Trade and Climate Change:
Global Value Chain and Policy Analysis

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vorgelegt von
M.Sc., Hendrik Mahlkow
aus Rostock

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Für Mama.

Acknowledgements

Four years ago, the world was different. Shortly after beginning my PhD, a global pandemic broke out. Two years after, Russia started a war in the middle of Europe that is still going on. The world has become more fragmented and more fragile, both politically and economically. At the same time, I never felt more settled personally than today. Pursuing a PhD was one of the best decisions I ever took. It satisfied my curiosity and fueled it further. All this happened while my son was born and my family and I lived in Berlin, Kiel, San Francisco, and Vienna. What an awesome ride. Looking back, these years were the happiest, most exiting, and fulfilling years of my life. None of this would have been possible without the support of people around me.

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I can’t phrase it any better than an eloquent friend once did: “It takes a village to raise a PhD student.” Thanks to all of you!

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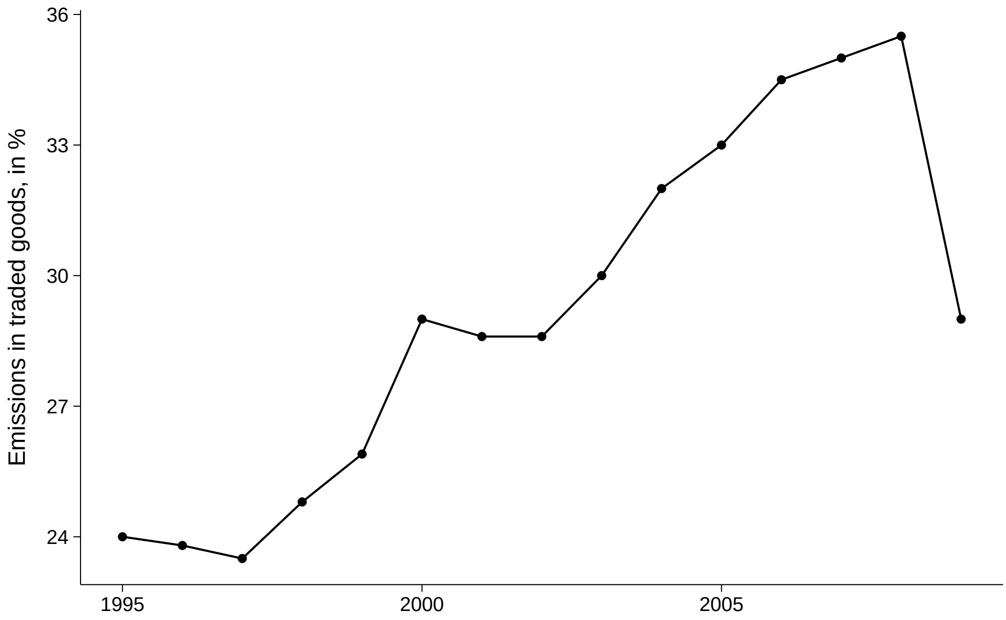
Introduction

Trade and climate change are huge multilateral issues that are high on the agenda of policymakers, from the UN Paris Agreement in 2015 to the recent disruptions of global supply chains during and after the COVID-19 pandemic[1]. Trade is arguably the main driver of globalization. It plays a crucial role to lift people out of poverty and to fulfill the 17 Sustainable Development Goals of the UN. Trade enables economic growth from specialization, productivity dispersion, and efficient resource allocations. At the same time, trade raises environmental concerns. Grossman and Krueger (1993) and Copeland and Taylor (1994) proposed three channels through which trade and macroeconomic changes affect the environment: scale, composition, and technique effects. The scale effect refers to how economic growth, often driven by trade, increases the scale of production and consumption. Ceteris paribus, that also scales up related pollution. The composition effect refers to a country's specialization in industries that are either more or less environmentally damaging based on its comparative advantage. Trade can alter specialization patterns. The technique effect refers to how trade can lead to (i) technological improvements and more efficient production processes, often driven by increased competition, or to (ii) endogenous environmental policy changes. These advancements can reduce the environmental impact per unit of production.

[1]See e.g., Chad P. Bown and Douglas A. Irwin "Why Does Everyone Suddenly Care About Supply Chains?", The New York Times, October 16, 2021.

Figure 1: Share of CO2 embodied in international trade.



Note: The numerator comprises the sum of direct emissions from the industry itself and those emissions that are embedded within the global value chain. The denominator encompasses total global emissions (Source: WIOD, own calculation based on Copeland et al., 2022).

Furthermore, trade can lead to an outsourcing of pollution, referred to as *pollution haven effect*, when firms reallocate their production to countries with less stringent environmental policies (Copeland and Taylor, 2004). In terms of global pollutants the concept is closely related to *carbon leakage*, which occurs when there is an increase in carbon dioxide emissions in one country as a direct result of an emissions reduction by a second country with a strict climate policy (Felder and Rutherford, 1993). Because of those strong inter-linkages and their political importance, scientists call for a coupling of climate and trade policies (Mehling et al., 2018; Jakob et al., 2022). In total, the embodied emissions in traded goods[2] account

[2]Embodied carbon emissions in traded goods refer to the total amount of CO2 emissions associated with the production – including all emissions along the value chain – and transportation of a product that is traded internationally.

for a fourth to a third of global CO2 emissions, see Figure 1. However, these accounting measures, even if they involve large quantities, do not tell us what global emissions would look like in a counterfactual world without trade or with different trade patterns.

Counterfactuals are hypothetical scenarios that explore *what* would happen *if* certain conditions or events were or had been different. They are centered around answering *"what if"* questions. For example, what are the distributional impacts if carbon prices are introduced globally? How do global emissions change if trade is balanced? How can trade policy mitigate climate change damages? This dissertation aims to contribute to our understanding of these questions. I will present theoretical extensions to quantitative trade models that explicitly incorporate (i) fossil fuels and carbon emissions, (ii) natural resources and land, and (iii) apply those extensions to answer questions of the trade and environment nexus.

In order to answer counterfactual questions, traditional CGE models have long been used, see e.g. Hertel (2013) for a survey of the influential GTAP model. However, in this thesis, I apply and extend a new strand of quantitative trade models, based on the seminal work of Eaton and Kortum (2002) and Caliendo and Parro (2015). A key difference between traditional CGE models, like the GTAP model, and new quantitative trade (NQT) models, like Caliendo and Parro (2015), is that the latter offers a tighter connection between theory and data. For NQT models, the theory directly governs the estimation of the key structural parameter for counterfactual analysis: the trade elasticity.[3] Estimation and computation go hand in hand. Their parsimony made this kind of models so influential in the last decade, see e.g. Costinot and Rodriguez-Clare (2014) for a review.

These NQT models are at the center of the "new quantitative trade theory" literature. They offer a theoretical foundation for the so-called gravity equation of international trade (Yotov et al., 2016), which models the

[3] In a multi-sector world as in Caliendo and Parro (2015) there is one trade elasticity per sector.

structure of bilateral trade flows as a function of bilateral costs and multilateral resistance (Anderson and Van Wincoop, 2003). In doing so, NQT models can be solved in relative changes, a practice made famous by Dekle et al. (2008) and referred to as "exact hat algebra". In addition to the points already mentioned, the increasing popularity of that model framework is based on the fact that input-output linkages can be explicitly incorporated. That makes the models well suited to study, for example, global value chains (Antràs and Chor, 2018), the impact of trade policy on carbon emissions (Shapiro, 2021), or embodied emissions in trade (Caron and Fally, 2022). I use NQT models throughout all chapters of the thesis.

The first chapter, which is joint work with Gabriel Felbermayr and Alexander Sandkamp, is the only paper that does not address an environmental question.[4] In fact, it examines the consequences of a decoupling of the *West* from the *East*. In the wake of the COVID19 pandemic and the beginning of the war in Ukraine, global value chains (GVCs) got disrupted. At the same time, tensions between political regimes are rising, especially between the US and China, the two powerhouses of trade and globalization. Against this backdrop, the economic consequences of persistent disruptions of GVCs are highly relevant for policymakers.

In order to analyze these consequences, we use a NQT model of international trade. It builds on the Ricardian framework developed by Eaton and Kortum (2002) and extended by Caliendo and Parro (2015) to incorporate input-output linkages between multiple sectors. This framework is especially useful for our analysis because input-output linkages play an important role in enhancing the effects of trade policy.[5] The first chapter serves as an introduction to the model framework, which is used and extended throughout the consecutive chapters of the thesis.

We find that a reciprocal economic decoupling between the EU and China

[4]Felbermayr, G., Mahlkow, H., & Sandkamp, A. (2023). Cutting through the value chain: The long-run effects of decoupling the East from the West. *Empirica, 50*(1), 75-108.

[5]See Caliendo and Parro (2022) for a recent overview of this topic.

would permanently reduce income in both economies by 0.8 percent and 0.9 percent respectively. A decoupling of Russia from the US and its allies would have much more severe long-term impacts for real income in Russia (minus 9.7 percent) than in the US and its allies (minus 0.2 percent). The reason for the uneven distribution of costs lies primarily in Russia's low economic importance compared with the US and its allies. Eastern European countries would be more strongly affected by a decoupling from Russia because of their more intensive inter-linkages with the Russian economy. A full decoupling between "East" (i.e., BRIC countries) and "West" (the US and its allies) would reduce income in both country groups on average by 3.9 percent and 1.3 percent respectively.

A key contribution of the first chapter lies in the parametrization of the model. We use the GTAP database[6] and derive all parameters for the *initial conditions* of the model. In contrast to other input-output tables, e.g. the World Input-Output Database (WIOD) or the OECD Inter-Country Input-Output Tables (ICIO), GTAP has a higher spatial and sectoral resolution. It features a consistent and reconciled cross-section of production, input-output, consumption, and trade data for 121 countries and 20 aggregated regions. It describes 65 sectors covering manufacturing, agriculture, transport and services. This "granularity" makes GTAP well suited for the analysis of GVCs, as well as for environmental questions throughout the rest of the thesis.

Two limitations of the GTAP data should be mentioned. First, not all data are directly observed for each country in the same year. Missing data is either extrapolated from previous years or imputed proportionally to world averages or to similar countries. This can introduce *temporal bias*, especially in rapidly changing economies. For example, if an economy has undergone significant changes in the intervening years, using older data to represent the current state can lead to inaccuracies. The extrapolated data may not accurately capture the current economic conditions or the

[6]Version 10 (Aguiar et al., 2019), which was the latest available release at the time the paper was written.

dynamics that have occurred since the last observed data point. Second, adjustments made to the data for creating a balanced, micro-consistent data set for CGE analysis can modify the raw data. This can lead to biases in detailed, country-specific analyses.

Part of those limitations are addressed in the second chapter, which is joint work with several colleagues.[7] We answer two key questions: (i) Will climate policy accelerate or brake structural change and economic development; (ii) what are the distributional effects of structural change on poor households in India as compared with distributional effects of climate policy. In the economics literature, the phenomenon of structural change is an intensively studied phenomenon and the composition of economic structure is an acknowledged measure of development (Kongsamut et al., 2001; Acemoglu et al., 2008; McMillan and Rodrik, 2011). We introduce this phenomenon in the field of climate policy modeling and distributional analysis.

Distributional effects are usually measured at the level of households and income groups, while drivers of climate policy and structural change are best represented at the level of national economies. In order to run a meaningful quantitative assessment, it is necessary to bridge these two scales. This study is one of the first doing this by bringing together information from different levels in a consistent way by coupling several models and methods in a three stage model cascade[8]. Therefore, we link the distributional analysis at the micro-level (households) to driving forces at the macro-level, i.e., price information conveyed to households include all macroeconomic feedbacks between climate policies, structural change, trade, and so on. The models are soft-coupled, i.e., they are solved independently, while results are fed back into each other. Our

[7]Leimbach, M., Huebler, M., Mahlkow, H., Montrone, L., Bukin, E., Felbermayr, G., Kalkuhl, M., Koch, J., Marcolino, M., Pothen, F., & Steckel, J. (2024). Macroeconomic Structural Change Likely Increases Inequality in India more than Climate Policy. *Revise and resubmit at Environmental Research Letters*.

[8]Our focus on future developments distinguishes the study from the rich literature on structural change and inequality, which is mainly empirical (Mehic, 2018; Hartmann et al., 2021; Rekha and Suresh Babu, 2022)

model cascade goes from a (i) global level – *integrated assessment* and reduced-form *structural change model* – to a (ii) national level – *trade model*[9] – and then to the analysis of the (iii) sub-national level of India – *household model*.

As previously mentioned, the country-level resolution of GTAP is not ideal for distributional analysis based on household data. As part of this paper, I develop an algorithm to dis-aggregate a country in the GTAP database into sub-national entities. I split India into 33 states by using regional value added data at the sector level, plus regional data on coal production. This approach reveals the spatial heterogeneity of distributional effects of national policies, as each state exhibits different production, trade, and comparative advantage patterns. The algorithm can easily be refined with more granular data, i.e., inter-state transportation costs, and extented to other countries. This presents interesting opportunities for further research.

We focus on India due to its considerable size and the wide disparities in economic development throughout the nation. It is sufficiently large to be relevant for global carbon emissions and exhibits high variability of local industrial dynamics which can be exploited for econometric analyses. In addition, the quality of Indian household data (National Statistical Survey) is generally good.

Our results indicate that carbon pricing tends to slow down economic structural change. They emphasize, however, that distributional effects of structural change are substantially stronger than those of carbon pricing. Consequently, socially sensitive policies supporting the process of structural transformation appear to be more important for poor households than downsizing climate (policy) ambitions.

Climate ambitions also indirectly motivate the research question behind

[9]We use the same model framework as in the first chapter, extended by the incorporation of carbon emissions from fossil fuel combustion and carbon taxes.

the third chapter, which is joint work with Joschka Wanner.[10] We ask whether global trade imbalances raise environmental concerns and therefore counteract climate ambitions. The research question was motivated by the fact that a large share of global carbon emissions arises in the production of goods that are consumed in a different country (see Figure 1). The flow of carbon embodied in trade is highly asymmetrical. At the same time, trade is highly and persistently unbalanced in value terms, too. Prominently, the two countries with the largest net ex- and imports of carbon (China and the US) have at the same time consistently been among the countries with the largest trade surplus and deficit, respectively. Until now, the role of trade imbalance in shaping global emission patterns has received little attention. In their recent handbook chapter, Copeland, Shapiro, and Taylor (2022) briefly refer to imbalances as one factor that could contribute to emissions outsourcing.

When we think about the impact of trade on the environment, countries differ in three dimensions: (i) the fossil fuels used in the production of goods or a countries' *production footprint*; (ii) the embodied emissions of final goods consumption or a countries' *consumption footprint*; and (iii) where the fossil fuels themselves originate from or a countries' *extraction footprint*. Under autarky, those footprints would be equal. Trade enables countries to detach their *footprints* from another. Trade imbalances potentially increase this detachment further which might drive up global carbon emissions. When we consider China and the US, trade re-balancing would limit the US' possibility to buy "dirty" imports in comparison to their "cleaner" exports. It would put a constraint on China to act as the world's supplier of carbon-intensive products, but ex-ante it is not clear where the production would take place instead.

To this end, we further extend the model framework, introduced in the previous chapters, by incorporating natural resources as production factors, different theory-consistent production functions, and a decomposition of

[10] Mahlkow, H., & Wanner, J. (2023). The Carbon Footprint of Global Trade Imbalances. *CESifo Working Paper No. 10729*.

embodied emissions in traded goods, based on (i) where the good is produced, (ii) where it is consumed, and (iii) where the fossil fuels used in the production of that good have been originally sourced from. In different counterfactual scenarios we calculate the magnitudes of the adjustments that an aggregate trade balancing would entail in terms of carbon emissions. For every individual country, the emission effect of removing its trade imbalance depends on the carbon intensities of its production and consumption patterns as well as on its fossil resource abundance. The simultaneous removal of all global trade imbalances is found to lower world carbon emissions by 0.89 percent or 295 million tons of carbon dioxide.

Is this a large effect? It is equivalent to the total annual emissions of Spain — the 21st largest emitter of CO2 in the world. One has to keep in mind that re-balancing global trade is not primarily an environmentally motivated policy. We show that the current pattern of global trade imbalances raises environmental concerns, because countries with a particularly carbon-intensive import mix tend to run a deficit, fostering the global production of emission-intensive goods, and fossil fuel exporters tend to run a surplus, increasing the globally available supply of these fuels.

While the previous chapter provided a comprehensive analysis of global trade imbalances and their environmental repercussions, it notably did not delve into the evaluation of specific *policies* addressing these issues. Moving forward, the fourth chapter shifts focus to the proactive role of *trade policy* in mitigating climate-induced welfare losses.[11] I analyze the effects of micro-level changes in crop yields – induced by future climate change – on sectoral specialization patterns and trade flows. In a second step, I identify regions particularly vulnerable to the economic consequences of climate change, which propagte through GVCs. In counterfactual scenarios, I derive the relative trade barrier liberalization required to offset climate change damages.

[11] Mahlkow, H. (2024). Climate Change Adaptation: Agricultural Productivity Shocks and Trade Policy Responses. *Unpublished*.

I add to an emerging literature on the role of trade policy for climate change adaption. Costinot et al. (2016) use similar micro-level productivity shocks and find that adaptation depends on a country's ability to change its production patterns, rather than its trade patterns. In contrast, Gouel and Laborde (2021) show that trade substitution is evenly important as adjusting production patterns.

Building on their analysis, I focus on productivity in agricultural sectors (e.g. crop failures), which I derive from the Global Agro-Ecological Zones (GAEZ) database provided by the Food and Agriculture Organization of the UN. The GAEZ database provides spatial information about future agricultural production risks and opportunities and adaptation options in a regular raster format of 5 arc-minute (about 9×9 km at the equator, over 9 million cells in total) grid cells. Climatic conditions are based on a time series of historical data of 1961-2010 and a selection of future climate simulations for four representative concentration pathways (RCPs) until 2100. This rich granular data offer sophisticated predictions about the bio-physical yield capacity of multiple crops under different climate change scenarios.

The results reveal that many crop yields in low-income countries will decline significantly on a national level, under RCP4.5, RCP6, and RCP8.5[12] with increasing magnitude. In order to utilize these results, I extend the model framework introduced in chapter 1 by incorporating *land* as an additional production factor. Therefore, I can use the climate change-induced productivity changes to shock the factor productivity of *land* in each country-sector individually. Accounting for general equilibrium effects, I investigate how shocks in one country spill-over through trade and GVCs to other countries. Similar to the previous chapters, I use the GTAP database to calibrate the initial equilibrium of the model. Unlike other influential MRIO tables, GTAP covers not only high- and middle-income countries. With 121 countries and 20 aggregated regions, GTAP is well

[12] The RCPs are labeled after a possible range of radiative forcing values in the year 2100 (4.5, 6, and 8.5 W/m2, respectively).

suited to study low-income countries that are particularly affected by climate-induced productivity shocks.

Countries who experience welfare losses are predominantly located in the Global South. These countries cannot compensate climate-induced productivity losses by (i) switching their production to more productive sectors, and (ii) import those crops whose local productivity declines, because they face high trade barriers. I develop a brute-force algorithm to calculate the necessary trade policy response of each country that would lose welfare under a business-as-usual scenario in order to compensate for the welfare losses. Usually, the largest non-tariff barriers reduction has to happen in countries with the highest initial losses. But this relation is not linear. Trade liberalization is an important adaptation policy to mitigate climate-induced welfare losses. If no coordination happens among countries who lose welfare, unilateral trade policy liberalization has to be higher. In contrast, if all countries, that experience climate-induced welfare losses, reduce their import barriers simultaneously, positive spill-over effects occur and global welfare increases by 0.5 percent.

To summarize, this thesis aims to contribute to the understanding of how international trade intersects with environmental sustainability. It utilizes NQT models, grounded in the new quantitative trade theory, to analyze the effects of trade policies and climate change on economic structures and global welfare. Except for the first chapter, which deals with the costs of decoupling the global economy, the remaining thesis investigates the influence of climate policies on economic development, examines the relationship between global trade imbalances and environmental issues, and assesses how trade policy can help mitigate climate-related welfare losses. The research combines detailed data analysis with theoretical models to provide clear insights into the trade-climate nexus, offering practical policy recommendations for harmonizing economic growth with environmental conservation.

Chapter 1

Cutting through the Value Chain: The long-run Effects of Decoupling the East from the West[1]

1.1 Introduction

Global value chains are currently being attacked on several fronts. The two most prominent threats are political. First, the COVID-19 pandemic has revealed the vulnerability of international value chains, prompting politicians to push for a re-shoring of production in order to reduce dependence on foreign suppliers and thus improve crisis resilience of the domestic economy.[2] The second threat stems from increased political

[1]Joint work with Gabriel Felbermayr and Alexander Sandkamp. We are grateful to participants of the Kiel Institute Research Seminar and the National Bank of Romania's Bucharest Economic Analysis and Research Seminar (BEARS) for their helpful comments and suggestions. We also thank Steffen Gans and Falk Wendorff for excellent research assistance.

[2]See for example Felbermayr et al. (2020, 2021). D'Aguanno et al. (2021) show that re-shoring production may even increase economic volatility. The reader is referred to Miroudot (2020) for a more general discussion.

tensions between China and Russia on one side, and the EU and the US on the other. The Russian invasion of Ukraine on 24th February 2022 has pushed the relationship between Russia and the political West to a new low, having provoked a cascade of economic sanctions and counter-sanctions.

Political struggles with China seem negligible in comparison. However, while the Sino-American trade war has raged for several years (**?**), relations between China and the EU are also by no means trouble-free. Following the opening of a Taiwanese representative office in Lithuania's capital Vilnius in November 2021, both Lithuanian firms and European companies using Lithuanian inputs complained about trade restrictions with China (European Commission, 2022). As a response, the EU has launched a case against China at the WTO, while simultaneously continuing the development of an Anti-Coercion Instrument. This recent spat has only been the latest in a series of conflicts between China and the EU. They are spurring a tendency to decouple, as both the EU and China are turning inwards to reduce their dependence on each other.[3]

Against this background, we use a computable general equilibrium model of international trade based on Caliendo and Parro (2015) to investigate the impact of five decoupling scenarios on trade and welfare. Incorporating intra- and international input-output linkages, the model quantifies the effects of changes in bilateral trade barriers on 65 sectors in 141 countries, covering 98 percent of economic activity worldwide. It is calibrated using the most recent version 10 of the input-output-database of the Global Trade Analysis Project (GTAP) as described by Aguiar et al. (2019) and allows quantifying both direct and indirect trade effects such as trade diversion and real income effects.

In the model, decoupling is achieved by a doubling of non-tariff barriers

[3]In March 2021, the ratification process of the Comprehensive Agreement on Investment (CAI) between the EU and China came to a halt following a series of sanctions and counter-sanctions amid the situation of the Uyghurs in Xinjiang province (European Parliament, 2021). For an overview of the challenges currently inherent in trade and investment relations between the EU and China, the reader is referred to Garcia-Herrero et al. (2020).

(NTBs) which strongly reduces trade while not completely eliminating it.[4] The first scenario assumes a doubling in NTBs between the EU and China (both unilateral and reciprocal). Keeping in mind the ongoing conflicts between China and the US, the second scenario analyses a decoupling between China on one side and the US and its allies (including the EU) on the other.[5] In light of the crisis in Ukraine, Scenario 3 simulates the effects of a trade war between Russia and the US and its allies. Scenario 4 models an even broader divide between the EU on one side and Brazil, Russia, India and China (BRIC) on the other. Scenario 5 investigates a trade dispute between the US allies and the BRIC countries.

The paper shows that a unilateral decoupling of China from the EU (i.e., a doubling of NTBs on Chinese imports from the EU) would almost eliminate bilateral imports - a phenomenon the literature calls trade destruction (Bown and Crowley, 2007). Perhaps less straightforward, Chinese exports to both the EU and the rest of the world also fall. This is because NTBs increase the cost of imported intermediates in China, thus reducing competitiveness of Chinese exporters that rely on foreign inputs. In addition, falling Chinese demand for EU products leads to a real depreciation of the Euro (in the model through falling EU prices), further reducing the competitiveness of Chinese exports relative to European goods.

Our model also makes predictions on how trade relations of both parties with third countries would evolve. In line with the literature (Bown and Crowley, 2007), we find that NTBs imposed on Chinese imports from the EU cause trade deflection (EU exports to other countries increase), import source diversion (China imports more from non-EU countries) and trade depression (the EU imports less from the rest of the world). A

[4]NTBs include a wide spectrum of instruments such as import controls, state aid, public procurement policies and trade defence instruments (Ederington and Ruta, 2016). They have been shown to have strong trade dampening effects (Kinzius et al., 2019; Ghodsi et al., 2017; Bratt, 2017). In principle, decoupling can also be achieved by prohibitively high tariffs or firms' autonomous decision to shift production back home.

[5]The country group "US allies" is defined as the US, the EU27, Albania, Australia, Canada, Iceland, Japan, New Zealand, Norway, Philippines, South Korea, Taiwan, Turkey, and the United Kingdom.

unilateral decoupling by the EU inverts these results. Not surprisingly, both parties would lose from a trade war (reciprocal imposition of NTBs), with welfare declining by 0.92 percent and 0.78 percent in China and the EU respectively. Engaging in a trade war with the US and its allies (including the EU) would be even more costly for China.

A trade war between Russia and the political West would inflict high economic damage on Russia, while the US and its allies would remain relatively unharmed on average. However, welfare declines are unevenly distributed, with Eastern European countries suffering most (even though still less than Russia). Overall, it becomes clear that relative economic size matters both for maximizing the welfare loss suffered by the political rival and for minimizing the own party's losses.

The paper relates to three strands of literature. First, it contributes to the literature investigating the impact of NTBs on trade. Several studies provide evidence for the trade dampening effects of NTBs, implying that they would constitute an effective instrument to achieve decoupling. By estimating ad-valorem tariff equivalents, Kee et al. (2009) show that NTBs restrict trade by almost as much as tariffs. Hoekman and Nicita (2011) even find a stronger trade dampening effect of NTBs compared to tariffs. In particular, the authors show that a 10 percent increase in NTBs is associated with a 1.7 percent reduction in trade. Similar conclusions are reached by Bouët et al. (2008) as well as Bratt (2017). Following the increased use of NTBs, the overall level of protection has not decreased between 1997 and 2015 despite the fall in tariffs during that period (Niu et al., 2017).

Ghodsi et al. (2017) investigate different types of NTBs, estimating trade dampening effects ranging between 5 and 30 percent, depending on the type of NTB imposed. More recently, Kinzius et al. (2019) show that NTBs reduce imports of affected products by up to 12 percent, with certain types of NTBs having an even stronger effect on trade.[6] We add to this literature

[6]A plethora of studies also investigates the impact of specific types of NTBs, such as

by modelling how the reduction in trade induced by the extreme measure of doubling NTBs translates into welfare changes. Crucially, we employ "exact hat algebra" (Dekle et al., 2008) to solve the model in changes rather than levels. This avoids the difficult endeavour of quantifying initial NTBs (Egger et al., 2015), which depend on manifold policy instruments.

Sanctions are a specific form of NTBs. Through an embargo, products become non-tradable across country pairs. The counterfactual analysis of the impact of sanctions on trade flows is often modelled by introducing non-tradable sectors (Etkes and Zimring, 2015; Crozet and Hinz, 2020; Hinz and Monastyrenko, 2022). We show that a doubling of NTBs acts almost as an embargo, even though it does not completely reduce trade flows to zero across country pairs. In an extension, we increase NTBs on energy imports from Russia up until they are completely eliminated. We also demonstrate that the damage inflicted by trade restrictions on the strategic rival increases with the economic size of the countries implementing them.[7]

The paper also relates to Amiti et al. (2019) and Fajgelbaum et al. (2020) who investigate the impacts of the recent waves of protectionism. While those studies focus on the impact of tariffs recently imposed by the US government, this paper investigates how NTBs could be used to seal off an economy from a particular trading partner.

Second, the paper contributes to the literature investigating the effect of trade barriers on untargeted countries. These are trade deflection as countries targeted by trade barriers export more to third countries (Bown and Crowley, 2006, 2007, 2010; Baylis and Perloff, 2010), import source diversion as countries imposing barriers on imports increase imports from non-targeted countries (Konings et al., 2001; Baylis and Perloff, 2010) and trade depression as targeted countries reduce imports from non-targeted

sanitary and phytosanitary measures (Crivelli and Gröschl, 2016), in particular against China (Beestermöller et al., 2017) or EU and US antidumping duties against China (Sandkamp, 2020; Felbermayr and Sandkamp, 2020; Sandkamp and Yalcin, 2021). For an overview, the reader is referred to Ederington and Ruta (2016).

[7] Our paper thus also relates to Chowdhry et al. (2022).

countries (Bown and Crowley, 2007). Incorporating all these phenomena through changes in relative prices, our model reveals the impacts of a trade war between China and the EU not only on the two economies but also on their trading partners.

Third, the paper relates to the literature on modelling trade flows in computable general equilibrium models (Costinot and Rodriguez-Clare, 2014). These models have their theoretical foundation in the so-called gravity equation of international trade (Yotov et al., 2016). They model the structure of bilateral trade flows as a function of bilateral costs. In doing so, these models can be solved in changes, a practice made famous by Dekle et al. (2008) and referred to as "exact hat algebra". The model used builds on the Ricardian framework developed by Eaton and Kortum (2002) and extended by Caliendo and Parro (2015) to incorporate input-output linkages between multiple sectors. This framework is especially useful for our analysis because input-output linkages play an important role in enhancing the effects of trade policy.[8]

We include services trade and NTBs in this framework in a fashion similar to Felbermayr et al. (2021, 2022). Unlike them, we use the latest version of GTAP (Aguiar et al., 2019) for the calibration of the model[9]. GTAP has the advantage that it not only contains a higher sectoral resolution (65 sectors) but also more countries (121 countries and 20 aggregate regions) than e.g. the World Input-Output Database (WIOD). Therefore, the model is based on detailed input-output linkages among a wide range of sectors and countries. Given the important role played by intermediate products in our model, the paper also relates to Gopinath and Neiman (2014); Halpern et al. (2015); Eaton et al. (2016); Alfaro et al. (2019); Antràs and Gortari (2020) as well as more generally to Goldberg et al. (2010) and Antràs (2020).

This paper is not the first to simulate the impact of an increase in NTBs on trade and welfare. Sforza and Steininger (2020) model the welfare effects

[8] See Caliendo and Parro (2022) for a recent overview of this topic.
[9] Version 10 when the paper was written.

of the COVID-19 induced shock to global production networks in both an open economy with current trade cost levels and a closed economy which is characterized by 100 percentage point higher trade costs (the same increase as the one we use). Eppinger et al. (2021) apply a similar approach, showing that the welfare loss resulting from a COVID shock is smaller in a de-globalised world. Both papers show that welfare is lower in a world with high trade barriers.

Instead of modelling a global decoupling, this paper investigates the impact of NTBs that are imposed between two very specific groups of countries. In contrast to Bachmann et al. (2022) and Chepeliev et al. (2022), who simulate the effects of decoupling from Russian energy exports, we investigate the impacts of a general decoupling that is not limited to energy trade. By revealing the true cost of an escalating trade war between China and Russia on one side and the EU and the US on the other, the findings are highly relevant for policymakers.

The remainder of the paper is structured as follows: Section 3.3 describes the model used for the analysis, while Section 3.4 provides an overview of the data used to calibrate the model. Section 3.5 presents the baseline results, followed by extensions and a discussion in Section 1.5. Section 3.6 concludes.

1.2 Model

The analysis is carried out with the help of the "Kiel Institute Trade Policy Evaluation" model ("KITE model") which is based on the trade model proposed by Caliendo and Parro (2015), who provide a multi-sector version of the Eaton and Kortum (2002) gravity model with input-output linkages.

1.2.1 Setup

There are N countries, indexed o and d, and J sectors, indexed j and k. Production uses one aggregate factor, which we consider as *labour*.[10] The factor is mobile across sectors $L_d = \sum_j^J L_d^j$, but not across countries. All markets are perfectly competitive. Sectors are either wholly tradable or non-tradable. In each sector, there is a continuum of goods $\omega^j \in [0,1]$. Households in d obtain utility from consumption C according to the following two-tier Cobb-Douglas utility function:

$$u_d = \prod_{j \in \mathcal{J}} \left(\exp \int_0^1 \ln C_d(\omega^j) d\omega^j \right)^{\alpha_d^j},$$

where α is the constant sectoral expenditure share and $\sum_{j \in \mathcal{J}} \alpha_d^j = 1$. Household income I_d is derived from the supply of labour L_d at wage w_d and a lump-sum transfer of tariff revenues. Goods are produced using labour l and *composite* intermediate input bundles m from all sectors. Countries differ in their productivity for different goods from the continua, inversely captured by the input requirement z, and the input cost shares γ. The production technology is Cobb-Douglas:

$$q_o^j(\omega^j) = \left[z_o^j(\omega^j) \right]^{-1} \left[l_o^j(\omega^j) \right]^{\beta_o^j} \left[\prod_{k=1}^{J} m_o^{k,j}(\omega^j)^{\gamma_o^{k,j}} \right]^{1-\beta_o^j}$$

where $\beta_o^j \in [0,1]$ is the cost share of labour and $\gamma_o^{k,j} \in [0,1]$ with $\sum_k \gamma_o^{k,j} = 1$ the share of sector k in sector j's intermediate. Overall efficiency of a producer is denoted by $z_o^j(\omega^j)$ and labour input by $l_o^j(\omega^j)$. Intermediate input bundles $m_o^{k,j}(\omega^j)$ from sector k used to produce ω^j are themselves Cobb-Douglas composites:

$$m_d^j = \exp \int_0^1 \ln d_d(\omega^j) d\omega^j,$$

[10]The factor is a composite of many factors, as for example labour, capital, and natural resources, which are all non-tradeable in our framework. In Section 1.5.3 we discuss the limitations to this approach.

where $d_d(\omega^j)$ is the demand for the specific variety ω^j as intermediate inputs. Unit costs (which equal the price due to perfect competition and constant returns to scale) are given by $c_o^j z_o(\omega^j)$, where the cost of the input bundles are given by

$$c_o^j = \Upsilon_o^j w_o^{\beta_o^j} \left[\prod_{k=1}^{J} (P_o^k)^{\gamma_o^{k,j}} \right]^{1-\beta_o^j} \tag{1.1}$$

where P_o^k is the price of a composite intermediate good from sector k, and the constant $\Upsilon_o^j = \prod_{k=1}^{J} (\gamma_o^{k,j} - \beta_o^j \gamma_o^{k,j})^{-\gamma_o^{k,j} + \beta_o^j \gamma_o^{k,j}} (\beta_o^j \gamma_o^j)^{-\beta_o^j \cdot \gamma_o^j}$. Hence, the cost of the input bundle depends on wages and the prices of *all* composite intermediate goods in the economy. A firm in country o can supply its output to country d at price

$$p_{od}^j = \phi_{od}^j \cdot \frac{c_o^j}{z_o^j(\omega^j)} \tag{1.2}$$

where ϕ_{od}^j denote generic bilateral sector-specific trade frictions.[11] These can take a variety of forms — e.g., tariffs, non-tariff barriers, export taxes. In that case we can specify

$$\phi_{od}^j = \tau_{od}^j \cdot \kappa_{od}^j \cdot \zeta_{od}^j \cdot NTB_{od}^j,$$

where τ_{od}^j represent sector-specific ad-valorem tariffs, $\kappa_{od}^j \geq 1$ iceberg trade costs, ζ_{od}^j export taxes or subsidies, and $NTB_{od}^j \geq 1$ non-tariff barriers.[12]

Producers of sectoral composites in country d search for the supplier with the lowest cost across all possible origin locations, i.e.,

$$p_d^j = \min_o \left\{ p_{od}^j \right\}. \tag{1.3}$$

Ricardian comparative advantage is induced à la Eaton and Kortum (2002) through a country-specific idiosyncratic productivity draw z^j from

[11]The "phiness" of trade à la Baldwin et al. (2003).

[12]Note that non-tariff barriers and iceberg trade costs are implemented in a similar fashion.

a Fréchet distribution.[13] As Caliendo and Parro (2015) show, the price of the composite good is then given as

$$P_d^j = A^j \left[\sum_{o=1}^{N} \lambda_o^j (c_o^j \phi_{od}^j)^{-\theta^j} \right]^{-1/\theta^j} \tag{1.4}$$

where $A^j = \Gamma(\xi^j)^{1/(1-\sigma^j)}$ is a constant with $\Gamma(\xi^j)$ being a Gamma function evaluated at $\xi^j = 1 + (1-\sigma^j)/\theta^j$ and σ^j is the elasticity of substitution between different goods in the continua of sector j.

Total expenditures on goods from sector j in country d are given by $X_d^j = P_d^j Q_d^j$. The expenditure on those goods originating from country o is called X_{od}^j, such that the share of j from o in d is $\pi_{od}^j = X_{od}^j / X_d^j$. In other words, it is the share of an exporter country in the total expenditure, by sector, of an importer country. This share can also be expressed as

$$\pi_{od}^j = \frac{\lambda_o^j (c_o^j \phi_{od}^j)^{-\theta^j}}{\sum_{h=1}^{N} \lambda_h^j (c_h^j \phi_{hd}^j)^{-\theta^j}} \tag{1.5}$$

which forms the core of a gravity equation.

1.2.2 General equilibrium

Total expenditures X_d^j on goods from sector j are the sum of the firms' and households' expenditures on the composite intermediate good, either as input to production or for final consumption

$$X_d^j = \sum_{k=1}^{J} (1-\beta_d^k) \gamma_d^{j,k} \sum_{o=1}^{N} X_o^k \frac{\pi_{do}^k}{\tau_{do}^k \zeta_{do}^k} + \alpha_d^j I_d \tag{1.6}$$

with $I_d = w_d L_d + R_d + D_d$, i.e., labour income, government revenue (tariff and export taxes minus export subsidies) and the aggregate trade

[13] The productivity distribution is characterized by a location parameter λ_o^j that varies by country and sector inducing *absolute* advantage, and a shape parameter θ^j that varies by sector determining *comparative* advantage. θ^j describes the elasticity of trade to trade costs.

balance. The first term on the right-hand side gives demand of sectors k in all countries o for intermediate usage of sector j varieties produced in country d, the second term denotes final demand. Sectoral trade balance is simply the difference between imports and exports

$$D_d^j = \sum_{o=1}^{N} X_{od}^j - X_{do}^j \tag{1.7}$$

and the aggregate trade balance $D_d = \sum_{j=1}^{J} D_d^j$, and $\sum_{d=1}^{N} D_d = 0$, with D_d being exogenously and D_d^j being endogenously determined.[14] The trade balance can then be expressed as

$$\sum_{j=1}^{J}\sum_{o=1}^{N} X_d^j \frac{\pi_{od}^j}{\tau_{od}^j \zeta_{od}^j} - D_d = \sum_{j=1}^{J}\sum_{o=1}^{N} X_o^j \frac{\pi_{do}^j}{\tau_{do}^j \zeta_{do}^j}. \tag{1.8}$$

The goods market clearing (4.7) and trade balance (4.9) conditions close the model.

1.2.3 Comparative statics in general equilibrium

We are interested in the effects of different decoupling scenarios on trade flows and welfare (measured as real income). Decoupling is introduced via doubling of non-tariff barriers of all imports from a specific trading partner. In order to quantify the comparative static effects of changes in non-tariff barriers on trade flows and welfare, we solve the model in changes, as suggested by Dekle et al. (2008). Let x denote the initial level of a variable and x' its counterfactual level. Then, trade cost shocks are given by $\hat{x}_{od}^j = x_{od}^{j\prime}/x_{od}^j$. In our analysis where we only consider a change in non-tariff barriers — leaving all other trade costs unchanged, as e.g. tariffs — this leads to $\hat{\phi}_{od}^j = NTB_{od}^{j\prime}/NTB_{od}^j = 2$ for country d that

[14] In a first step, we compute a benchmark scenario by setting all aggregate trade imbalances D_d to zero. This approach follows Ossa (2014) in order to account for the problem that the change in *real* income (Eq. 4.15) otherwise depends on what *nominal* units D_d is measured in. The new equilibrium serves as a baseline for the counterfactual scenarios.

decouples from imports of country o in sector j.[15] In a similar fashion as iceberg trade costs, non-tariff barriers are ≥ 1. For example, if importer d decouples from exporter o and the initial $NTB_{od}^{j} = 1.1$, a 100 percent increase in non-tariff barriers yields a counterfactual $NTB_{od}^{j\prime} = 2.2$. The change in welfare is

$$\hat{W}_d = \frac{\hat{I}_d}{\prod_{j=1}^{J} (\hat{P}_d^j)^{\alpha_d^j}}. \tag{1.9}$$

In Appendix A.3, we present the system of equations in changes required to solve the model.

1.2.4 Overview of the scenarios

We consider five scenarios: (1) a decoupling of the EU 27 and China; (2) a decoupling of the US and its allies from China; (3) a decoupling of the US and its allies from Russia; (4) a decoupling of the EU 27 from the BRIC countries; and (5) a decoupling of the US and its allies from the BRIC countries. In principle, decoupling - i.e., shifting production away from the trading partner and back to the own economy - can be achieved without government intervention if firms decide to shift their production back home. It can also be enforced by the government through import bans, prohibitively high tariffs or NTBs such as state aid or public procurement policies. Within the model, decoupling cannot be implemented explicitly. Instead, it is modelled by a doubling in NTBs on imports (i.e., an increase by 100 percentage points) in all sectors relative to current levels.[16] As shown in Section 3.5, this results in a strong reduction in imports without completely eliminating them.[17]

[15] Non-tariff barriers are difficult to quantify due to a lack of sufficient global data coverage. We rely on the “exact hat algebra” approach, famously described by Dekle et al. (2008), and solve the model in changes. Therefore, we do not need to know the initial level of non-tariff barriers.

[16] The paper thus differs from Felbermayr et al. (2020, 2021) who exclude oil and gas from the analysis.

[17] Of course, in reality decoupling can be more subtle, leading to smaller reductions in imports. We discuss this in an extension in Section 1.5.

Exports remain untreated, as it is assumed that countries want to reduce their import dependence only. This assumption is not realistic in case of the sanctions imposed against Russia, as the EU and the US also impose restrictions on their exports to Russia. Such behaviour is captured by the scenario simulating an increase in Russian NTBs. Within the model, imposing NTBs on, say, the EU's exports to Russia has the same effect as Russia imposing NTBs on its imports from the EU.

Each scenario is divided into three sub-scenarios that simulate a unilateral decoupling (modelled by an increase in NTBs on imports of the decoupling country) as well as a trade war (both countries increasing NTBs on each other's imports). For example, the three sub-scenarios of Scenario 1 simulate a unilateral decoupling by the EU vis-à-vis China (i.e., a doubling in NTBs on EU imports from China, Scenario 1A), a unilateral decoupling by China vis-à-vis the EU (i.e., a doubling in NTBs on Chinese imports from the EU, Scenario 1B) as well as a reciprocal decoupling / trade war (i.e., a doubling in NTBs on EU imports from China and a doubling in NTBs on Chinese imports from the EU, Scenario 1C).

For each sub-scenario, we simulate changes in bilateral trade flows between the trading partners (measuring trade destruction), changes in exports to the rest of the world (trade deflection), changes in imports from the rest of the world (import source diversion and trade depression), the change in total exports as well as the change in welfare. For country groups such as the EU or BRIC, the welfare change is computed as an average across countries, weighted by the share of a single country's value-added within the group (before the imposition of NTBs). The change in trade flows is calculated by the groups' sum of respective real trade flows before and after decoupling. Real flows are calculated by dividing nominal trade flows by the sectoral price change in the destination.

1.3 Data

To simulate the effects of a (simultaneous) decoupling of trading partners in general equilibrium, we need to identify the model parameters. Consumption shares and input coefficients (α, β, and γ), as well as bilateral trade shares (π), value added (wL), and initial trade imbalances (D) are obtained from the GTAP input-output table (Aguiar et al., 2019). The latest version of GTAP provides data for the year 2014.[18] We choose GTAP because of its rich geographical (121 countries and 20 aggregated regions) and sectoral (65 sectors) coverage. In contrast to the World Input Output Database (WIOD, used for example by Bachmann et al. (2022)), GTAP includes separate fossil fuels sectors such as gas, coal and oil. This makes the model particularly well suited to analyse decoupling from Russia. For a full list of all countries, see Appendix A.4.

