role of digital technologies, and the importance of multilateral cooperation.

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