Model outcomes crucially depend on the productivity dispersion parameters θ^j. Therefore, we take well established gravity estimates from the literature (Fontagné et al., 2018).[19] For the service sectors, we rely on an estimate for the aggregate service sector provided by Egger et al. (2012).

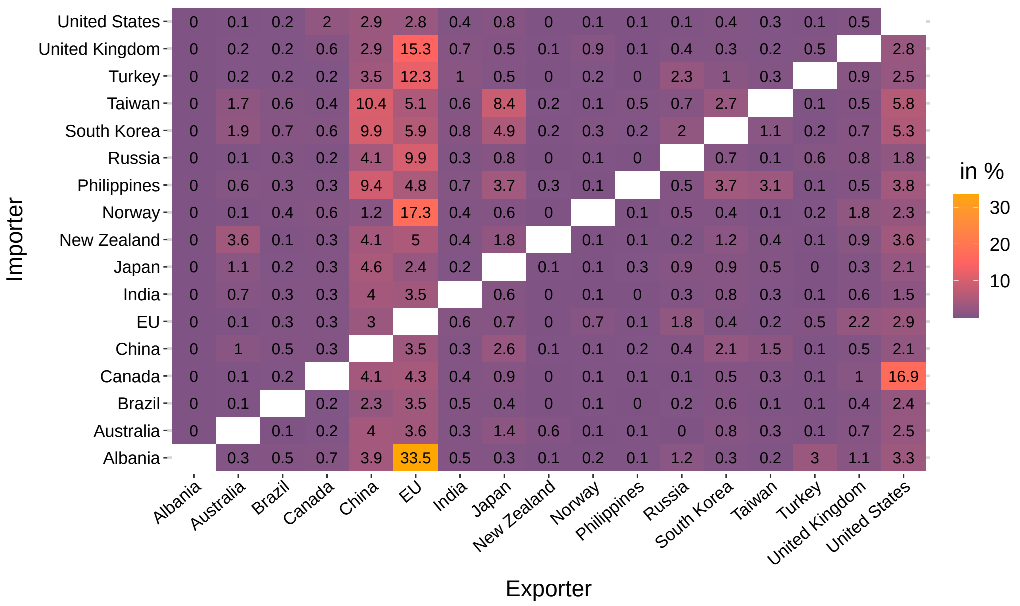
In Section 3.5 we show that relative economic size matters for the welfare loss following decoupling. The extent of relative economic size becomes clear when looking at bilateral imports in percent of the importer's GDP in Figure 1.1. Russia's imports from the EU equal almost 10 percent of its GDP, while for the EU, imports from Russia only amount to 1.8 percent of its GDP. When the political West forms a coalition, the imbalance becomes even more severe. Russia's imports from the US and its allies equal 15.2 percent of its GDP, while for the US and its allies, imports from Russia only amount to 2.7 percent of their joint GDP.[20]

[18]This is the most recent year for which input-output data for 141 countries/regions is available. We do not predict baseline values for some future year, since this would introduce additional margins of error.

[19]Their GTAP 10 estimates are from October 2020 and can be found on their homepage.

[20]Note that the latter number cannot be directly summed up by the values in Figure 1.1 because the shares must be weighted by the relative GDP share in the coalition.

Figure 1.1: Bilateral imports in percent of GDP.



Note: Own calculation based on 2014 values of the GTAP 10 database.

1.4 Results

Scenario 1: Decoupling between China and the EU Table 1.1 presents the results for a decoupling between the EU and China (Scenario 1). A unilateral decoupling of the EU from China almost completely eliminates bilateral imports (Scenario 1A). More specifically, EU imports from China fall by 95.82 percent (Column 1). In contrast, Chinese exports to the rest of the world increase by 8.22 percent (Column 3) as Chinese exporters find alternative markets following the increase in the cost of exporting to the EU (trade deflection). Nevertheless, the increased exports to the rest of the world are unable to fully compensate for the loss in export business to the EU, so that overall, Chinese exports fall by 8.49 percent (Column 7). This is accompanied by a reduction in welfare of 0.55 percent in China (Column 9).

Table 1.1: Scenario 1 "EU-China decoupling", changes in percent.

Decoupling scenario	Δ Bilateral exports		Δ Exports to RoW		Δ Imports from RoW		Δ Total exports		Δ Welfare	
	China (1)	EU (2)	China (3)	EU (4)	China (5)	EU (6)	China (7)	EU (8)	China (9)	EU (10)
1A EU	-95.82	-15.92	8.22	-5.30	-8.62	6.43	-8.49	-6.43	-0.55	-0.58
1B China	-10.31	-97.35	-5.57	5.42	7.16	-4.03	-6.33	-5.49	-0.46	-0.28
1C Bilateral	-96.21	-97.70	2.25	-0.49	-2.22	2.27	-13.56	-10.81	-0.92	-0.78

Table 1.2: Scenarios 1 and 2, changes in percent.

Decoupling scenario	Δ Bilateral exports		Δ Exports to RoW		Δ Imports from RoW		Δ Total exports		Δ Welfare	
Panel A: Scenario 1 "EU-China decoupling"										
	China (1)	EU (2)	China (3)	EU (4)	China (5)	EU (6)	China (7)	EU (8)	China (9)	EU (10)
1A EU	-95.82	-15.92	8.22	-5.30	-8.62	6.43	-8.49	-6.43	-0.55	-0.58
1B China	-10.31	-97.35	-5.57	5.42	7.16	-4.03	-6.33	-5.49	-0.46	-0.28
1C Bilateral	-96.21	-97.70	2.25	-0.49	-2.22	2.27	-13.56	-10.81	-0.92	-0.78
Panel B: Scenario 2 "US allies-China decoupling"										
	China (1)	US al. (2)	China (3)	US al. (4)	China (5)	US al. (6)	China (7)	US al. (8)	China (9)	US al. (10)
2A US al.	-93.90	-44.84	48.75	-9.68	-37.67	11.66	-35.43	-19.92	-2.44	-0.79
2B China	-34.46	-95.54	-26.45	11.88	45.09	-8.27	-31.18	-19.42	-2.10	-0.49
2C Bilateral	-95.74	-97.32	11.70	-0.75	-10.76	3.88	-51.70	-28.88	-3.55	-0.95

Table 1.3: Scenarios 1, 2, and 3, changes in percent.

Decoupling scenario	Δ Bilateral exports		Δ Exports to RoW		Δ Imports from RoW		Δ Total exports		Δ Welfare	
Panel A: Scenario 1 "EU-China decoupling"										
	China (1)	EU (2)	China (3)	EU (4)	China (5)	EU (6)	China (7)	EU (8)	China (9)	EU (10)
1A EU	-95.82	-15.92	8.22	-5.30	-8.62	6.43	-8.49	-6.43	-0.55	-0.58
1B China	-10.31	-97.35	-5.57	5.42	7.16	-4.03	-6.33	-5.49	-0.46	-0.28
1C Bilateral	-96.21	-97.70	2.25	-0.49	-2.22	2.27	-13.56	-10.81	-0.92	-0.78
Panel B: Scenario 2 "US allies-China decoupling"										
	China (1)	US al. (2)	China (3)	US al. (4)	China (5)	US al. (6)	China (7)	US al. (8)	China (9)	US al. (10)
2A US al.	-93.90	-44.84	48.75	-9.68	-37.67	11.66	-35.43	-19.92	-2.44	-0.79
2B China	-34.46	-95.54	-26.45	11.88	45.09	-8.27	-31.18	-19.42	-2.10	-0.49
2C Bilateral	-95.74	-97.32	11.70	-0.75	-10.76	3.88	-51.70	-28.88	-3.55	-0.95
Panel C: Scenario 3 "US allies-Russia decoupling"										
	Russia (1)	US al. (2)	Russia (3)	US al. (4)	Russia (5)	US al. (6)	Russia (7)	US al. (8)	Russia (9)	US al. (10)
3A US al.	-95.68	-39.68	107.35	-1.59	-34.19	3.19	-28.74	-3.80	-7.30	-0.13
3B Russia	-27.53	-96.22	-22.51	2.03	50.58	-1.11	-25.87	-3.67	-4.71	-0.09
3C Bilateral	-96.36	-97.69	58.79	-0.06	-9.09	1.90	-45.21	-5.72	-9.71	-0.17

Perhaps less straightforward, EU exports to China also decline, albeit to a lesser extent (15.92 percent, Column 2 of Table 1.1). This result is driven

Table 1.4: Scenarios 4, 5, and 6, changes in percent.

Decoupling scenario	Δ Bilateral exports		Δ Exports to RoW		Δ Imports from RoW		Δ Total exports		Δ Welfare	
Panel A: Scenario 4 "EU-BRIC decoupling"										
	BRIC (1)	EU (2)	BRIC (3)	EU (4)	BRIC (5)	EU (6)	BRIC (7)	EU (8)	BRIC (9)	EU (10)
4A EU	-95.96	-21.75	13.19	-8.88	-10.20	15.44	-11.48	-11.56	-0.84	-1.05
4B BRIC	-16.09	-96.96	-7.08	11.14	9.98	-8.11	-9.12	-11.31	-0.83	-0.58
4C Bilateral	-96.48	-97.57	4.79	0.35	-1.62	6.24	-18.10	-19.99	-1.45	-1.42
Panel B: Scenario 5 "US allies-BRIC decoupling"										
	BRIC (1)	US al. (2)	BRIC (3)	US al. (4)	BRIC (5)	US al. (6)	BRIC (7)	US al. (8)	BRIC (9)	US al. (10)
5A US al.	-93.75	-47.85	55.02	-14.10	-38.12	22.12	-39.25	-28.36	-2.75	-1.10
5B BRIC	-37.77	-95.41	-25.16	19.65	43.66	-13.14	-33.15	-28.95	-2.43	-0.70
5C Bilateral	-95.72	-97.42	16.10	-0.46	-10.82	8.35	-54.75	-41.41	-3.86	-1.32
Panel C: Scenario 6 "US allies-Russia bilateral energy decoupling"										
	Russia (1)	US al. (2)	Russia (3)	US al. (4)	Russia (5)	US al. (6)	Russia (7)	US al. (8)	Russia (9)	US al. (10)
6 Energy	-56.69	-26.82	56.08	-0.46	-22.57	2.01	-19.51	-1.99	-6.62	-0.10

by two mechanisms. First, NTBs imposed by the EU against China reduce EU demand for Chinese products. In addition to falling bilateral imports, this leads to falling prices of Chinese products.[21] This real depreciation makes Chinese products more attractive relative to European ones, thus reducing EU exports to China. In addition, falling prices in China also increase competitiveness of Chinese products in the rest of the world, resulting in the aforementioned trade deflection (Column 3) as well as trade depression, i.e., a fall in Chinese imports from the rest of the world (Column 5).[22]

Second, increasing prices of imports from China due to NTBs mean that EU imports are diverted away from China and towards other countries. In fact, EU imports from the rest of the world increase by 6.43 percent (import source diversion, Column 6). At the same time, some production

[21] In the real world, one would observe a nominal depreciation of the Chinese Renminbi against the Euro following a fall in demand for Chinese currency. Within the model, a real depreciation takes place in the form of lower prices in China relative to the EU.

[22] The model takes such general equilibrium effects into account through its balanced trade condition. Aggregate trade deficits/surpluses are assumed to remain constant. If China exports less to the EU following higher NTBs, this implies that China can either export more to the rest of the world (trade deflection) or reduce imports from both the EU and the rest of the world (trade depression). Both of these adjustment mechanisms can be observed in Scenario 1A.

shifts from China to Europe. Production is thus shifted to less productive producers outside China. This decrease in specialisation increases average production costs of affected goods. In particular, more expensive intermediate products also increase production costs of companies in the EU and consequently reduce their international competitiveness, causing a fall in exports (and rise in imports). Consequently, EU exports to the rest of the world fall by 5.3 percent (Column 4) so that overall, European exports decline by 6.43 percent (Column 8). Welfare in the EU falls by 0.58 percent (Column 10).

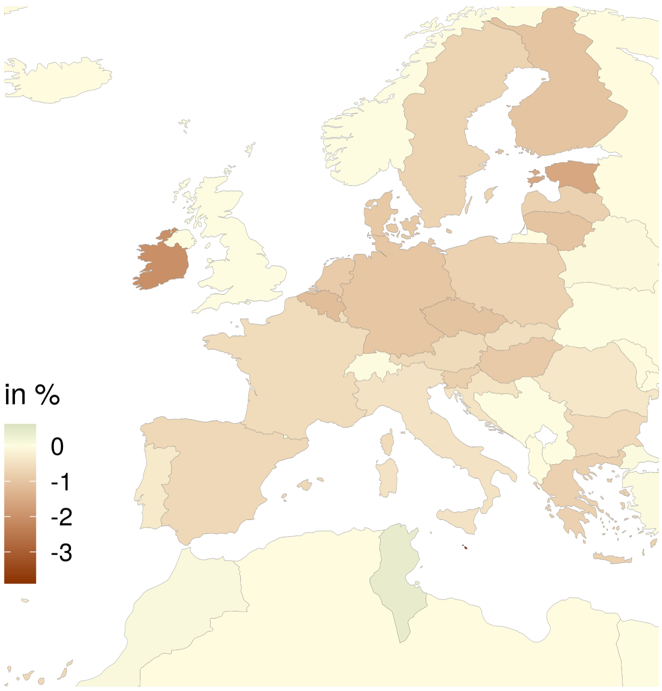
A unilateral decoupling by China has exactly opposite effects (Scenario 1B). Chinese imports from the EU fall by 97.43 percent (Column 2), while Chinese imports from the rest of the world increase by 7.16 percent (Column 5). Following the fall in competitiveness caused by higher prices of intermediates and a real depreciation of the Euro relative to the Renminbi, Chinese exports to the EU (the rest of the world) fall by 10.31 percent (5.57 percent, Columns 1 and 3). Overall, Chinese exports fall by 6.33 percent (Column 7) in this scenario, resulting in a welfare loss of 0.46 percent (Column 9).

Meanwhile, European exports are deflected to the rest of the world (an increase of 5.42 percent, Column 4). Overall, EU exports nevertheless decline by 5.49 percent (Column 8). At the same time, falling EU prices reduce imports from the rest of the world (Column 6). The EU experiences a welfare loss of 0.28 percent (Column 10). The EU thus suffers less from a restriction on its exports to China (Scenario 1B) than on its imports (Scenario 1A). This is not surprising given the trade deficit the EU has with China.

A full-blown trade war between China and the EU (Scenario 1C) puts trade between the two economies almost to a complete standstill. Chinese exports (imports) to (from) the EU decline by 96.2 percent (97.7 percent) in this scenario (Columns 1 and 2). For China with its trade surplus with the EU, downward pressure on prices resulting from a fall in demand from the EU outweighs the loss in competitiveness due to higher prices of intermediates, so that Chinese exports to the rest of the world increase by 2.25 percent (Column 3), while imports fall by 2.22 percent (Column 5).

For the EU with its trade deficit vis-à-vis China, higher prices of intermediates from China dominate the negative price effects resulting from falling demand from China. Consequently, EU exports to the rest of the world decline by 0.49 percent (Column 4), while imports increase by 2.27 percent (Column 6). Overall, Chinese and EU exports fall by 13.56 percent and 10.81 percent respectively (Columns 7 and 8). Welfare declines by 0.92 percent in China (Column 9) and 0.78 percent in the EU (Column 10).

Figure 1.2: Welfare effects by European country in Scenario 1C, changes in percent.



A trade war thus harms both China and Europe. However, welfare losses are not evenly distributed, as Figure 1.2 shows. Within the EU, small open economies such as Malta (-3.89 percent), Ireland (-2.04 percent) and Estonia (-1.59 percent) lose most.[23] Outside the EU, most countries remain relatively unaffected, as pictured in Figure A.1 in the Appendix A. For example, welfare in Russia falls by 0.02 percent. A few countries such as Cambodia (+0.62 percent), Bangladesh (+0.44 percent) and Tunisia (+0.38 percent) even slightly gain from a trade war between China and the EU. Welfare gains for the US a negligible (+0.005 percent).

Scenario 2: Decoupling between China and US allies Scenario 2 models a decoupling of China from the US and its allies, which for the purposes of this paper are defined as the EU27, Albania, Australia, Canada, Iceland, Japan, New Zealand, Norway, Philippines, South Korea, Taiwan, Turkey, and the United Kingdom.[24] The results are reported in Table 1.5, which is structured in the same way as Table 1.1. The effects of decoupling on bilateral trade between China and the US and its allies are qualitatively similar to Scenario 1. Bilateral imports of the party imposing NTBs are almost eliminated completely, while bilateral exports also fall (Columns 1 and 2 of Table 1.5). The decline in bilateral exports of the imposing party is stronger than in Scenario 1 because the US and its allies constitute a larger market for Chinese products than just the EU. Consequently, the fall in demand for Chinese products is larger, causing larger real adjustments in the bilateral exchange rate.

Table 1.5: Scenario 2 "US allies-China decoupling", changes in percent.

Decoupling scenario	Δ Bilateral exports		Δ Exports to RoW		Δ Imports from RoW		Δ Total exports		Δ Welfare	
	China (1)	US al. (2)	China (3)	US al. (4)	China (5)	US al. (6)	China (7)	US al. (8)	China (9)	US al. (10)
2A US al.	-93.90	-44.84	48.75	-9.68	-37.67	11.66	-35.43	-19.92	-2.44	-0.79
2B China	-34.46	-95.54	-26.45	11.88	45.09	-8.27	-31.18	-19.42	-2.10	-0.49
2C Bilateral	-95.74	-97.32	11.70	-0.75	-10.76	3.88	-51.70	-28.88	-3.55	-0.95

Another reason for the strong decline in bilateral exports can potentially be found in the production networks China has with several countries

[23]Detailed results are provided by Table A.1 in the Appendix A.
[24]These are mainly countries with which the US has some form of military alliance.

among the US allies, in particular its neighbours (Aichele and Heiland, 2018). Global supply chains are characterised by multiple border crossings (Johnson and Noguera, 2017). If a value chain for a particular product crosses borders between China and the US allies several times, NTBs imposed on US allies' imports can have strong impacts on their exports, too. For example, presume that a product is initially produced in China, then exported to South Korea where it is combined with another input before being sent back to China for final manufacturing. If South Korea imposes NTBs on imports from China, this also reduces its exports. With multiple border crossings not uncommon in modern value chains, NTBs imposed on imports can have strong impacts on a country's exports to the partner country that is targeted by the trade restrictions. This is particularly true for the country group US allies, as it includes several countries with close trade relationships with China.

In Scenario 2A (B), driven by price adjustments, we observe trade deflection of Chinese (US allies') exports following the imposition of NTBs by US allies (China, Columns 3 and 4). Trade depression is also present, as imports by the targeted country from the rest of the world decline (Columns 5 and 6). On the other hand, following the fall in competitiveness of products produced with the help of intermediates subject to NTBs as well as real price adjustment following shifts in relative demand, exports by the implementing country group to both the targeted country and the rest of the world decline (Columns 1 to 4), while imports from the rest of the world increase (import source diversion, Columns 5 and 6). Effects on overall exports and welfare are negative for both parties (Columns 7 to 10). As shown in Scenario 2C, China loses three times more from a trade war (-3.55 percent, Column 9) than the US and its allies (-0.95 percent, Column 10). This is not surprising as the share of Chinese exports going to this country group is larger than China's share in US allies' exports, in particular as US allies trade a lot among themselves.

Scenario 3: Decoupling between Russia and US allies Against the background of the crisis in Ukraine, a decoupling by the US and its allies from Russia seems particularly relevant. Scenario 3 thus simulates the effects of an increase in NTBs between the US and its allies on one side and Russia on the other. Qualitatively, the results, presented in Table 1.6, are similar to those in Scenario 2. However, the magnitude of the welfare effects differs strongly from those experienced in a trade war between the US allies and China. The US and its allies are a much bigger trade partner for Russia than Russia is for the US and its allies. Even when just considering the EU, Russia only accounted for 4.8 percent of the EU's total trade in 2020, while the EU accounted for 37.3 percent of Russian trade (European Commission, 2022). Consequently, a unilateral imposition of NTBs by the US and its allies against imports from Russia (Scenario 3A) hits Russia much harder (7.3 percent drop in welfare, Column 9) than the imposing countries (0.13 percent fall, Column 10).

Export barriers imposed by the US and its allies against Russia are captured by Scenario 3B.[25] Restricting exports to Russia does less economic harm than restricting imports from the country. However, welfare in Russia still falls by 4.71 percent in this scenario (Column 9). A trade war, i.e., a restriction on both Russia's exports and imports (Scenario 3C), reduces welfare in Russia by 9.71 percent (Column 9) but only by 0.17 percent in the US and its allies (Column 10). Overall, a trade war with Russia is much less costly for the US and its allies than a trade war with China. Once again, this is not surprising given that China accounted for 22 percent of the EU's imports and 10 percent of its exports in 2021, whereas Russia accounted for less than 7 percent of EU imports and 4 percent of exports (UN, 2022).

[25]Within the model, barriers imposed on, say, EU exports to Russia have the same effect as barriers imposed by Russia on imports from the EU.

Table 1.6: Scenario 3 "US allies-Russia decoupling", changes in percent.

Decoupling scenario	Δ Bilateral exports		Δ Exports to RoW		Δ Imports from RoW		Δ Total exports		Δ Welfare	
	Russia (1)	US al. (2)	Russia (3)	US al. (4)	Russia (5)	US al. (6)	Russia (7)	US al. (8)	Russia (9)	US al. (10)
3A US al.	-95.68	-39.68	107.35	-1.59	-34.19	3.19	-28.74	-3.80	-7.30	-0.13
3B Russia	-27.53	-96.22	-22.51	2.03	50.58	-1.11	-25.87	-3.67	-4.71	-0.09
3C Bilateral	-96.36	-97.69	58.79	-0.06	-9.09	1.90	-45.21	-5.72	-9.71	-0.17

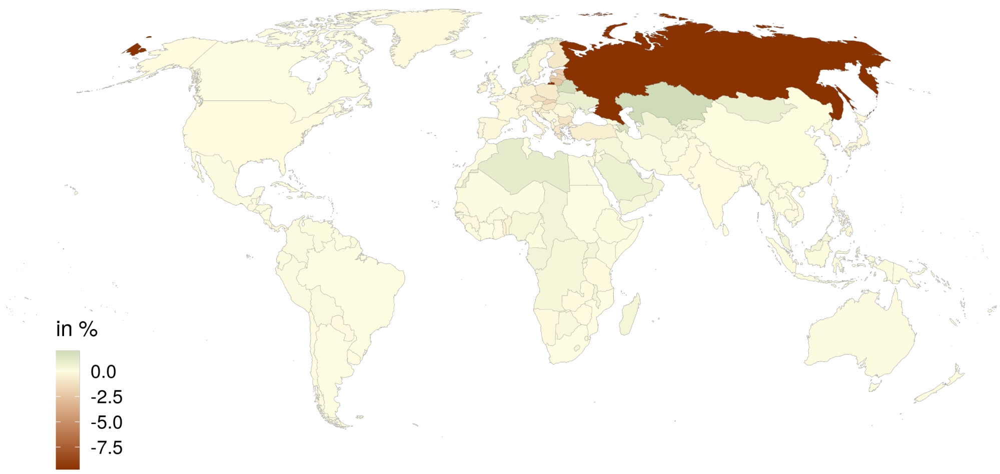
Table 1.7: Scenarios 3 and 4, changes in percent.

Panel A: Scenario 3 "US allies-Russia decoupling"										
Decoupling scenario	Δ Bilateral exports		Δ Exports to RoW		Δ Imports from RoW		Δ Total exports		Δ Welfare	
	Russia (1)	US al. (2)	Russia (3)	US al. (4)	Russia (5)	US al. (6)	Russia (7)	US al. (8)	Russia (9)	US al. (10)
3A US al.	-95.68	-39.68	107.35	-1.59	-34.19	3.19	-28.74	-3.80	-7.30	-0.13
3B Russia	-27.53	-96.22	-22.51	2.03	50.58	-1.11	-25.87	-3.67	-4.71	-0.09
3C Bilateral	-96.36	-97.69	58.79	-0.06	-9.09	1.90	-45.21	-5.72	-9.71	-0.17
Panel B: Scenario 4 "EU-BRIC decoupling"										
	BRIC (1)	EU (2)	BRIC (3)	EU (4)	BRIC (5)	EU (6)	BRIC (7)	EU (8)	BRIC (9)	EU (10)
4A EU	-95.96	-21.75	13.19	-8.88	-10.20	15.44	-11.48	-11.56	-0.84	-1.05
4B BRIC	-16.09	-96.96	-7.08	11.14	9.98	-8.11	-9.12	-11.31	-0.83	-0.58
4C Bilateral	-96.48	-97.57	4.79	0.35	-1.62	6.24	-18.10	-19.99	-1.45	-1.42

Within the EU, the welfare effects following a trade war with Russia are, however, quite unevenly distributed, as Figure 1.3 shows.[26] Eastern European countries lose most from such a conflict. In the Baltic States, welfare declines by 2.48 percent in Lithuania, 2.02 percent in Latvia and 1.98 percent in Estonia. Slovakia (-1.68 percent), the Czech Republic (-1.16 percent) and Bulgaria (-1.11 percent) also experience above average declines in welfare. Even countries with limited direct exposure suffer because of indirect effects. For example, Russia is neither amongst the top ten export destinations nor amongst the top ten origin countries of Slovenia (Statistical Office Slovenia, 2022). Nevertheless, the country suffers above average welfare effects (-0.8 percent) in Scenario 3C because of indirect links with Russia via its European trading partners. Outside Europe, welfare in the US declines by 0.04 percent. China even profits slightly from a conflict between Russia and the US allies (+0.02 percent).

[26]Detailed results are provided by Table A.2 in the Appendix A.

Figure 1.3: Welfare effects by country in Scenario 3C, changes in percent.



Scenario 4: Decoupling between BRIC and the EU Scenario 4 models a trade conflict between the EU on one side and Brazil, Russia, India and China on the other. The aim of this Scenario is to investigate the consequence of China and Russia "teaming up" with other large emerging economies. The purchases of Russian oil by China and India in the first half of 2022 (Bruegel, 2022) may constitute a first step in this direction. The results, presented in Table 1.8, are qualitatively similar to Scenarios 1 and 2. Bilateral imports of the trading partner imposing the NTB are almost eliminated (Columns 1 and 2). Exports of the country group subject to NTBs are deflected to the rest of the world, while exports of the implementing country group decline (Columns 3 and 4). In contrast, imports from the rest of the world into the imposing country group increase (import source diversion), while those into the targeted country group decline (trade depression, Columns 5 and 6). Total exports as well as welfare fall in both country groups (Columns 7 to 10). In terms of foregone welfare, the EU suffers more from a trade war with the BRIC countries than from a decoupling purely from China.

Table 1.8: Scenario 4 “EU-BRIC decoupling”, changes in percent.

Decoupling scenario	Δ Bilateral exports		Δ Exports to RoW		Δ Imports from RoW		Δ Total exports		Δ Welfare	
	BRIC (1)	EU (2)	BRIC (3)	EU (4)	BRIC (5)	EU (6)	BRIC (7)	EU (8)	BRIC (9)	EU (10)
4A EU	-95.96	-21.75	13.19	-8.88	-10.20	15.44	-11.48	-11.56	-0.84	-1.05
4B BRIC	-16.09	-96.96	-7.08	11.14	9.98	-8.11	-9.12	-11.31	-0.83	-0.58
4C Bilateral	-96.48	-97.57	4.79	0.35	-1.62	6.24	-18.10	-19.99	-1.45	-1.42

Scenario 5: Decoupling between BRIC and US allies Scenario 5 splits the world into the US and its allies on one side and the BRIC countries on the other. As in the other scenarios, bilateral trade falls drastically following the imposition of NTBs (Columns 1 and 2). Trade deflection, import source diversion and trade depression are also present (Columns 3 to 6). Total exports of affected parties drop in all three sub-scenarios (Columns 7 and 8) and are accompanied by a fall in welfare in both the BRIC countries (-3.86 percent, Column 9) and US allies (-1.32 percent, Column 10).

Table 1.9: Scenario 5 “US allies-BRIC decoupling”, changes in percent.

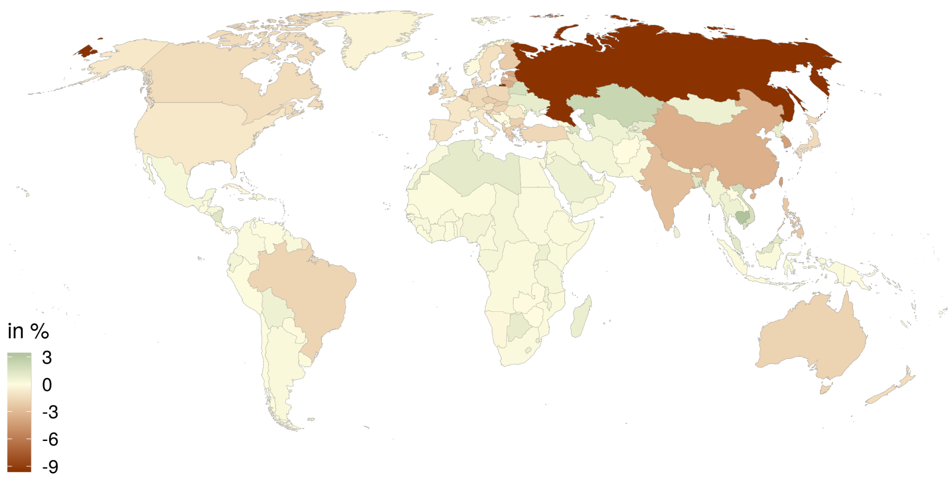
Decoupling scenario	Δ Bilateral exports		Δ Exports to RoW		Δ Imports from RoW		Δ Total exports		Δ Welfare	
	BRIC (1)	US al. (2)	BRIC (3)	US al. (4)	BRIC (5)	US al. (6)	BRIC (7)	US al. (8)	BRIC (9)	US al. (10)
5A US al.	-93.75	-47.85	55.02	-14.10	-38.12	22.12	-39.25	-28.36	-2.75	-1.10
5B BRIC	-37.77	-95.41	-25.16	19.65	43.66	-13.14	-33.15	-28.95	-2.43	-0.70
5C Bilateral	-95.72	-97.42	16.10	-0.46	-10.82	8.35	-54.75	-41.41	-3.86	-1.32

Table 1.10: Scenarios 5 and 6, changes in percent.

Panel A: Scenario 5 “US allies-BRIC decoupling”										
Decoupling scenario	Δ Bilateral exports		Δ Exports to RoW		Δ Imports from RoW		Δ Total exports		Δ Welfare	
	BRIC (1)	US al. (2)	BRIC (3)	US al. (4)	BRIC (5)	US al. (6)	BRIC (7)	US al. (8)	BRIC (9)	US al. (10)
5A US al.	-93.75	-47.85	55.02	-14.10	-38.12	22.12	-39.25	-28.36	-2.75	-1.10
5B BRIC	-37.77	-95.41	-25.16	19.65	43.66	-13.14	-33.15	-28.95	-2.43	-0.70
5C Bilateral	-95.72	-97.42	16.10	-0.46	-10.82	8.35	-54.75	-41.41	-3.86	-1.32
Panel B: Scenario 6 “US allies-Russia bilateral energy decoupling”										
	Russia (1)	US al. (2)	Russia (3)	US al. (4)	Russia (5)	US al. (6)	Russia (7)	US al. (8)	Russia (9)	US al. (10)
6 Energy	-56.69	-26.82	56.08	-0.46	-22.57	2.01	-19.51	-1.99	-6.62	-0.10

Figure 1.4 takes a closer look at Scenario 5C and illustrates the welfare changes for each country following a trade war between the US allies and the BRIC countries. Welfare losses are not evenly distributed. Within the BRIC countries, Russia loses by most (-9.62 percent), followed by China (-3.5 percent), India (-2.84 percent) and Brazil (-1.75 percent). Among the US allies, small open economies that are strongly interlinked with China experience the highest welfare losses. These are first and foremost Taiwan (-4.43 percent), South Korea (-4.25 percent) and Japan (-1.53 percent). Within the EU, Malta (-6.34 percent), Estonia (-3.95 percent) and Lithuania (-3.67 percent) are most strongly affected.[27] The US experience a 0.91 percent welfare loss.

Figure 1.4: Welfare effects by country in Scenario 5C, changes in percent.



[27]Detailed results are provided in Table A.3 in the Appendix A.

1.5 Extensions

1.5.1 Decoupling between Russia and US allies - energy sector

In an extension, we simulate the effect of an embargo by the EU, the US and its allies on Russian energy exports only. In the model, NTBs on these countries' imports of coal, gas, oil and petroleum products from Russia are increased until trade in these sectors is completely eliminated.[28] Results are presented in Table 1.11 below. Since energy products make up a large proportion of Russian exports, it is not surprising to see bilateral exports from Russia to the EU, the US and its allies fall by almost 57 percent (Column 1). Russian exports to the rest of the world would increase by 56 percent in the model (Column 3). This is in line with developments in the first half of 2022, which witnessed increasing Russian exports of oil to China and India (Bruegel, 2022). However, the drop in exports to the political West cannot be compensated completely, meaning that total Russian exports fall by 19.5 percent (Column 7) and welfare declines by 6.6 percent (Column 9). Compared with the welfare decline of 7.3 percent for Russia in Scenario 3A (doubling of NTBs by the EU, the US and its allies on all Russian exports) this reiterates the importance of energy exports for the Russian economy.

Table 1.11: Scenario 6 "US allies-Russia bilateral energy decoupling", changes in percent.

Decoupling scenario	Δ Bilateral exports		Δ Exports to RoW		Δ Imports from RoW		Δ Total exports		Δ Welfare	
	Russia (1)	US al. (2)	Russia (3)	US al. (4)	Russia (5)	US al. (6)	Russia (7)	US al. (8)	Russia (9)	US al. (10)
6 Energy	-56.69	-26.82	56.08	-0.46	-22.57	2.01	-19.51	-1.99	-6.62	-0.10

The EU, the US and its allies are only mildly affected, experiencing welfare declines of 0.1 percent on average. Welfare in Germany - Europe's largest

[28]We increase NTBs in five specific GTAP sectors: Coal; Gas; Gas Manufacture; Oil; Petroleum & Coke. See Section A.4.3 for the full list of all sectors.

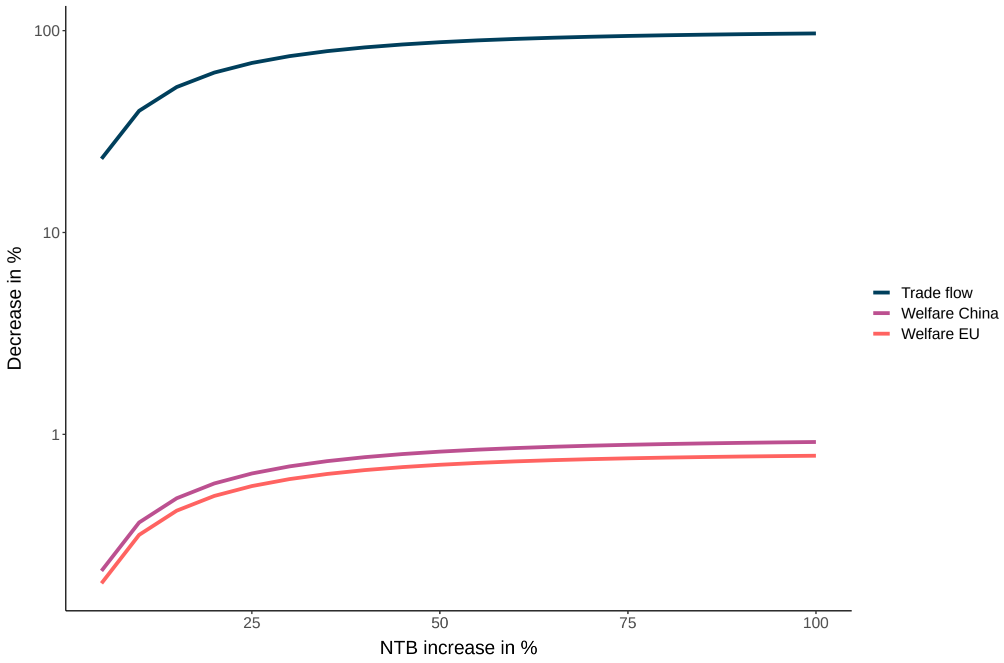
economy - is expected to decline by 0.3 percent. This effect is in a similar order of magnitude, albeit slightly smaller than the lower bound of 0.5 percent estimated by Bachmann et al. (2022). As discussed in Subsection 1.5.3, this difference results from the different time-horizon of our model.

1.5.2 Varying levels of NTBs

Within the model, decoupling is simulated by doubling NTBs because this strongly reduces bilateral trade without completely eliminating it. In doing so, we follow other papers such as Sforza and Steininger (2020), who characterize a closed economy as one in which trade costs are doubled. Of course 100 percent may seem somewhat arbitrary, and we could as well have chosen 90 percent or 110 percent. As an extension to Scenario 1C, we therefore model a continuous increase in NTBs between the EU and China. Different degrees of mutual decoupling are simulated, with NTB increases ranging from 5 to 100 percent.

Changes in bilateral trade flows and welfare are depicted in Figure 1.5. The functions are strictly concave and approach their maxima quickly. An NTB increase of 50 percent already decreases bilateral trade flows by 87.64 percent, compared to 96.87 percent following an NTB increase of 100 percent. Welfare falls by 0.71 and 0.82 percent for the EU and China in case of an NTB increase of 50 percent, compared to 0.78 and 0.92 percent respectively for a 100 percent increase in NTBs. Our baseline results are thus not sensitive to whether NTBs are increased by 90 percent or 100 percent.

Figure 1.5: EU - China bilateral decoupling for NTB increases of 5 to 100 percent.



Note: Decreases of bilateral trade flows (imports and exports) and welfare in percent. Y-axis is log transformed.

1.5.3 Limitations of the model

When considering the policy implications of our model results, it is important to stress that we estimate long-run effects in a comparative statics framework. We thus compare the status quo equilibrium with a counterfactual equilibrium in a decoupled world. With respect to energy trade, this means that new infrastructure such as pipelines or LNG terminals have already been constructed. If decoupling were to happen within a short period of time, many firms would find themselves being cut-off from their suppliers, prices of affected products may skyrocket, and several firms may be forced to temporarily suspend production until supply chains adjust. The current decoupling between the political West and Russia is a case in point. While our estimates suggest only mild long run effects for the West (-0.17 percent on average, -0.4 percent for Germany) short run effects are expected to be stronger (0.5 percent to 3 percent reduction in German GDP, (Bachmann et al., 2022)). In fact, GDP forecasts already had to be adjusted more severely (for example a reduction of 3.5 percentage points in the estimated growth rate for Germany in 2023, (Holtemöller et al., 2022)). The short-term effects on welfare can thus be expected to be much more negative than our estimated long-run effects.

A second limitation of the model lies in the fact that it assumes a certain degree of substitutability across sourcing countries. In principle, all goods can be produced in all countries, albeit at varying production costs. While this assumption is realistic at the sectoral level, it is certainly not true at the product level. The assumption is less restrictive in the long-run, although certain raw materials cannot be substituted within a policy relevant time horizon.

In line with many Ricardian trade models, we only use one aggregate factor of production. The factor is a composite of many factors, as for example labour, capital, and land, which are all non-tradeable in our model. In a similar framework, Costinot and Rodriguez-Clare (2014) have shown that the introduction of the additional factor capital, which is not only fully mobile across sectors but also across countries, slightly increases gains from trade.

In the context of a decoupling between the East and the West, an unrestricted movement of capital between the country blocks seems unrealistic. In order to avoid the difficult endeavour of setting the right amount of rigidity in cross-country capital movements, we follow the most restrictive variant and include capital in our aggregate non-tradeable production factor. However, even though capital products are not modelled explicitly, intermediate goods can in fact be interpreted as capital goods. For example, cars used as inputs in the agricultural sector can be seen as capital goods that are also tradable internationally.

1.6 Conclusion

Since the early 2000s, the political landscape has shifted away from ever closer market integration through global trade and towards a decoupling - if not break up - of global value chains. Perhaps most worrying, tensions between China on one side and the EU and the US on the other could tear apart value chains that have added so much to economic growth. In order to contribute to a better understanding of the impacts these actions could have on both trade and welfare, this paper has modelled the effect of such a divide of the world with NTBs on trade and welfare. Employing a general equilibrium trade model calibrated with the latest version of GTAP, we simulate the effects of five decoupling scenarios on 121 countries, taking into account detailed input-output linkages among 65 economic sectors.

Within the model, a Chinese increase in NTBs against EU exports by 100 percentage points exhibits all the trade effects that are already well documented in the empirical literature: First trade destruction, i.e., an almost complete elimination of Chinese imports from the EU. Second import source diversion, i.e., an increase in Chinese imports from the rest of the world following a fall in competitiveness of Chinese firms due to higher prices of intermediates and a real exchange rate appreciation. For the same reason, China also exports less to both the EU and the rest of the world. Third trade deflection, as EU exports are deflected to other countries following a fall in EU prices and fourth, trade depression, i.e., a fall in EU imports from the rest of the world, also following lower EU prices. Welfare declines in both economies following such a unilateral decoupling by China. The above results are reversed if the EU decoupled from China instead.

A trade war, in which both China and the EU raise their bilateral NTBs, reduces welfare in China and the EU by 0.92 and 0.78 percent, respectively. The rest of the world mainly remains unaffected by such a conflict. The model also shows that forging alliances increases the damages inflicted on the strategic rival. In particular, a trade war between China and the US and its allies (including the EU) incurs a welfare loss of 3.55 percent for China, while the welfare decline for the US and its allies only amounts to 0.95 percent. The same is true - albeit to a lesser extent - for a trade war between the BRIC countries and the EU. Welfare losses to the EU amount to 1.42 percent in this scenario, while the BRIC countries suffer a loss of 1.45 percent on average.

Our findings also offer a lesson for the conflict between Russia and the West. As relative size matters, trade restrictions are more harmful for the target if more countries implement them. For the same reason, Russia would lose much more from a trade war with the West than China. Specifically, a reciprocal decoupling of Russia from the US and its allies reduces welfare in Russia by 9.71 percent. In contrast, welfare of US allies remains almost unaffected (-0.17 percent), although Eastern European countries lose substantially (up to 2.48 percent in the case of Lithuania). In fact, implementing countries often experience smaller welfare losses if they act together. Increasing economic sanctions thus comes at relatively low costs for the US and its allies on average, at least in the long run. Small Eastern European countries which lose more could be compensated. Finally, a trade war between the US and its allies on one side and the BRIC countries on the other would reduce welfare in both country groups by 1.32 percent and 3.86 percent respectively.

Teaming up can thus increase the harm imposed on the strategic rival. However, if one country group decouples, it is never the best option for the other country group to retaliate, as this would increase the cost for both parties. Overall, the simulation results confirm what economic intuition would dictate: Intentionally dividing the world with non-tariff barriers would reduce welfare in all countries involved in the conflict and should thus never be done light-heartedly.

Chapter 2

Macroeconomic Structural Change Likely Increases Inequality in India more than Climate Policy[1]

2.1 Introduction

Policy makers in low- and middle income countries, including India's Prime Minister Modi or Nigeria's President Buhari, often argue that climate policy must not interfere with economic development and poverty eradication[2]. There seems to be an underlying intuition that climate policy will (i) hinder or delay structural economic change and (ii) be largely regressive,

[1]Joint work with Marian Leimbach, Michael Hübler, Lorenzo Montrone, Eduard Bukin, Gabriel Felbermayr, Matthias Kalkuhl, Johannes Koch, Marcos Marcolino, Frank Pothen, and Jan Steckel.

[2]"[T]he consequences of the industrial age powered by fossil fuel are evident, especially on the lives of the poor [...]. Developing countries should have enough room to grow." (Prime Minister Modi of India at COP21 in Paris)
"Our major objective for the gas sector is to transform Nigeria into an industrialized nation with gas playing a major role and we demonstrated this through enhanced accelerated gas revolution." (President Muhammadu Buhari, March 29, 2021)

i.e., mostly at the costs of poor people.

In this article, we focus on India and aim to identify the conditions under which this intuition can be resonated. A number of recent studies analyse the distributional effects of climate policy, and carbon pricing in particular (da Silva Freitas et al., 2016; Dorband et al., 2019; Chepeliev et al., 2021; Steckel and Jakob, 2021; Känzig, 2021; Soergel, 2021), detecting both regressive as well as progressive effects [3] (see Ohlendorf et al. (2021) for a review). Regressive impacts are mainly detected for developed countries, while in developing countries the impact can be expected to be (more) progressive. Cross-country differences in energy use across income groups can explain these different results (Dorband et al., 2019). Studies focusing on labour market effects report regressive effects as low-skilled labour in energy-intensive sectors is strongly affected by the transition (Marin and Vona, 2019; Yip, 2018). Other studies, that additionally take general equilibrium and broader income effects into account (Böhringer et al., 2021; Goulder et al., 2019; Dissou and Siddiqui, 2014), find that even in developed countries the regressive consumption expenditure effect of climate policy tends to be dominated by progressive income effects.[4]

Accounting for income effects, e.g. increasing wages for the poor, is at the heart of structural change-induced development effects. In fact, as a major result of the literature on growth, structural change and inequality, Ciarli et al. (2019) find that wage differences are the major explaining factor of increasing inequality. Here, we analyse the distributional effects (e.g. the distribution of wage income and consumption incidences) of climate policies at the household level, accounting for general equilibrium and structural change effects along the low-carbon transition path. While the meaning of structural change is context-sensitive, we adopt a definition

[3]"Regressive" means that poor households are more adversely affected than rich households, "progressive" vice versa.

[4]While Vona (2023) considers standalone climate policy to be regressive and discusses green policy packages to support political acceptance for a just transition path, other studies, e.g., Soergel (2021), Garaffa et al. (2021), and Fujimori et al. (2020), demonstrated that poor households can benefit from redistributional transfers (e.g. carbon tax recycling).

from the economics literature (Herrendorf et al., 2014) that embeds structural change in a broader concept of economic development, and specifies it as the reallocation of economic activity across broad sectors, such as agriculture, manufacturing, and services.

Arguably, India is undergoing a transformation from an agriculture-based economy towards an industry- and service-based economy. How - and how fast - this economic transformation unfolds will have distributional consequences that interact with those from climate policies. By investigating the interaction of climate policy with economic structural change and analysing their combined and separated distributional effects, this study fills a relevant research gap. In the economics literature the phenomenon of structural change is an intensively studied phenomenon and the composition of economic structure is an acknowledged measure of development (Kongsamut et al., 2001; Acemoglu et al., 2008; McMillan and Rodrik, 2011). We introduce this phenomenon in the field of climate policy modelling and distributional analyses of climate policy effects. This includes an inherent focus on future developments, which distinguishes this study from the rich literature on structural change and inequality, which is mainly empirical (Mehic, 2018; Hartmann et al., 2021; Rekha and Suresh Babu, 2022).

We also contribute to the discussion on growth and welfare impacts of climate policy (Clarke et al., 2014; Köberle et al., 2021; Mercure et al., 2018; Dai et al., 2016), where it is a major dispute whether climate policies come with positive or negative costs (e.g. due to a redirection or crowding-out of investments) in addition to the predominant positive effects of avoided climate change damages. We contribute by adding the structural change development perspective and find out that climate policy tends to slow down structural change. Only two other studies have a comparable focus - Lefevre et al. (2022) and Ciarli and Savona (2019). The former, however, does not look into distributional effects on the household level as we do. The latter provides a review of how different climate change assessment models integrate aspects of structural change, however applies a concept of structural change which is much less focussed on the sectoral composition.

Distributional effects are best measured at the micro level (i.e., households and income groups), while drivers of climate policy and structural change are best represented at the macro level (i.e., national economies). In order to run a meaningful quantitative assessment, we develop a novel modelling framework that bridges these levels by coupling several models and combining long-term growth and medium-term trade dynamics related to structural change with detailed household income and expenditure data for India.[5] Our integrated modelling approach allows us to separate the distributional effects of climate policy and of structural change. We find the distributional effects of structural change to be more regressive. Concomitant socially sensitive policies supporting the process of structural transformation appear to be more important for poor households than downsizing climate policy ambitions. Policies should be designed in a way that supporting the poor and tackling climate change become congruent policy goals.

The paper is structured as follows: After introducing the applied methodological framework, we first present key macro-level output of our scenario analysis, which is performed along the dimensions of climate policy and structural change. For the climate policy dimension, we distinguish between a baseline, 2°C and 1.5°C climate stabilization scenario. With regard to the second dimension, we compute structural change scenarios in line with existing shared socio-economic pathways (SSPs) (O'Neill et al., 2014; Riahi et al., 2017). Second, we discuss development and climate policy effects, and show how the latter vary under different structural change scenarios. Then, we present the results from the micro level that highlight and compare the distributional effects of structural change and climate policy. In the final sections, we critically discuss the results and provide conclusions.

[5] Alternative methods predominantly make use of an extension of computable general equilibrium (CGE) models by representing different household groups (van Ruijven et al., 2015; Weitzel et al., 2015).

2.2 Methods

2.2.1 Overview of the methodology

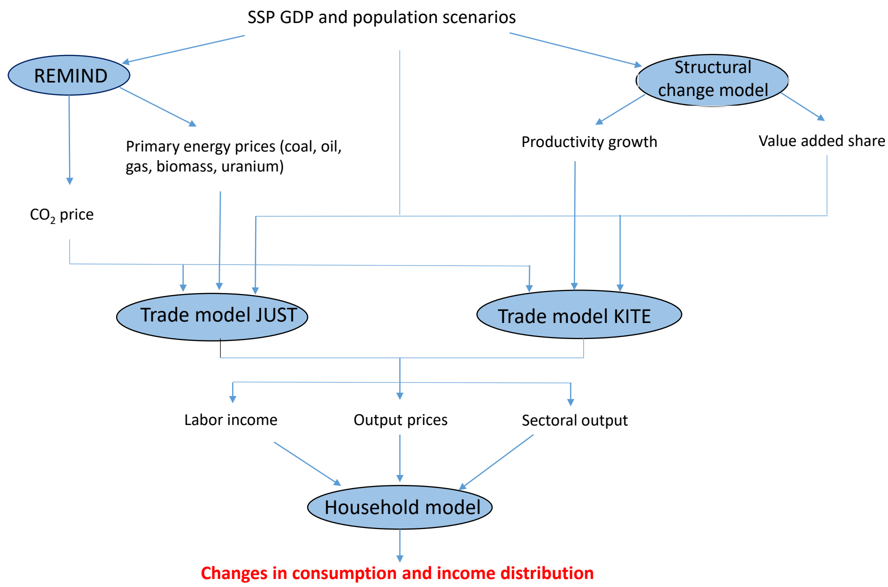
This study is based on a large numerical scenario analysis using a cascade of models and methods. A newly developed model-coupling framework exchanges information and connects models at the macro, meso, and micro levels. At the macro level, we use input from existing socioeconomic scenarios (SSPs) and apply the Regional Model of Investments and Development (REMIND) (Baumstark et al., 2021) - a large-scale Integrated Assessment Model (IAM) - and a reduced-form structural change model (Leimbach et al., 2023). At the meso level, we apply two advanced trade models - the Kiel Institute Trade Policy Evaluation (KITE) model (Felbermayr et al., 2023) and the Justus (Liebig) University Sustainable Transition (JUST) model (Pothen and Hübler, 2021). To extend the scope of climate policy and international trade modelling, we combine different model types with their specific strengths and foci. While the integrated assessment model REMIND features intertemporal dynamics and a full-fledged energy system, the advanced trade models KITE and JUST provide multiple sectors and a theory-based trade module with trade in intermediate goods. We use two trade models to test the robustness of the results. Details on all four models are provided in the Appendix Section B.1. Finally, we apply a household model that splits Indian households into five income quintiles on the micro level (see Section 2.3).

2.2.2 Model coupling

The models and methods scrutinized in our model cascade are soft-linked via the exchange of parameter values and simulation results. Figure 2.1 shows the main data flows. The relevant scenario data, which are derived from REMIND and the structural change model, and used as inputs for the JUST and KITE model, are: GDP, value-added shares of agriculture, manufacturing, and services, a uniform CO2 price (imposed on all Indian production sectors and private and public consumption) and, in the case of JUST, the prices of global energy carriers (coal, crude oil, and natural gas). In the trade models, the productivities of the Indian production sectors grow over time such that the exogenously given shares of agriculture, industry and services and the Indian GDP growth are represented.

The output variables generated by the trade models as inputs for the household model are: sectoral labour income, sectoral output, and output prices. These output variables vary based on the reaction of the trade models to the input from the macro level mainly in two ways. First, an exogenously increased sectoral productivity ceteris paribus results in an extended sectoral output quantity and a lower output price because the output-to-input-ratio has been improved. The increased total factor productivity implies a higher labour productivity and hence a higher wage rate, which together with increased input and output eventually results in higher labour income. Second, carbon pricing raises the prices of fossil fuel inputs and hence the sectoral production costs, where the costs increase in the CO2 intensity of production. Since output prices equal marginal production costs, they rise accordingly. Ceteris paribus, the corresponding output and total input decline to a larger extent in more CO2-intensive sectors, such that the demand for energy including fossil fuels and labour declines. At the same time, based on the models' elasticities of substitution, fossil fuels are substituted by other inputs, such as labour. Because the total factor endowments with labour, capital and land are fixed, these factors are reallocated towards less CO2-intensive sectors. As a result, climate policy reduces labour income to a larger extent in more CO2-intensive sectors and creates positive or less negative income effects in less CO2-intensive sectors. Strategic terms-of-trade effects on international markets can add positive or negative income effects.

Figure 2.1: Data flow between models.



2.2.3 Household model

In the household model, we perform a micro simulation based on a) the results obtained from the macro and meso models for India, and b) the distribution of employment, income, and expenditures in India observed in the 2012 Household Consumer Expenditure (NSS 68th Round) survey.[6] Using the household survey data, we calculate the income of each Indian household based on total expenditures per capita. We assign each household to one of five income quintiles based on its income. As a reference, the median expenditure level of the poorest quintile in India refers to 527 US dollars in 2012, while for the richest the median level is 2129 US dollars.[7] We furthermore classify each household based on the head's sector of employment. Finally, we compute the households' expenditure shares by aggregating the detailed expenditure categories first to match the corresponding production sectors as defined by the Global

[6]Details of the survey are documented here: (http://www.icssrdataservice.in/datarepository/index.php/catalog/135)

[7]Here, and in all following sections, dollar values are provided in constant 2005 market exchange rate (MER) prices.

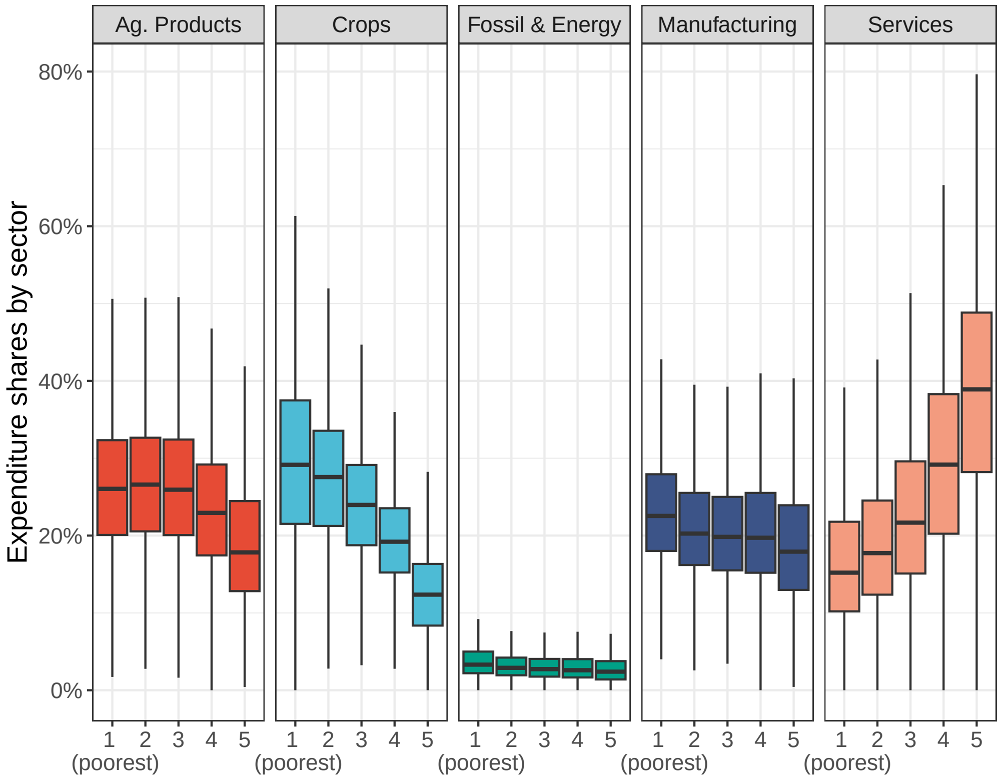
Trade Analysis Project (GTAP) database. Then, those sectors are further aggregated to five macro-sectors (Table B.1 in Section B.6 of the Appendix B provides a detailed description of the matching between consumption items, GTAP sectors and aggregated sectors used in this study).

We analyse the distributional effects of changes in household expenditures (consumption incidence) and income (income effect). The consumption basket in 2012 is the reference and all changes in the consumption incidence are measured based on the assumption that the consumption basket of each income quintile does not change between the base and the target year, which is 2030 in this study. Figure 2.3 shows the 2012 expenditure shares for commodities and services from five aggregated sectors. On average, all households spend most for agricultural products (including crops), with substantial expenditures on manufactured goods and services. Notably, the differences in expenditure shares across income groups are significant. While poor households spend comparatively more on agricultural products, rich households spend comparatively more on services. Expenditure shares of goods that are expected to be sensitive to climate policies, such as coal, gas, petroleum, electricity or transport, are comparatively small.

To capture the income effects of climate policy and structural change, we refer to the head of household's sector of employment to approximate the changes in income that the household will experience as a result of development, structural change, and climate policy. Figure 2.3 shows the distribution of sectoral employment across income quintiles. According to the survey data, poor households tend to have comparatively high employment shares in the agricultural and construction sectors, whereas rich households have high employment shares in the services and manufacturing sectors. For the sake of transparency, we keep the composition of income groups constant over time and assume that each household is employed in the same sector as in the benchmark year 2012.[8]

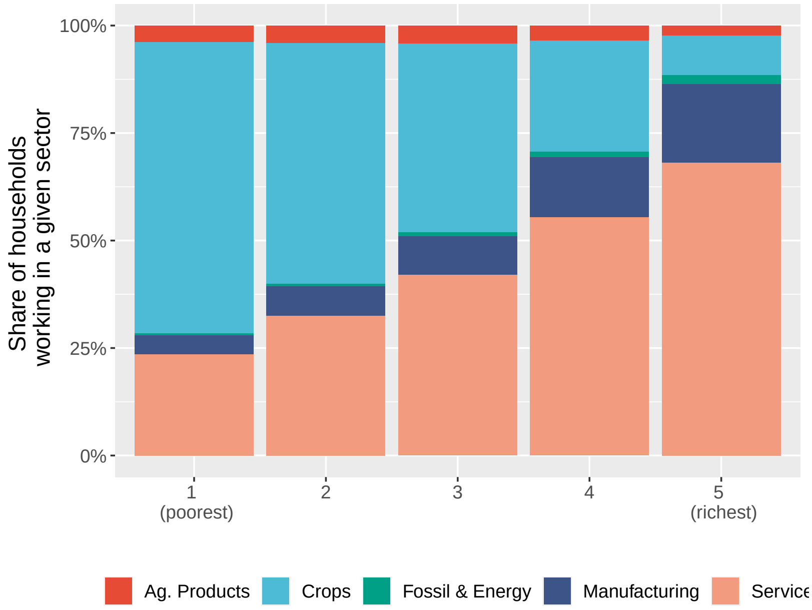
[8]While ignoring some dynamic effects, the simplifying assumptions regarding the employment structure as well as the consumption basket within the household model have only a minor impact on the analysis of distributional effects in Section 2.3.3,

Figure 2.2: Expenditure shares in India by sector and income quintile.



Note: Expenditure shares in India by income quintile and sector (boxes cover the range between the 25th and 75th percentile of the data – the inter-quartile range; whiskers extend to the furthest data point within 1.5 times the inter-quartile range; lines within the box mark the median).

Figure 2.3: Employment shares in India by sector and income quintile.



Income changes arise from labour income changes, which in this study are approximated by changes in sectoral labour income and value-added, respectively, computed by the trade models. While the two trade models assume perfect mobility of labour across all sectors within each country/region and therefore result in a uniform wage across all sectors in each country/region, computed changes in labour income resemble wage-specific changes that one would expect under imperfect mobility of labour as assumed in the household model.

$$HHIncome_{i,s,t+1} = HHIncome_{i,s,t} \times (1 + \Delta wage_{i,s}) \qquad (2.1)$$

where $HHIncome_{i,s,t}$ is the average income of a household of income quintile i employed in sector s. Index t indicates the period, covering the base year 2015 (period 1) and the target year 2030 (period 2). $\Delta wage_{i,s}$ is calculated as the relative change in labour income (value-added) in the sector of employment of household i between the periods t and$t + 1$.

because that analysis focuses on comparing pairs of scenarios which all start from the same harmonized assumptions.

For the base year, income is approximated by total expenditures per capita. The income effect (Section 2.3.3) is calculated as the difference in $HHIncome_{i,s,t+1}$ between two specified scenarios aggregated over all sectors s.

Based on the computed income of each household employed in sector s in $t+1$, we calculate the new total expenditures of each household ($HHconsumption_{i,s,t+1}$). The total expenditures are the sum of the expenditures on all goods q. Changes in the expenditures on (domestically produced and imported) goods q are a result of relative changes in the prices of these goods (Δp_q) computed by the trade models. The composition of the household's consumption basket defined by its expenditure shares ($expshare_{i,s,q}$) remains unchanged:

$$HHconsumption_{i,s,t+1} = \sum_q (1 + \Delta p_q) \times (expshare_{i,s,q} \times HHIncome_{i,s,t+1}) \tag{2.2}$$

We then compare the new total expenditures with the new income of the household to calculate the consumption incidence:

$$incidence_{i,s,t+1} = \frac{HHIncome_{i,s,t+1} - HHconsumption_{i,s,t+1}}{HHconsumption_{i,s,t+1}} \tag{2.3}$$

The consumption effect (Section 2.3.3) is calculated as the difference of the consumption incidence between two specified scenarios aggregated over all sectors s.

2.2.4 Scenario design

Our scenario analysis is performed along two dimensions: (i) climate policy and (ii) structural change. Table 2.1 classifies the underlying scenarios. Regarding the climate policy dimension, we distinguish between a baseline, a 2°C and a 1.5°C climate stabilization scenario. We use the latter for a robustness test only. Within the climate policy scenarios, climate stabilization is achieved via carbon pricing. The baseline scenario represents a current policy scenario and covers in a stylized way climate policies that are already implemented today (Chaturvedi et al., 2021; Dubash et al., 2018). In this baseline scenario, a low carbon price trajectory is modelled (Baumstark et al., 2021) based on Nationally Determined Contributions (NDCs) until 2020. The policy implementation, however, is assumed to miss the NDC targets by 2030. Instead, carbon prices are assumed to grow and converge more slowly, leading to emission trajectories in line with bottom-up studies on the effect of currently implemented policies (den Elzen et al., 2019) – resulting in a carbon price for India of less than one US dollar in 2030. The future carbon price in the climate policy scenarios is computed by the REMIND model. The underlying assumption is a staged accession climate policy regime (a similar form of which was used in a study on climate policies and poverty eradication by Soergel (2021)). Regionally differentiated carbon prices exist depending on the differentiated responsibilities and capacities of countries and world regions. A global uniform carbon price becomes effective in 2050. The carbon price is uniformly imposed on fossil fuel inputs in all Indian sectors. Other greenhouse gases or process emissions, such as methane in agriculture, are not considered. Revenues from carbon pricing are recycled distributional-neutral. Each couple of baseline and climate policy scenarios assumes population and GDP growth according to the associated SSP scenario. A small difference in GDP exists between the baseline and climate policy scenario due to the endogenous climate policy impact.

The dimension of structural change is covered by three SSP scenarios (see

Table 2.1: Scenario classification.

Climate policy scenario	Structural change scenario			
	SSP1	SSP2	SSP5	W/o str change
Baseline	SSP1-Base	SSP2-Base	SSP5-Base	NoSC-Base
Climate policy 2°C	SSP1-CP	SSP2-CP	SSP5-CP	NoSC-CP
Climate policy 1.5°C	SSP1-CP-1.5	SSP2-CP-1.5	SSP5-CP-1.5	NoSC-CP-1.5

Appendix B.2 for a general characteristic of the SSPs). All applied SSPs[9] – SSP1 ("Sustainability"), SSP2 ("Middle of the road") and SSP5 ("Fossil fuelled development") – follow a different economic growth path with different pace of changes in the economic structure. Transformation is fastest under SSP5 followed by SSP1 and SSP2 (see Section 2.3.1). Two additional scenarios represent a development without structural change (NoSC-base and NoSC-CP). Within this setting, we start from an SSP2 scenario in 2015 and keep the value-added shares of the different sectors constant over time.

2.3 Results

2.3.1 Structural change and climate policy

Following the economic literature, we quantify structural transformation as the change in the sector shares of total labour and value-added (defined as the sum of labour and capital income). Resulting structural transformation pathways computed by the structural change model are shown in Figures 2.4 and 2.5 (Leimbach et al., 2023). A general pattern applies across all SSPs: the major part of future development and output growth is based on increasing activities in the service sector. Decreasing labour and value-added shares of agriculture are associated with initially increasing labour shares and nearly constant value-added shares in the manufacturing sector. While the stagnation of value-added shares in this sector can be observed

[9]The chosen SSPs are limited to those that can be computed by the REMIND model.

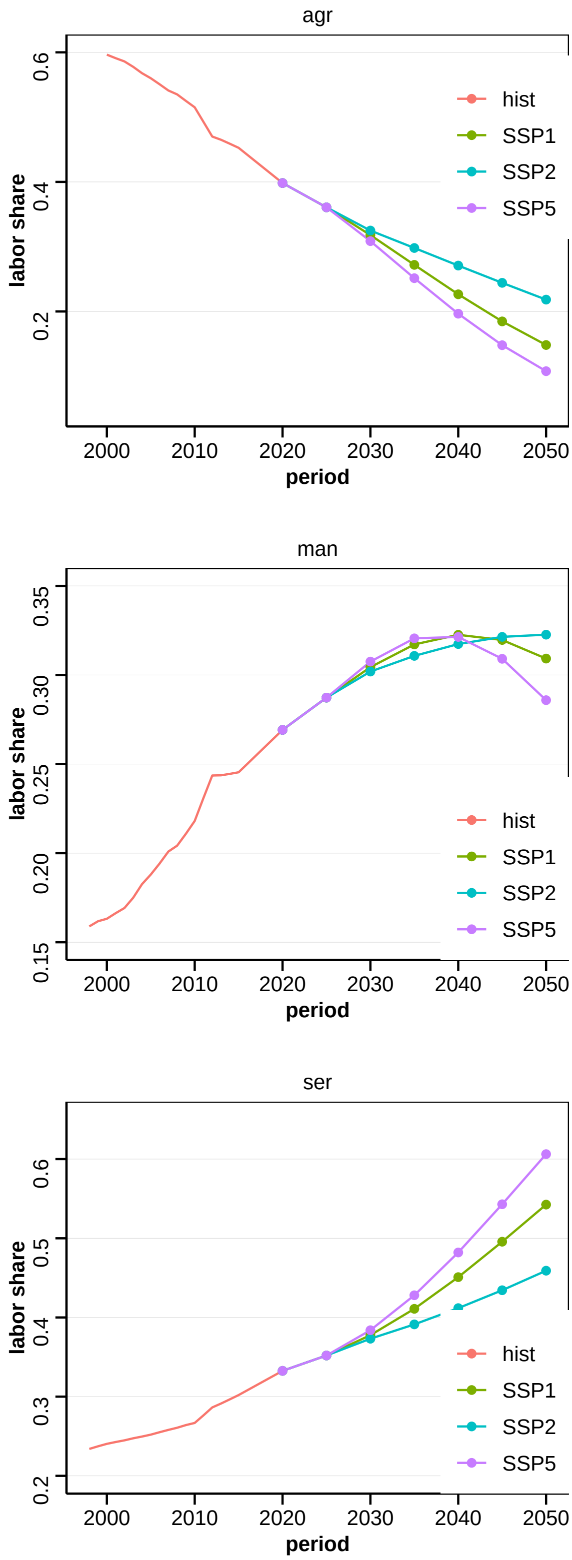
in other countries as well, compared to other major emerging economies in Asia (e.g., China, South Korea, Indonesia), India exhibits relatively small shares (Choudhry, 2021). Within our scenarios, substantial reallocation of economic activities towards manufacturing and services is projected for India under SSP1. A peak of employment share in the manufacturing sector can be expected between 2035 and 2040. The structural transition is even faster under SSP5 where this peak is likely to appear between 2030 and 2035, while the value-added share in manufacturing starts to decline already before 2030. The transformation process will be slower under SSP2, with the peak in manufacturing value-added and labour shares not occurring before 2040.

In this study, we apply a carbon price computed by the REMIND model to simulate climate policy in India. In order to achieve the 2°C and 1.5°C temperature goal, different carbon prices are needed under the different structural change scenarios. The computed CO2 prices for India in 2030 under SSP1, SSP2, and SSP5 amount to 20, 25, and 50 US dollars per tonne of CO2, respectively, in the 2°C scenario, and 85, 84, and 135 US dollars per tonne of CO2, respectively, in the 1.5°C scenario. In Europe, by comparison, the respective CO2 prices in 2030 are between 75 US dollars per tonne of CO2 (SSP1-CP) and 520 US dollars per tonne of CO2 (SSP5-CP1.5).

2.3.2 Development impacts of carbon pricing

To put the magnitude of the distributional effects (discussed in the next section) into perspective, we first analyse changes in prices and income between the base year 2015 and the target year 2030. Figures B.2 and B.3 in the Appendix show the related changes as computed by the JUST and KITE trade models. We first observe price changes between 10 and 40 percent in most aggregated sectors with moderate variation across SSPs. Second, results show an income effect which is larger (changes between 100 and 300 percent) than the price effect, and more substantial

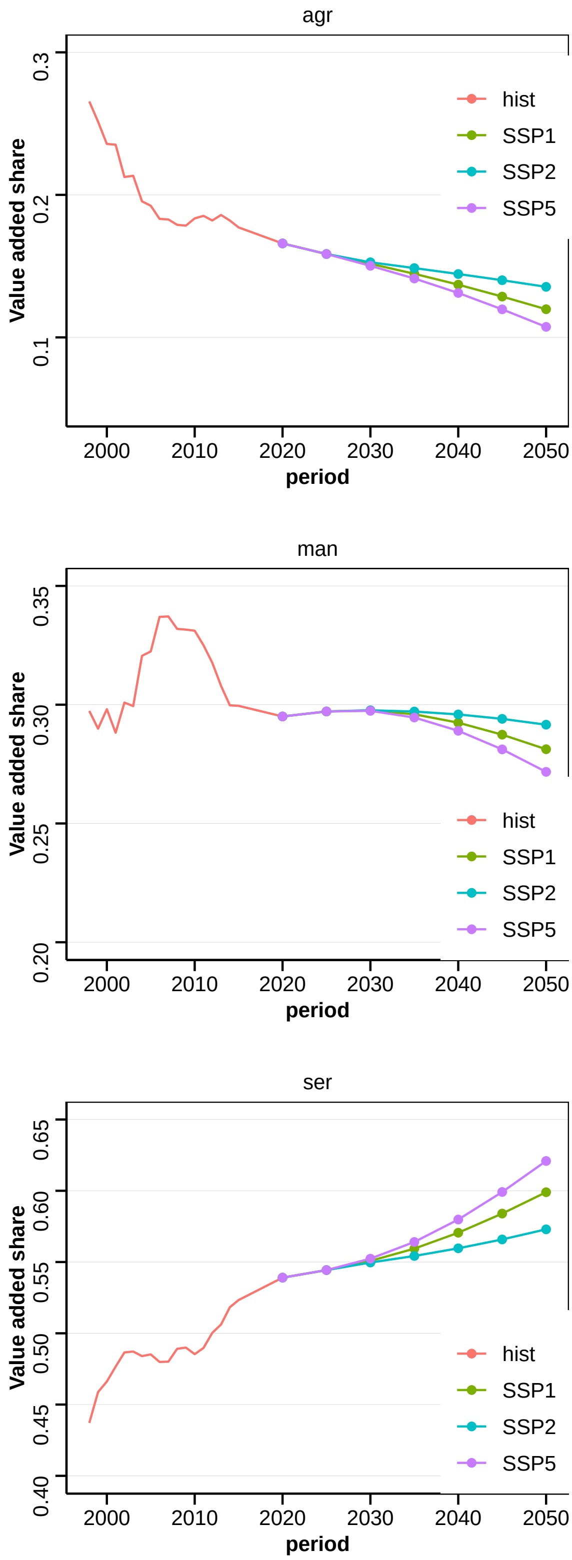
Figure 2.4: Labour shares in India under different SSPs.



Note: Structural change in India under different SSPs; labour shares of agricultural (agr), manufacturing (man) and service (ser) sectors (historical values are from World Bank's World Development Indicators).[a]

[a]Accessed May 6 2021 at https:databank.worldbank.org/source/world-development-indicators

Figure 2.5: Value-added shares in India under different SSPs.



Note: Structural change in India under different SSPs; value-added shares of agricultural (agr), manufacturing (man) and service (ser) sectors (historical values are from World Bank's World Development Indicators).

under scenarios with strong structural change (SSP1 and SSP5). Overall, decreasing prices in some sectors and increasing incomes in all sectors imply higher consumption opportunities in 2030 than in 2015 for all households.

Figures B.2 and B.3 also present the incremental effects of carbon pricing under a 2°C climate policy. Without accounting for avoided climate change damages, carbon pricing in general has a negative impact on consumption due to increasing prices. Furthermore, as also shown by Figure 2.6, the income-reducing effect of carbon pricing in the energy sector is most substantial (see explanation in Section 2.2.2), followed by manufacturing containing carbon intensive industries. Price and income effects of several percent or more than ten percent for carbon intensive sectors are in accordance with previous climate policy modelling results (e.g. Hübler and Löschel, 2013). Furthermore, due to differences in the CO2 intensity, climate policy reduces production (and income) in the agricultural sector on average more than that of the service sector. With given demand (expenditure shares) for sectoral goods, the price of agricultural goods increases more than that of services (see Figure 2.6). However, while income and price changes caused by carbon pricing are significant, they are much smaller than the corresponding changes along the economic development path. Even energy prices are subject to a much larger intertemporal effect (10-50 percent) than carbon pricing effect (3-15 percent). To some extent, this relationship is due to the comparatively small CO2 price. Climate policy impacts grow if India faced a higher carbon price as in the 1.5°C scenario (see Section 2.4 and Figure B.3 in the Appendix B).

Nevertheless, the impact of carbon pricing on income and consumption opportunities differs significantly under different assumptions on structural change. As shown in Figure 2.6[10], adverse impacts turn out to be always highest across all sectors under the fast structural change scenario SSP5 and much lower under SSP1 and SSP2. Price changes between 1

[10]Here and in the following, we present results from one trade model (KITE) only. Corresponding results based on the JUST model are presented in the Appendix B and discussed in the Discussion section.

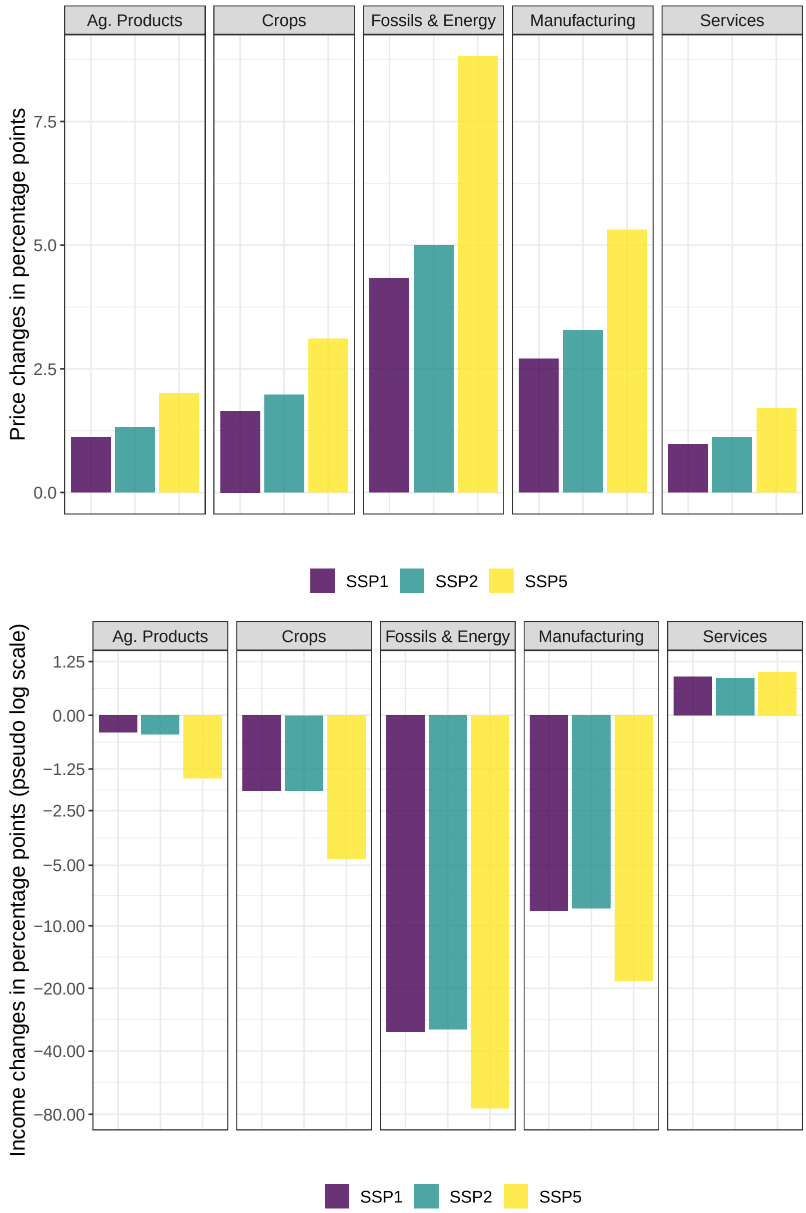
and 4 percent under SSP1 compare with changes between 2 and 8 percent under SSP5. The same pattern also applies to the distributional effects (see Appendix B Figure B.11). Households of each income group face higher impacts from carbon pricing under SSP5. The most substantial regressive effect is associated with this scenario as well. Based on KITE model output, poor Indian households suffer from an income loss of 7 percent, while rich Indian households face income losses of less than 4 percent under SSP5.

The observed variation of the impact of carbon pricing on the level and distribution of gains and losses results from the properties of the different structural change scenarios (e.g., differences in sectoral labour and output shares, income and price changes induced by the implied sectoral productivities). Among those properties are few elements that are not directly related to structural change, e.g. population growth. High emission intensity in SSP5 is another feature that only partly relates to economic structural change in the narrow sense, but which via the implied impact on the carbon price[11] has distributive effects.

In order to separate the impacts of carbon pricing and structural change, we set up another comparison experiment. We, first, run a reference scenario without structural change and without climate policy (NoSC-Base – see Methods section). Additionally, we run a counterfactual scenario with climate policy included (NoSC-CP) and another counterfactual scenario that just includes structural change according to SSP2 but no climate policy (SSP2-Base). This set-up allows us to address a question which is crucial from a development perspective: does climate policies accelerate or hinder structural change? This study finds mixed results. While structural change manifests in decreasing value-added shares of the agricultural sector and increasing value-added shares of the service sector, carbon pricing induces increasing shares in both sectors (see Figure 2.7). Both effects can be explained by the mechanisms described in Section 2.2.2. The

[11]The carbon price itself is a joint outcome of the climate policy and the structural change scenario.

Figure 2.6: Price and income changes induced by carbon pricing.



Note: Sectoral output price changes (upper panel) and sectoral income changes (lower panel) in India induced by carbon pricing compatible with 2°C climate policy under different assumptions of structural change (SSP1, SSP2, SSP5). The figures show the difference in the percentage changes over in time (between 2015 and 2030) between climate policy scenarios (SSP1-CP, SSP2-CP, SSP5-CP) and the corresponding baseline scenarios (SSP1-Base, SSP2-Base, SSP3-Base). Sectoral output from the KITE model is aggregated to five sectors with Agricultural Products and Crops representing the agricultural sector, and Fossil & Energy and Manufacturing representing the manufacturing sector.

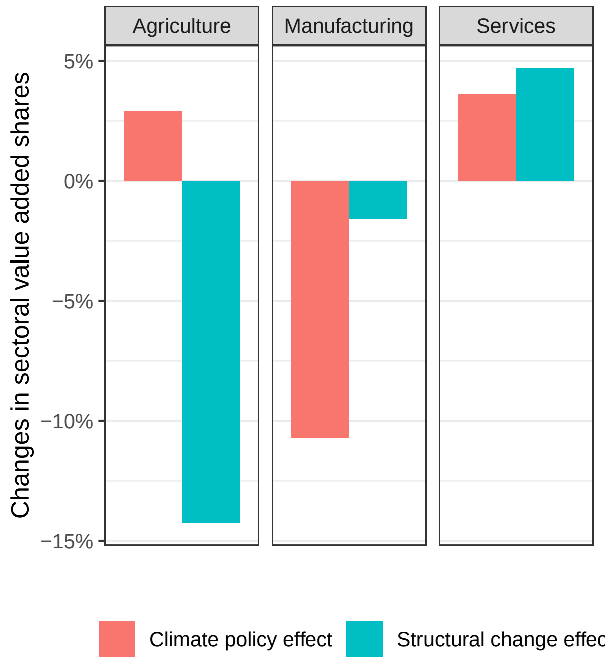
decline in value-added in the manufacturing sector due to climate policy is substantial and can be interpreted as a risk for development. While India has undergone a transformation process that - in contrast to that of China – is characterized by a smaller share of the manufacturing sector, it is not a fully developed country for which declining manufacturing shares are already part of the usual transformation process. Due to its high share of investment goods, the manufacturing sector is crucial for India's development. Climate policy tends to slow down economic structural change. While this holds on a macroeconomic level with three sectors, in the presentation of our results, the manufacturing sector is an aggregate of heterogeneous subsectors with different CO2 intensities and hence various positive and negative effects of climate policy and structural change (for further details, see Appendix, Section B.1.4 "Comparison of trade model features and results" and Figures B.9 and B.10). Some manufacturing subsectors (such as computer and electronics or transport equipment) expand their value-added shares due to climate policy.

2.3.3 Distributional effects

As Figure 2.8 shows, both climate policy and structural change have negative average consumption and income effects across income groups. The consumption incidence[12], which measures basically the change in purchasing power of a given income, is between 1 and 3.5 percent lower than without climate policy and structural change, respectively; additionally, incomes of households is up to 17 percent lower. Yet, the changes induced by structural change alone are on average twice as high as those from climate policy alone. There is an even larger difference between the distributional effects of climate policy and structural change. While both tend to have regressive effects (i.e., poor households are more adversely affected than rich households), the spread between household groups is very different. Climate policy causes more evenly distributed losses

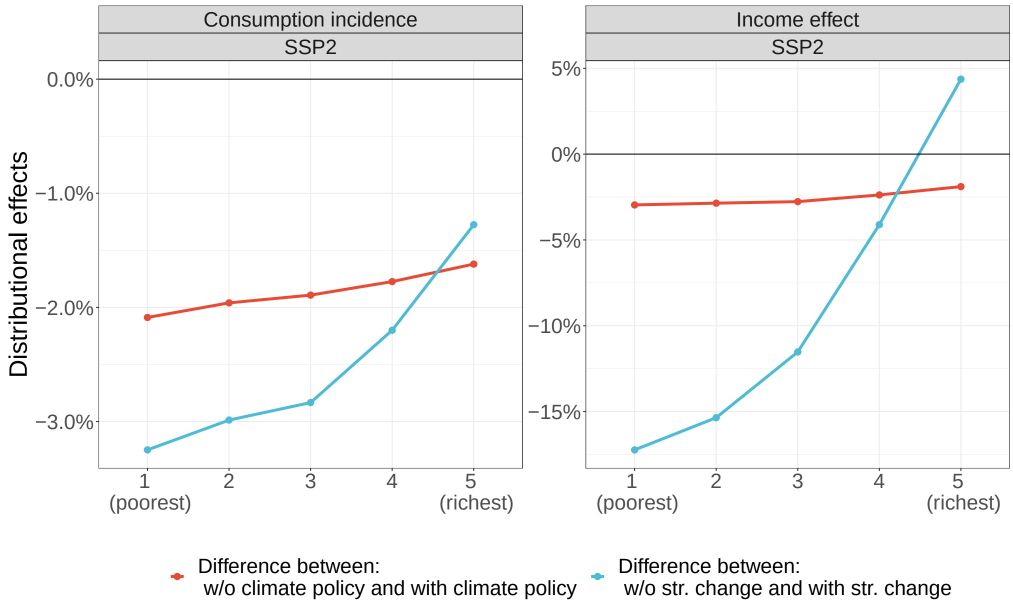
[12] See Equation (2.3) in Section 2.2.3 for a definition of consumption incidence.

Figure 2.7: Changes in Indian sectoral value-added shares caused by structural change and climate policy.



Note: Changes in Indian sectoral value-added shares (in 2030) caused by structural change (red bar) and 2°C climate policy (blue bar). The former represents the difference between scenarios with and without structural change (no climate policy); the latter represents the difference between scenarios with and without climate policy (no structural change); changes are measured in percent of sectoral shares of baseline scenario NoSC-Base (no policy, no structural change); based on KITE model results.

Figure 2.8: Consumption incidence and changes in income due to climate policy and structural change.



Note: Consumption incidence and changes in income across Indian income groups due to 2°C climate policy and structural change. The red lines represent the differences in consumption incidence (left panel) and income (right panel) in a scenario with climate policy (SSP2-CP) and a scenario without climate policy (SSP2-Base). The blue lines represent the respective differences between scenarios with (SSP2-Base) and without structural change (NoSC-Base). Negative values indicate that consumption incidence/income values are lower in scenarios with climate policy and structural change, respectively; based on KITE model results.

of consumption and income, whereas structural change places a severe burden on the poor. The income of poor households is 17 percent lower with structural change than without it, whereas rich households even gain on the order of 5 percent.

Why does structural change make the poor worse off in relative terms? This question can be answered by looking at household characteristics (see Section 2.3). Poor households are mainly employed in the agricultural sector (see Figure 2.3). Structural change shifts more activity, and thus income, to the service sector and reduces the increase of income in the agricultural sector (see Figure 2.7). Consequently, poor households become worse off if they are not able to switch to other sectors. While allowing for labour mobility in the distributional analysis could dampen the estimated income effects, the assumption of labour immobility appears to be reasonable because the examined time horizon covers only 15 years. Current workers, who work throughout the period, tend to find it difficult to move to another sector, while it is easier for the next generation to choose a different sector by acquiring the respective skills in early years already. Furthermore, price differences between the scenario with structural change and the scenario without structural change disproportionately favour rich households. In contrast to poor households, which spend relatively more on agricultural products (food), rich households spend more on services (see Figure 2.3). Therefore, they benefit more from a more substantial drop in prices for services compared to a less substantial reduction of prices for crops (see Figure B.6).

2.4 Discussion

Given that India is projected to have the largest population in the world, a global effort to tackle climate change depends crucially on its ability to decarbonize its economy (Intergovernmental Panel on Climate Change, 2022). However, the changes in energy prices and employment opportunities implied by decarbonization policies may be socially contentious (Kalkuhl et al., 2019; Montrone et al., 2022) and reduce the willingness of political decision-makers in India to implement ambitious climate policies in line with the Paris climate targets. While this study finds results that support this position, by taking structural change effects along the low-carbon transition path into account the overall conclusion is in the opposite direction.

As a first major result, we demonstrate how the impact of carbon pricing in India differs depending on the assumptions on the development of the structure of India's economy. Distributional impacts of carbon pricing are largest under scenarios with fast structural change. While this is a result not highlighted in the literature so far, the robustness is contained as features not specifically associated with structural change. The robustness, however, is supported by results from the 1.5°C climate policy scenario (see Appendix B, Figures B.3 and B.12). The gap between impacts on the poorest and the richest households is always the largest in SSP5.

As a second major result, we find that carbon pricing implies a risk of delaying the structural transformation process, mainly by changing the relative competitiveness of Indian manufacturing sectors over time. This development effect goes beyond the second-order impact found by Lefevre et al. (2022) in a global study with a time horizon of 2050 and therefore more time for the economies to adapt. Changes in output and value-added shares can be expected to be large on a disaggregated sector level (see Figures B.9 and B.10 in the Appendix B). The change in sectoral composition is somewhat smaller, but still significant at the aggregate level (see Figure 2.7). Carbon pricing results in a decline in the manufacturing sector share due to the sector's high share of energy and emission intensive production, and because India is able to import manufactured goods to meet its demand from countries with a more competitive and greener production.[13] Output shares of the agricultural and service sectors consequently increase. This result also holds under the more ambitious 1.5°C climate policy (see Figure B.8 in the Appendix B). While climate policy strongly supports structural transformation within the energy sector (Malik et al., 2021) through the intrasectoral reallocation of labour, it partially undermines the reallocation effects driven by structural change.

Our results show that carbon pricing implies a larger agricultural sector at the expense of activities in the manufacturing sector. While this can be beneficial for the large share of poor households employed in agriculture (where labour mobility is low) in the short term, it may also delay industrialization and the transition to an advanced technology-based economy with the creation of better-paid jobs in the manufacturing and service

[13] We explicitly allow for import substitution in our framework.

sectors. Recent studies provide new evidence supporting the role of the manufacturing sector as a growth engine (Szirmai and Verspagen, 2015; Cantore et al., 2017).

Given the interacting distributional effects of carbon pricing and structural change, disentangling and comparing them provides new insights. A third major result of our scenario analysis emphasizes the dominance of the distributional effects of structural change. The structural transformation that India is facing – with or without climate policy – may substantially reduce wages in sectors where mostly poor people are working. Thus, structural change is likely to increase inequality more than climate policy. This result is supported by the more ambitious 1.5°C climate policy scenario (see Appendix B, Figure B.12) although the absolute level of the climate policy impact increases under this scenario, resulting in a larger negative price effect and a similar average income effect compared to structural change. Climate policy has a rather neutral distributional effect - with regard to the income effect, slightly regressive in the results from the KITE model and slightly progressive in the JUST model results (see Appendix B, Figure B.11). This is in line with those previous studies that see comparatively small distributional effects for India (e.g. Steckel and Jakob, 2021). While at a somewhat lower per capita income level, this result is also consistent with Dorband et al. (2019) who find distributional effects to shift from progressive towards regressive for per capita income levels that are typical for emerging economies. On the other hand, Budolfson et al. (2021) find this crossing point at around 20,000 US dollars, which is significantly above Indians near-term GDP per capita level.

The application of two trade models helps to further evaluate the robustness of our results. Findings discussed in the Results section based on results from the KITE model are predominantly supported by results from the JUST model. This applies to the sensitivity of distributional effects of carbon pricing on the structural change assumptions (see Figures B.4 and B.11 in the Appendix B) despite income changes in the opposite direction in some sectors. It also partly applies to the impact of carbon pricing on structural change (Appendix B, Figure B.7), where a slight increase (decrease) of economic activity in the agricultural (service) sector indicates a slowdown of structural change. Yet, the strong decline of the aggregate manufacturing sector is not observable in the JUST model.

2.5 Conclusion

By taking structural change effects along the low-carbon transition path into account, we put the adverse effects of climate policies into perspective, concluding that socially sensitive policies supporting the process of structural transformation appear to be more important for poor households than downsizing climate policy ambitions. According to our results, climate policy turns out to have a rather small distributional effect across household groups and structural change a more pronounced effect with stronger income and consumption losses for poor households. Consequently, supporting the poor and tackling climate change are not mutually exclusive but congruent policy goals. A number of studies have demonstrated how transfers and the recycling of revenues from carbon pricing can help the poor (Soergel, 2021; Goulder et al., 2019; Dissou and Siddiqui, 2014; Budolfson et al., 2021). Other studies indicate that climate change damages tend to hit the poor hardest (Sedova and Kalkuhl, 2020) and climate policy is able to avoid this. Our results point to an additional mechanism supporting the poor. A policy portfolio that stimulates (rural) economic development and structural transformation, enabling high value-added jobs in the manufacturing and service sectors, seems to be most effective. Such a policy portfolio may include employment programmes (Klonner and Oldiges, 2022), education, digitalization and trade openness; and it supports labour mobility because distributional effects of long-term structural adjustments will be more severe if mobility is constrained.

While investigating a new research strand, this study can be perceived as a first attempt to quantify distributional effects from the interaction of climate policy and economic structural change. The robustness of the results is subject to certain assumptions and limitations, including: (i) the impact of land use competition on food prices is not taken into account, (ii) climate change damages are not taken into account, (iii) partial representation of the complex way of impact of structural change on inequality (Aizenman et al., 2012). Future research is needed to deal with these aspects as well as with the sensitivity of the distributional effects with respect to the specification of the scenario elements (e.g., the climate policy target, structural change projections, or the time horizon).

Chapter 3

The Carbon Footprint of Global Trade Imbalances[1]

3.1 Introduction

A quarter to a third of global CO2 emissions is embodied in goods that are traded internationally. In 2017, the two countries with the largest trade deficits in the world (the United States and the United Kingdom) were at the same time the countries with the two largest net imports of carbon emissions. China, on the other hand, had the largest trade surplus and also by far the largest amount of net exports of carbon emissions. The third largest net carbon exporter (South Korea) also had a very large trade surplus (3rd largest in the world). Contrary examples (such as Germany, which had the second largest trade surplus but was a net carbon importer) notwithstanding, the question arises whether global trade imbalances

[1]Joint work with Joschka Wanner. We thank Jakob Kutsch and Jakob Stender for excellent research assistance, as well as Simon Bolz, Sonja Peterson, Joe Shapiro, Yuta Suzuki, and participants at the European Trade Study Group 2021 in Ghent, FIW Research Conference "International Economics" 2022 in Vienna, European Association of Environmental and Resource Economists Conference 2022 in Rimini, the GTAP Conference 2022, European Association of Environmental and Resource Economists Conference 2023 in Limassol, and the INFER/INTECO Conference 2023 in Valencia, as well as seminars at Berkeley, Kiel University, Kiel Institute, and WIFO for helpful comments.

allow specialization and consumption patterns that magnify the global carbon footprint.

The question is not straightforward to answer. First of all, maybe the United States and China are net importer and net exporter of carbon *only because* they are net importer and exporter overall, respectively. The data can give an answer to this if we consider the embodied emissions per dollar of exports and per dollar of imports, i.e. the ex- and import carbon intensities. Focusing on the two most prominent examples for now, it turns out that Chinese exports are about twice as carbon-intensive as its imports, while US exports are only about half as carbon-intensive as its imports. This pattern magnifies these countries' imbalances in embodied emissions in comparison to their trade value imbalances. It further suggests that there may be scope for lower overall emissions if a trade re-balancing limited the United States' possibility to buy more of its "dirty" imports than it sells comparably "clean" exports (decoupling its *consumption footprint* of emissions associated with products ending up in the US from its *production footprint* of emissions being emitted by US producers) and put a constraint on China to act as the world's supplier of carbon-intensive products (with a corresponding over-proportional production footprint). However, eliminating trade imbalances would reshuffle trade and production all around the world and we cannot rule out a-priori that some of China's "dirty" production will end up in countries that produce the same products with an even larger use of fossil fuels and hence higher emissions. Therefore, if we want to know the "carbon footprint of global trade imbalances", we need to simulate the balancing of all current accounts in a quantitative model.

Beyond the differences in production vs. consumption carbon intensity, another group of countries with large trade surpluses, including, e.g., Russia, Saudi Arabia, or Australia, points to an additional important dimension: the role of trade in fossil fuels. A considerable share of these countries' exports is the sale of fossil fuels. The fact that the production of fossil fuels is itself carbon intensive shows up in their carbon trade balance, the fact that the burning of these fossil fuels in their destination countries will cause additional emissions does not. This implies that the fossil fuel exporters' *extraction footprint* can exceed the emissions associated with their production or consumption. The possibility of running a trade surplus enables fossil fuel exporters to focus their production on fossil fuel extraction to a larger extent than they could if they had to align their production more strongly with their own consumption patterns. Therefore, global trade imbalances can have important implications for fossil fuel supply, which also have to be taken into account when quantifying the carbon footprint of imbalances.

For our quantitative analysis, we develop a Ricardian trade model along the lines of Eaton and Kortum (2002). To capture the full integration of countries into global value chains, we include a sectoral input-output structure as in Caliendo and Parro (2015). Additionally, we incorporate carbon emissions from fossil fuel combustion with varying carbon intensities for different types of fossil fuels. Together with the input-output structure, this allows a fine-grained consideration of embodied carbon flows and a clean distinction of countries' production, consumption, and extraction footprints. As an environmentally extended version of Caliendo and Parro (2015), the model is closely related to the contributions by Shapiro (2021), Caron and Fally (2022), and Klotz and Sharma (2023), which in turn are the latest additions to a young, but growing literature incorporating emissions into structural gravity models (Egger and Nigai, 2015; Shapiro, 2016; Larch and Wanner, 2017, 2019; Shapiro and Walker, 2018).[2]

We use the quantitative framework for two types of counterfactual analyses. First, we eliminate individual countries' trade imbalances, altering the rest of the world's surpluses and deficits only to the extent necessary to

[2]Shapiro (2021) is observationally equivalent to the original Caliendo and Parro (2015) framework, but additionally captures global emissions and its welfare implications; Caron and Fally (2022) include a more detailed modeling of fossil fuel production and trade and incorporate non-homothetic preferences; Klotz and Sharma (2023) incorporate fossil fuel use and emissions in transportation.

ensure that global supply equals global demand. We calculate how the country's different emission footprints react to the elimination of the trade imbalance and how global emissions are affected. We use these country-level re-balancing exercises to identify patterns in countries' consumption habits and production specialization, as well as resource abundance, that determine which imbalances are particularly problematic in terms of their effect on global emissions. Second, we simulate a global re-balancing in which all countries' surpluses and deficits are jointly erased. This allows us to assess whether the current pattern of trade imbalances around the world is in fact partly responsible for the high level of global carbon emissions. In addition to insights on the level of global emissions, this counterfactual is also informative concerning the distribution of carbon emissions across the globe and how this is shaped by trade imbalances.

We find that a global re-balancing of international trade would lower global emissions by 0.9 percent. While this is not a huge number on first sight, it is considerable given that (i) the scenario does not explicitly implement any environmental policy and (ii) prior literature finds that a move to total autarky for all countries would lower emissions by a rather mild (considering the extreme scenario) 5 percent (**?**). In terms of individual countries' imbalances, the US deficit indeed fosters emissions by sustaining the carbon-intensive US consumption. Most of the individual countries' imbalances that are particularly environmentally detrimental, however, are found to be the surpluses of major fossil fuel exporters with their disproportionately large extraction footprints.

Our exercises come with one important disclaimer. Unlike a growing literature on the *sources* of trade imbalances (cf. e.g., Reyes-Heroles, 2016; Felbermayr and Yotov, 2021; Cuñat and Zymek, 2023), our paper purely examines the *consequences* of their removal, standing in the tradition of Dekle, Eaton, and Kortum (2007, 2008). To this respect, we do not point towards a policy that would eliminate the imbalance, but we calculate the magnitudes of the adjustments that such a balancing would entail in terms of carbon emissions.

Until now, the role of trade imbalance in shaping global emission patterns has received little attention. In their recent handbook chapter, Copeland, Shapiro, and Taylor (2022) briefly refer to imbalances as one factor that could contribute to emissions outsourcing. Li, Chen, Li, Li, and Chen (2020) consider embodied energy in the US-Chinese bilateral trade imbalance, showing that the United States implicitly net imports large amounts of energy from China.

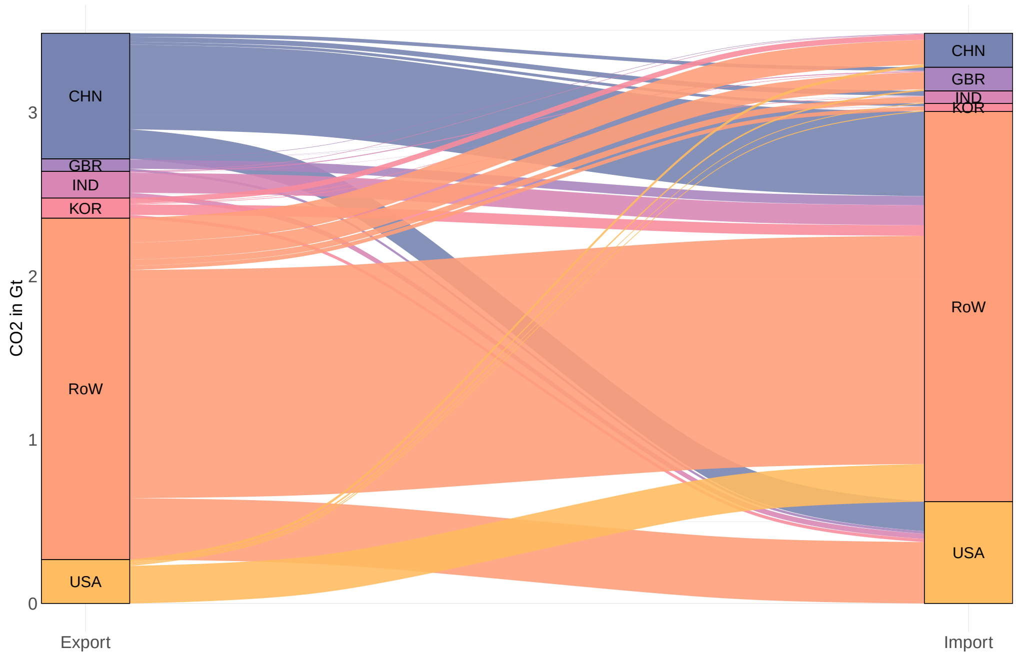
The remainder of this paper is structured as follows. Section 3.2 presents a collection of stylized facts about global trade imbalances in terms of both values and embodied emissions, their interrelation with one another and with the countries' resource abundance. Section 3.3 lays out the quantitative model and Section 3.4 introduces the data used for the quantification. In Section 3.5, we present the results of the counterfactual exercises. Section 3.6 concludes.

3.2 Trade imbalances and embodied emissions: A look at the data

In this section, we take a look at the data and establish four stylized facts about value and embodied emission trade imbalances across countries and time. While not novel individually and in part very straightforward, the aim of this *collection* of stylized facts is to motivate that trade imbalances have the potential to play an important role in shaping the level and distribution of global carbon emissions. In this section, in line with the calibration of our quantitative model later on, we use data from the Global Trade Analysis Project 11 database (GTAP, see Aguiar et al., 2022), which captures the period from 2004 to 2017.

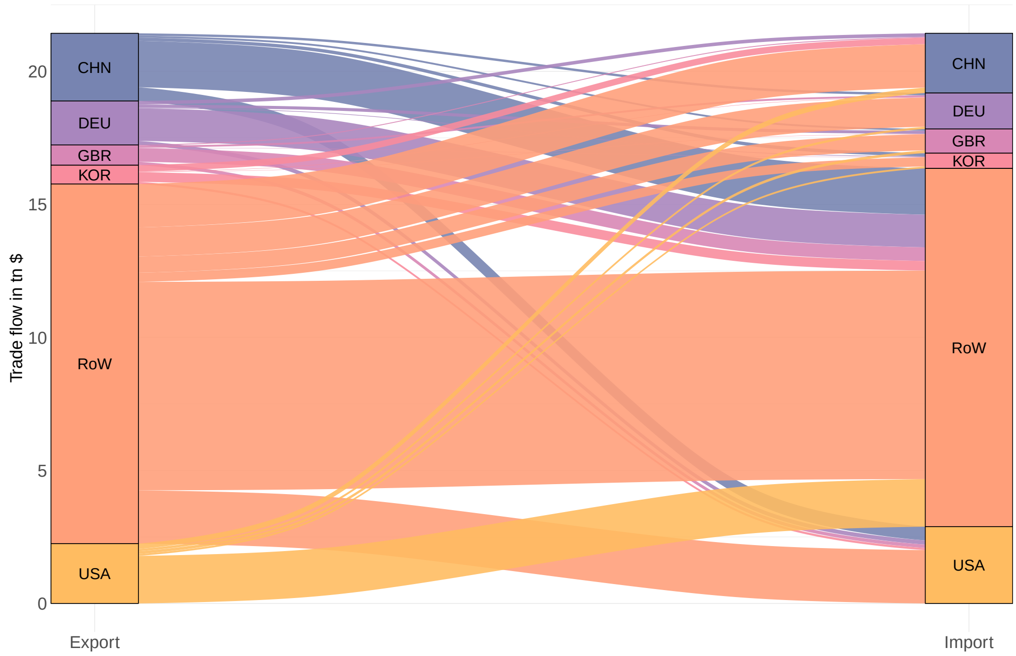
Stylized Fact 1. *Embodied emissions in international trade are highly and persistently asymmetric.*

Figure 3.1: Bilateral flows of embodied CO2 emissions in international trade, 2017.



Bilateral flows of embodied CO2 emissions for the five countries with the largest absolute imbalance of embodied carbon emissions in trade, plus an aggregated "Rest of the World", are depicted in Figure 3.1. The height of a country's box on the vertical axis relates to the corresponding total embodied emissions in their exports (left) and imports (right) in 2017. China, Great Britain, India, South Korea and the USA account together for 40.1 percent of total embodied carbon emissions in exports and for 31.6 percent of total embodied carbon emissions in imports. For individual countries, the contrast can be very stark: while China exports 766 Mt, it only imports 207 Mt of embodied CO2. For the US, the pattern is similarly extreme, but in the opposite direction. Their exports embody 268 Mt, while the embodied emissions in their imports amount to 622 Mt of CO2. As the US, Great Britain is also a net importer of embodied CO2, while India and South Korea are net exporters. China is also the country with the largest share of net exports to total exports in embodied emissions, which amount to 73 percent, followed by South Korea with 60 percent. Figure 3.1 implies large gaps between production and consumption footprints. Importantly, these

Figure 3.2: Bilateral trade flows, 2017.



imbalance patterns have been very persistent.[3] All individual countries keep their role as a net ex- or importer of embodied emissions throughout the period. This persistence magnifies the importance of understanding the role that the trade imbalances play in shaping global emissions. If trade imbalances contribute to a production and consumption pattern around the world that goes in hand with higher carbon emissions and this pattern persists over time, the resulting additional emissions will add up over time.

Stylized Fact 2. *Trade is highly and persistently asymmetric in value terms, too.*

Figure 3.2 shows bilateral trade flows of goods and services of the five countries with the world's largest absolute trade imbalances. The height of a country's box on the vertical axis relates to their total exports (left) and imports (right) in trillions of USD in 2017. It hence reproduces Figure 3.1,

[3] See Figure C.1 in the Appendix C for a representation of the pattern in Figure 3.1 since 2004 (the first base year of the GTAP 11 data base).

substituting embodied emissions for values. Even though the asymmetry in value trade is not as drastic as in embodied emissions trade, the value imbalances are substantial, too. China, Germany, Great Britain, South Korea, and the USA account together for 37 percent of total exports and of total imports. China has a trade surplus of 303 bn USD, followed by Germany (299 bn), and South Korea (137 bn). The USA have the largest trade deficit with 638 bn USD, followed by Great Britain (150 bn USD). Even though this stylized fact is well-established, we restate it here because it takes center-stage in our analysis which asks whether these well-known imbalances have an additional, so far overlooked environmental implication to them. Similarly to the embodied emissions imbalances over time shown, this pattern is highly persistent.[4] If trade imbalances were a short-lived phenomenon, potential emission implications would be of little concern. This year's surpluses would turn into next year's deficits and a specialization pattern made possible in one year that leads to particularly high carbon emissions would be followed by a different pattern that would imply comparably low emissions. The persistence implies, however, that a high-emission global imbalance distribution could be a sustained phenomenon.

Stylized Fact 3. *Countries with large value deficits [surpluses] tend to import more [less] emission-intensive products than they export.*

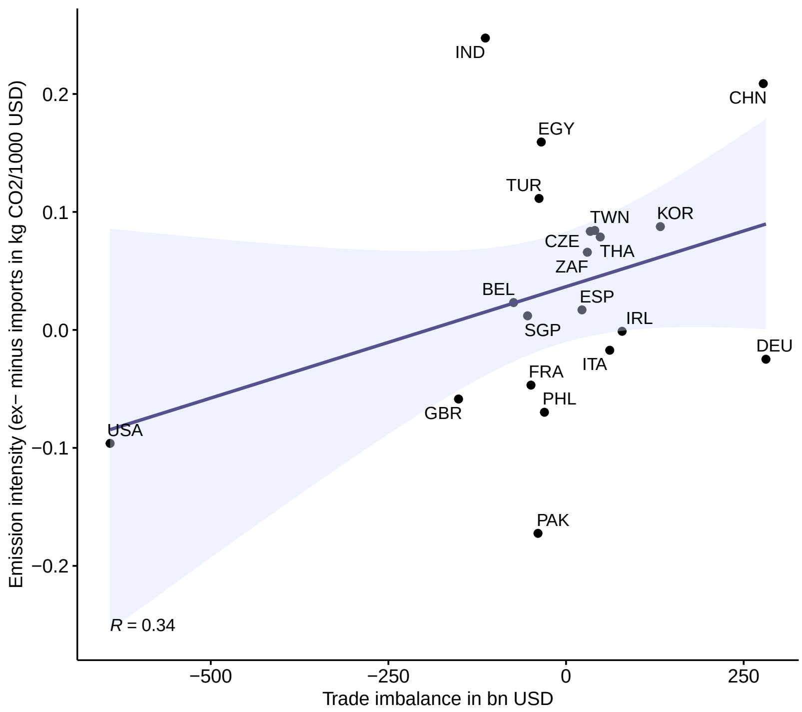
In order to assess whether global trade imbalances are likely to drive world emissions up or down, we need to know which type of countries is running the major deficits and which type of countries is running the major surpluses. If countries that sell less carbon-intensive products internationally than they buy were the surplus countries, imbalances might actually be environmentally beneficial. As Figure 3.3 makes clear, however, the opposite tends to be true: the imbalances are positively correlated with the relative carbon-intensity of exports.[5,6] Countries supplying "dirty"

[4]See Figure C.2 in the Appendix C for a graphical representation.

[5]The relative carbon-intensity of exports is calculated by subtracting the country's carbon intensity per imported USD from its carbon intensity per exported USD.

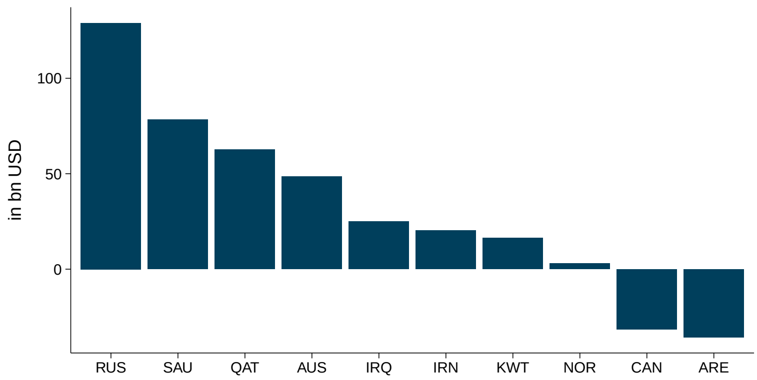
[6]Note that Figure 3.3 only shows countries that are net fossil fuel importers. As

Figure 3.3: Correlation of trade imbalances and carbon intensities of exports vs. imports, 2017.



Note: Figure displays the 20 fossil fuel net-importers with the largest trade imbalances (Source: GTAP 11).

Figure 3.4: Trade imbalance of the 10 largest fossil net-exporters, 2017.



goods to the rest of world, while importing comparably clean products, tend to run surpluses. On the other hand, the countries exporting relatively "cleanly" tend to run deficits. Most clearly and most importantly, this pattern is evident for the United States and China, as we already briefly discussed in the introduction. The (far from perfect) separation into clean deficit and dirty surplus countries suggests that today's global trade imbalances may contribute to upholding a trade pattern that implies higher carbon emissions than would prevail in a world of balanced trade.

Stylized Fact 4. *Many large fossil fuel exporters are consistently running strong trade surpluses.*

The relative carbon intensity of a country's production vs. consumption is not the only dimension that determines how the country's trade surplus or deficit impacts carbon emissions. Importantly, international trade is not only about products of varying carbon intensities, but it's also about the products, the use of which *causes* carbon emissions, namely fossil fuels. If countries that are rich in fossil resources (and hence have large extraction footprints) run trade surpluses, this has the potential to drive up the global supply of fossil fuels and in turn the global level of emissions. As Figure

discussed in the introduction, fossil fuel exporters' imbalances likely play a special role and they are therefore considered in a separate stylized fact below. Considering the 20 countries with the largest imbalance (including net fuel exporters) lowers the correlation from 0.34 to 0.25.

3.4 shows, this is exactly the case for many of the world's largest fossil fuel net-exporters.[7] Out of the top ten, eight countries have a trade surplus in 2017, which are partly huge in relation to these countries' overall GDPs.[8] It seems, therefore, that current global trade imbalances may contribute to high carbon emissions in a second way, namely by fostering the global supply of fossil fuels.

To sum up, we have shown that international trade is highly unbalanced both in value and in embodied emissions terms. While this need not be bad news for global emission levels, the fact that there are positive associations between running a trade surplus and both exporting fossil-fuel intensive products and exporting fossil fuels, there is strong reason to suspect that today's global imbalances are indeed driving up global carbon emissions and — given the persistence of the observed imbalances — will continue to do so. To quantitatively assess *the carbon footprint of global trade imbalances*, however, we need to take into account the equilibrium adjustments that would result from a global re-balancing. In the following section, we present a model that will allow us to simulate such a re-balancing.

3.3 Model

We build a Ricardian quantitative trade model a la Eaton and Kortum (2002, henceforth EK), which incorporates a sectoral structure with input-output linkages, trade imbalances, and carbon emissions from fossil fuel combustion. It closely follows the sectoral extension of EK by Caliendo and Parro (2015, henceforth CP), but additionally includes fossil fuel extraction and carbon emissions from fossil fuel combustion in the production of other goods or for final consumption. As an environmental extension of

[7]Based on GTAP 11. Fossil exports are calculating by summing up the export values of the *coal, oil, natural gas* and *petroleum* sectors.

[8]Qatar's trade surplus is as high as 38 percent of their GDP, followed by Kuwait (13 percent), Saudi Arabia (11 percent) and Russia (8 percent).

the framework by CP, the model is also closely related to Shapiro (2021), Caron and Fally (2022), and Klotz and Sharma (2023).

As our focus is on the effect of changes in trade imbalances (as in Dekle, Eaton, and Kortum, 2007, 2008), we will keep the expressions as simple as possible by not considering tariffs as in CP or other policy variables that would allow explicit climate policies (such as a carbon tax).

3.3.1 Preferences

There is a set of countries $\mathcal{N}$, denoted by i and n, and a set of sectors $\mathcal{J}$, indexed by j and k. Both primary and secondary fossil fuel sectors are part of $\mathcal{J}$ and the distinction between the different types of sectors will be discussed further below. In each sector, there is a continuum of goods $\omega^j \in [0, 1]$. Households in n obtain utility from consumption C according to a two-tier Cobb-Douglas utility function:

$$u_n = \prod_{j \in \mathcal{J}} \left(\exp \int_0^1 \ln C_n(\omega^j) d\omega^j \right)^{\alpha_n^j}$$

where α is the constant sectoral expenditure share, $\sum_{j \in \mathcal{J}} \alpha_n^j = 1$. Note that the choice of a lower-tier Cobb-Douglas instead of a more general CES utility function does not affect any results and is solely motivated by the attempt to keep parameters to the necessary minimum (see Eaton and Kortum, 2012, for the corresponding comparison in the one-sector EK framework). While the aggregation of utility from different varieties *within* one sector is the same for all countries, expenditures shares *across* sectors vary between countries, allowing for differently emission-intensive consumption patterns. This flexibility is crucial as the trade deficit or surplus of a country that consumes a lot of fossil fuels or products that require high fuel input in production will have different emission implications than the deficit or surplus of a country with a high share of e.g. clean services expenditure.

3.3.2 Production

There are three types of sectors that are all part of the overall set $\mathcal{J}$: primary fossil fuels ($p \in \mathcal{P}$), secondary fossil fuels ($s \in \mathcal{S}$), and ordinary sectors ($o \in \mathcal{O} = \mathcal{J} \setminus \{\mathcal{P}, \mathcal{S}\}$). Primary fossil fuels are the fuels extracted from the earth, secondary fossil fuels are the ones burnt in production or consumption. The two may but do not have to coincide and the sets $\mathcal{P}$ and $\mathcal{S}$ therefore overlap, but are not identical. E.g. in the case of coal, what is extracted and what is used at later points is the same, while for oil, we distinguish the primary sector raw oil and the secondary sector petroleum.

All goods are produced using labour l and composite intermediate input bundles m from the own and other sectors. In all sectors, countries differ in their productivity for different goods from the continua, inversely captured by the input requirement a, and in the input cost shares γ. Primary fossil fuel sectors additionally use a sector-specific natural resource input r^p, which we think of as the different types of fossil fuel reserves. Secondary fossil fuel sectors that are not also primary sectors are linked to one specific primary fossil fuel sector (which we will index by p^s) in requiring a fixed quantity input from it, with the relative physical inputs shares for the primary fuel and other inputs determined by two additional technology parameters ν^{p^s} and ν^s. Intuitively, e.g. one liter of petroleum cannot be produced without a fixed quantity of raw oil. Other than the latter Leontief component, the production technologies are Cobb-Douglas and hence given by:

$$q_n(\omega^o) = [a_n(\omega^o)]^{-1} [l_n(\omega^o)]^{\gamma_n^{l,o}} \prod_{j \in \mathcal{J}} \left[m_n^j(\omega^o)\right]^{\gamma_n^{j,o}} \quad \forall o \in \mathcal{O},$$

$$q_n(\omega^p) = [a_n(\omega^p)]^{-1} [r_n^p(\omega^p)]^{\gamma_n^{r,p}} [l_n(\omega^p)]^{\gamma_n^{l,p}} \prod_{j \in \mathcal{J}} \left[m_n^j(\omega^p)\right]^{\gamma_n^{j,p}} \quad \forall p \in \mathcal{P},$$

$$q_n^s(\omega^s) = [a_n(\omega^s)]^{-1} \times \min \left\{ \nu_n^{p^s} m_n^{p^s}, \nu_n^s [l_n(\omega^s)]^{\tilde{\gamma}_n^{l,s}} \prod_{j \in \mathcal{J} \setminus \{p^s\}} \left[m_n^j(\omega^s)\right]^{\tilde{\gamma}_n^{j,s}} \right\} \quad \forall s \in \mathcal{S} \setminus \mathcal{P},$$

with $\gamma_n^{l,o} + \sum_{j \in \mathcal{J}} \gamma_n^{j,o} = 1$, $\gamma_n^{r,p} + \gamma_n^{l,p} + \sum_{j \in \mathcal{J}} \gamma_n^{j,p} = 1$, and $\tilde{\gamma}_n^{l,s} + \sum_{j \in \mathcal{J} \setminus \{p^s\}} \tilde{\gamma}_n^{j,s} =$

1. Note that we distinguish $\tilde{\gamma}$ to indicate that these are not the overall cost shares in the exclusively secondary fossil fuel sectors. We still refer to the actual cost shares in this sector by γ, too, but note that they are endogenous in these sectors and will react to changes in the relative price of the primary fossil input compared to the remaining inputs. The intermediate input bundles are themselves Cobb-Douglas composites[9]:

$$m_n^j = \exp \int_0^1 \ln d_n(\omega^j) d\omega^j,$$

where $d_n(\omega^j)$ are the demands for the specific varieties ω^j as intermediate inputs. Unit costs (which equal the price due to perfect competition and constant returns to scale) in the ordinary, primary fossil fuel and secondary fossil fuel sectors are given by $c_n^o a_n(\omega^j)$, $c_n^p a_n(\omega^p)$, and $c_n^s a_n(\omega^s) \forall s \notin \mathcal{P}$, where the cost of the input bundles are given by

$$c_n^o = \Upsilon_n^o \left[w_n\right]^{\gamma_n^{l,o}} \prod_{j \in \mathcal{J}} \left[P_n^j\right]^{\gamma_n^{j,o}} \qquad \forall o \in \mathcal{O}, \tag{3.1}$$

$$c_n^p = \Upsilon_n^p \left[p_n^{r^p}\right]^{\gamma_n^{r,p}} \left[w_n\right]^{\gamma_n^{l,p}} \prod_{j \in \mathcal{J}} \left[P_n^j\right]^{\gamma_n^{j,p}} \qquad \forall p \in \mathcal{P}, \tag{3.2}$$

$$c_n^s = \frac{P^{p^s}}{\nu_n^{p^s}} + (\nu_n^s)^{-1} \Upsilon_n^s \left[w_n\right]^{\tilde{\gamma}_n^{l,s}} \prod_{j \in \mathcal{J} \setminus \{p^s\}} \left[P_n^j\right]^{\tilde{\gamma}_n^{j,s}} \qquad \forall s \in \mathcal{S} \setminus \mathcal{P}, \tag{3.3}$$

where $\Upsilon_n^o = (\gamma_n^{l,o})^{-\gamma_n^{l,o}} \prod_{j \in \mathcal{J}} (\gamma_n^{j,o})^{-\gamma_n^{j,o}}$, $\Upsilon_n^p = (\gamma_n^{r,p})^{-\gamma_n^{r,p}} (\gamma_n^{l,p})^{-\gamma_n^{l,p}} \prod_{j \in \mathcal{J}} (\gamma_n^{j,p})^{-\gamma_n^{j,p}}$, $\Upsilon_n^s = (\tilde{\gamma}_n^{l,s})^{-\tilde{\gamma}_n^{l,s}} \prod_{j \in \mathcal{J} \setminus \{p^s\}} (\tilde{\gamma}_n^{j,s})^{-\tilde{\gamma}_n^{s,o}}$, w denotes the wage, P the price of a composite intermediate bundle, and p^{r^p} is the price of a specific fossil resource factor. Input requirement coefficients in all sectors are assumed to be drawn from type-III extreme value (Weibull) distributions, i.e. $Pr[a_n(\omega^j) \leq a] = 1 - \exp(-(A_n^j a)^{\theta^j})$, where A is a location parameter capturing a country's overall technology level in a sector capturing (the productivity component of) comparative advantage across sectors and θ is a dispersion parameter (inversely) capturing the extent of comparative advantage differences within sectors.[10]

[9]Note that just as in the utility function, this could be generalized to a CES composite without changing any of the final results.

[10]Note that both EK and CP equivalently have countries draw productivities from a

Importantly, the production structure implies that countries not only differ in their productivities, but also in the extent to which they rely on fossil fuel inputs in producing different goods. Just as the differences in the "greenness" of consumption, this can have important implications for how a country's trade surplus/deficit affects global emissions: it can enable "dirty" (i.e. fossil fuel intensive) producers to serve a larger share of global demand or it can help them cover more of their own demand with cleaner products from abroad. Note also the two-layer structure of comparative advantage: the probabilistic EK notion of comparative advantage determines which countries produce which products *within* sectors and additionally, comparative advantage *across* sectors as determined by sectoral productivities and input costs determines which countries specialize into production in which sectors. Crucially, in the primary fossil fuel sector, factor endowment differences enter as another source of comparative advantage, complementing the otherwise Ricardian trade structure in the model with a Heckscher-Ohlin component.

How can international trade allow emission-relevant specialization patterns in our model then? In one important dimension, countries can specialize in producing fossil fuel intensive goods vs. products that rely on less fossil fuel inputs — with different implications for the consequences of the countries' trade imbalances on emissions. In a second dimension, countries can specialize in ordinary goods or in the *production* of fossil fuels. If countries of this latter (fossil resource abundant) type run a trade surplus, this increases global fossil fuel supply and hence drives up global emissions, pointing to a potentially problematic role of imbalances of fossil fuel exporters.

type-II extreme value (Frechet) distribution instead. We follow Eaton and Kortum (2012) here and use the original Ricardian technology measure of input requirements.

3.3.3 International trade

Gravity

Both consumers and producers source the goods they buy from the lowest-cost supplier. International trade faces iceberg trade costs t^j_{ni}, i.e. t units have to be shipped to deliver one unit from i to n. The cost distribution for country i delivering goods to country n depend on i's productivity and input costs, as well as on bilateral frictions between i and n and is given by

$$Pr[c_{ni}(\omega^j) \leq c] = 1 - e^{-(A^j_{ni}c)^{\theta^j}},$$

with $A^j_{ni} = A^j_i/(t^j_{ni}c^j_i)$. Country i is hence likelier to be able to provide goods at a low price to n if (i) its overall productivity in the respective sector is high (large A), (ii) its input costs are low (small c), and/or (iii) its trade costs with n are low (small t).

Under perfect competition, producers price at their costs. The price at which consumers and producers in country n end up buying a good ω is the minimum price across the bilateral cost distributions just shown. The resulting price distribution inherits the Weibull form from the technology and cost distributions and is given by:

$$F^j_n(p) = 1 - e^{-(\bar{A}^j_n p)^{\theta^j}}, \quad \text{with} \quad \bar{A}^j_n = \left[\sum_{i \in \mathcal{N}} (A^j_{ni})^{\theta^j}\right]^{1/\theta^j}.$$

$\bar{A}$ summarizes how the three price influences (technology, input costs, and geography as captured by the trade costs) *all around the world* shape the price level in a country. Specifically, we can obtain sectoral price indices by integrating over the price distributions:

$$P^j_n = \exp\left(\int_0^\infty \ln(p) dF^j_n(p)\right) = \frac{\exp(-\varepsilon/\theta^j)}{\bar{A}^j_n}, \tag{3.4}$$

where $\varepsilon = 0.5772\ldots$ is Euler's constant. Note that the possibility of non-tradable sectors is implicitly also captured. In these non-tradable sectors, trade costs are prohibitively high ($t^j_{ni} = \infty$) and the price hence simplifies to $P^j_n = \exp(-\varepsilon/\theta^j)/A^j_{nn}$.

Country n's total spending on goods from sector j is X^j_n. The share of this expenditures that is spent on goods from country i equals the share in which i is the lowest cost supplier and is given by a sectoral version of the EK gravity expression[11]:

$$\pi^j_{ni} = \frac{X^j_{ni}}{X^j_n} = \left(\frac{A^j_{ni}}{\bar{A}^j_n}\right)^{\theta^j} . \tag{3.5}$$

International trade links carbon emissions across countries in a direct and an indirect way. Directly, countries with a comparative advantage in fossil fuel intensive goods will specialize in the production of these goods, emit more CO_2, and tend to implicitly export more emissions to other countries than importing from them. Indirectly, emissions in different countries are additionally linked because the fossil fuels causing them are themselves traded. Lower (higher) demand for fossil fuels in one country will drive down (up) the price for fossil fuels and hence on the one hand incentivize other countries to produce more (less) fossil fuel intensively, but on the other hand incentivize fossil resource-abundant countries to extract less (more) fossil fuels from the ground.

Trade balance

Total expenditures for sector j combines expenditure on intermediate bundles and for final consumption:

$$X^j_n = \sum_{k \in \mathcal{J}} \gamma^{j,k}_n \sum_{i \in \mathcal{N}} X^k_i \pi^k_{in} + \alpha^j_n I_n, \tag{3.6}$$

[11] As described in EK, this share can be calculated as the probability that i has the lowest costs of delivering a good ω to n: $Pr[c_{ni}(\omega^j) \leq \min\{c_{ns}(\omega^j); s \neq i\}] = \int_0^\infty \prod_{s \neq i}[\exp(-(A^j_{ns}c)^{\theta^j})]d(\exp(-(A^j_{ni}c)^{\theta^j}))$. To move to EK's explicit gravity equation for trade *flows*, multiply the trade shares with the destination country's total sectoral expenditure, solve the market clearing condition for $(A^j_i/c^j_i)^\theta$, substitute the expression into (3.5) and simplify using (3.4).

where the final absorption I_n consists of labour income (given by the total labour endowment L_n times the wage), resource income from the different types of fossil resources (given by the respective endowments R_n^p times the resource prices) and the trade deficit (D_n):

$$I_n = w_n L_n + \sum_{p \in \mathcal{P}} p_n^{r^p} R_n^p + D_n. \tag{3.7}$$

Trade is multilaterally balanced up to the exogenously given trade deficit:

$$\sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{J}} \left(X_n^j \pi_{ni}^j \right) - D_n = \sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{J}} \left(X_i^j \pi_{in}^j \right). \tag{3.8}$$

International trade allows countries to decouple their production and consumption patterns. They can specialize in producing certain varieties and they can focus their production on the sectors in which they have a comparative advantage. At the same time, they are free to still consume a product basket that is determined by their preferences rather than their comparative advantage. Just because a country extracts a lot of fossil fuels, it does not have to spend a large share of its income on these fuels. Trade balance puts a limit to the decoupling: the overall value of produced goods has to equal the overall value of the purchased ones. If a country wants to export another dollar worth of its products, it has to also import an additional dollar worth from elsewhere. With trade imbalances, the limit is softened. Up to the level of the deficit or surplus, they decouple not only *what* a country produces and buys, but also *how much*. The equilibrium effects of this further decoupling on carbon emissions are ambiguous. One country's surplus necessarily is another country's deficit. A deficit [surplus] will increase [lower] the respective country's consumption footprint. Globally, deficits in countries with "green" preferences, relatively "brown" production technologies, and large levels of production of fossil fuels will tend to lower emissions, while deficits in countries demanding fossil-intensive products that produce with small fossil input shares will tend to increase them.

3.3.4 Equilibrium

The definition of an equilibrium closely mimics the expression by CP, somewhat expanded by the presence of the fossil fuel sector and the non-constant input cost shares in a subset of these sectors.

Definition 1. *For given labour endowments L_n, resource endowments R_n^p, technology parameters A_n^j, θ^j $\gamma_n^{l,o}$, $\gamma_n^{j,o}$, $\gamma_n^{r,p}$, $\gamma_n^{l,p}$, $\gamma_n^{j,p}$, $\tilde{\gamma}_n^{l,s}$, $\tilde{\gamma}_n^{j,s}$, $\nu_n^{p^s}$ and ν_n^s, trade costs t_{ni}^j, and trade imbalances D_n, an equilibrium is a set of wages w_n, fossil resource prices $p_n^{r^p}$, composite intermediate goods prices P_n^j, and input cost shares in secondary fossil fuel production $\gamma_n^{l,s}$ and $\gamma_n^{j,s}$ that satisfy conditions* (3.1)–(3.8).

Equilibrium in relative changes

Just as in CP, the determination of an equilibrium for a given policy change simplifies if, following Dekle, Eaton, and Kortum (2007, 2008), equilibrium conditions are re-expressed in terms of relative changes where possible. Denote values of any variable or parameter in the baseline equilibrium by x, under the counterfactual scenario by $x^{'}$, and its relative change by $\hat{x} = x^{'}/x$. Then, the equilibrium can be defined in relative changes as follows:

Definition 2. *Let $\{w_n, p_n^{r^p}, P_n^j, \gamma_n^{l,s}, \gamma_n^{j,s}\}$ be a baseline equilibrium for global trade imbalances D_n and $\{w_n^{'}, p_n^{r^p{'}}, P_n^{j'}, \gamma_n^{l,s'}, \gamma_n^{j,s'}\}$ be a counterfactual equilibrium for global trade imbalances $D_n^{'}$. Then, $\{\hat{w}_n, \hat{p}_n^{r^p}, \hat{P}_n^j, \hat{\gamma}_n^{l,s}, \hat{\gamma}_n^{j,s}\}$ satisfy the following equilibrium conditions* (3.9a)–(3.15b)*:*

Cost changes of the input bundles:

$$\hat{c}_n^o = [\hat{w}_n]^{\gamma_n^{l,o}} \prod_{j \in \mathcal{J}} \left[\hat{P}_n^j\right]^{\gamma_n^{j,o}} \quad \forall o \tag{3.9a}$$

$$\hat{c}_n^p = \left[\hat{p}_n^{r^p}\right]^{\gamma_n^{r,p}} [\hat{w}_n]^{\gamma_n^f} \prod_{j \in \mathcal{J}} \left[\hat{P}_n^j\right]^{\gamma_n^{j,p}} \quad \forall p \tag{3.9b}$$

$$\hat{c}_n^s = \gamma_n^{p^s,s} \hat{P}_n^{p^s} + (1 - \gamma_n^{p^s,s}) [\hat{w}_n]^{\tilde{\gamma}_n^{l,s}} \prod_{j \in \mathcal{J} \setminus \{p^s\}} \left[\hat{P}_n^j\right]^{\tilde{\gamma}_n^{j,s}} \forall s \notin \mathcal{P} \tag{3.9c}$$

Input cost share changes:

$$\hat{\gamma}_n^{p^s,s} = \frac{\hat{P}_n^{p^s}}{\hat{c}_n^s} \quad \forall s \notin \mathcal{P} \tag{3.10a}$$

$$\hat{\gamma}_n^{l,s} = \hat{\gamma}_n^{j,s} = (\hat{c}_n^s)^{-1} [\hat{w}_n]^{\tilde{\gamma}_n^{l,s}} \prod_{j \in \mathcal{J} \setminus \{p^s\}} \left[\hat{P}_n^j\right]^{\tilde{\gamma}_n^{j,s}} \quad \forall s \notin \mathcal{P} \wedge j \neq p^s \tag{3.10b}$$

Price index change:

$$\hat{P}_n^j = \left[\sum_{i \in \mathcal{N}} \pi_{ni}^j \left(\hat{c}_i^j\right)^{-\theta^j}\right]^{\frac{-1}{\theta^j}} \tag{3.11}$$

Bilateral trade share change:

$$\hat{\pi}_{ni}^j = \left[\frac{\hat{c}_i^j}{\hat{P}_n^j}\right]^{-\theta^j} \tag{3.12}$$

Counterfactual total expenditure by country and sector:

$$X_n^{j'} = \sum_{k \in \mathcal{J} \setminus \{\mathcal{S} \setminus \mathcal{P}\}} \left(\gamma_n^{j,k} \sum_{i \in \mathcal{N}} \hat{\pi}_{in}^k \pi_{in}^k X_i^{k'}\right) + \sum_{s \in \mathcal{S} \setminus \mathcal{P}} \left(\hat{\gamma}_n^{j,s} \gamma_n^{j,s} \sum_{i \in \mathcal{N}} \hat{\pi}_{in}^s \pi_{in}^s X_i^{s'}\right) + \alpha_n^j I_n^{'} \tag{3.13}$$

Counterfactual final absorption:

$$I_n^{'} = \hat{w}_n w_n L_n + \sum_{p \in \mathcal{P}} \hat{p}_n^{r^p} p_n^{r^p} R_n^p + D_n^{'} \tag{3.14}$$

Factor price changes:

$$\hat{p}_n^{r^p} = \frac{\gamma_n^{r,p} \sum_{i \in \mathcal{N}} \hat{\pi}_{in}^p \pi_{in}^p X_i^{p'}}{p_n^{r^p} R_n^p} \tag{3.15a}$$

$$\hat{w}_n = \frac{1}{w_n L_n} \left(\sum_{j \in \mathcal{J} \setminus \{\mathcal{S} \setminus \mathcal{P}\}} \left(\gamma_n^{l,j} \sum_{i \in \mathcal{N}} X_i^{k'} \hat{\pi}_{in}^k \pi_{in}^k\right) + \sum_{s \in \mathcal{S} \setminus \mathcal{P}} \left(\hat{\gamma}_n^{l,s} \gamma_n^{l,s} \sum_{i \in \mathcal{N}} X_i^{s'} \hat{\pi}_{in}^s \pi_{in}^s\right) \right) \tag{3.15b}$$

Note that this second equilibrium definition has the advantage that there is no need to identify the level of the technology parameters A and ν and of the bilateral trade frictions t anymore. Also, for the primary production factors L and R^p, information on the baseline income earned from them is sufficient rather than separate information on their quantities and prices. Further note that rather than simply restating the counterfactual counterpart of (3.8) in our depiction of the equilibrium in changes, we directly translate trade balancing into the implied changes of the factor prices in order to have the equations exactly coincide with the ones used in our solution algorithm, which simply iterates over Equations (3.9a)–(3.15a), with a dampening factor included in the factor price updates.[12] Finally note that in order to keep the expressions as simple as possible, we only consider exogenous changes in trade balances. Naturally, e.g. counterfactual trade cost changes could readily be incorporated.

3.3.5 Carbon emissions

Territorial emissions / production footprints

Carbon emissions stem from fossil fuel combustion and are therefore modeled to be proportional to the usage of the secondary fossil fuel composite, either as an intermediate in production or in final consumption, weighted by the varying carbon intensities ι^s of the different fossil fuel types. Classic national emissions (i.e. production footprints) are hence given by

$$E_n = \sum_{s \in \mathcal{S} \setminus \mathcal{P}} \frac{\iota^s X_n^s}{P_n^s} + \sum_{p \in \mathcal{P} \cap \mathcal{S}} \frac{\iota^p (X_n^p - \gamma_n^{p,s^p} Y_n^{s^p})}{P_n^p}, \tag{3.16}$$

where s^p is defined analogous to p^s above as the secondary fossil fuel factor s that uses primary fossil fuel p as its necessary input and $Y_n^{s^p} \equiv \sum_i \pi_{in} X_i^{s^p}$

[12]As the equilibrium is only defined up to a a normalization, we adjust factor prices in each iteration in such a way as to keep global nominal factor income constant.

is n's total production in this secondary fossil fuel sector. The second part of (3.16) accounts for the fact that gas inputs into the "gas distribution" sector are not actually burnt and cause emissions at this stage, but only turns into CO_2 once the output from the "gas distribution" sector is consumed or used as an input in a different sector. Subtracting this part of the demand for the respective primary fossil fuel sector hence avoids a double-counting of emissions. Note that the territorial emissions that we denote as production footprints as part of our footprint trinity in fact also contain a consumption component which stems from the combustion of fossil fuels in final consumption (think of car fuel, for example).

Consumption footprints

With international trade, territorial emissions (i.e. production footprints) generally don't coincide with the amount of emissions embodied in the products *consumed* in a country. Our model including input-output linkages across sectors and countries allows us to track emissions along the whole global value chain and contrast territorial emissions to a country's consumption footprint, which is given by:

$$CF_n = \sum_{s \in \mathcal{S}} \underbrace{\iota^s [{}^{s,\cdot} \oslash \mathbf{P}^s]'}_{\text{emission intensity}} \underbrace{[\mathbf{I} - \mathbf{A}]^{-1}}_{\text{Leontief Inverse}} \underbrace{[{}_n \odot {}_n I_n]}_{\text{final demand}} + \underbrace{\frac{\iota^s \alpha_n^s I_n}{P_n^s}}_{\text{consumption emissions}}, \quad (3.17)$$

where ${}^{s,\cdot} = [\gamma_1^{s,1}, \ldots, \gamma_1^{s,J}, \gamma_2^{s,1}, \ldots, \gamma_N^{s,J}]'$ collects secondary fuel input shares in all sectors and countries (while avoiding double accounting of emissions by putting the respective share to zero if the secondary fossil fuel is processed further and re-sold, rather than burnt[13]), $\mathbf{P}^s = [P_1^s, \ldots, P_N^s]' \otimes \mathbf{i}_J'$ collects secondary fossil fuel prices of all countries, $\otimes$ denotes the Kronecker product, $\mathbf{i}_J$ is a unit vector of length J, $\mathbf{A} = \begin{pmatrix} \mathbf{A}_{11} & \ldots & \mathbf{A}_{N1} \\ \cdot & \cdot & \cdot \\ \mathbf{A}_{1N} & \ldots & \mathbf{A}_{NN} \end{pmatrix}$ is the global input coefficient matrix, $\mathbf{A}_{in} = \begin{pmatrix} \gamma_i^{1,1}\pi_{in}^1 & \ldots & \gamma_i^{1,J}\pi_{in}^1 \\ \cdot & \cdot & \cdot \\ \gamma_i^{J,1}\pi_{in}^J & \ldots & \gamma_i^{J,J}\pi_{in}^J \end{pmatrix}$ is a bilateral input coefficient matrix, ${}_n = [\pi_{n1}^1, \ldots, \pi_{n1}^J, \pi_{n2}^1, \ldots, \pi_{nN}^J]'$ collects country

[13] Recall the discussion of gas inputs into the "gas distribution" sector above.

n's trade shares with all partners and in all sectors, $_n = [\alpha_n^1, \ldots, \alpha_n^J]' \otimes \mathbf{i}_N'$ collects country n's consumption shares across sectors, and $\oslash$ and $\odot$ denote element-wise division and multiplication, respectively. If a country e.g. uses a lot of steel, but does not produce it itself, this will drive up the consumption footprint, but not the production footprint. The calculation of the consumption footprint will also take into account whether this steal is sourced from countries with a dirty, e.g. coal-intensive, or a cleaner energy mix.

Extraction footprints

Territorial emissions and consumption footprints are the two common ways of carbon accounting. In line with Kortum and Weisbach (2021), we also consider a third dimension. Specifically, besides where the fossil fuels are burnt and where the products end up being consumed, we consider where the fossil fuels themselves originate from. We refer to this third way of carbon accounting as extraction footprints and they are given by:

$$EF_n = \sum_{p \in \mathcal{P} \cap \mathcal{S}} \iota^p \sum_{i \in \mathcal{N}} \frac{\pi_{in}^p (X_i^p - \gamma_i^{p,s^p} Y_i^{s^p})}{P_i^p} + \sum_{s \in \mathcal{S} \setminus \mathcal{P}} \sum_{i \in \mathcal{N}} \pi_{in}^{p^s} \iota^s \sum_{m \in \mathcal{N}} \frac{\pi_{mi}^s X_m^s}{P_m^s}. \tag{3.18}$$

The first part corresponds to the primary fossil fuels that are at the same time secondary fossil fuels, i.e. that are directly burnt as part of the production process of other goods. Here, we simply need to know which quantity of the fuel a country sells overall and how carbon-intensive the fuel is (and to account for the fact that part of the input use is not actually burnt in the process, but is used as an input in the "complimentary" secondary fuel sector). The second summand corresponds to the primary fossil fuels that are used as an input for a different, secondary fossil fuel which then goes on in a further step to be burnt and actually cause the carbon emissions. We don't attribute these secondary fossil fuels' emissions to the secondary producer (i.e. for example to the country where the oil refinery is located), but trace them back to where the primary fuel originated from (i.e. where for example the raw oil was extracted). For this second part, we obtain in the last sum (over m) the total sales of the solely secondary fossil fuels of country i. We can translate them into emissions using the emission intensity ι and they are connected to the corresponding primary fuel in a fixed way due to the Leontief component of the production structure. Knowing which share of the primary fuel was sourced from country n is therefore equivalent to knowing which part of the emissions from i's secondary fuels s can be traced back to the extraction of country n.

3.3.6 Counterfactual scenarios

The primary counterfactual analysis will consider the complete elimination of trade imbalances, i.e. a scenario in which $D_n^{'} = 0 \; \forall \; n$. Additionally, we will also consider what happens if only a specific individual country n eliminates its deficit or surplus. In this case, we need to make sure that world trade remains balanced. Specifically, if n was a surplus country initially, we calculate its share in the surpluses over all surplus countries. In the counterfactual scenario, we put its surplus to zero and lower all deficit countries' deficit by n's baseline share of the global surpluses. If n was a deficit country, we obtain its deficit share out of all trade deficits and proceed accordingly.

3.4 Data

To simulate the effects of a (simultaneous) removal of trade imbalances in general equilibrium, we need to identify the model parameters. Consumption shares and input coefficients (α, β, and γ), as well as bilateral trade shares (π), labour income (wL), fossil resource income ($p^{r^p} R^p$), and initial trade imbalances (D) are obtained from input-output tables. Sectoral dispersion parameters (θ) are taken from the online database of Fontagné, Martin, and Orefice (2018).[14] For the service sectors we rely on estimates of Egger, Larch, and Staub (2012).

The main input for our simulation comes from the GTAP 11 database (Aguiar, Chepeliev, Corong, and van der Mensbrugghe, 2022). The data supplies the model with all information that is needed from input-output tables (α, β, γ, π, wL, $p^{r^p}R^p$, D) for the year 2017.[15] We also calculate carbon intensities of different fossil fuel types (ι) from the database. We choose GTAP because of its rich geographical (141 countries and 19 aggregated regions) and sectoral (65 sectors) coverage. It includes 5 fossil sectors (coal, oil, gas, petroleum and coal products, gas manufacture and distribution). For a full list of all countries see Appendix C.1.

3.5 Results

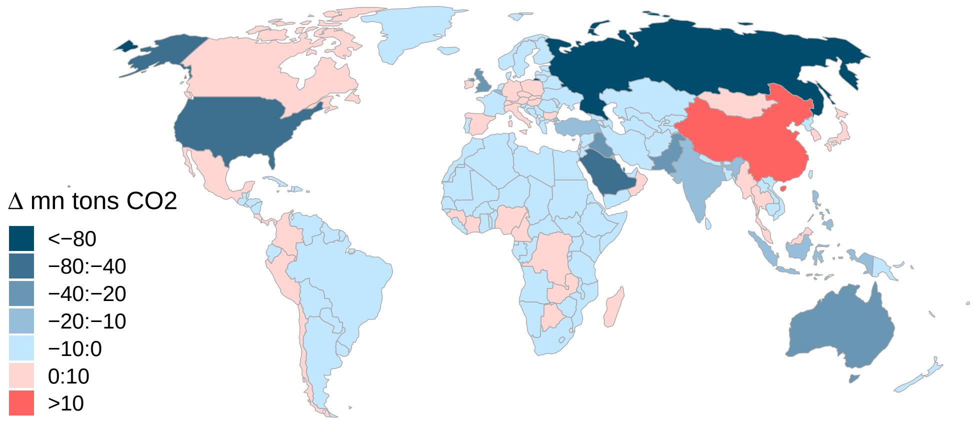
Quantitative trade models à la Eaton and Kortum (2002) allow the investigation of counterfactual scenarios, taking into account full general equilibrium effects. We use the model presented in Section 3.3 to conduct scenarios in which we — partly or fully — re-balance global trade. We first simulate the elimination of an individual country's imbalance for each country separately in turn. Afterwards, we analyze the case of globally balanced trade, i.e. of a simultaneous elimination of all trade imbalances.[16]

[14]Their GTAP 10 estimates are from October 2020 and can be found on their website.

[15]This is the most recent year for which input-output data for 160 countries/regions is available. We do not predict baseline values for some future year since this would introduce additional margins of error.

[16]Please note that the presented results are still preliminary and based on a simplified version of the model presented in Section 3.3, featuring the full input-output structure, but a single factor and Cobb-Douglas production functions in all sectors.

Figure 3.5: Change in global carbon emissions from the removal of the corresponding country's trade imbalance, each country balanced separately.



3.5.1 Balancing individual country's trade separately

In this section, we conduct a set of counterfactual experiments, in which we always set one country's trade imbalance to zero. For the removed trade imbalance of a single country the value of their imbalance is subtracted from the imbalances of the remaining 159 countries to ensure that world supply still equals world demand. If the single country has a trade surplus the imbalances of trade deficit countries are reduced proportionally,[17] leaving the values of the other trade surplus countries unchanged. This is done vice versa if the single country has a trade deficit. As each country's individual trade re-balancing is separately considered here, this leads to 160 different counterfactuals.

Figure 3.5 shows the change of global carbon emissions for all 160 counterfactuals. The value of each country represents the change in global carbon emission in the scenario where the respective country's imbalance is removed.[18] Generally and in line with our expectations based on the styl-

[17]If the trade surplus of a single country accounts for 2 percent of all trade deficits, the trade imbalance of each deficit country is reduced by 2 percent.

[18]For the exact values of the change in global carbon emissions see Column (2) of Table C.3 in the Appendix C.

ized facts established in Section 3.2, we find that eliminating country-level trade imbalances is environmentally beneficial in most cases. For 77.5 percent of countries, trade re-balancing leads to lower global emissions. For those countries, where re-balancing leads to an increase of global emissions, this increase is far smaller than the strongest decrease we see for countries like Russia or the US.

The large effect on global emissions resulting from an elimination of the huge US trade deficit fits the intuition described in the stylized facts and in the model section. The US not only import more than they export, but they also import clearly more carbon-intensive products. Taking away the United States' possibility to sustain parts of their immense consumption footprint by consistently running a deficit indeed leads to a lower-emission new global production and consumption pattern. Specifically, global CO2 emissions would go down by 78 Mt or 0.24 percent.[19] This is roughly equivalent to Bangladesh's total annual emissions. Note that the global emission reduction in response to a US re-balancing does not mostly stem from lower US territorial emissions. The US in fact decreases its production footprint by 27 Mt, while its consumption footprint falls much more drastically by 324 Mt percent and a larger share of the global reduction hence comes from countries that previously served the US market with carbon-intensive products to larger extents or from countries that are indirectly affected from the global reshuffling of the international trade network resulting from the elimination of the world's largest trade deficit.[20]

The largest drop in global emissions results from the elimination of the Russian trade surplus. Bringing down Russia's 118 billion US-Dollar surplus to zero would lower global emissions by 113 Mt or 0.35 percent. This is roughly equivalent to Venezuela's total annual emissions. The Russian example is linked to our final stylized fact on fossil fuel exporters run-

[19] All emission quantities refer to CO2 emissions only and to the model base year 2017.

[20] For a graphical representation of all countries' production, consumption, and extraction footprint changes in reponse to a US re-balancing, see Figure C.4 in the Appendix C.

ning surpluses and the corresponding concern that this type of imbalance fosters global fossil fuel supply and therefore global emissions. Taking away the Russian surplus reduces Russia's possibility to maintain its very large extraction footprint. Indeed, the Russian extraction footprint drops strongly by 249 Mt when Russian trade is re-balanced. The reduction in Russian production emissions is much less pronounced (33 Mt) and the Russian consumption footprint actually increases strongly (by 105 Mt). The global reduction hence results mostly from other countries burning less Russian fossil fuels and consuming goods that have less Russian fossil fuels embodied in them.[21]

Taking a further look at which countries' trade re-balancing lowers global emissions, the role of fossil fuel exports becomes even more evident: out of the top six countries, only the US has an initial deficit, while in all other cases the emission reductions result from bringing down surpluses of high-extraction footprint fossil fuel exporters, namely Russia, Qatar (53 Mt world emission reduction), Saudi-Arabia (46 Mt), Iraq (31 Mt) and Australia (26 Mt).

In many cases, in which re-balancing a country's trade leads to higher global emissions, this is also perfectly in line with our expectations. Take for example Canada: it is the world's eight largest fossil fuel exporter and it has a trade deficit. If Canada needs to earn every dollar it wants to spend on imports by selling exports, it does so by extracting and selling more fossil fuels. Or take Germany: German imports are more carbon-intensive than its exports, but it doesn't import as much as it could actually afford. Closing the German spending gap considerably drives up the German consumption footprint.

One case that is not straightforwardly in line with the expectations is the Chinese re-balancing. Just as Germany, China has a strong trade surplus, but different from Germany, Chinese exports are more emission-intensive

[21] For a graphical representation of all countries' production, consumption, and extraction footprint changes in reponse to a Russian re-balancing, see Figure C.5 in the Appendix C.

than its imports. Intuitively, limiting China's role as a pollution haven for other countries' emission-intensive consumption by erasing its surplus should reduce global emissions. Two factors appear to counteract the expected effect. First, Chinese consumption is very emission-intensive in absolute terms. Specifically, it is 72 percent more emission-intensive than the global average. Even though its exports are even dirtier, it is globally emission-increasing if China increases its consumption. In line with this effect, the Chinese consumption footprint increases dramatically by 263 Mt. Second, we need to keep in mind general equilibrium adjustments of the global trade system. As Chinese demand increases, Chinese producers will focus to a larger extent on serving the domestic market. Countries that previously sourced large amounts from China will have to consider alternative suppliers. While Chinese production is relatively emission-intensive, alternative sources may be even dirtier, implying that the shift leads to higher overall emissions.

The patterns in Figure 3.5 are of course driven to a considerable amount by the sheer size of national trade imbalances. To make effects more comparable across countries, we calculate the change in global emissions per million dollar trade imbalance.[22] This metric indicates e.g. that while the US trade deficit has a huge carbon footprint in absolute terms, it is not particularly dirty in relative terms — the large effect is primarily driven by the magnitude of the deficit.

We can use this standardized measure of the countries' imbalances' carbon footprints to evaluate more systematically how a country's emission and trade patterns determine whether its trade re-balancing increases or lowers global emissions. Specifically, we separately run the following regression for surplus and deficit countries:

$$\frac{\sum_n E_n^{'} - E_n}{D_i} = \beta_0 + \beta_1 \frac{CF_i}{E_i} + \beta_2 \frac{EF_i}{E_i} + \varepsilon_i, \tag{3.19}$$

where $E_n^{'}$ refers to the counterfactual emissions in case country i's trade

[22] See Figure C.3 in the Appendix C for a graphical representation.

is re-balanced (i.e. $D_i' = 0$). We hence investigate whether the relative carbon footprint of a country's imbalance is determined by it consuming more embodied emissions than it emits and/or by it extracting more fossil fuels than it burns domestically.

Table 3.1: Change in global emissions per rebalanced trade balance

	(1)	(2)
CF/E	162.879**	-77.194*
	(59.147)	(32.100)
EF/E	-57.660***	96.363***
	(8.377)	(13.678)
Obs.	59	101
R^2	0.506	0.374

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: Dependent variable: Change in global emissions in ton CO2 per re-balanced absolute trade balance in mn USD. CF: Consumption footprint. EF: Extraction footprint. E: Production footprint. Column (1): Subset of countries with a trade surplus. Column (2): Subset of countries with a trade deficit.

Column (1) of Table 3.1 displays the results for surplus countries. Eliminating a trade surplus is less environmentally beneficial, if the country consumes more embodied carbon relative to how much it emits and more beneficial if the country extracts more fossil fuels relative to how much it burns. Think of the German example as an illustration of the former and the Russian example as an illustration of the latter effect. The regression makes clear that these cases are part of a systematic pattern.

The opposite pattern emerges for deficit countries, as shown in Column (2). Eliminating a trade deficit is more environmentally beneficial if the country consumes more embodied carbon relative to how much it emits and more beneficial if the country extracts more fossil fuels relative to how much it burns. The US and the Canadian deficits illustrate these systematic patterns.

Hence, in line with the mechanisms described in the model section, from an environmental point of view, trade surpluses of countries with a relatively high consumption footprint and trade deficits of countries with a relatively high extraction footprint are desirable, while deficits of countries with a relatively high consumption footprint and surpluses of countries with a relatively high extraction footprint are undesirable. We have seen that the majority of actual trade imbalances fall into an undesirable category and their individual removal would therefore lower global emissions.

3.5.2 Balancing all countries' trade simultaneously

In our next counterfactual scenario, we set the trade imbalances of all 160 countries and regions simultaneously to zero. Given the trade imbalance patterns established in Section 3.2, as well as the insights from the re-balancing of individual countries' international trade, we clearly expect that a global re-balancing will lower world emissions. However, it is clear that the exact implications of this large shock on the world trade network cannot be inferred from aggregating the 160 separate, smaller shocks considered in the previous subsection, but a distinct quantitative analysis is required that takes into account that effects will partly offset one another and that adjustment mechanisms will differ, when many countries simultaneously massively alter their import demand and export supply.

Overall, we find that the simultaneous removal of all trade imbalances reduces global carbon emission by 0.9 percent or 295 Mt of CO2 per year. Is this a large effect? It is approximately equivalent to the total annual emissions of Spain — the number 21 emitter of CO2 in the world. One has to keep in mind that re-balancing global trade is not primarily an environmentally motivated scenario. Compare the effect for example to the simultaneous introduction of carbon tariffs for all country pairs at a level that equalizes bilateral carbon price differentials studied by Larch and Wanner (2017): they find a much smaller global emission reduction of 0.5 percent for this explicit climate policy measure. Or to the total contribution of international trade to global carbon emissions studied by Shapiro (2016): he finds that international trade in total increases emissions by 5 percent compared to a situation of total autarky. Comparing this to our effect of a global re-balancing suggests that 18 percent of international trade's total contribution to global emissions are due to the imbalances currently characterizing world trade.

Figure 3.6 breaks down the global emission reduction into changes in national carbon footprints, differentiating the production, consumption, and extraction footprints.[23] Note the difference in how to read these maps in comparison to Figure 3.5: there, each country's colouring reported the change in *global* emissions in response to a country-level re-balancing, while now, each country's coloring reports the *national* emission change in response to a global re-balancing.

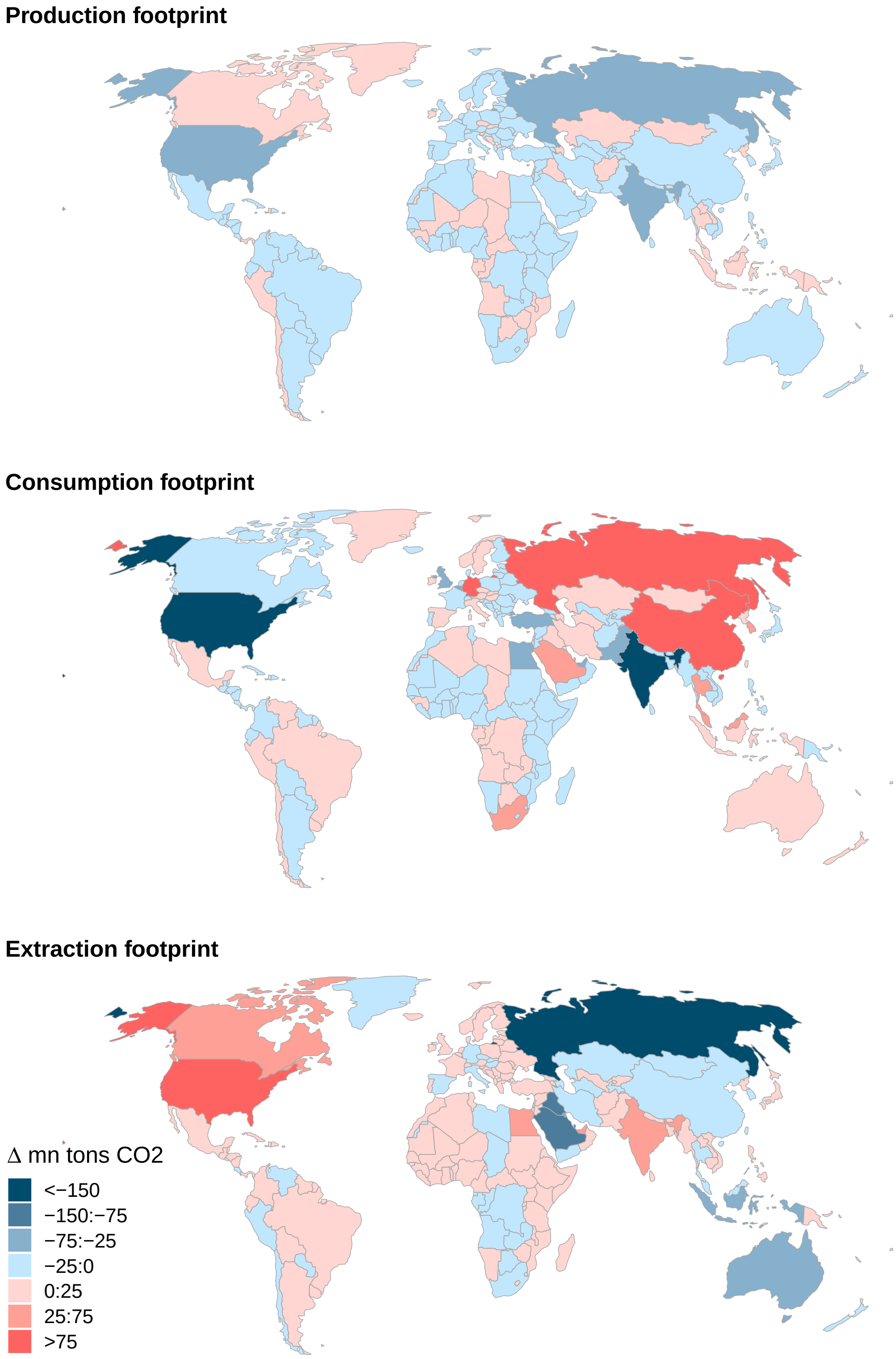
Figure 3.6 shows several very interesting features of the global re-balancing exercise. First, while global emissions decrease, emissions do not go down in all individual countries, and national effects are very heterogeneous. This is true regardless of which of the three accounting types we consider.

Second, the three footprints don't necessarily move in the same direction for the same country. The United States for example dramatically reduces its consumption footprint and also reduces, though much less strongly, its production footprint. However, it reacts to not being able to source as much fossil fuels from abroad anymore by extracting more fuels domestically, i.e. it increases its extraction footprint considerably. Russia, on the other hand, spends much more and hence considerably increases its consumption footprint. However, its production footprint falls and the slashing of its trade surplus goes in hand with a drastic reduction in Russian fossil fuel extraction.

Third, the distribution of production footprint changes is most homogeneous and least extreme. In 75 percent of countries, the production footprint decreases in response to the global re-balancing. The effects

[23] For the exact values of change in carbon emissions and welfare see Table C.4 in the Appendix C.

Figure 3.6: Percentage changes in carbon emissions, all countries balanced simultaneously.



range from a 8.96 Mt increase in Iraq to 39.42 Mt decrease in the United States. Other key contributors to lower global emissions from a production point of view are India (-31.32 Mt) and Russia (-37.58 Mt).

Fourth, changes in consumption footprints are much more heterogeneous and extreme. Emission reductions from a consumption point of view are much more concentrated. The United States and India lead the field here, with enormous drops in their consumption footprints by 343 and 154 Mt, respectively. Different than in the production-based accounting, there are some countries with very considerable emission increases in this case, too. For Example, the consumption footprints of the large initial trade surplus countries China, Germany, and Russia increase by 199, 93, and 102 Mt, respectively.

Fifth, changes in extraction footprints are also very strong and heterogeneous but additionally are in particularly strong contrast to some of the movements of production and consumption footprints. The effects range from 221 Mt decrease in Russia to a 156 Mt increase in the United States. These countries' footprints were among the most affected in the consumption-based accounting, too, but with opposite signs. Generally, the fossil supply view shows that if we follow the global emission reduction back to where the fuels originate, it is mainly driven by Russia, Arabic countries, and Australia extracting less fossil fuels when they eliminate their initial trade surpluses.

3.6 Conclusions

International trade allows countries to decouple the amount of carbon emissions associated with their production from the emissions embodied in their consumption and in their supply of fossil fuels. Trade balance puts a bound to the decoupling: while a country does not have to export one ton of carbon for every ton imported, under trade balance, it has to export one dollar worth of products for every dollar imported. Trade imbalances soften this restriction. The implications of this softening depend on which types of countries end up consuming more than producing or vice versa. We show that the current pattern of global trade imbalances raises environmental concerns, because countries with a particularly carbon-intensive import mix tend to run a deficit (i.e. import more than they could afford under trade balance), fostering the global production of emission intensive goods, and fossil fuel exporters tend to run a surplus, increasing the globally available supply of these fuels.

We develop a multi-sector Ricardian quantitative trade model with carbon emissions from fossil fuel combustion to simulate the re-balancing of individual countries' current accounts and of global trade. In terms of individual countries' imbalances, world emissions could be brought down most by eliminating the US trade deficit or the trade surplus of major fossil fuel exporters, such as Russia, Qatar, Saudi-Arabia, or Australia. The overall global imbalances are found to contribute considerably to global carbon emissions: re-balancing global trade entirely would bring down global emissions by 0.9 percent, reducing the overall carbon footprint of international trade by 18 percent.

Chapter 4

Climate Change Adaptation: Agricultural Productivity Shocks and Trade Policy Responses[1]

4.1 Introduction

Feeding the world is an expensive undertaking. Food production uses up half of the Earth's habitable land, and expending this land comes with considerable costs and externalities. Climate change poses a threat to productivities of currently used cropland in many places and therefore will shift international comparative advantage. But productivity shocks will be heterogeneous across space and sectors. One adaptation strategy lies in international trade. If productivity of some goods in country A decreases, but in country B increases, country A can import more of these goods from B and focus on the production of goods that are not negatively affected by climate change. This is possible if trade costs (e.g., tariffs, non-tariff

[1]This project benefited by funding from the German Federal Ministry of Education and Research (BMBF) under the funding line *#01LA1828D*. I am thankful for the outstanding research assistant of Jakob Kutsch, as well as participants at the European Trade Study Group 2023 in Surrey for helpful comments.

barriers, costs of logistics) between A and B are sufficiently low. If trade costs are high, adverse productivity shocks can lead to a higher share of resources devoted to this sector to compensate production shortfalls in A. The relocation to a less productive sectors would rewind structural transformation and may cause significant welfare losses.

In this paper, I study how climate change affects agricultural productivity around the world and which trade policy response is necessary to compensate for climate-induced welfare losses. First, I derive productivity shocks from an extremely rich granular data set on agricultural yields – before and after climate change – for 71 different crops for each of 2.3 million fields covering the surface of the earth. Second, I use a Ricardian quantitative trade with input-output linkages and trade across 141 countries, covering 98 percent of World's GDP. I add *land* production factors and sectoral productivities to this model. Third, I develop a brute-force algorithm so calculate each country's necessary trade policy liberalization to compensate climate-induced welfare losses.

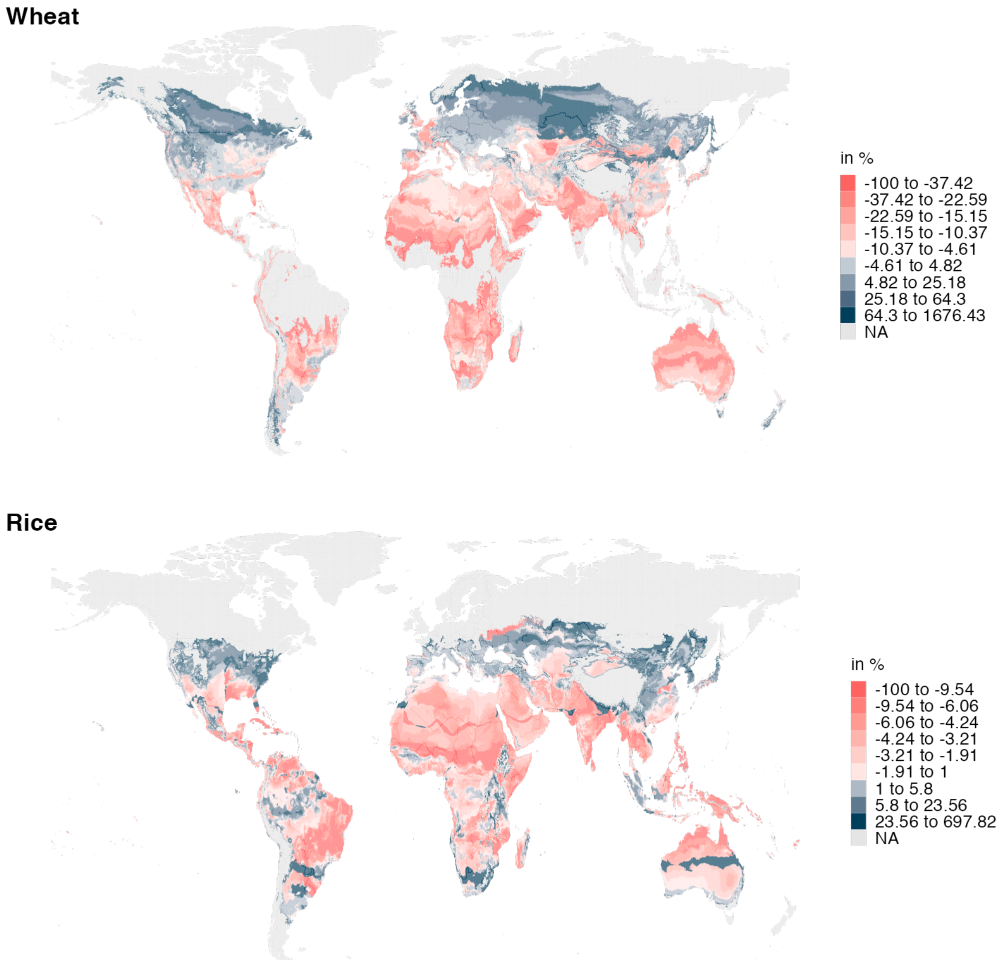
I contribute to several strands of the literatures. First, there is important work on climate change impacts on social welfare, going from micro-level shocks to macro-level consequences. For example, the impact of weather on economic growth (Kotz et al., 2021) through underlying channels including, e.g., human health (Barreca et al., 2016; Burgess et al., 2017; Burke et al., 2018), worker productivity (Somanathan et al., 2021), and houshold consumption (Lai et al., 2022). Second, I contribute to the literature on climate change adaptation through trade. Costinot et al. (2016) use micro-level shocks and study the welfare consequences of climate change. They find that adaptation depends on a country's ability to change its production patterns, rather than its trade patterns. In contrast, Gouel and Laborde (2021) show that trade substitution is evenly important than adjusting production patterns. Janssens et al. (2020) come to the same conclusion, but unlike Gouel and Laborde (2021), who examine climate-induced welfare effects, the authors analyse climate-induced hunger risks. Cruz and Rossi-Hansberg (2021) develop a dynamic intergrated assesment model in which individuals can adapt to global warming via trade, migration, innovations or natality rates. They focus on the climate damage function of temperature and find a relative small impact of trade as an adaptation mechanism. The work of Nath (2022) is closely related to my paper. The author uses a static general equilibrium trade model and analyse how sectoral reallocation between agriculture and non-agriculture production might help to adapt to climate change. In contrast to this paper, Nath (2022) uses local temperature projections to derive climate-induced sectoral productivity changes. Third, this paper relates to recent work enriching New Quanitative Trade (NQT) models with "natural" production factors: Going from one additional factor, such as crude oil (Farrokhi, 2020), to a few fossil resources (Mahlkow and Wanner, 2023), to multiple commodities (Fally and Sayre, 2018).

This paper makes three main contributions. (i) I contribute to a growing literature on the climate change impact on social welfare, taking micro-level shocks and deriving macro-level consequences (ii) I analyse how trade policy may help to adapt to climate change impacts. (iii) I enhance the seminal framework by Caliendo and Parro (2015) with land as an additional production factor that is used by agricultural production.

To analyse the impact of climate change on agriculture productivity, I take advantage of rich micro-level data from the Global Agro-Ecological Zones (GAEZ) data set, which was jointly developed by the UN Food and Agriculture Organization and the International Institute for Applied Systems Analysis (Fischer et al., 2021). GAEZ is based on agronomic models and high-resolution data on geographic characteristics such as soil, topography, elevation, and, crucially, climatic conditions. Using this data, GAEZ predicts the obtainable yield - crop by crop - at 2.3 million high-resolution grid cells (about 9 km by 9 km at the equator) covering the surface of the earth. GAEZ is available both under contemporary growing conditions and under climate change scenarios used by the UN's Intergovernmental Panel on Climate Change (IPCC).[2]

[2]Climatic conditions are based on a time series of historical data of 1961-2010 and a

Figure 4.1: Climate-induced yield changes.



Note: Yield changes from historical values in 1981-2010 to 2071-2100 under RCP 6.0. The latter is the mean value of two ESMs (*HadGEM2–ES* and *GFDL–ESM2M*) and among rain-fed and irrigated crops. Own calculation, based on GAEZ.

Using GAEZ, Figure 4.1 shows gridded yield changes under future climate change for rice and wheat under RCP 6.0.[3] Both crops show considerable spatial heterogeneity. In general, locations in the temperate zone will experience yield increases, while in the tropics and subtropics yields will decline. This pattern is more pronounced for wheat than rice. For rice, also some areas in Sub-Saharan Africa and in the Amazon will see yield increases. Yields will decrease in the majority of cells, 61.9 percent for wheat and 63.5 percent for rice. In 10 percent of cells rice yields will decrease more than 10.2 and for wheat more than 39.5 percent.

A potential adaptation strategy to mitigate negative climate change impacts is international trade. Trade can help countries diversify their economies and reduce their reliance on sectors that are vulnerable to climate change. Trade can also reduce risks associated with climate change by allowing a country to access a wider range of goods and services from different regions under heterogeneous climate change effects.[4] For example, if wheat yields in India will decrease substantially under climate change (see Figure 4.1), the country could import the quantity that is necessary to meet its domestic demand from countries that might experience a positive productivity shock, e.g. Germany. If workers can move out of wheat production into other sectors whose products can also be sold internationally, labour market impacts can even be positive.[5] On the other hand, besides the spatial correlation of climate change-induced productivity shocks (Dingel et al., 2019), foreign shocks spread to other countries trough trade and GVCs, e.g. through foreign supply shocks (Eppinger et al., 2021). The most closely related study of climate change-induced shocks that transmit through trade and input-output linkages is by

selection of future climate simulations using recent IPCC AR5 Earth System Model (ESM) outputs for four Representative Concentration Pathways (RCPs). Hence, GAEZ results consistently quantify impacts on land productivity of historical climate conditions as well as of potential future climate change.

[3]Yield changes for other crops can be found in Figures D.2 to D.7 in the Appendix D.

[4]Burgess and Donaldson (2010) provide empirical evidence that trade mitigates economic costs associated with local weather shocks by enabling import substitution.

[5]This depends on the overall change in comparative advantage among the trading partners. The sign of the labour market impacts is not clear from a reduced-form perspective.

Rudik et al. (2022). The authors extend the framework of Caliendo et al. (2019) and decompose the role of market-based adaptation to climate change. They show that input-output linkages matter for determining welfare effects of climate change and provide structural estimations of the temperature response function on sectoral productivities. In contrast, in this paper I use computed productivities from agronomic models under a global, more granular spatial coverage.

The adaptation potential of trade depends on the extent of barriers to trade, such as tariffs or non-tariff barriers, e.g., time-consuming administrative procedures, technical requirements, and differences in regulations. If trade barriers are low, countries can adapt to local production shocks by changing production patterns and trading different goods and quantities. Ederington and Ruta (2016) calculate trade restrictiveness, using the framework of Kee et al. (2009), and show that agriculture trade faces high restrictiveness both in developing and developed countries. Non-tariff barriers (NTBs) result in substantially more restrictiveness compared to tariffs. For a country with high trade barriers it is more difficult to substitute national production through imports, making the country more exposed to local productivity shocks. But the average numbers of Ederington and Ruta (2016) do not reveal counterfactual effects of future climate change impacts. For example, average agricultural NTBs in developing countries might be high, but NTBs on imports from large producers with low trade costs might be low. Then, import substitution might be feasible and less costly. But this also depends on how demand and supply will develop under climate change in the rest of the world. To account for those global circumstances I extend and apply a NQT model.

The remainder of the paper is structured as follows: In Section 4.2, I describe the NQT model of international trade that allows me to compute a counterfactual world with climate change impacts and trade policy responses. In Section 4.3 I describe the data and estimation procedure, before computing the counterfactual scenarios in Section 4.4. Section 4.5 concludes.

4.2 Model

For the analysis, I use the Ricardian trade model of Caliendo and Parro (2015), who provide a multi-sector version of the Eaton and Kortum (2002) gravity model with input-output linkages. I extend the model with the production factor *land* and decompose total factor productivity into *land* and *labour* productivity.

4.2.1 Preferences

There are N countries, indexed o and d, and J sectors, indexed j and k. In each sector, there is a continuum of goods $\omega^j \in [0, 1]$. Households in n obtain utility from consumption C according to a two-tier Cobb-Douglas utility function:

$$u(C_d) = \prod_{j=1}^{J} C_d^{j\ \alpha_d^j} \quad \text{with} \quad \sum_{j=1}^{J} \alpha_d^j = 1.$$

where α_d^j is the constant consumption share on industries j's goods. While the aggregation of utility from different varieties *within* one sector is the same for all countries, expenditures shares *across* sectors vary between countries, allowing for differently agricultural-intensive consumption patterns.

4.2.2 Production

Sectors j use two production factors: labour and intermediate inputs. Labour is fully mobile across sectors $L_n = \sum_j^J L_d^j$, but not across countries. It can be seen as an aggregate factor[6]. Each country is endowed with an exogenous quality-adjusted amount of land which is used across sectors

[6]The factor is a composite of many factors, e.g., labour, capital, and other natural resources (despite land), which are all non-tradeable in my framework.

$H_d = \sum_j^J H_d^j$. From the model perspective, land can also be considered as "mobile".[7]

All goods are produced using composite intermediate input bundles m from the own and other sectors. In all sectors, countries differ in their productivity for different goods from the continua and in the intermediate input cost shares γ. Total factor productivity is composed of two terms, a country-sector specific "fundamental productivity" A, and a variety-specific productivity z. The production technologies are Cobb-Douglas and hence given by:

$$q_d^j(\omega^j) = A_d^j z_d(\omega^j) \left[l_d^j(\omega^j)\right]^{\beta_d^j} \left[h_d^j(\omega^j)\right]^{\eta_d^j} \left[\prod_{k=1}^{J} m_d^{k,j}(\omega^j)^{\gamma_d^{k,j}}\right]^{1-\beta_d^j-\eta_d^j}$$

with $l_d^j + \eta_d^j + \sum_{k \in J} \gamma_d^{k,j} = 1$. l_d is the labour input, β_d the labour input share, h_d the land input, and η_d the land input share. With constant returns to scale and perfectly competitive markets, unit cost are given by

$$c_d^j = \frac{\Upsilon_d^j w_d^{\beta_d^j} r_d^{\eta_d^j}}{A_d^j z_d^j(\omega^j)} \left[\prod_{k=1}^{J} (P_d^k)^{\gamma_d^{k,j}}\right]^{1-\beta_d^j-\eta_d^j}$$

where $\Upsilon_d^j = (\beta_d^j)^{-\beta_d^j} (\eta_d^j)^{-\eta_d^j} \prod_{k \in \mathcal{J}} (\gamma_d^{k,j})^{-\gamma_d^{k,j}}$, w denotes the wage, r is the land rent, and P the price of a composite intermediate bundle. Hence, the cost of the input bundle depends on wages, land rents and the prices of *all* composite intermediate goods in the economy. Producers of composite intermediate goods supply Q_d^j at minimum costs by purchasing intermediate goods ω^j from the lowest cost supplier across countries, so that

$$Q_d^j = \left[\int d_d^j(\omega^j)^{1-1/\sigma^j} d\omega^j\right]^{\sigma^j/(\sigma^j-1)}.$$

$\sigma^j > 0$ is the elasticity of substitution across intermediate goods within sector j, and $d_d^j(\omega^j)$ the demand for intermediate goods ω^j from the lowest

[7]Mobile in a sense that the production on each field can switch among sectors.

cost supplier such that

$$d_d^j(\omega^j) = \left(\frac{p_d^j(\omega^j)}{P_d^j}\right)^{-\sigma^j} Q_d^j$$

where P_d^j is the unit price of the composite intermediate good

$$P_d^j = \left[\int p_d^j(\omega^j)^{1-\sigma^j} d\omega^j\right]^{1/(1-\sigma^j)}$$

and $p_d^j(\omega^j)$ denotes the lowest price of intermediate good ω^j in n across all possible origin locations, i.e.

$$p_d^j = \min_o \left\{p_{od}^j\right\}. \tag{4.1}$$

Composite intermediate goods are used in the production of intermediate goods ω^j and as the final good in consumption as C_d^j, so that the market clearing condition is written as

$$Q_d^j = C_d^j + \sum_{k=1}^{J} \int m_d^{j,k}(\omega^j) d\omega^j \tag{4.2}$$

4.2.3 International trade

Trade in goods is costly, such that the offered price of ω^j from i in n is given by

$$p_{od}^j = \phi_{od}^j \cdot \frac{c_o^j}{z_o^j(\omega^j)} \tag{4.3}$$

where ϕ_{od}^j denote generic bilateral sector-specific trade frictions.[8] These can take a variety of forms — e.g., tariffs, non-tariff barriers, export taxes.

[8]The "phiness" of trade à la Baldwin et al. (2003).

In that case we can specify

$$\phi_{od}^j = \tau_{od}^j \cdot \kappa_{od}^j \cdot \zeta_{od}^j,$$

where τ_{od}^j represent sector-specific ad-valorem tariffs, $\kappa_{od}^j \geq 1$ iceberg trade costs, and ζ_{od}^j export taxes or subsidies. Tariff revenue $(\tau_{od}^j - 1)$ and export tax revenue (or subsidy cost) $(\zeta_{od}^j - 1)$ is collected (or spent) by the importing country and exporting country, respectively, and transferred lump-sum to its households.

Ricardian comparative advantage is induced à la Eaton and Kortum (2002) through a country-specific idiosyncratic productivity draw z^j from a Fréchet distribution.[9]

The price of the composite good is then given as

$$P_d^j = A^j \left[\sum_{o=1}^{d} \lambda_o^j (c_o^j \phi_{od}^j)^{-\theta^j} \right]^{-1/\theta^j} \tag{4.4}$$

which, for the non-tradable sector or embargoed sector towards *all* non-domestic sources collapses to

$$P_d^j = A^j (\lambda_d^j)^{-1/\theta^j} c_d^j \tag{4.5}$$

where $A^j = \Gamma(\xi^j)^{1/(1-\sigma^j)}$ with $\Gamma(\xi^j)$ being a Gamma function evaluated at $\xi^j = 1 + (1 - \sigma^j)/\theta^j$. Total expenditures on goods from sector j in country d are given by $X_d^j = P_d^j Q_d^j$. The expenditure on those goods originating from country o is called X_{od}^j, such that the share of j from o in d is $\pi_{od}^j = X_{od}^j / X_d^j$. In other words, it is the share of an exporter country in the total expenditure, by sector, of an importer country. This share can

[9]The productivity distribution is characterized by a location parameter λ_o^j that varies by country and sector inducing *absolute* advantage, and a shape parameter θ^j that varies by sector determining *comparative* advantage. θ^j describes the elasticity of trade to trade costs

also be expressed as

$$\pi_{od}^{j} = \frac{\lambda_{o}^{j}(c_{o}^{j}\phi_{od}^{j})^{-\theta^{j}}}{\sum_{h=1}^{d}\lambda_{h}^{j}(c_{h}^{j}\phi_{hd}^{j})^{-\theta^{j}}} \tag{4.6}$$

4.2.4 General equilibrium

Total expenditures on goods from sector j are the sum of the firms' and households' expenditures on the composite intermediate good, either as input to production or for final consumption

$$X_{d}^{j} = \sum_{k=1}^{J}(1-\beta_{d}^{k})\gamma_{d}^{j,k}\sum_{o=1}^{d}X_{o}^{k}\frac{\pi_{do}^{k}}{\tau_{do}^{k}\zeta_{do}^{k}} + \alpha_{d}^{j}I_{d} \tag{4.7}$$

with $I_d = w_d L_d + r_d H_d + R_d + D_d$, i.e., labour income, land resource rent, government revenue (tariff and export taxes minus export subsidies) and the aggregate trade balance. Sectoral trade balance is simply the difference between imports and exports

$$D_{d}^{j} = \sum_{o=1}^{d} X_{od}^{j} - X_{do}^{j} \tag{4.8}$$

and the aggregate trade balance $D_d = \sum_{j=1}^{J} D_d^j$, and $\sum_{d=1}^{d} D_d = 0$, with D_d being exogenously and D_d^j being endogenously determined. The trade balance can then be expressed as

$$\sum_{j=1}^{J}\sum_{o=1}^{d}X_{d}^{j}\frac{\pi_{od}^{j}}{\tau_{od}^{j}\zeta_{od}^{j}} - D_{d} = \sum_{j=1}^{J}\sum_{o=1}^{d}X_{o}^{j}\frac{\pi_{do}^{j}}{\tau_{do}^{j}\zeta_{do}^{j}}. \tag{4.9}$$

The goods market clearing (4.7) and trade balance (4.9) conditions close the model.

4.2.5 Solving for counterfactual equilibria

As suggested by Dekle et al. (2007, 2008), a counterfactual general equilibrium for alternative trade costs in the form of $\hat{\phi}^j_{od} = \phi^{j\prime}_{od}/\phi^j_{od}$ — i.e., where any variable $\hat{x}$ denotes the relative change from a previous value x to a new one x' — can be solved for in changes such that

$$\textit{Input costs} \qquad \hat{c}^j_d = \hat{w}_d^{\beta^j_d}\left[\frac{\hat{r}_d}{\hat{A}^j_d}\right]^{\eta^j_d}\left(\prod_{k=1}^{J}[\hat{P}^k_d]^{\gamma^{k,j}_d}\right)^{1-\beta^j_d-\eta^j_d} \tag{4.10}$$

$$\textit{Prices} \qquad \hat{P}^j_d = \left(\sum_{o=1}^{d}\pi^j_{od}[\hat{\phi}^j_{od}\hat{c}^j_o]^{-1/\theta^j}\right)^{-\theta^j} \tag{4.11}$$

$$\textit{Trade shares} \qquad \pi^{j\prime}_{od} = \pi^j_{od}\left(\frac{\hat{c}^j_o}{\hat{P}^j_d}\hat{\phi}^j_{od}\right)^{-1/\theta^j} \tag{4.12}$$

$$\textit{Expenditures} \qquad X^{j\prime}_d = \sum_{k=1}^{J}(1-\beta^k_d)\gamma^{j,k}_d\left(\sum_{o=1}^{d}\frac{\pi^{k\prime}_{do}}{\tau^{k\prime}_{do}\zeta^{k\prime}_{do}}X^{k\prime}_o\right) + \alpha^j_d I'_d \quad \text{with} \tag{4.13}$$

$$\begin{aligned}
\textit{Income} \qquad & I'_d = \hat{w}_d w_d L_d + \hat{r}_d r_d H_d \\
\textit{Tariff revenue} \qquad & \quad + \sum_{k=1}^{J}\sum_{o=1}^{d}(\tau^{k\prime}_{od}-1)\left(\frac{\pi^{k\prime}_{od}}{\tau^{k\prime}_{od}}\right)X^{k\prime}_d \\
\textit{Export tax revenue} \qquad & \quad + \sum_{k=1}^{J}\sum_{o=1}^{d}(\zeta^{k\prime}_{do}-1)\left(\frac{\pi^{k\prime}_{do}}{\tau^{k\prime}_{do}\zeta^{k\prime}_{do}}\right)X^{k\prime}_o \\
\textit{Trade balance} \qquad & \quad - D'_d
\end{aligned}$$

$$\textit{Trade balance} \qquad D_d = \sum_{j=1}^{J}\sum_{o=1}^{d}\frac{\pi^{j\prime}_{od}}{\tau^{j\prime}_{od}\zeta^{j\prime}_{od}}X^{j\prime}_d - \sum_{j=1}^{J}\sum_{o=1}^{d}\frac{\pi^{j\prime}_{do}}{\tau^{j\prime}_{do}\zeta^{j\prime}_{do}}X^{j\prime}_o. \tag{4.14}$$

As a measure of welfare changes I use changes in real income, obtained as

$$\hat{W}_d = \frac{\hat{I}_d}{\prod_{j=1}^{J}(\hat{P}^j_d)^{\alpha^j_d}}. \tag{4.15}$$

The model provides static level effects on real income and trade. As dynamic effects of trade integration are not taken into account, it provides a lower bound for the potential effects of climate adaptation through trade.

4.3 Data

4.3.1 Model parameters

The core data for this study are taken from the Global Trade Analysis Project (GTAP) database (Aguiar et al., 2019). The data provide a snapshot of the global economy in 2014, including domestic inter-industry flows and bilateral trade flows. The full database covers 141 regions, of which 121 are individual countries, and 65 sectors. The GTAP data are based on official trade flows. The backbone of the data are national input-output (I-O) tables.

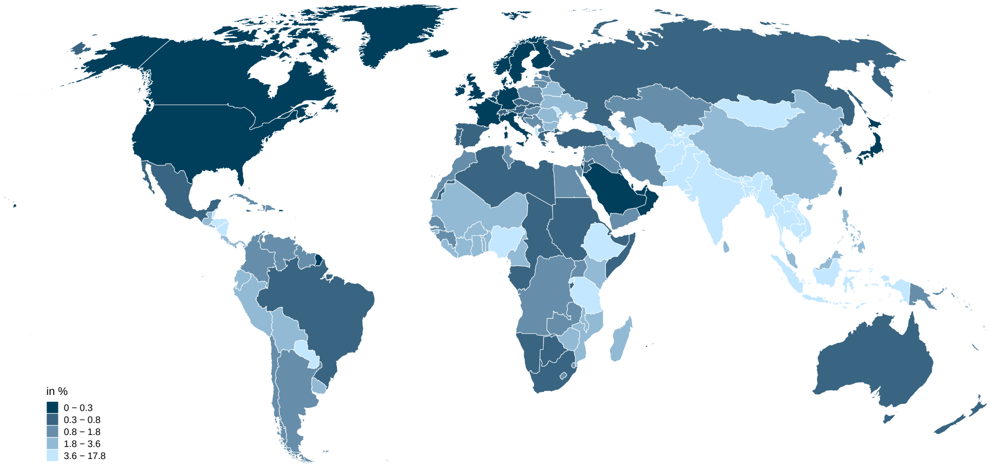
GTAP combines multiple I-O tables in a consistent manner. The complex process requires a high level of expertise and attention to detail, otherwise small inconsistencies and measurement errors of individual I-O tables would add up significantly.

From GTAP, I derive all model parameters[10], such as production factor shares of labour β, land η, intermediate input costs γ, trade shares π, consumption shares α, tariffs τ, export subsidies ζ, labour income wL, and land rents rH.

The extent to which climate-induced yield changes affect the economy and social welfare depends on the importance of agriculture on total value added. More specifically, GAEZ's obtainable yield predictions depend on the crop production suitability of a location, e.g. the soil and local weather pattern. I assume that this location specific characteristics is captured by

[10]Despite the trade elasticities θ^j, which I take from Fontagné et al. (2018), who use a gravity framework to estimate trade elasticites for all GTAP sectors despite services. Service flows do not face tariffs. Therefore, I rely on an estimate for the aggregate service sector provided by Egger et al. (2012).

Figure 4.2: Land rents in percent of total value added.



Note: Source: GTAP 10, own calculations.

the land rent a landowner receives. Figure 4.2 shows land rents ($r_d H_d$) in percent of total value added per country.

4.3.2 Climate impacts on crop yields

I focus on agricultural crop sectors to model the impact of climate change because (i) the link between climate conditions and agricultural productivities is well established, and (ii) future climate conditions under different RCPs are modeled extensively. I use the micro-level GAEZ data set (Fischer et al., 2021), which provides yields for 72 crops under temporary climate conditions and under future climate change. GAEZ is based on detailed data from a range of sources, including satellite imagery, ground observations, and computer models. The spatial resolution is about 9 km by 9 km at the equator[11], 2.3 million grid cells on the earth's surface. Primarily, GAEZ is used by farmers and government agencies to asses the production *potential* for different crops in any given location on earth.

[11]Owing to the curvature of the earth, grid cells at different latitudes cover different areas.

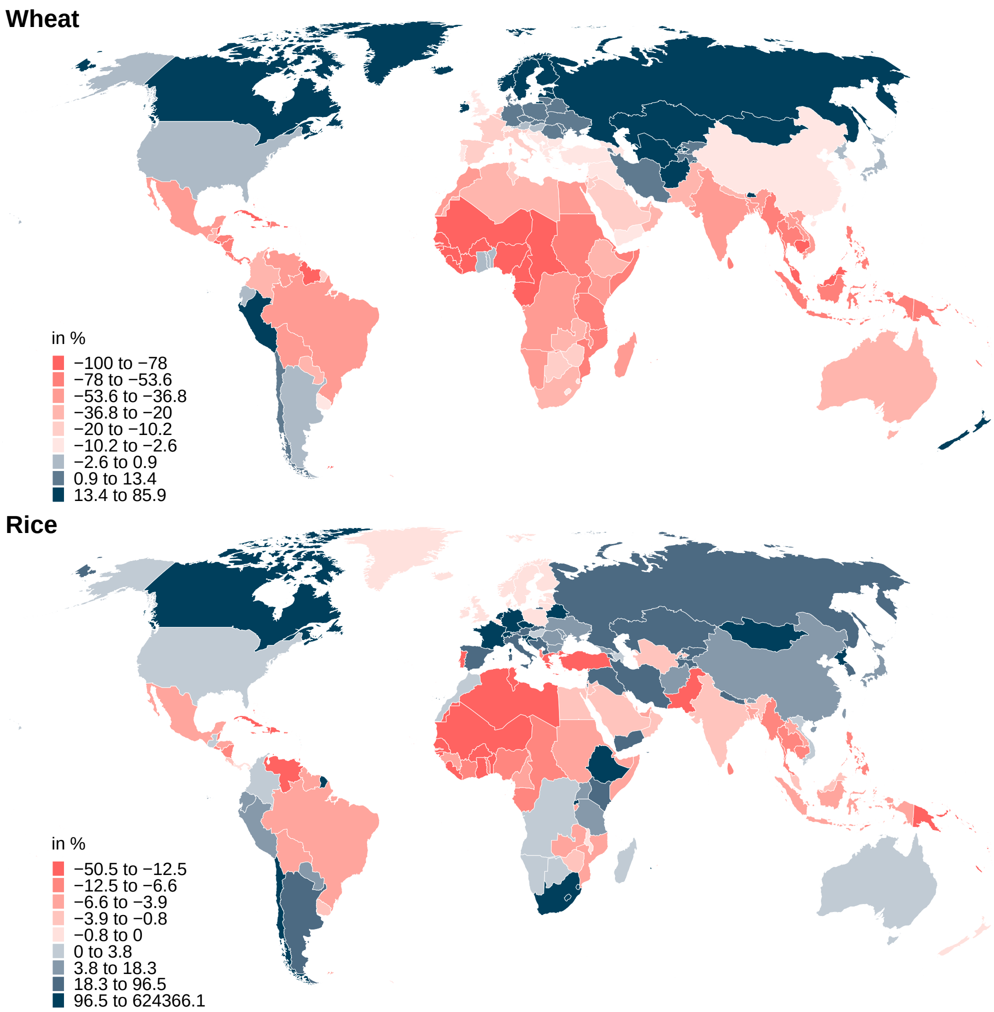
GAEZ productivity estimates are available for each cell, regardless a crop actually growing there. GAEZ uses state-of-the-art agronomic models, combining a vector of (i) attributes describing the growing characteristics in each cell, (ii) multiple parameters that govern how a given set of growing characteristics map into the yield of a specific crop, (iii) assumptions about farming techniques and inputs, such as irrigation, fertilizers, machinery, and labour, that might influence crop yields at each cell.

GAEZ provides pre–climate change estimates of average agricultural productivity A_g^c over a period from 1981 to 2010 for crop c and grid-cell $g \in \mathcal{G}_d \equiv [1, ..., \mathcal{G}_d]$ in country d. For the pre-climate change estimates GAEZ uses an average of model runs on past daily weather realizations. This average takes into account the idiosyncratic variability of weather patterns from year to year in a coherent manner. I use this *historical* values as a "baseline" to calculate yield changes under future climate conditions.

Future climatic conditions are based on simulations from recent IPCC AR5 earth system model (ESM) outputs for four representative concentration pathways (RCPs). I use two ESMs, *HadGEM2-ES* (Collins et al., 2011) and *GFDL-ESM2M* (Dunne et al., 2013), to account for model uncertainty, and four RCPs to account for future greenhouse gas concentration uncertainty. RCPs are based on a range of assumptions about future social, economic, and technological developments, and provide a common framework for evaluating the potential impacts of different emission pathways on the climate. There are four RCPs, each representing a different level of future greenhouse gas concentrations.[12] The only difference to the "baseline" estimates, instead of past weather realizations GAEZ uses predicted future daily stream of weather from 2071 to 2100 to estimate future crop yields

[12]RCP 2.6: This scenario represents a rapid and deep reduction in greenhouse gas emissions, resulting in atmospheric concentrations of around 430 parts per million (ppm) of CO2-equivalent by the year 2100. RCP 4.5: This scenario represents a moderate reduction in greenhouse gas emissions, resulting in atmospheric concentrations of around 640 ppm CO2-equivalent by 2100. RCP 6.0: This scenario represents a stabilization of greenhouse gas concentrations at around 710 ppm CO2-equivalent by 2100. RCP 8.5: This scenario represents a continuation of high levels of greenhouse gas emissions, resulting in atmospheric concentrations of around 970 ppm CO2-equivalent by 2100.

Figure 4.3: Productivity changes under RCP 6.0.



$A_g^{\prime c}$.

The change in productivity of agricultural sector j is then calculated the following

$$\hat{A}_d^j = \frac{\sum_{c \in \mathcal{J}_c} \sum_{g \in \mathcal{G}_d} s_g A_g^{\prime c}}{\sum_{c \in \mathcal{J}_c} \sum_{g \in \mathcal{G}_d} s_g A_g^c}, \tag{4.16}$$

where $c \in \mathcal{J}_c \equiv [1, ..., \mathcal{J}_c]$.[13] This approach assumes a certain within-sector substitutability that isn't modeled directly. If two crops within $\mathcal{J}_c$ face opposite climate impacts in the same absolute amount this would be

[13]For a sector-crop concordance see Table D.2.

leveled out in the aggregate, $\hat{A}_d^j$ would be one.[14] Alternatively, I could calculate $\hat{A}_g^j$ for each grid cell and average the changes over all cells $g \in \mathcal{G}_d$ in each country d. But this would add additional degrees of freedom because I have to decide how to treat infinite changes, if $A_g^c = 0$ and $A_g'^c > 0$.

I assume that only current fields can be used for crop production. The share of current cropland per cell is s_g and is derived from the GAEZ data set, see Figure D.1 in the Appendix D. The approach permits within-field crop substitution, but prohibits substitution at the extensive margin. Cropland expansion is a potential adaptation strategy to decreasing yields, but exogenous land use change requires a different model framework[15] which goes beyond the scope of this paper.

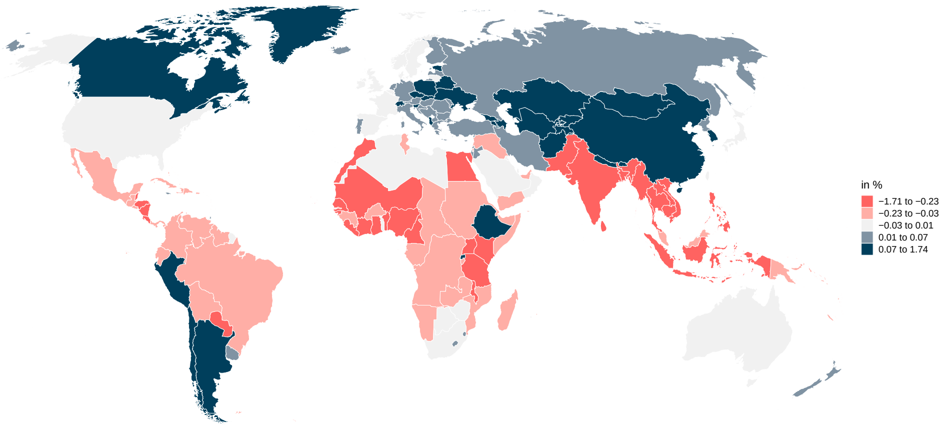
Figure 4.3 shows the values of $\hat{A}_d^j$ for $j =$ *wheat*[16] and *rice* under RCP 6.0. The across-country heterogeneity of climate impacts for both crops is striking. For wheat, especially countries around the equator lose productivity, while countries in higher latitudes gain productivity. Productivity changes range from minus 100 percent in Burkina Faso, Puerto Rico, Rest of Central America, and Senegal, to plus 75.4 in Finland and 85.9 percent in Norway. For rice, the within-region heterogeneity is higher. Productivity changes range from minus 50.5 and 50.4 percent in Tunisia and Rest of North Africa to plus 5,197 in Netherlands and 624,366 percent in Canada. For the latter, productivity changes are so high because initial productivities A are very low under a historical climate.

[14] Even though this consideration is highly unlikely given the narrow sector-crop matching.

[15] To model land use change properly, dynamic feedback loops with market prices and emissions are required, see e.g. Domınguez-Iino (2022).

[16] GTAP sector "wht", see Table D.2 in the Appendix D for the concordance of GAEZ crops c to GTAP sector j.

Figure 4.4: Welfare change in Scenario 1 “business as usual” under RCP 6.0.



4.4 Results

I consider three different trade policy scenarios to deal with climate-induced productivity changes: (1) business as usual with current trade policies; (2) “sufficient” unilateral trade liberalization; and (3) multilateral trade liberalization.

Each scenario is computed for each of the four RCPs, to account for uncertainty about future climate change. Productivity shocks for each RCP are the ensemble mean of two ESMs, and for irrigated and rain-fed yields.

Scenario 1: Business as usual.
Under the “business as usual” countries adjust their trade and production patterns to climate-induced productivity changes under current trade policies. Not surprisingly, under increasing greenhouse gas concentrations more and more countries lose welfare as more productivity changes become negative (compare Figure 4.4 to Figures D.8, D.9, and D.10 in the Appendix D). Under RCP 6.0, welfare in Pakistan (minus 1.71 percent), Cambodia (minus 1.5), and Nigeria (minus 1.19) declines the most. The highest increases happen in Rest of South Asia (1.74 percent), Belarus (1.52), and Tajikistan (1.31). Under RCP 2.6 and 4.0, the majority of

Table 4.1: Scenario 1, production change in billion USD.

	RCP 2.6		RCP 4.0		RCP 6.0		RCP 8.5	
	L	G	L	G	L	G	L	G
Ag. Products	-7.0	7.3	-13.9	12.9	-17.0	14.9	-27.9	25.9
Crops	-16.1	15.8	-31.0	27.6	-36.8	31.3	-57.9	49.1
Fossils & Energy	1.6	-2.7	2.5	-4.0	1.9	-3.3	3.2	-5.9
Manufacturing	5.4	1.0	9.3	-1.3	10.7	-2.7	16.7	-7.2
Services	-7.2	7.5	-13.1	19.8	-15.3	25.6	-25.0	41.7
N	40	101	61	80	73	68	74	67

Note: Change in production in bil. USD for countries who lose welfare (*L*) and gain welfare (*G*) per RCP. See Table D.1 for the aggregation of GTAP sectors.

countries experience welfare gains, while it is opposite under RCP 6.0 and 8.5.

Table 4.1 presents the production changes for countries who lose (*L*) and gain welfare (*G*) under different RCP scenarios. Because climate-induced productivity changes directly affect crop sectors, aggregate crop production is most affected by cross-country re-allocations. For countries who lose welfare, crop production decreases by 36.8 bn USD under RCP 6.0. That accounts for 2.5 percent of total crop production in that country group. Crop production in countries that gain welfare increases by 31.3 bn USD. But the increase is not sufficient to compensate all losses. That pattern is similar for all RCP scenarios. Sectors further down in the agriculture supply chain also suffer losses. Production of agricultural products, which include processed commodities such as crops and animal products, decreases in countries that lose welfare. The same happens to service sectors whose input for crop and food production is less needed in that country group anymore, e.g. transport and warehousing. As a response to the climate shock, workers move out of agriculture and service sectors into manufacturing, fossil fuels and energy production. Under RCP 6.0, production in manufacturing and fossil fuels increases by 10.7 and 1.9 bn USD in the country group that loses welfare. But these production gains cannot compensate the bigger losses in the three other categories (see Table 4.1).

Table 4.2 shows trade flow changes for both countries groups under RCP 6.0.[17] Country group *L* substitutes diminishing crop production by imports from country group *W*. Crop imports increase by 8.83, agricultural products by 1.1 percent. Although manufacturing production increases in *L* (see Table 4.1), total exports only increase by 0.3 percent. Meanwhile, crop and agricultural exports decrease by 7.94 and 1.32 percent.

Table 4.2: Scenario 1, trade flow changes in RCP 6.0, in percent.

	Δ Bilateral imports		Δ Internal trade		Δ Total exports	
	L	W	L	W	L	W
Ag. Products	1.10	-1.56	-0.97	0.72	-1.32	0.84
Crops	8.83	-9.28	-4.85	5.41	-7.94	6.53
Fossils & Energy	-0.41	0.45	-0.26	-0.25	0.25	-0.29
Manufacturing	-0.24	0.36	0.13	-0.01	0.30	-0.08
Services	-0.39	0.59	0.21	0.04	0.49	-0.08

Note: Change in trade flows in percent for countries that lose welfare (*L*) and gain welfare (*G*) in Scenario 1 under RCP 6.0. Bilateral imports refer to imports between both country groups. Internal trade refers to trade within each country group. See Table D.1 for the aggregation of GTAP sectors.

Table 4.3 shows the drivers behind the welfare changes of Scenario 1. In Column (1) welfare change is regressed on the import share of agricultural goods and the average productivity change, weighted by initial production, for all countries under RCP 8.5. Unsurprisingly, the climate-induced change in productivity is positive associated with welfare change. A one percent increase in productivity is associated with a 0.003 percent increase in welfare, holding all else equal. Columns 2 to 4 only use the subset of welfare losers, 74 countries out of 141, because theory lets us suspect counteracting effects of the independent variables. For example, a high

[17] See Table D.3, D.4, and D.5 in the Appedix D for other RCPs.

agricultural import share might have a dampening effect on welfare for the winners, because it indicates a higher level of specialization (within agriculture and/or across sectors). Indeed, for welfare losers a one percent increase in the import share is associated with an increase in welfare by 0.012 percent. Adding trade exposure, the average productivity change of trading partners weighted by their respective import share for each destination, to the regression does not lead to a significant result. This indicates that the primarily effect on welfare change comes from the productivity change and the importance of local agricultural production. That point is further highlighted in Column (4). A one percent increase in the share of total production from agriculture is associated with a welfare decrease of 0.047 percent. Adding the agriculture share to the regression also drops the significance level of the import share. This result is in line with Costinot et al. (2016), who found that the adjustment of production patterns within country is more important than the adjustment of trade patterns across countries.

Table 4.3: Change in welfare.

	(1)	(2)	(3)	(4)
Import share	0.004+	0.012***	0.012***	0.004
	(0.002)	(0.003)	(0.003)	(0.004)
Δ Productivity	0.003**	0.018***	0.015**	0.015**
	(0.001)	(0.005)	(0.005)	(0.005)
Trade exposure			0.005+	0.004
			(0.003)	(0.003)
Agriculture share				-0.047***
				(0.013)
Num.Obs.	141	74	74	74
Adj. R2	0.128	0.321	0.349	0.460

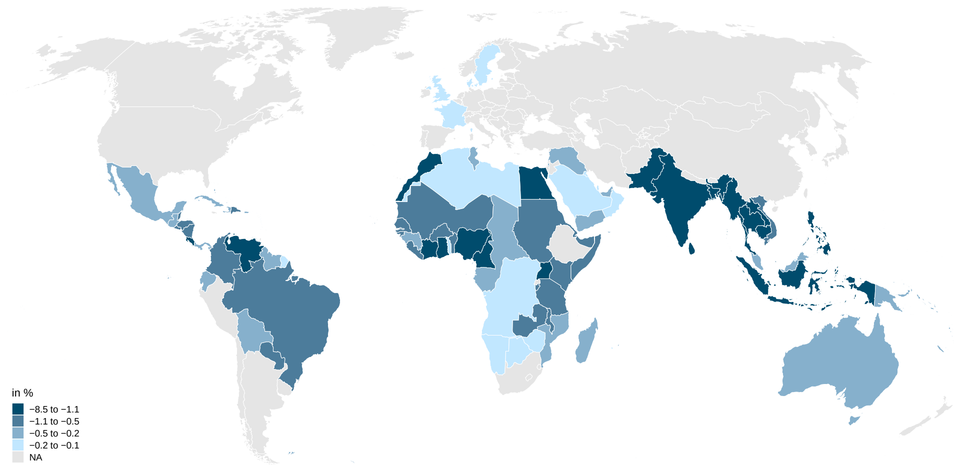
+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: Dependent variable is welfare change in percent in Scenario 1 under RCP 8.5. Import share is the share of imported over total agricultural goods. Change in productivity is the mean of $\hat{A}_d^j$ weighted by the baseline production value of j. Trade exposure is the average productivity change of trading partners weighted by the import share. Agriculture share is the share of agricultural production over total production. Column (1) contains all countries, while Columns (2) to (4) only considers countries that loose welfare.

Scenario 2: "Sufficient" unilateral trade liberalization

Scenario 2 models an "sufficient" unilateral trade policy response to counteract the welfare decrease for each country that loses welfare under Scenario 1. Therefore, I reduce NTBs on imports for country d till $\hat{W}_d = 0$ (see Eq. 4.15) individually, all else being equal. Figure 4.5 displays the necessary reduction in import barriers to compensate climate-induced welfare losses under RCP 6.0. Each country's number indicates an "sufficient" trade liberalization, only if that country reduces their NTBs under climate change and all other countries do not change their trade policies. Highest NTB reductions have to occur in Pakistan (8.5 percent), Nigeria (6.5), and India (2.9). Pakistan and Nigeria also experience the highest welfare losses

Figure 4.5: NTB changes in Scenario 2 under RCP 6.0.



Note: NTB change necessary to compensate climate-induced welfare losses (Scenario 1) per country. NA values indicate countries that gain welfare in Scenario 1.

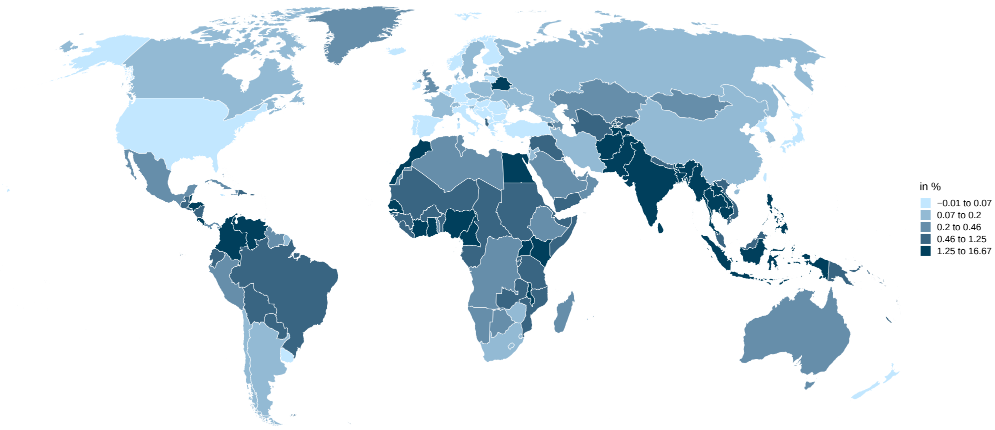
in Scenario 1. With increasing greenhouse gas concentrations and more severe yield losses, necessary NTB reductions also have to get bigger.[18] Under RCP 8.5, Nigeria needs to reduce import NTBs by 11.8 percent to compensate climate-induced welfare losses.

Scenario 3: Multilateral trade liberalization

Scenario 3 models all unilateral NTB reductions of Scenario 2 simultaneously. Figure 4.6 shows welfare changes under RCP 6.0. Countries that lose welfare under Scenario 1 experience high welfare gains. The biggest increases happen in Pakistan (16.67 percent), Nigeria (7.48), and India (5.77). It shows that the NTB reduction necessary to compensate a single country's climate-induced welfare loss, all else being equal, leads to high welfare gains when they are executed multilaterally. But also countries outside the group that liberalizes trade benefit, e.g., Nepal's welfare increases by 0.44, rest of South Asia by 0.43, and Rwanda by 0.14 percentage points from Scenario 1 to 3. That shows important spill-over

[18] Compare Figure D.11, D.12, and D.13 in the Appedix for other RCPs.

Figure 4.6: Welfare change in Scenario 3 under RCP 6.0.



effects from countries that liberalize trade policies to the countries that do not. Unsurprisingly, since this massive policy change shifts global production and trade patterns, there are some countries that are worse off. Countries that lose the most welfare from Scenario 1 to 3 are Kyrgyzstan (0.05 percentage points), South Korea (0.03 percentage points), and Belarus (0.02 percentage points), but they still experience welfare gains. In contrast to Taiwan and Japan, that have small welfare gains under Scenario 1 (0.004 and 0.01 percent) and lose welfare under Scenario 3 (minus 0.006 and 0.002 percent).

4.5 Conclusion

In this paper I carry out a quantitative assessment of the trade and welfare effects of future climate change globally. I use a Ricadian NQT trade model to simulate the general equilibrium effects of trade liberalization along the whole value chain in response to climate-induced productivity changes in agriculture.

I show that climate change affects agricultural productivities differently around the world. In particular, countries who experience welfare losses are predominantly located in the global south. These countries cannot compensate climate-induced productivity losses by (i) switching their production to more productive sectors, and (ii) import those crops whose local productivity declines, because they face high trade barrieres. I show for each country which reduction in non-tariff barriers on imports is necessary to compensate welfare losses. Usually, the largest NTB reductions have to happen in countries with the highest initial losses. But this relation is not linear.

Trade liberalization is an important adaptation policy to mitigate climate-induced welfare losses. If no coordination happens among countries who lose welfare, unilateral trade policy liberalization has to be higher. In contrast, if all countries, that experience climate-induced welfare losses, reduce their import NTBs simultaneously, positive spill-over effects occur globally. Also the country group that already gains from climate change increases their welfare even further.

Mitigating future climate change is a rewarding endeavour. Under a low concentration pathway (RCP 2.6) almost all countries benefit from crop productivity increases, while for higher RCPs welfare costs get tremendous. The international community should therefore make every effort to cut carbon emissions.

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Appendix A

Cutting through the Value Chain: The long-run Effects of Decoupling the East from the West

A.1 Further results

Table A.1: Scenario 1C, changes in percent.

Country	Δ Welfare	Δ Total Exports	Δ Total Imports	Δ Exports China	Δ Exports RoW	Δ Imports China	Δ Imports RoW
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Austria	-0.63	-2.92	-2.98	-97.79	-0.16	-96.59	1.95
Belgium	-1.17	-3.56	-3.34	-98.17	-0.22	-96.28	1.39
Bulgaria	-0.62	-2.40	-2.13	-97.05	-0.84	-96.75	1.00
China	-0.92	-13.56	-17.14		2.25		-2.22
Cyprus	-0.86	-3.36	-3.17	-98.40	2.11	-97.01	-0.11
Czechia	-1.06	-2.87	-3.49	-97.08	-4.17	-95.81	5.03
Germany	-1.00	-6.40	-7.07	-97.71	0.20	-96.20	2.44
Denmark	-0.95	-4.40	-4.82	-97.35	0.96	-95.60	1.16
Spain	-0.66	-3.53	-4.27	-97.69	-0.99	-95.87	2.54
Estonia	-1.59	-3.23	-3.84	-97.46	-2.20	-96.49	2.49
Finland	-1.04	-4.93	-5.41	-97.89	3.64	-96.22	0.44
France	-0.60	-4.54	-4.57	-97.24	-0.84	-96.13	2.31
Greece	-0.79	-3.07	-3.07	-98.19	-1.92	-95.68	2.26
Croatia	-0.45	-1.48	-1.58	-98.09	-0.49	-96.48	1.02
Hungary	-0.92	-3.90	-4.40	-97.93	-2.74	-96.47	3.19
Ireland	-2.04	-3.79	-5.63	-98.30	2.28	-97.47	0.39
Italy	-0.47	-4.05	-4.30	-97.08	-2.10	-96.27	2.70
Lithuania	-1.03	-1.63	-2.03	-96.52	-1.85	-96.39	2.01
Luxembourg	-0.56	-3.35	-2.79	-98.15	0.55	-97.33	-2.03
Latvia	-0.78	-1.21	-1.55	-95.60	-1.54	-96.24	3.29
Malta	-3.89	-7.59	-8.87	-98.37	-4.89	-97.71	16.56
Netherlands	-0.90	-2.92	-3.89	-97.71	-1.85	-96.14	3.98
Poland	-0.77	-2.44	-2.88	-98.01	-2.84	-96.15	4.03
Portugal	-0.34	-2.17	-1.71	-98.72	-1.22	-96.56	1.41
Romania	-0.39	-1.28	-1.29	-97.66	-2.62	-96.43	3.34
Slovakia	-0.55	-3.55	-2.50	-99.35	-2.99	-96.09	4.27
Slovenia	-0.81	-1.46	-1.93	-97.61	-1.29	-96.59	3.60
Sweden	-0.76	-3.54	-3.96	-97.73	1.71	-96.14	0.76

Table A.2: Scenario 3C, changes in percent.

Country	Δ Welfare	Δ Total Exports	Δ Total Imports	Δ Exports Russia	Δ Exports RoW	Δ Imports Russia	Δ Imports RoW
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Albania	-0.36	-0.84	-1.05	-98.36	-2.20	-86.47	2.65
Australia	0.07	0.18	0.48	-98.69	-2.72	-97.29	0.56
Austria	-0.28	-1.90	-1.77	-97.45	1.35	-97.09	0.21
Belgium	-0.51	-2.37	-2.28	-97.58	-1.07	-95.36	2.41
Bulgaria	-1.11	-5.44	-5.73	-97.86	-3.30	-96.76	11.08
Canada	0.01	-0.18	-0.09	-97.84	-0.56	-96.72	-0.05
China	0.02	0.13	0.36	-2.52	0.67	96.43	-3.32
Cyprus	-1.15	-7.39	-6.74	-98.77	3.46	-96.20	0.02
Czechia	-1.16	-3.41	-4.15	-97.48	1.40	-99.39	7.82
Germany	-0.40	-2.42	-2.86	-97.48	0.97	-96.83	2.52
Denmark	-0.08	-1.55	-1.34	-97.59	-0.99	-92.68	0.54
Spain	-0.22	-1.48	-1.58	-97.71	0.85	-93.89	2.52

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Table A.2: Scenario 3C, changes in percent.

Country	Δ Welfare	Δ Total Exports	Δ Total Imports	Δ Exports Russia	Δ Exports RoW	Δ Imports Russia	Δ Imports RoW
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Estonia	-1.98	-12.84	-11.90	-95.42	-5.50	-92.55	-1.27
Finland	-0.88	-6.82	-7.93	-97.37	2.55	-97.01	2.93
France	-0.16	-1.40	-1.26	-97.94	1.19	-93.05	0.22
United Kingdom	-0.09	-1.48	-1.15	-98.43	-0.71	-95.12	0.66
Greece	-0.95	-9.36	-8.45	-98.07	-8.65	-92.14	10.30
Croatia	-0.49	-4.49	-4.67	-98.15	-2.08	-95.69	9.21
Hungary	-0.86	-5.95	-6.99	-97.27	-2.41	-98.65	9.56
Ireland	-0.32	-0.67	-0.83	-98.68	1.51	-96.86	-0.58
Italy	-0.31	-2.40	-2.95	-96.49	0.62	-98.33	11.13
Japan	-0.14	-1.38	-1.63	-98.44	0.31	-99.06	3.48
South Korea	-0.36	-1.99	-2.41	-97.95	-0.12	-96.13	2.57
Lithuania	-2.48	-14.12	-13.86	-95.77	-6.13	-98.70	35.82
Luxembourg	-0.33	-1.84	-1.61	-98.58	0.96	-97.47	-1.38
Latvia	-2.02	-7.28	-7.35	-97.24	-1.88	-94.32	15.98
Malta	-1.05	-3.08	-2.90	-98.93	0.37	-86.67	-0.70
Netherlands	-0.12	-2.74	-3.22	-97.10	-2.97	-96.75	4.85
Norway	0.55	0.86	3.22	-98.64	-9.77	-94.28	6.75
New Zealand	-0.04	-0.60	-0.58	-97.57	0.27	-98.85	0.48
Philippines	-0.13	-0.76	-0.81	-98.16	0.16	-99.08	0.90
Poland	-0.78	-6.08	-6.38	-97.39	-1.94	-98.36	10.85
Portugal	-0.25	-0.96	-1.06	-98.27	0.99	-90.18	1.98
Romania	-0.28	-3.37	-3.27	-96.93	-1.11	-96.85	5.31
Russia	-9.71	-45.21	-64.00		58.79		-9.09
Slovakia	-1.68	-6.01	-6.74	-98.57	1.64	-97.90	11.58
Slovenia	-0.83	-3.05	-3.25	-97.95	2.83	-95.58	-0.66
Sweden	-0.26	-1.98	-2.22	-97.66	1.14	-98.03	4.10
Turkey	-0.63	-4.99	-4.84	-97.17	0.00	-91.19	2.64
Taiwan	-0.22	-0.93	-1.30	-97.17	-0.42	-94.38	0.07
United States	-0.04	-1.33	-1.00	-98.36	0.16	-92.96	-0.45

Table A.3: Scenario 5C, changes in percent.

Country	Δ Welfare	Δ Total Exports	Δ Total Imports	Δ Exports BRIC	Δ Exports RoW	Δ Imports BRIC	Δ Imports RoW
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Albania	-1.94	-7.33	-6.44	-99.15	-1.81	-93.77	6.03
Australia	-1.87	-18.99	-22.73	-98.68	18.04	-95.45	-1.22
Austria	-1.06	-5.53	-5.18	-97.66	0.25	-96.59	5.24
Belgium	-2.59	-9.31	-8.40	-98.57	-1.98	-95.77	7.43
Bulgaria	-1.94	-7.80	-7.54	-97.67	-6.39	-96.52	16.76
Brazil	-1.75	-43.60	-39.66		-5.12		13.05
Canada	-1.43	-6.06	-7.38	-96.14	-3.08	-95.19	13.96
China	-3.50	-51.32	-64.34		12.91		-13.83
Cyprus	-2.37	-13.08	-11.94	-98.60	6.52	-96.35	0.38
Czechia	-2.10	-6.32	-7.20	-97.56	-4.73	-97.01	27.74
Germany	-1.55	-10.36	-11.09	-97.72	-0.41	-96.08	10.92
Denmark	-1.27	-7.12	-7.17	-97.75	-1.74	-94.73	5.37
Spain	-1.07	-6.95	-7.64	-97.80	-1.48	-94.73	7.87
Estonia	-3.95	-16.14	-15.77	-96.44	-9.02	-94.07	6.40

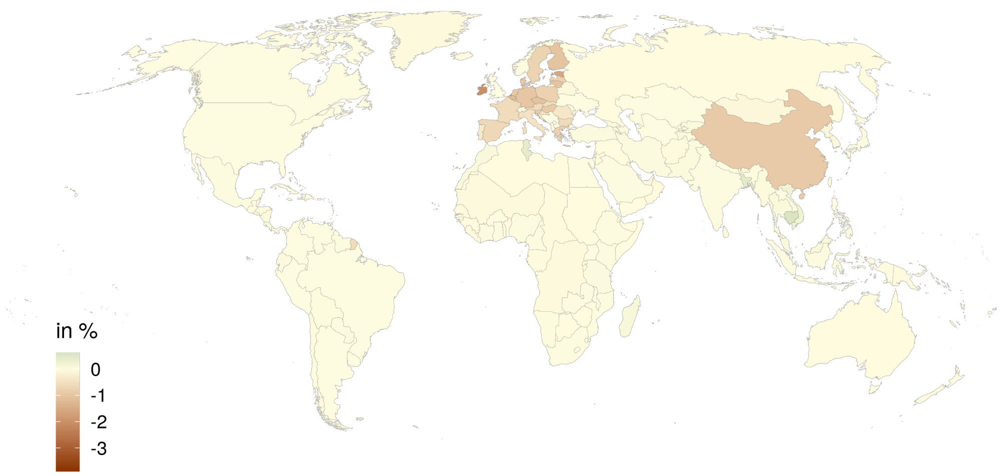
Continued on next page

Table A.3: Scenario 5C, changes in percent.

Country	Δ Welfare	Δ Total		Δ Exports		Δ Imports	
		Exports	Imports	BRIC	RoW	BRIC	RoW
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Finland	-2.16	-13.98	-15.32	-97.73	5.17	-96.55	9.98
France	-0.94	-7.30	-6.91	-97.69	-1.30	-95.29	6.16
United Kingdom	-1.18	-10.60	-9.51	-98.58	-4.74	-95.64	8.65
Greece	-1.98	-14.42	-12.86	-98.26	-9.68	-93.26	16.19
Croatia	-1.18	-6.54	-6.88	-98.25	-3.80	-95.67	17.04
Hungary	-1.76	-9.91	-11.03	-97.86	-6.51	-97.61	28.38
India	-2.84	-37.77	-32.50		17.51		-9.87
Ireland	-2.68	-5.83	-7.72	-98.51	2.67	-97.30	2.84
Italy	-0.89	-7.77	-8.02	-97.01	-4.02	-96.75	24.38
Japan	-1.53	-24.72	-23.21	-97.25	3.84	-95.91	5.03
South Korea	-4.25	-27.85	-28.50	-97.29	8.07	-95.18	-3.40
Lithuania	-3.67	-15.97	-16.00	-96.24	-11.27	-98.07	63.82
Luxembourg	-2.24	-6.30	-5.43	-98.38	0.61	-97.35	-2.59
Latvia	-3.16	-8.79	-9.31	-97.29	-5.89	-94.69	29.96
Malta	-6.34	-12.08	-13.26	-98.63	-4.66	-96.10	18.56
Netherlands	-1.28	-6.78	-8.09	-97.81	-6.74	-95.71	16.66
Norway	-0.13	-3.49	-2.47	-98.08	-10.08	-95.46	10.29
New Zealand	-1.40	-14.13	-15.32	-95.06	9.48	-95.69	0.71
Philippines	-2.37	-22.24	-17.73	-97.46	-2.13	-94.92	9.04
Poland	-1.66	-8.66	-9.28	-97.74	-7.27	-97.03	29.37
Portugal	-0.83	-4.70	-4.01	-97.86	-2.84	-94.45	6.58
Romania	-0.75	-5.17	-4.70	-97.59	-6.55	-96.07	15.13
Russia	-9.62	-45.12	-63.59		50.88		-16.95
Slovakia	-2.08	-9.08	-8.34	-99.01	-4.18	-97.12	30.29
Slovenia	-2.10	-5.09	-5.97	-97.91	-0.86	-94.28	7.33
Sweden	-1.21	-7.19	-7.53	-97.77	1.39	-96.65	11.29
Turkey	-1.62	-11.41	-10.72	-97.81	-6.55	-93.70	12.43
Taiwan	-4.43	-25.44	-30.13	-97.17	18.63	-96.34	-10.37
United States	-0.91	-17.05	-14.61	-96.47	-3.73	-95.62	9.92

A.2 Additional figures

Figure A.1: Welfare effects by country in Scenario 1C, changes in percent.



A.3 Solving for counterfactual equilibria

As suggested by **?**, a counterfactual general equilibrium for alternative trade costs in the form of $\hat{\phi}^j_{od} = \phi^{j\prime}_{od}/\phi^j_{od}$ — i.e. where any variable $\hat{x}$ denotes the relative change from a previous value x to a new one x' — can be solved for in changes such that

$$\textit{Input costs} \qquad \hat{c}^j_d = \hat{w}_d^{\beta^j_d} \left(\prod_{k=1}^{J} [\hat{P}^k_d]^{\gamma^{k,j}_d} \right)^{1-\beta^j_d} \tag{A.1}$$

$$\textit{Prices} \qquad \hat{P}^j_d = \left(\sum_{o=1}^{N} \pi^j_{od} [\hat{\phi}^j_{od} \hat{c}^j_o]^{-1/\theta^j} \right)^{-\theta^j} \tag{A.2}$$

$$\textit{Trade shares} \qquad \pi^{j\prime}_{od} = \pi^j_{od} \left(\frac{\hat{c}^j_o}{\hat{P}^j_d} \hat{\phi}^j_{od} \right)^{-1/\theta^j} \tag{A.3}$$

$$\textit{Expenditures} \qquad X^{j\prime}_d = \sum_{k=1}^{J} (1-\beta^k_d)\gamma^{j,k}_d \left(\sum_{o=1}^{N} \frac{\pi^{k\prime}_{do}}{\tau^{k\prime}_{do}\zeta^{k\prime}_{do}} X^{k\prime}_o \right) + \alpha^j_d I'_d \quad \text{with} \tag{A.4}$$

$$\begin{aligned}
\textit{Income, value added} \qquad I'_d &= \hat{w}_d w_d L_d \\
\textit{Tariff revenue} \qquad &+ \sum_{k=1}^{J} \sum_{o=1}^{N} (\tau^{k\prime}_{od} - 1) \left(\frac{\pi^{k\prime}_{od}}{\tau^{k\prime}_{od}} \right) X^{k\prime}_d \\
\textit{Export tax revenue} \qquad &+ \sum_{k=1}^{J} \sum_{o=1}^{N} (\zeta^{k\prime}_{do} - 1) \left(\frac{\pi^{k\prime}_{do}}{\tau^{k\prime}_{do}\zeta^{k\prime}_{do}} \right) X^{k\prime}_o \\
\textit{Trade balance} \qquad &- D'_d
\end{aligned}$$

$$\textit{Trade balance} \qquad D_d = \sum_{j=1}^{J} \sum_{o=1}^{N} \frac{\pi^{j\prime}_{od}}{\tau^{j\prime}_{od}\zeta^{j\prime}_{od}} X^{j\prime}_d - \sum_{j=1}^{J} \sum_{o=1}^{N} \frac{\pi^{j\prime}_{do}}{\tau^{j\prime}_{do}\zeta^{j\prime}_{do}} X^{j\prime}_o . \tag{A.5}$$

A.4 Data

A.4.1 List of countries included in the model

Albania; United Arab Emirates; Argentina; Armenia; Australia; Austria; Azerbaijan; Belgium; Benin; Burkina Faso; Bangladesh; Bulgaria; Bahrain; Belarus; Bolivia; Brazil; Brunei; Botswana; Canada; Switzerland; Chile; China; Cote d'Ivoire; Cameroon; Colombia; Costa Rica; Cyprus; Czechia; Germany; Denmark; Dominican Republic; Ecuador; Egypt; Spain; Estonia; Ethiopia; Finland; France; United Kingdom; Georgia; Ghana; Guinea; Greece; Guatemala; Hong Kong SAR China; Honduras; Croatia; Hungary; Indonesia; India; Ireland; Iran; Israel; Italy; Jamaica; Jordan; Japan; Kazakhstan; Kenya; Kyrgyzstan; Cambodia; South Korea; Kuwait; Laos; Sri Lanka; Lithuania; Luxembourg; Latvia; Morocco; Madagascar; Mexico; Malta; Mongolia; Mozambique; Mauritius; Malawi; Malaysia; Namibia; Nigeria; Nicaragua; Netherlands; Norway; Nepal; New Zealand; Oman; Pakistan; Panama; Peru; Philippines; Poland; Puerto Rico; Portugal; Paraguay; Qatar; Romania; Russia; Rwanda; Saudi Arabia; Senegal; Singapore; El Salvador; Slovakia; Slovenia; Sweden; Togo; Thailand; Tajikistan; Trinidad Tobago; Tunisia; Turkey; Taiwan; Tanzania; Uganda; Ukraine; Uruguay; United States; Venezuela; Vietnam; South Africa; Zambia; Zimbabwe.

A.4.2 List of regions included in the model

1. South Central Africa: Angola, Democratic Republic of the Congo.
2. Rest of Central America: Belize.
3. Rest of Caribbean: Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, British Virgin Islands, Cayman Islands, Cuba, Dominica, Grenada, Haiti, Montserrat, Netherlands Antilles, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and Grenadines, Turks and Caicos

Islands, Virgin Islands (US).

4. Rest of Central Africa: Central African Republic, Chad, Congo, Equatorial Guinea, Gabon, Sao Tome and Principe.
5. Rest of East Asia: Korea, Democratic People's Republic of, Macao, Special Administrative Region of China.
6. Rest of Eastern Africa: Burundi, Comoros, Djibouti, Eritrea, Mayotte, Seychelles, Somalia, Sudan.
7. Rest of Eastern Europe: Moldova.
8. Rest of European Free Trade Association: Iceland, Liechtenstein.
9. Rest of Europe: Andorra, Bosnia and Herzegovina, Faroe Islands, Gibraltar, Guernsey, Holy See (Vatican City State), Isle of Man, Jersey, Monaco, Montenegro, North Macedonia, San Marino, Serbia.
10. Rest of North America: Bermuda, Greenland, Saint Pierre and Miquelon.
11. Rest of North Africa: Algeria, Libya, Western Sahara.
12. Rest of Oceania: American Samoa, Cook Islands, Fiji, French Polynesia, Guam, Kiribati, Marshall Islands, Federated States of Micronesia, Nauru, New Caledonia, Niue, Northern Mariana Islands, Palau, Papua New Guinea, Pitcairn, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, United States Minor Outlying Islands, Vanuatu, Wallis and Futuna Islands.
13. Rest of South Asia: Afghanistan, Bhutan, Maldives.
14. Rest of South African Customs Union: Eswatini, Lesotho.
15. Rest of Southeast Asia: Myanmar, Timor-Leste.
16. Rest of South America: Falkland Islands (Malvinas), French Guiana, Guyana, South Georgia and the South Sandwich Islands, Suriname.

17. Rest of Former Soviet Union: Turkmenistan, Uzbekistan.
18. Rest of the World: Antarctica, Bouvet Island, British Indian Ocean Territory, French Southern Territories.
19. Rest of Western Africa: Cape Verde, Gambia, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Saint Helena, Sierra Leone
20. Rest of Western Asia, Iraq, Lebanon, Palestinian Territory (Occupied), Syrian Arab Republic (Syria), Yemen.

A.4.3 List of sectors included in the model

Accommodation, Food & Service Activities; Air Transport; Beverages & Tobacco; Cane & Beet; Cattle; Cattle Meat; Chemical Products; Coal; Computer, Electronic & Optical Products; Construction; Dairy Products; Dwellings; Education; Electrical Equipment; Electricity; Fabricated Metal Products; Fibres crops; Fishing; Forestry; Furniture; Gas; Gas Manufacture; Human Health & Social Work; Information & Communication; Insurance; Iron & Steel; Land Transport; Leather Manufacture; Lumber; Machinery & Equipment; Manufacture of Textiles; Motor Vehicles; Non-Ferrous Metals; Oil; Oil Seeds; Other Animal Products; Other Business Services; Other Crops; Other Financial Intermediation; Other Food; Other Grains; Other Meat; Other Mineral Products; Other Mining Extraction; Other Services (Government); Other Transport Equipment; Paper & Paper Products; Petroleum & Coke; Pharmaceuticals; Processed Rice; Raw milk; Real Estate Activities; Recreation & Other Services; Rice; Rubber & Plastics Products; Sugar & Molasses; Veg & Fruit; Vegetable Oils; Warehousing; Water Supply; Water Transport; Wearing Apparel; Wheat; Wholesale & Retail Trade; Wool.

Appendix B

Macroeconomic Structural Change Likely Increases Inequality in India more than Climate Policy

B.1 Models

B.1.1 Integrated assessment model

The Regional Model of Investments and Development (REMIND) is an Integrated Assessment model (IAM) that provides a holistic view of the global energy–economy–emissions system and explores self-consistent transformation pathways [34]. It investigates a broad range of possible futures and their relation to technical and socioeconomic developments, as well as policy choices. REMIND is a multi-regional model incorporating the economy of each region with a detailed representation of the energy sector34. In each region, a representative household maximizes utility according to per capita consumption. Each region generates macroeconomic output (GDP) based on a nested constant elasticity of substitution (CES) production function using the production factors of labour, capital, and final energy as inputs. Using non-linear optimization, REMIND solves for an intertemporal Pareto optimum in capital and energy investments in the model regions for the time horizon 2005 to 2100, fully accounting for interregional trade in a composite good and different energy carriers. REMIND thereby enables analyses of technology options and policy proposals for climate change mitigation, with the distinct capability of representing the scale-up of new technologies and the integration of renewable energies in power markets. The spatial resolution of REMIND is flexible. The applied version distinguishes 12 world regions with India modelled as a single region.

REMIND is calibrated to a wide range of data to ensure the consistency of the scenarios with historical developments and realistic future projections. To align with SSP GDP, population, and final energy trajectories, REMIND calibrates its production function, thereby fixing labour productivities. Historical data for the year 2005 is used to calibrate most of the free variables (e.g., primary energy mixes, secondary energy mixes, standing energy conversion capacities, trade in all traded goods). Technology parameters are projected into the future, in general assuming a convergence across regions in the very long term.

B.1.2 Structural change scenario model

The structural change scenarios are constructed on the basis of a regression model which combines country-level data from different sources. Based on given initial shares of labour, value-added, and energy for 2015, and using estimated regression coefficients, projections are computed with updated SSP GDP and population scenarios (Koch and Leimbach, 2023) as independent variables. A detailed description of the regression approach can be found in Leimbach et al. (2023). The structural change scenarios represent projections of sectoral shares that are independent of units and can therefore, in contrast to absolute level values, directly be adopted by other models. The shares of the agriculture, manufacturing, and service sectors in economy-wide employment, value-added, and final energy use are projected until 2050. The development of these key variables of economic activity is provided for each SSP scenario.

B.1.3 New quantitative trade models

The scenario simulation results produced by the two macro models are fed into two advanced numerical trade models based on the theoretical Ricardian trade model introduced by Eaton and Kortum (2002). In the Eaton and Kortum model, international trade is driven by Ricardian specialization in lowest-cost varieties of each good without assuming regional preferences for goods. The implementations use a computable general equilibrium (CGE) framework that is commonly described as a new quantitative trade (NQT) model. They are similar to the model originally developed by Caliendo and Parro (2015). They represent a multi-sector version of the Eaton and Kortum model, where countries/regions produce and sell domestically as well as internationally according to their relative comparative advantage. Both models incorporate domestic and international input–output linkages, such that trade includes final and intermediate goods and services. Trade policy analyses can be conducted by tightening or easing trade barriers in the form of tariffs or non-tariff barriers. Output prices are combined to a domestic price index in a consumption bundle. Likewise, the prices of the imported goods are combined to an import bundle similar to the standard Armington approach. These two bundles are then combined to a compound price index that the final consumer of each country perceives. Similarly, the producer of each sector and country perceives a compound price index of intermediate goods that are domestically produced and imported.

The first established advanced global trade model is called Justus (Liebig) University Sustainable Transition (JUST). The static version of the model, focusing on German climate and energy policy, has been introduced by Pothen and Hübler [56]. This model uses Global Trade Analysis Project [1] (GTAP) data version 9 with the benchmark year 2011. The recursive dynamic version presented by Pothen and Hübler (2018) adds scenarios of economic growth, energy use, and CO2 emissions until 2050. Hübler and Pothen (2021) version of the model expresses relative changes between two scenarios and focuses on the sand sector. The new model under scrutiny builds on these previous model versions, but focuses on the Indian economy and uses new SSP scenarios.

The JUST model encompasses 19 countries and aggregated world regions, including India, China, Brazil, the United States, Canada, the former Soviet Union, and the biggest European economies. Each country/region has one representative consumer and a representative producer in each sector. The model covers 17 production sectors and goods (see Appendix, Table A.1). For each time period, the model solution presents a global general equilibrium with market clearance, zero profits, and balanced (private and

[1] https://www.gtap.agecon.purdue.edu/.

public) budgets. This equilibrium consists of the market-clearing prices of goods and factors and the corresponding quantities.

The second advanced trade model is called the Kiel Institute Trade Policy Evaluation (KITE). It is a new, updated and further elaborated model that provides a novel tool for simulating various types of trade and climate policy effects (Felbermayr et al., 2022). The KITE model extends the framework of Caliendo and Parro (2015) by incorporating carbon emissions and climate policies (Mahlkow and Wanner, 2023) and allowing for subnational input–output linkages across Indian states. KITE uses version 10 of the GTAP database with the benchmark year 2014 (Aguiar et al., 2019). The model provides a very rich geographical and sectoral resolution. It features 65 production sectors (see Table A.1) as well as 141 countries and aggregated world regions. India is further disaggregated into 33 states, which reveals the spatial heterogeneity of distributional effects. Each state exhibits different production, trade, and comparative advantage patterns.

B.1.4 Comparison of trade model features and results

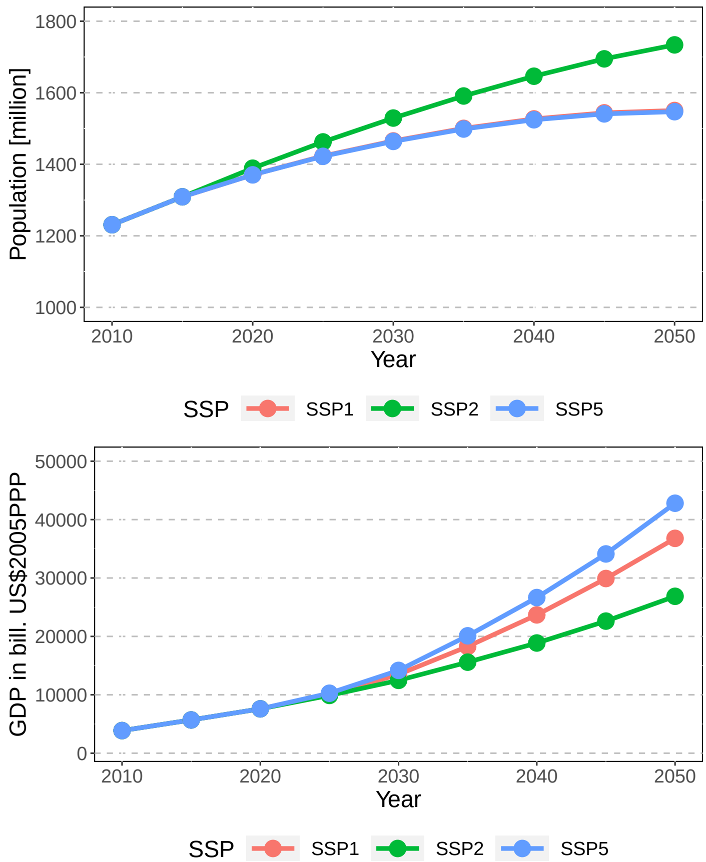
On the model implementation side, the KITE model is programmed in terms of relative changes between a counterfactual and a baseline scenario, while JUST is written and solved in absolute terms for each scenario. While the KITE model uses a Cobb-Douglas production function that combines inputs at one level (see Felbermayr et al., 2022), the JUST model uses more complex nest structures with different elasticities of substitution (see Pothen and Hübler, 2021). They combine labour, capital and intermediate goods inputs (from abroad and the domestic economy) with energy as well as fossil fuel inputs and electricity within the energy aggregate. While the production factor labour is internationally immobile in both models, it is mobile across sectors within each model region. In JUST, additionally, the production factor capital is internationally immobile but mobile across sectors with each model region, and natural resource endowments are region- and sector-specific. Both models represent the full global input-output matrix including trade in intermediate goods. Furthermore, both models include existing taxes and subsidies. Therefore, they represent a second-best world, where the effects of CO2 pricing can be complex due to the interaction with existing taxes and subsidies. On the data side, KITE uses GTAP 10, while JUST uses GTAP 9. Additionally, in JUST, the key parameter values governing international trade are estimated in a structural estimation. While international energy carrier prices are governed by the REMIND data in JUST and increase over time (Figure B.2), they have more flexibility in KITE resulting in stronger adjustments or energy prices and quantities and hence more flexibility in terms of reactions to climate policy and structural change.

With increasing carbon prices, in the KITE model, decarbonization is mainly achieved by drastically phasing out fossil fuels, especially coal, and significantly reducing industrial production in the manufacturing sector (Figure 2.6). As a result, the value-added shares of the agriculture and service sector significantly expand (Figure 2.7). In the JUST model, carbon emission reductions are mainly achieved by expanding agricultural production given the low carbon intensity and low marginal abatement costs in agriculture (Appendix Figure B.7). This expansion is in accordance with the need to improve the nutrition of the large (and increasing) Indian population. In JUST, however, the transport sector (TRNS) shrinks due to climate policy (Appendix Figure B.7). In both models, the manufacturing sector is an aggregate of heterogeneous subsectors with different CO2 intensities and hence various effects of climate policy and structural change (Appendix Figures B.7 and B.10). While in JUST, the overall share of the manufacturing sector stays almost constant (Appendix Figure B.7), decarbonization is achieved via intrasectoral restructuring within the manufacturing sector (Appendix Figures B.7) and strategic benefits on international markets. In both models, coal production is by far to the largest extent reduced among all sectors (Appendix Figures B.7 and B.10); the phase-out of fossil fuels in JUST, however, is overall less significant than in KITE.

B.2 SSP scenario characteristics

- SSP1 (“Sustainability”): medium/high GDP per capita growth based on fast technological progress; less energy intensive; high share of renewable energies already in the baseline scenario; comparatively high energy prices in the short term, and lower energy prices (apart from oil) in the long term; fast structural change towards manufacturing and services;
- SSP2 (“Middle of the road”): continuation of long-term trends (e.g., population growth, technological progress, energy, and land use); medium GDP per capita growth; comparatively high energy intensity (similar to SSP5); medium energy prices; moderate structural change towards manufacturing and services;
- SSP5 (“Fossil fuelled development”): high GDP growth based on fast technological progress; energy intensive; abundant fossil resources; energy prices are low in the short term but high in the long term as energy demand is substantial; fast structural change towards services.

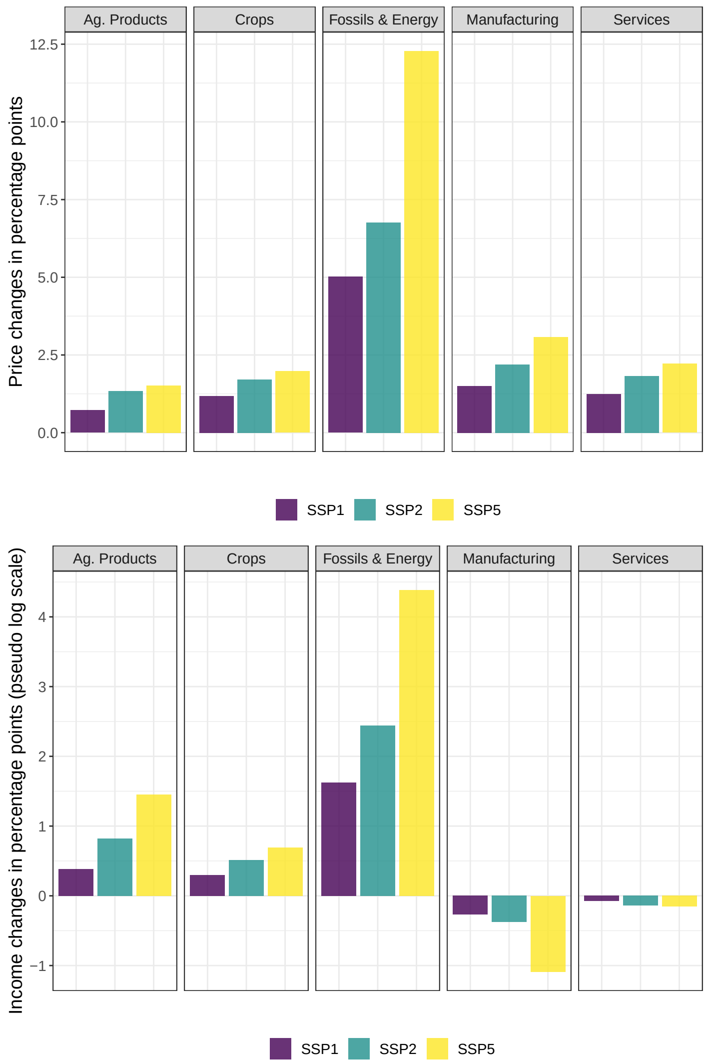
Figure B.1: Projections of population (upper panel) and GDP (lower panel) in India within different SSPs.



Note: Population growth for SSP1 aligns almost completely with SSP5.

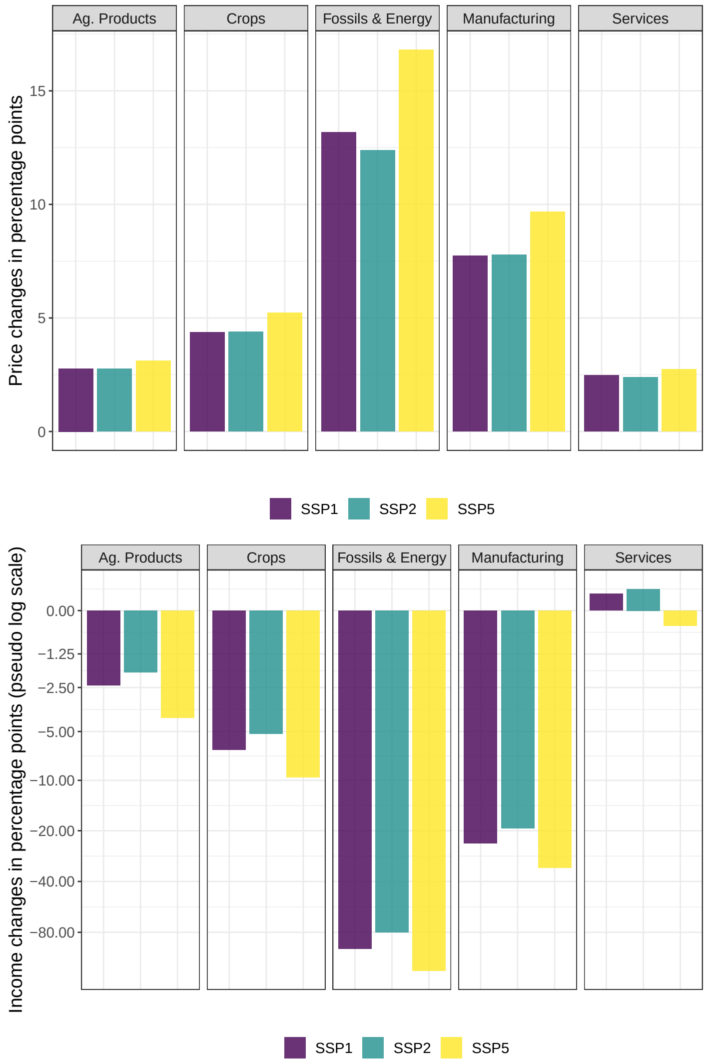
B.3 Income and price changes across SSPs

Figure B.2: Sectoral output price and income changes in India induced by carbon pricing compatible with 2°C climate policy (JUST model).



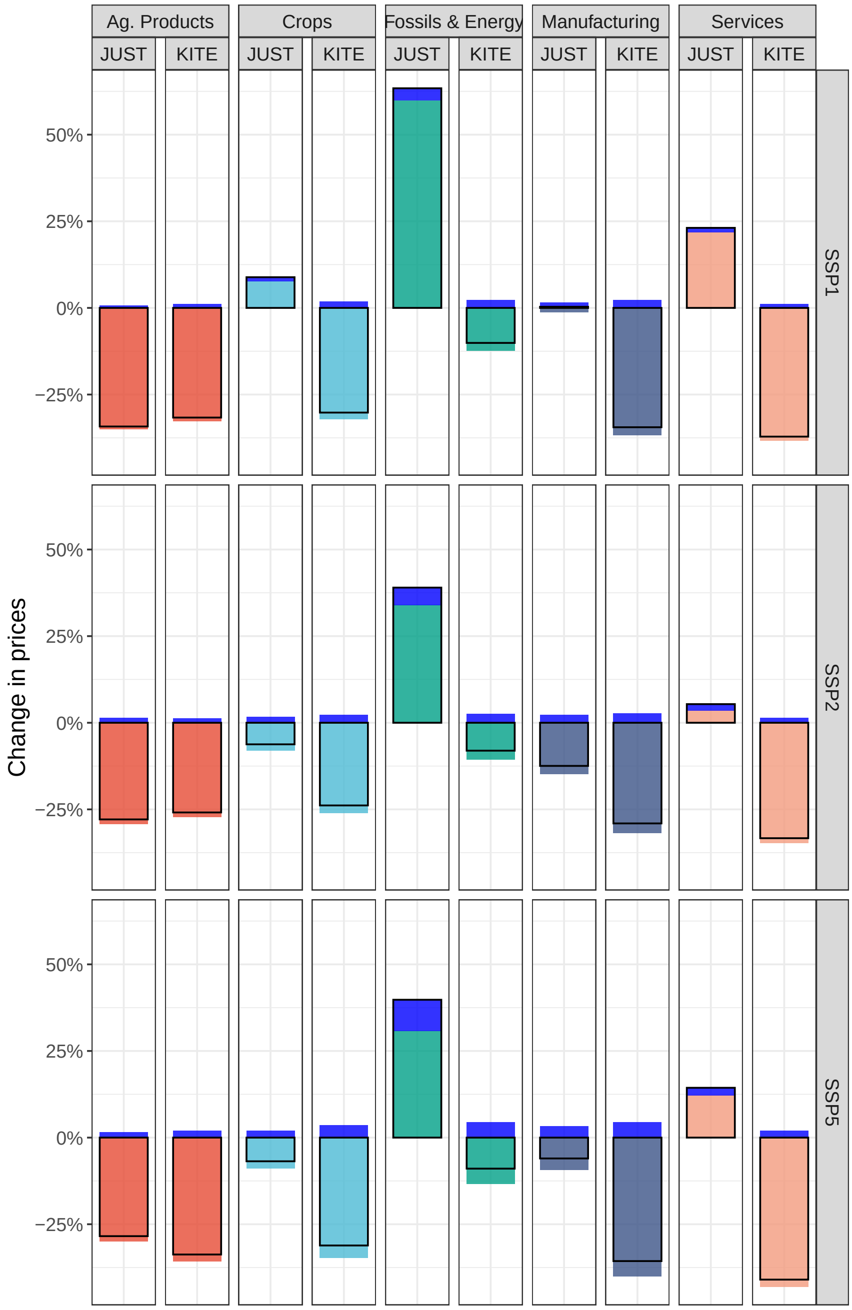
Note: Sectoral output price changes (left panel) and sectoral income changes (right panel) in India induced by carbon pricing compatible with 2°C climate policy under different assumptions of structural change (SSP1, SSP2, SSP5). The figures show the difference in the percentage changes over time (between 2015 and 2030) between climate policy scenarios (SSP1-CP, SSP2-CP, SSP5-CP) and the corresponding baseline scenarios (SSP1_Base, SSP2_Base, SSP5_Base). Sectoral output from the JUST model is aggregated to five sectors with Agricultural Products and Crops representing the agricultural sector, and Fossil & Energy and Manufacturing representing the manufacturing sector.

Figure B.3: Sectoral output price changes and sectoral income changes in India induced by carbon pricing with 1.5°C climate policy (KITE model).



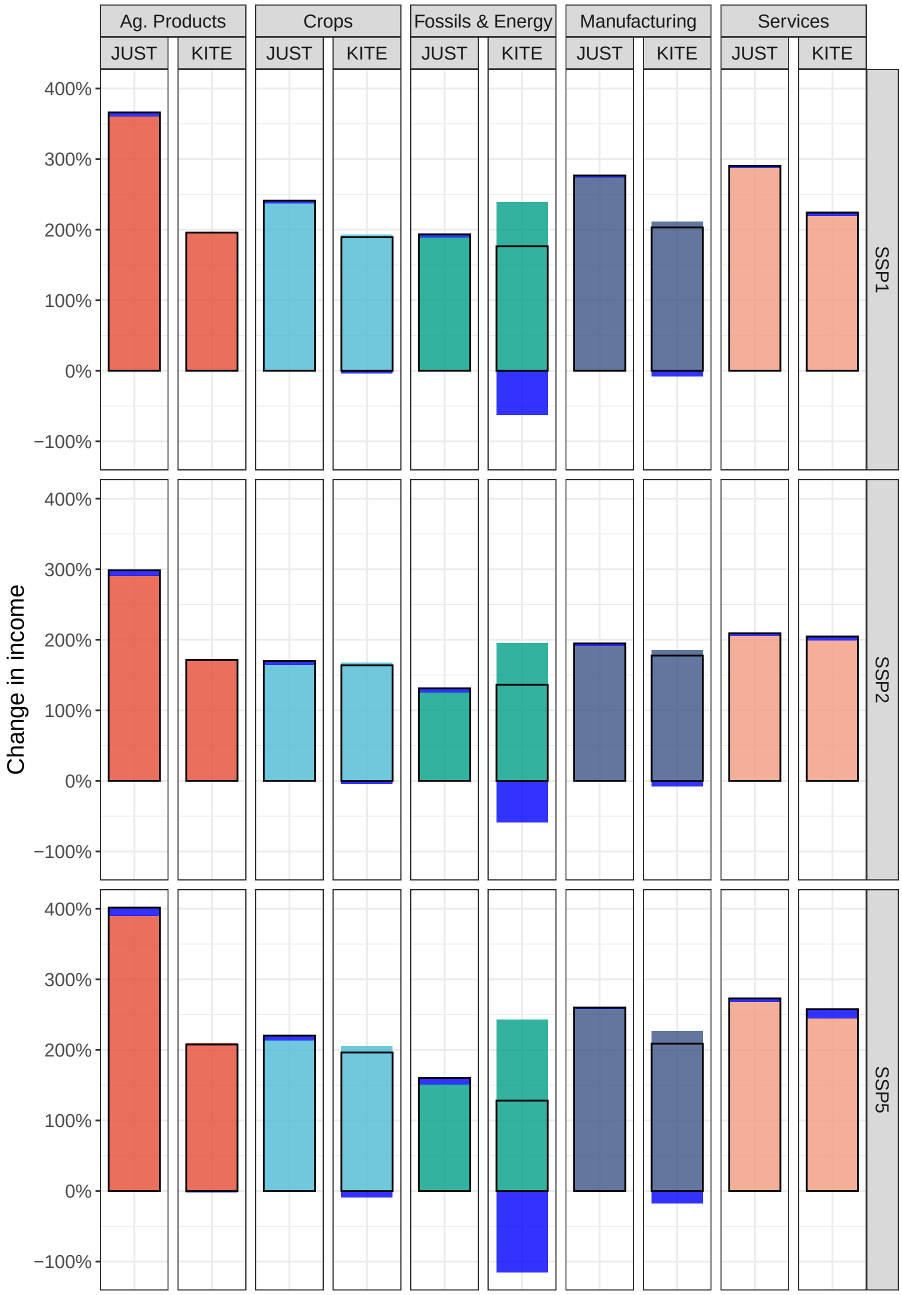
Note: Sectoral output price changes (left panel) and sectoral income changes (right panel) in India induced by carbon pricing compatible with 1.5°C climate policy under different assumptions of structural change (SSP1, SSP2, SSP5). The figures show the difference in the percentage changes over time (between 2015 and 2030) between climate policy scenarios (SSP1-CP-1.5, SSP2-CP-1.5, SSP5-CP-1.5) and the corresponding baseline scenarios (SSP1_Base, SSP2_Base, SSP5_Base). Sectoral output from the KITE model is aggregated to five sectors with Agricultural Products and Crops representing the agricultural sector, and Fossil & Energy and Manufacturing representing the manufacturing sector.

Figure B.4: Sectoral output price changes in India computed by the models KITE and JUST.



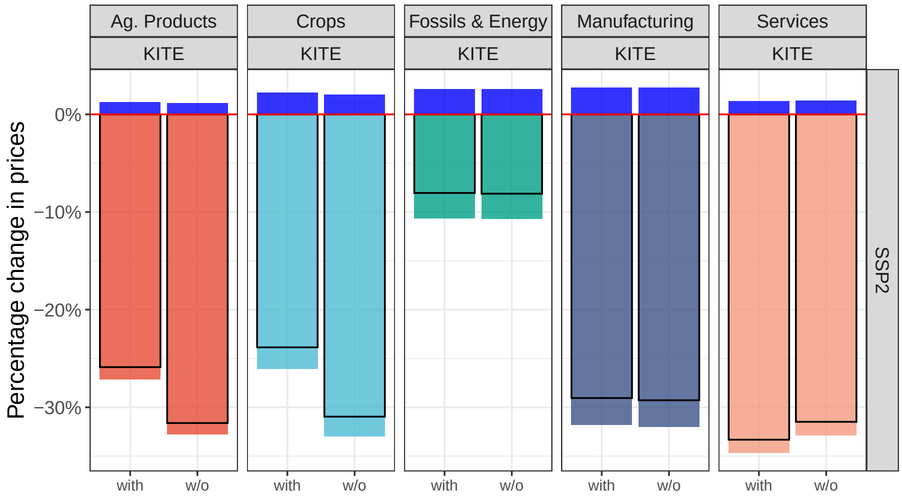
Note: Sectoral output price changes in India computed by the models KITE and JUST. Each bar shows the relative difference between 2015 and 2030. The differential impact of climate policy is represented by the embedded dark blue bar. Sectoral output from KITE and JUST is aggregated to five sectors with Agricultural Products and Crops representing the agricultural sector, and Fossil & Energy and Manufacturing representing the manufacturing sector.

Figure B.5: Sectoral income changes in India computed by the models KITE and JUST.



Note: Sectoral income changes in India computed by the models KITE and JUST. Each bar shows the relative difference between 2015 and 2030. The differential impact of climate policy is represented by the embedded dark blue bar. Sectoral output from KITE and JUST is aggregated to five sectors with Agricultural Products and Crops representing the agricultural sector, and Fossil & Energy and Manufacturing representing the manufacturing sector.

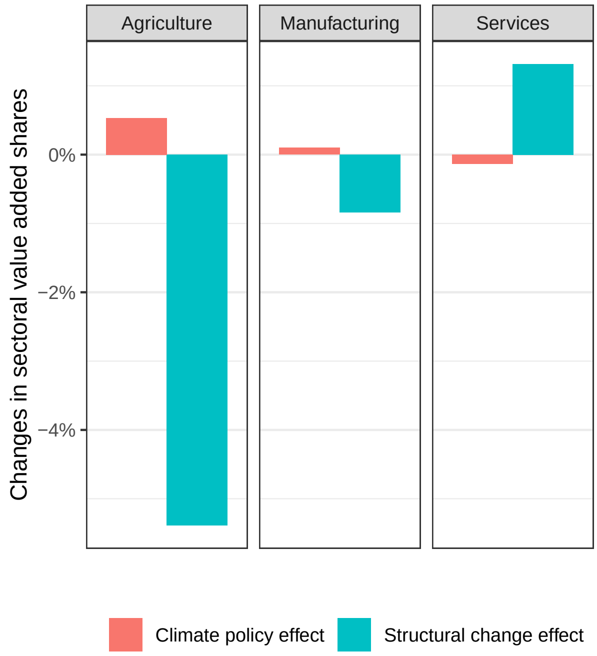
Figure B.6: Sectoral output price changes in India computed by the KITE model.



Note: Sectoral output price changes in India computed by the KITE model. Each bar shows the relative difference between 2015 and 2030. Each panel pairs off price changes from SSP2 scenarios with structural change ("with") and without structural change ("w/o"). The differential impact of climate policy is represented by the embedded dark blue bar. Sectoral output from KITE is aggregated to five sectors with Agricultural Products and Crops representing the agricultural sector, and Fossil & Energy and Manufacturing representing the manufacturing sector.

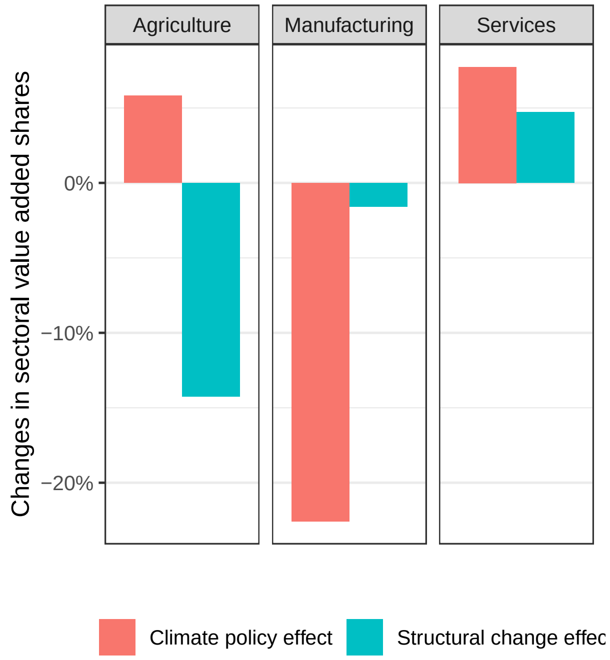
B.4 Development impacts of carbon pricing

Figure B.7: Change in Indian sectoral value-added shares (in 2030) caused by structural change and 2°C climate policy.



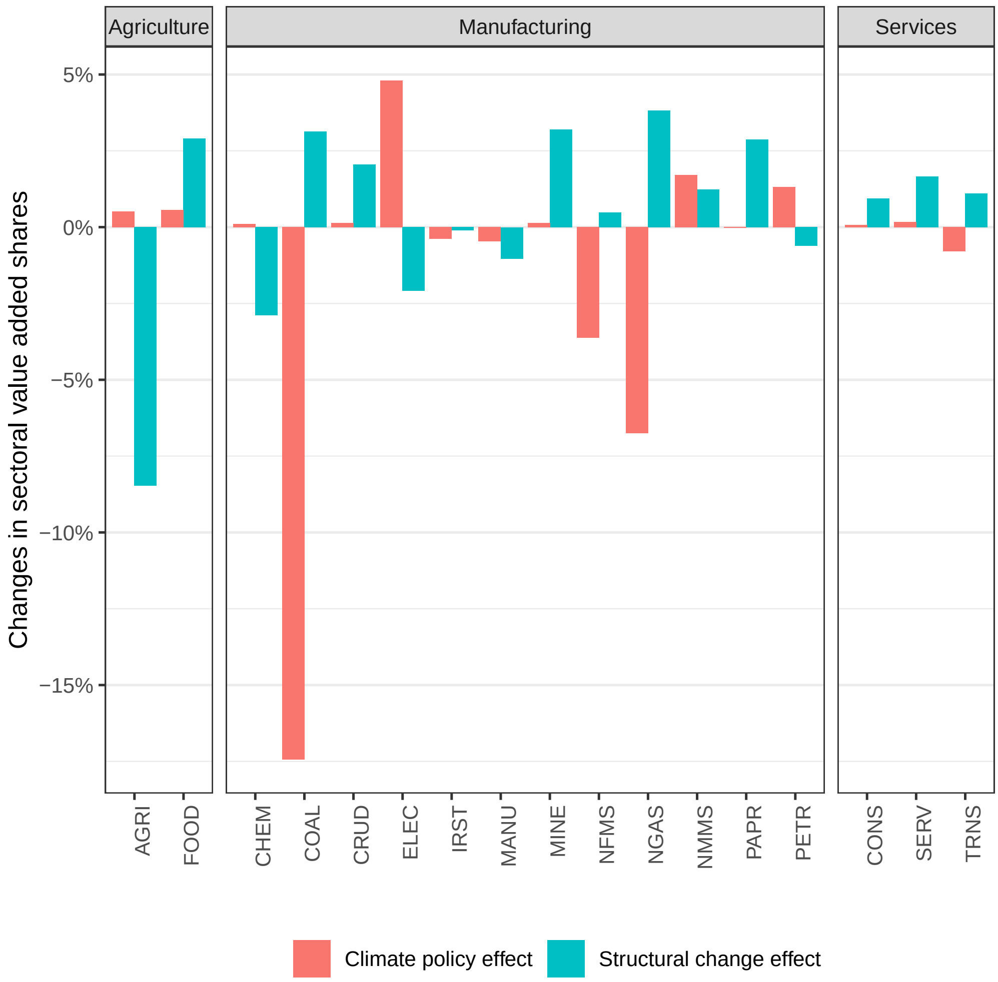
Note: Change in Indian sectoral value-added shares (in 2030) caused by structural change (red bar) and 2°C climate policy (blue bar). The former represents the difference between scenarios with and without structural change (no climate policy); the latter represents the difference between scenarios with and without climate policy (no structural change). Changes are measured in % of sectoral shares of baseline scenario NoSC_Base (no policy, no structural change); based on JUST model results.

Figure B.8: Change in Indian sectoral value-added shares (in 2030) caused by structural change and ambitious climate policy.



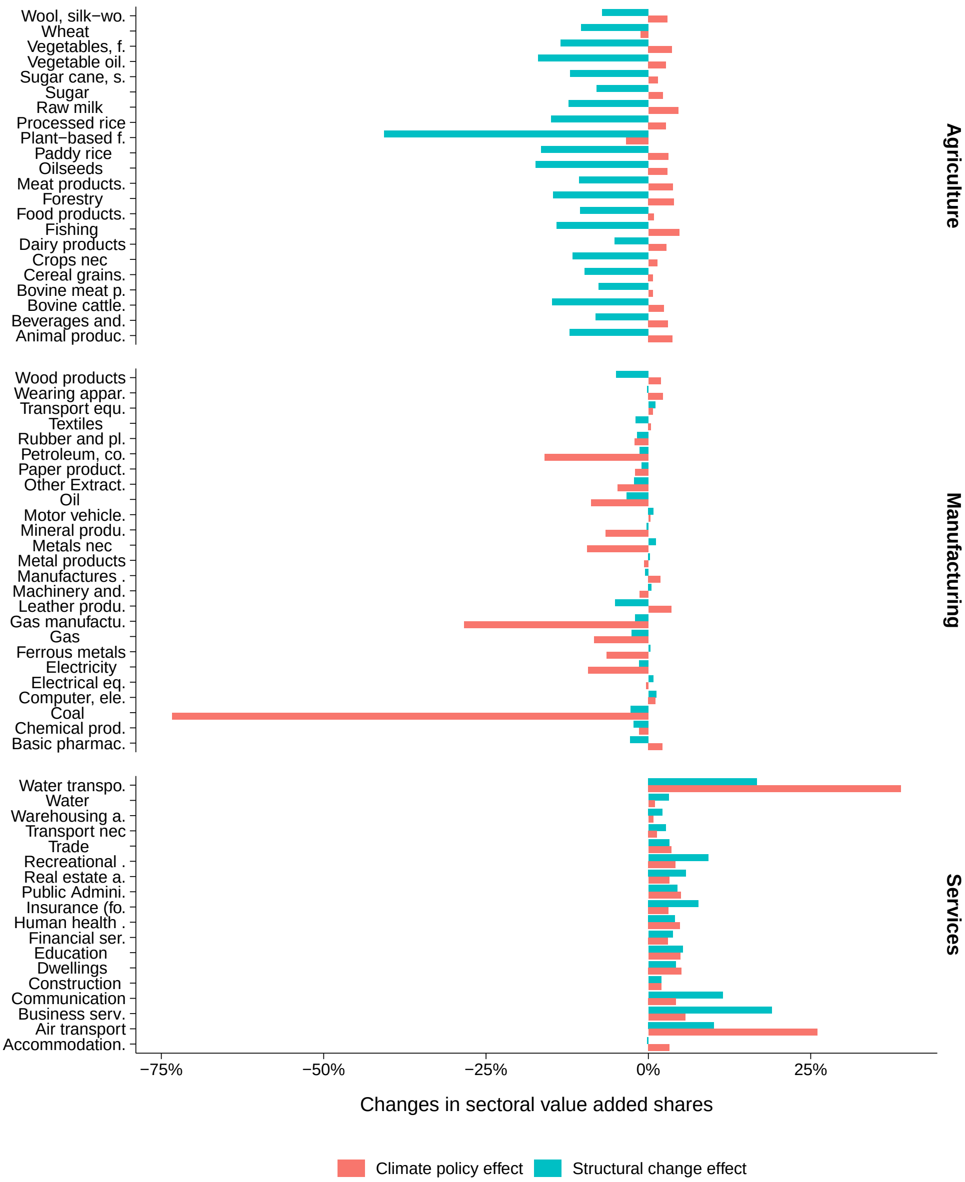
Note: Change in Indian sectoral value-added shares (in 2030) caused by structural change (red bar) and ambitious (1.5°C compatible) climate policy (blue bar). The former represents the difference between scenarios with and without structural change (no climate policy); the latter represents the difference between scenarios with and without climate policy (no structural change). Changes are measured in % of sectoral shares of baseline scenario NoSC_Base (no policy, no structural change); based on KITE model results.

Figure B.9: Changes in Indian sectoral value-added shares caused by structural change and 2°C climate policy, JUST.



Note: Changes in Indian sectoral value-added shares caused by structural change and 2°C climate policy; measured in % of the respective sectoral value-added shares in the baseline scenario NoSC_Base (no policy, no structural change); based on JUST model results; see Table A.1 for sector description.

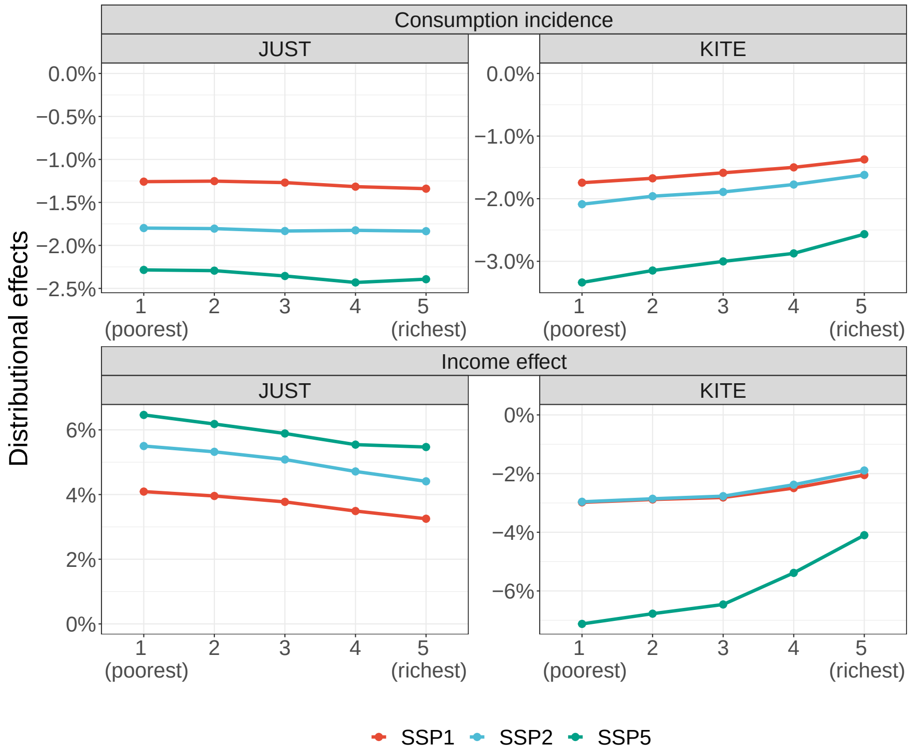
Figure B.10: Changes in Indian sectoral value-added shares caused by structural change and 2°C climate policy, KITE.



Note: Changes in Indian sectoral value-added shares caused by structural change and 2°C climate policy; measured in % of the respective sectoral value-added shares in the baseline scenario NoSC_Base (no policy, no structural change); based on KITE model results; see Table A.1 for sector description.

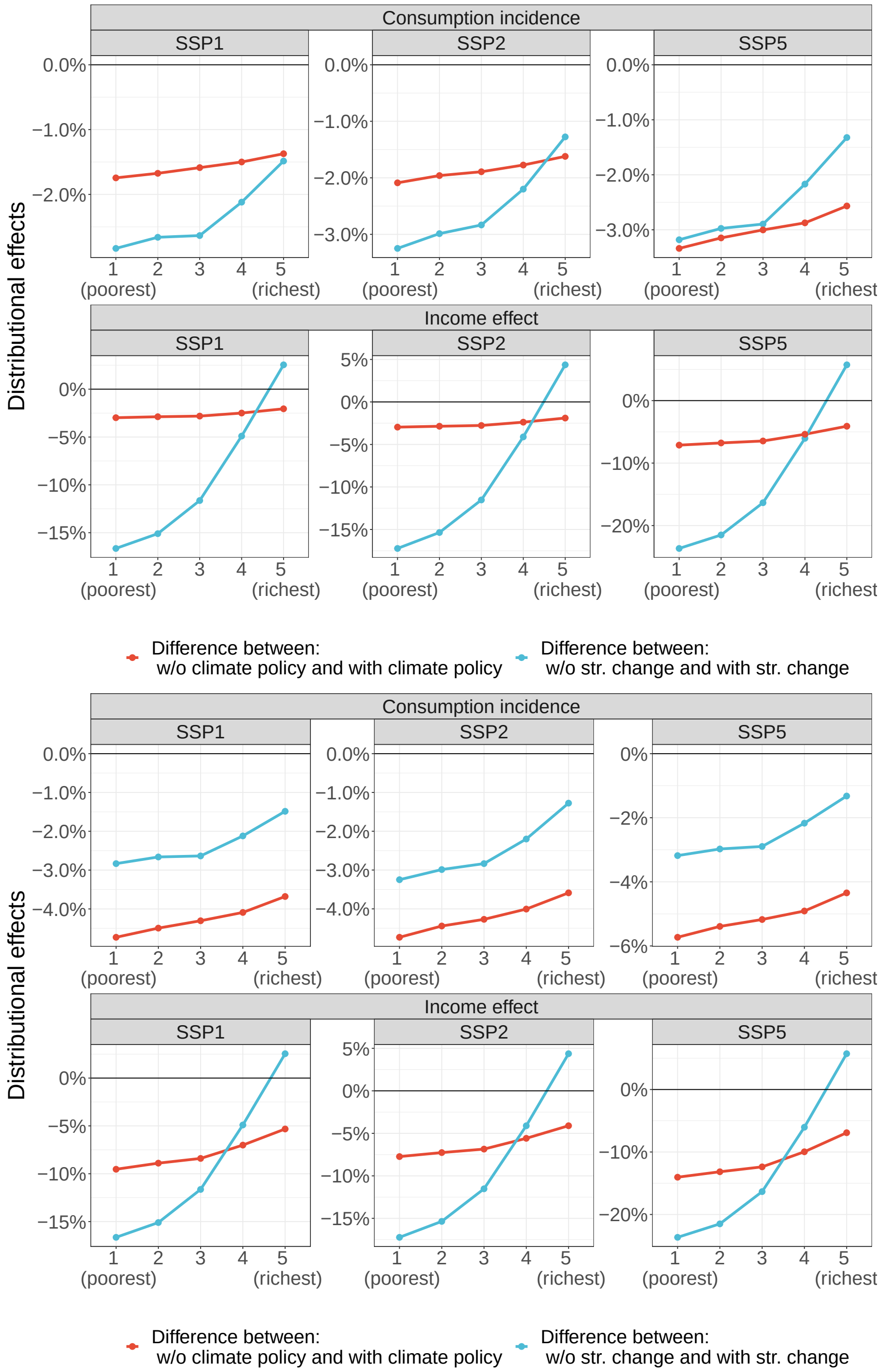
B.5 Distributional impacts of carbon pricing and structural change

Figure B.11: Consumption incidence and changes in income across Indian income groups due to 2°C climate policy.



Note: Consumption incidence and changes in income across Indian income groups due to 2°C climate policy under different assumptions on structural change (SSP1, SSP2, SSP5) based on JUST and KITE model output. Negative values indicate that consumption incidence/income values are lower in scenarios with carbon pricing.

Figure B.12: Consumption incidence and changes in income across Indian income groups due to climate policy and structural change.



Note: Consumption incidence and changes in income across Indian income groups due to climate policy (upper panel: 2°C scenario, lower panel: 1.5°C scenario) and structural change based on KITE model ourput. The red lines represent the differences in consumption incidence and income in a scenario with climate policy (SSP1-CP, SSP2-CP, SSP5-CP, SSP1-CP-1.5, SSP2-CP-1.5, SSP5-CP-1.5) and a scenario without climate policy (SSP1-Base, SSP2-Base, SSP5-Base). The blue lines represent the respective differences between scenarios with (SSP1-Base, SSP2-Base, SSP5-Base) and without structural change (NoSC-Base). Negative values indicate that consumption incidence/income values are lower in scenarios with climate policand structural change, respectively.

B.6 Sector mapping

Both advanced trade models use GTAP data. While the default setting in KITE is the sectoral resolution given by GTAP (Column (1) in Table B.1), the JUST model uses the sectoral aggregation as shown in Column (3) of Table B.1. To provide consistent and comparable sectoral results, KITE und JUST results are aggregated to five sectors (Column 4). These sectors are finally mapped onto the three sectors (agriculture, manufacturing and services) used at the macro level of this study.

Table B.1: Sector mapping related to the JUST and KITE trade models

GTAP (KITE)	Explanation	JUST sectors	KITE+JUST aggregation	Macro aggregation
pdr	Rice	AGRI	Crops	Agriculture
wht	Wheat	AGRI	Crops	Agriculture
gro	Other Grains	AGRI	Crops	Agriculture
v_f	Vegetables	AGRI	Crops	Agriculture
osd	Oil Seeds	AGRI	Crops	Agriculture
c_b	Sugar Crops	AGRI	Crops	Agriculture
pfb	Fibre Crops	AGRI	Crops	Agriculture
ocr	Other Crops	AGRI	Crops	Agriculture
ctl	Cattle	AGRI	Ag. Products	Agriculture
oap	Other Animal Prod.	AGRI	Ag. Products	Agriculture
rmk	Raw Milk	AGRI	Ag. Products	Agriculture
wol	Wool	AGRI	Ag. Products	Agriculture
frs	Forestry	AGRI	Ag. Products	Agriculture
fsh	Fishing	AGRI	Ag. Products	Agriculture
coa	Coal Mining	COAL	Fossil & Energy	Manufacturing
oil	Crude Oil Extraction	CRUD	Fossil & Energy	Manufacturing
gas	Gas Extraction	NGAS	Fossil & Energy	Manufacturing
oxt	Other Mining	MINE	Fossil & Energy	Manufacturing
cmt	Cattle Meat	FOOD	Ag. Products	Agriculture
omt	Other Meat	FOOD	Ag. Products	Agriculture
vol	Vegetable Oils	FOOD	Ag. Products	Agriculture
mil	Dairy Products	FOOD	Ag. Products	Agriculture
pcr	Processed Rice	FOOD	Ag. Products	Agriculture
sgr	Sugar, Molasses	FOOD	Ag. Products	Agriculture
ofd	Prepared Fish	FOOD	Ag. Products	Agriculture
b_t	Beverages, Tobacco	FOOD	Ag. Products	Agriculture
tex	Textile Manufacture	MANU	Manufacturing	Manufacturing
wap	Apparel Manufacture	MANU	Manufacturing	Manufacturing
lea	Leather Products	MANU	Manufacturing	Manufacturing

Continued on next page

Table B.1 – *Continued from previous page*

GTAP (KITE)	Explanation	JUST sectors	KITE+JUST aggregation	Macro aggregation
lum	Wood Products	MANU	Manufacturing	Manufacturing
ppp	Paper Products	PAPR	Manufacturing	Manufacturing
p_c	Petroleum, Coke	PETR	Manufacturing	Manufacturing
chm	Chemicals	CHEM	Manufacturing	Manufacturing
bph	Pharmaceuticals	CHEM	Manufacturing	Manufacturing
rpp	Rubber, Plastics	CHEM	Manufacturing	Manufacturing
nmm	Non-Metallic Mineral	MANU	Manufacturing	Manufacturing
i_s	Iron, Steel	IRST	Manufacturing	Manufacturing
nfm	Non-Ferrous Metals	NFMS	Manufacturing	Manufacturing
fmp	Metal Products	MANU	Manufacturing	Manufacturing
ele	Computer Manufacture	MANU	Manufacturing	Manufacturing
eeq	Electrical Equipment	MANU	Manufacturing	Manufacturing
ome	Machinery	MANU	Manufacturing	Manufacturing
mvh	Motor Vehicles	MANU	Manufacturing	Manufacturing
otn	Transport Equipment	MANU	Manufacturing	Manufacturing
omf	Other Manufacturing	MANU	Manufacturing	Manufacturing
ely	Electricity Supply	ELEC	Fossil & Energy	Manufacturing
gdt	Gas Manufacture	NGAS	Fossil & Energy	Manufacturing
wtr	Water Supply	SERV	Services	Services
cns	Construction	CONS	Services	Services
trd	Trade, Repair	SERV	Services	Services
afs	Accommodation	SERV	Services	Services
otp	Land Transport	TRNS	Services	Services
wtp	Water Transport	TRNS	Services	Services
atp	Air Transport	TRNS	Services	Services
whs	Warehousing	SERV	Services	Services
cmn	Communication	SERV	Services	Services
ofi	Financial Intermediation	SERV	Services	Services
ins	Insurance	SERV	Services	Services
rsa	Real Estate	SERV	Services	Services
obs	Business Services	SERV	Services	Services
ros	Recreation, Services	SERV	Services	Services
osg	Government Services	SERV	Services	Services
edu	Education	SERV	Services	Services
hht	Health, Social Work	SERV	Services	Services
dwe	Dwellings	SERV	Services	Services

Appendix C

The Carbon Footprint of Global Trade Imbalances

C.1 Data

Table C.1: GTAP 11 data overview, year 2017

GTAP code	Country	Trade imbalance	Value added
		in mn USD	
AFG	Afghanistan	-10962.01	17534.50
ALB	Albania	-2084.21	11624.34
ARE	United Arab Emirates	-45213.71	380190.19
ARG	Argentina	-16467.65	614827.57
ARM	Armenia	-2504.12	10680.23
AUS	Australia	44716.61	1276879.82
AUT	Austria	11352.65	373994.76
AZE	Azerbaijan	5830.05	39803.11
BEL	Belgium	-77291.52	434968.51
BEN	Benin	-6352.55	10655.25
BFA	Burkina Faso	-945.36	12771.27
BGD	Bangladesh	-23678.83	289266.25
BGR	Bulgaria	-461.37	53554.38
BHR	Bahrain	-889.43	35709.76
BLR	Belarus	-4782.38	48861.35
BOL	Bolivia	-3421.33	34853.30
BRA	Brazil	20756.47	1899122.24
BRN	Brunei	280.87	12191.09
BWA	Botswana	653.22	15641.08
CAF	Central African Republic	-224.17	1991.14
CAN	Canada	-35213.06	1555823.75
CHE	Switzerland	290.61	678568.63
CHL	Chile	11268.76	273848.55
CHN	China	169462.16	11604584.72
CIV	Cote d'Ivoire	65.11	48344.80
CMR	Cameroon	-3325.64	34297.76
COD	Congo - Kinshasa	2235.81	36566.63
COG	Congo - Brazzaville	2953.58	10316.62
COL	Colombia	-10532.70	296636.04
COM	Comoros	-350.67	960.17
CRI	Costa Rica	243.64	57987.47
CYP	Cyprus	-1361.80	18784.73
CZE	Czechia	33764.33	201846.49
DEU	Germany	274099.24	3368948.40
DNK	Denmark	-12819.62	263413.85
DOM	Dominican Republic	-1896.96	75781.84
DZA	Algeria	-18.88	161263.67
ECU	Ecuador	-571.04	101034.63
EGY	Egypt	-39506.28	237762.88
ESP	Spain	19449.08	1229429.22

Continued on next page

Table C.1 – *Continued from previous page*

GTAP code	Country	Trade imbalance	Value added
		in mn USD	
EST	Estonia	-2263.66	23607.38
ETH	Ethiopia	-19787.73	74451.15
FIN	Finland	-1280.01	230256.52
FRA	France	-52728.59	2424048.54
GAB	Gabon	1746.44	14765.89
GBR	United Kingdom	-158873.81	2513779.14
GEO	Georgia	-4762.61	15189.47
GHA	Ghana	-5033.30	55668.03
GIN	Guinea	1306.41	9370.98
GNQ	Equatorial Guinea	3416.36	12161.01
GRC	Greece	-15642.04	170621.56
GTM	Guatemala	-3502.57	70221.50
HKG	Hong Kong SAR China	-6400.83	330476.10
HND	Honduras	-2228.27	22600.02
HRV	Croatia	-2400.38	49892.40
HTI	Haiti	-222.59	488.97
HUN	Hungary	13297.51	128689.27
IDN	Indonesia	27412.07	1004428.04
IND	India	-153446.90	2557019.65
IRL	Ireland	78522.20	315075.54
IRN	Iran	19750.17	507665.12
IRQ	Iraq	27813.47	195671.75
ISR	Israel	-12401.69	314326.08
ITA	Italy	58076.44	1824860.15
JAM	Jamaica	-5072.57	12620.69
JOR	Jordan	-14046.57	39101.77
JPN	Japan	-16560.47	4845079.50
KAZ	Kazakhstan	6064.39	156855.99
KEN	Kenya	-13198.26	78993.63
KGZ	Kyrgyzstan	-8570.46	6626.25
KHM	Cambodia	-1432.88	21567.78
KOR	South Korea	121166.80	1521324.37
KWT	Kuwait	14973.24	121700.99
LAO	Laos	-523.18	17241.27
LBN	Lebanon	-16820.45	50127.60
LKA	Sri Lanka	-7996.45	80303.86
LTU	Lithuania	-4588.10	41138.62
LUX	Luxembourg	-4961.38	56938.91
LVA	Latvia	-4587.40	25358.64
MAR	Morocco	-11949.43	107715.16
MDG	Madagascar	-5.44	12875.94
MEX	Mexico	20313.53	1112055.76
MLI	Mali	-2055.71	14363.57
MLT	Malta	-4584.88	11913.43

Continued on next page

Table C.1 – *Continued from previous page*

GTAP code	Country	Trade imbalance	Value added
		in mn USD	
MNG	Mongolia	3266.21	11112.12
MOZ	Mozambique	-3792.03	12184.89
MUS	Mauritius	-2717.46	12292.48
MWI	Malawi	-2240.94	8604.44
MYS	Malaysia	49154.61	314167.80
NAM	Namibia	-1444.49	12407.94
NER	Niger	-536.59	10836.20
NGA	Nigeria	-5987.55	371978.92
NIC	Nicaragua	-765.97	13087.63
NLD	Netherlands	-19662.40	735370.41
NOR	Norway	1593.87	356961.67
NPL	Nepal	-9769.62	26237.56
NZL	New Zealand	6337.09	195992.05
OMN	Oman	-4524.81	81328.24
PAK	Pakistan	-46274.90	331450.34
PAN	Panama	-7308.85	59047.92
PER	Peru	12197.26	213160.79
PHL	Philippines	-32366.15	332338.11
POL	Poland	-1364.46	467511.27
PRI	Puerto Rico	-5464.08	102332.93
PRT	Portugal	-4591.61	199166.84
PRY	Paraguay	-3807.03	37558.38
PSE	Palestinian Territories	-2921.53	14982.85
QAT	Qatar	61635.19	166365.10
ROU	Romania	-9396.41	196511.51
RUS	Russia	117792.74	1558243.56
RWA	Rwanda	-1034.68	8708.94
SAU	Saudi Arabia	72364.16	699253.17
SDN	Sudan	-5348.82	126007.19
SEN	Senegal	-6114.24	18905.88
SGP	Singapore	-50121.32	298543.27
SLV	El Salvador	-2859.15	24200.11
SRB	Serbia	-2770.33	40849.83
SVK	Slovakia	12750.34	88612.48
SVN	Slovenia	-3259.74	42458.45
SWE	Sweden	8965.28	489046.11
SWZ	Eswatini	1.82	4468.83
SYR	Syria	-8673.42	14254.95
TCD	Chad	1588.71	9829.16
TGO	Togo	-3787.83	5021.02
THA	Thailand	34377.77	428723.51
TJK	Tajikistan	-2838.82	7101.17
TTO	Trinidad & Tobago	2144.04	22847.23
TUN	Tunisia	-4393.39	38060.62

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Table C.1 – *Continued from previous page*

GTAP code	Country	Trade imbalance in mn USD	Value added
TUR	Turkey	-47818.06	797091.82
TWN	Taiwan	33999.93	587944.27
TZA	Tanzania	-6187.20	47841.16
UGA	Uganda	-4427.63	29712.91
UKR	Ukraine	-4477.49	100601.88
URY	Uruguay	-690.31	59700.06
USA	United States	-715675.77	19122440.09
UZB	Uzbekistan	-3516.47	60860.11
VEN	Venezuela	7623.93	241153.28
VNM	Vietnam	-13373.02	213178.23
XAC	XAC	10140.37	68598.85
XCA	XCA	-1197.30	1422.08
XCB	XCB	-19863.45	142383.60
XEA	XEA	1523.27	66711.45
XEC	XEC	-8444.85	18323.36
XEE	XEE	-2639.72	7973.61
XEF	XEF	-572.81	28797.50
XER	XER	-9180.85	68013.25
XNA	XNA	31077.54	39272.78
XNF	XNF	7277.34	65982.31
XOC	XOC	-14452.18	51387.64
XSA	XSA	-93.24	6731.35
XSC	XSC	-590.75	2311.48
XSE	XSE	-5421.19	62743.72
XSM	XSM	-223.12	12708.54
XSU	XSU	3548.67	38080.99
XTW	XTW	-26.81	94.25
XWF	XWF	-7987.35	14963.57
XWS	XWS	-7035.12	19454.74
ZAF	South Africa	25448.79	364549.77
ZMB	Zambia	1620.75	25126.16
ZWE	Zimbabwe	-2424.02	16935.33

Table C.2: Emission footprints in 2017

GTAP code	Emission footprint in mn tons CO2		
	Production	Extraction	Consumption
AFG	6.61	6.58	19.63
ALB	5.93	3.31	8.20
ARE	190.79	632.55	241.96
ARG	178.94	121.41	192.99
ARM	5.77	0.01	7.98

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Table C.2 – *Continued from previous page*

GTAP code	Emission footprint in mn tons CO2		
	Production	Extraction	Consumption
AUS	401.61	1710.57	404.76
AUT	68.12	4.33	90.85
AZE	32.80	155.12	33.73
BEL	105.97	0.58	145.10
BEN	6.78	0.04	12.93
BFA	5.22	0.03	6.36
BGD	80.26	55.01	132.31
BGR	46.62	22.06	38.23
BHR	31.91	44.32	24.20
BLR	56.70	6.07	52.21
BOL	20.38	63.69	24.75
BRA	451.39	538.78	496.28
BRN	7.54	44.51	7.68
BWA	7.56	5.01	12.37
CAF	0.27	0.01	0.37
CAN	585.53	1323.78	515.19
CHE	51.85	0.60	117.28
CHL	95.37	6.62	94.12
CHN	9358.72	6021.62	8397.05
CIV	11.17	10.61	15.79
CMR	6.53	13.61	10.44
COD	2.25	5.03	7.63
COG	5.40	66.87	4.70
COL	74.68	338.10	95.17
COM	0.43	0.01	0.83
CRI	9.95	0.08	16.47
CYP	6.67	0.06	11.44
CZE	102.89	42.52	78.07
DEU	763.53	152.90	821.39
DNK	40.10	31.23	62.59
DOM	24.20	0.07	31.22
DZA	138.28	463.74	150.19
ECU	34.04	97.34	42.59
EGY	217.49	171.96	225.50
ESP	283.78	5.58	294.90
EST	8.42	2.84	10.60
ETH	14.88	0.16	33.22
FIN	49.13	4.29	53.62
FRA	341.11	3.20	476.56
GAB	2.71	43.01	4.03
GBR	429.57	194.04	617.45
GEO	10.01	0.62	14.48
GHA	13.17	37.05	25.64

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Table C.2 – *Continued from previous page*

GTAP code	Emission footprint in mn tons CO2		
	Production	Extraction	Consumption
GIN	3.64	0.03	4.86
GNQ	4.99	42.03	4.33
GRC	71.28	19.23	86.04
GTM	16.20	1.81	24.19
HKG	104.14	1.03	164.12
HND	9.40	0.07	13.10
HRV	18.48	3.29	23.66
HTI	0.11	0.01	0.23
HUN	51.19	5.85	46.26
IDN	497.35	1180.44	525.04
IND	2230.23	1000.13	2033.70
IRL	56.82	8.15	61.15
IRN	534.17	996.91	490.91
IRQ	96.28	801.14	132.55
ISR	67.84	10.94	88.60
ITA	347.65	13.78	421.53
JAM	8.98	0.04	11.12
JOR	24.58	0.16	34.70
JPN	1140.99	4.25	1232.25
KAZ	210.14	524.78	170.96
KEN	20.39	0.58	35.07
KGZ	9.13	2.73	17.16
KHM	11.25	0.13	16.76
KOR	607.11	3.31	488.01
KWT	80.84	488.89	73.44
LAO	17.69	14.61	10.48
LBN	28.49	0.10	42.35
LKA	24.40	0.10	42.41
LTU	13.18	0.22	18.02
LUX	11.49	0.08	16.32
LVA	9.87	0.12	14.12
MAR	60.63	0.20	74.50
MDG	5.43	0.05	7.01
MEX	442.75	372.66	486.19
MLI	3.28	0.03	5.22
MLT	8.62	0.03	9.00
MNG	19.37	118.88	15.87
MOZ	7.13	36.50	11.93
MUS	4.92	0.07	7.32
MWI	1.10	0.18	3.66
MYS	230.97	192.34	194.14
NAM	4.18	0.05	9.67
NER	2.09	2.48	3.39

Continued on next page

Table C.2 – *Continued from previous page*

GTAP code	Emission footprint in mn tons CO2		
	Production	Extraction	Consumption
NGA	89.98	391.70	131.37
NIC	5.36	0.02	7.85
NLD	193.93	60.64	177.08
NOR	54.55	525.77	60.76
NPL	15.48	0.12	32.01
NZL	37.74	18.81	46.91
OMN	64.57	262.00	65.36
PAK	190.55	16.71	240.42
PAN	42.63	0.23	24.51
PER	53.02	37.20	64.60
PHL	132.70	29.79	185.14
POL	308.61	165.73	279.79
PRI	11.44	0.04	21.09
PRT	60.84	0.27	63.07
PRY	7.77	0.11	14.40
PSE	3.34	0.02	8.01
QAT	87.45	707.22	44.60
ROU	74.67	42.68	85.76
RUS	1570.73	3581.05	1179.06
RWA	1.01	0.04	2.17
SAU	452.90	1924.04	389.41
SDN	16.08	11.75	24.25
SEN	8.65	0.10	14.41
SGP	92.94	0.57	116.22
SLV	7.31	0.03	11.37
SRB	47.88	32.50	40.17
SVK	33.05	0.44	30.45
SVN	16.06	3.78	18.49
SWE	40.63	0.36	73.73
SWZ	0.67	0.46	3.03
SYR	28.07	8.68	33.10
TCD	1.06	20.75	1.34
TGO	2.21	0.02	5.45
THA	258.24	52.62	225.92
TJK	7.19	4.05	9.86
TTO	19.89	60.23	9.63
TUN	28.40	7.50	28.57
TUR	411.69	51.22	454.72
TWN	274.79	0.65	203.00
TZA	10.82	3.00	19.28
UGA	4.26	0.04	9.67
UKR	188.43	75.42	130.78
URY	8.24	0.02	12.59

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Table C.2 – *Continued from previous page*

GTAP code	Emission footprint in mn tons CO2		
	Production	Extraction	Consumption
USA	4932.65	4202.15	5542.54
UZB	106.39	136.32	100.99
VEN	120.47	296.47	109.84
VNM	194.56	143.61	206.70
XAC	20.18	358.65	26.75
XCA	0.48	0.11	1.10
XCB	39.26	6.21	53.86
XEA	24.51	34.41	33.37
XEC	8.37	30.70	15.32
XEE	8.25	0.12	10.10
XEF	4.46	0.05	6.21
XER	49.16	21.30	50.14
XNA	6.70	0.04	2.40
XNF	43.13	173.72	47.97
XOC	23.38	11.06	30.23
XSA	3.69	0.52	4.55
XSC	3.55	0.07	5.13
XSE	31.52	128.94	43.18
XSM	5.05	2.71	5.16
XSU	68.31	203.29	56.38
XTW	0.01	0.00	0.03
XWF	32.26	0.40	19.63
XWS	8.33	4.06	14.48
ZAF	436.15	502.87	304.39
ZMB	6.05	1.89	9.21
ZWE	9.83	6.34	12.79

Figure C.1: Embodied CO2 emissions imbalance in international trade, by year.

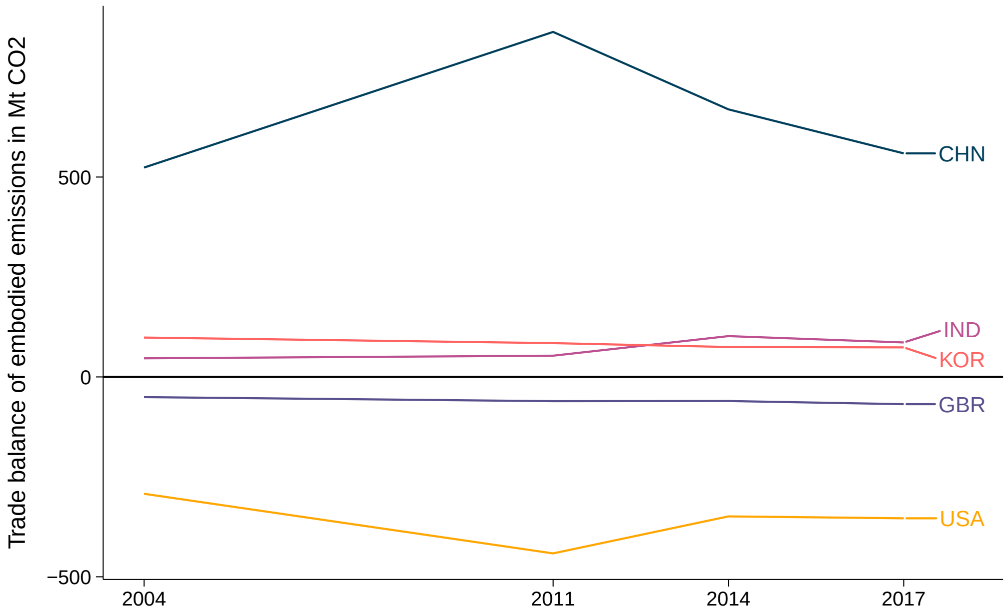
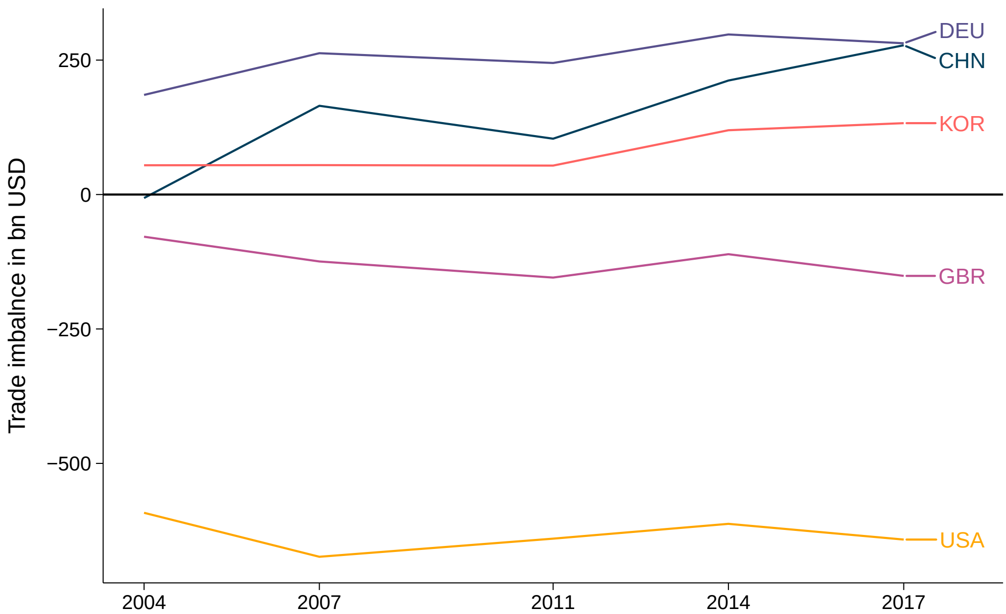


Figure C.2: Trade imbalance, by year.



C.2 Detailed results

C.2.1 Figures

Figure C.3: Change in global carbon emissions per absolute value of removing trade imbalance per country, each country balanced separately.

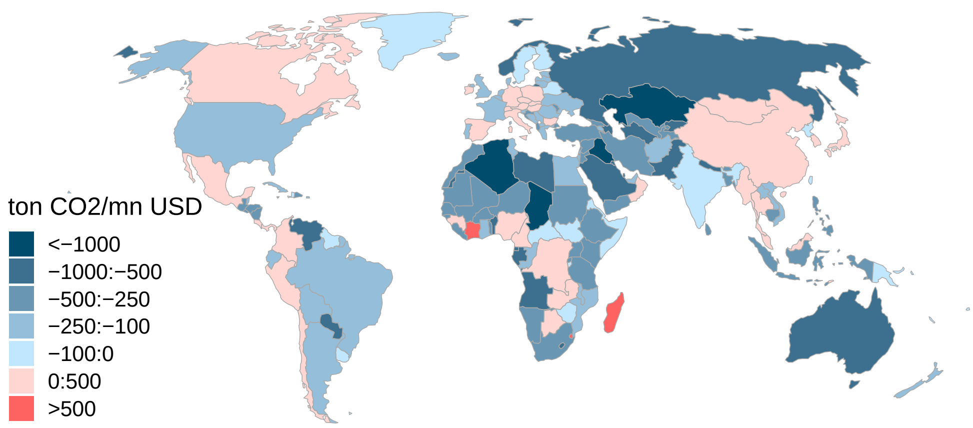


Figure C.4: Percentage change in carbon emissions, USA balanced.

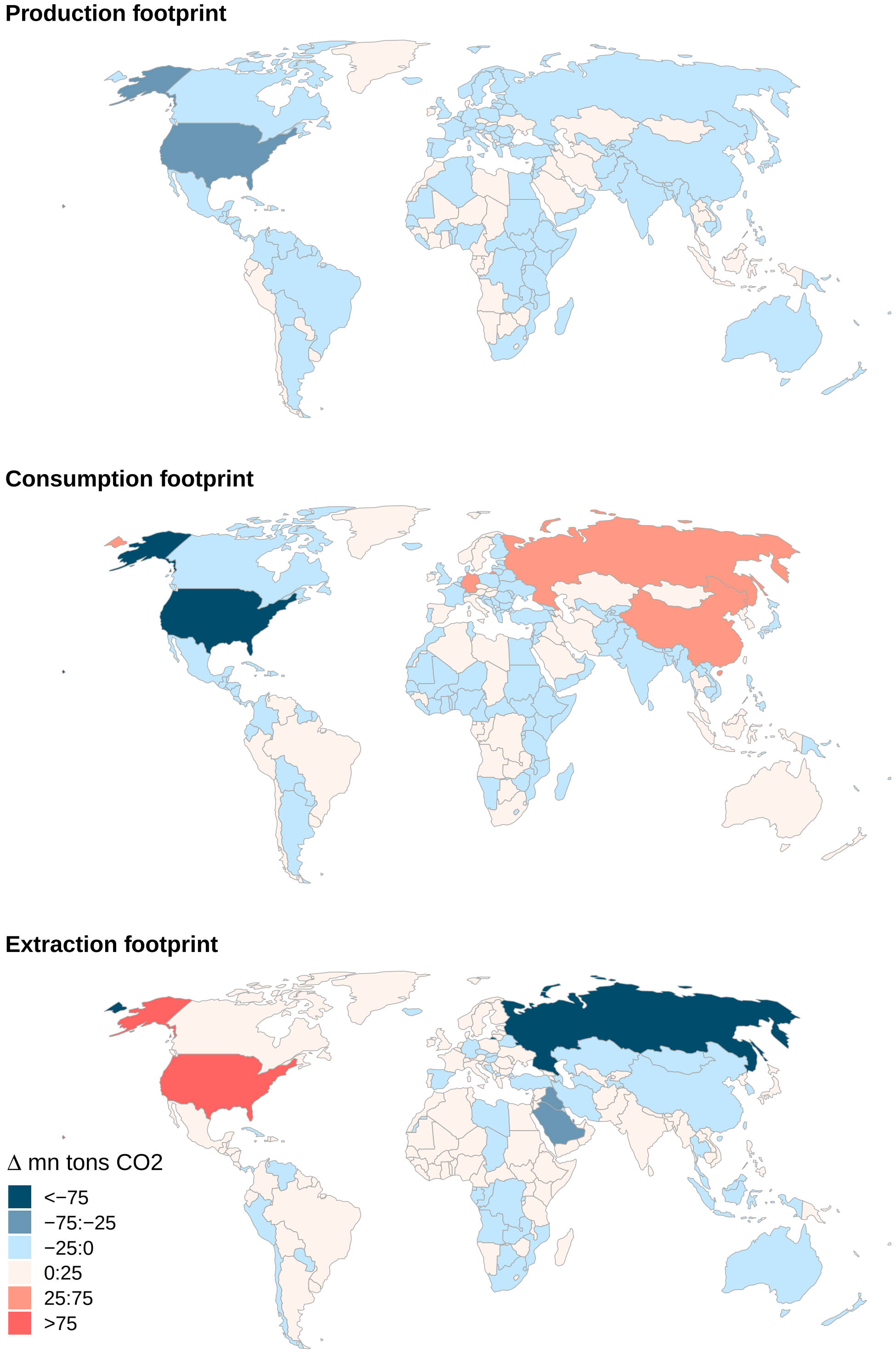
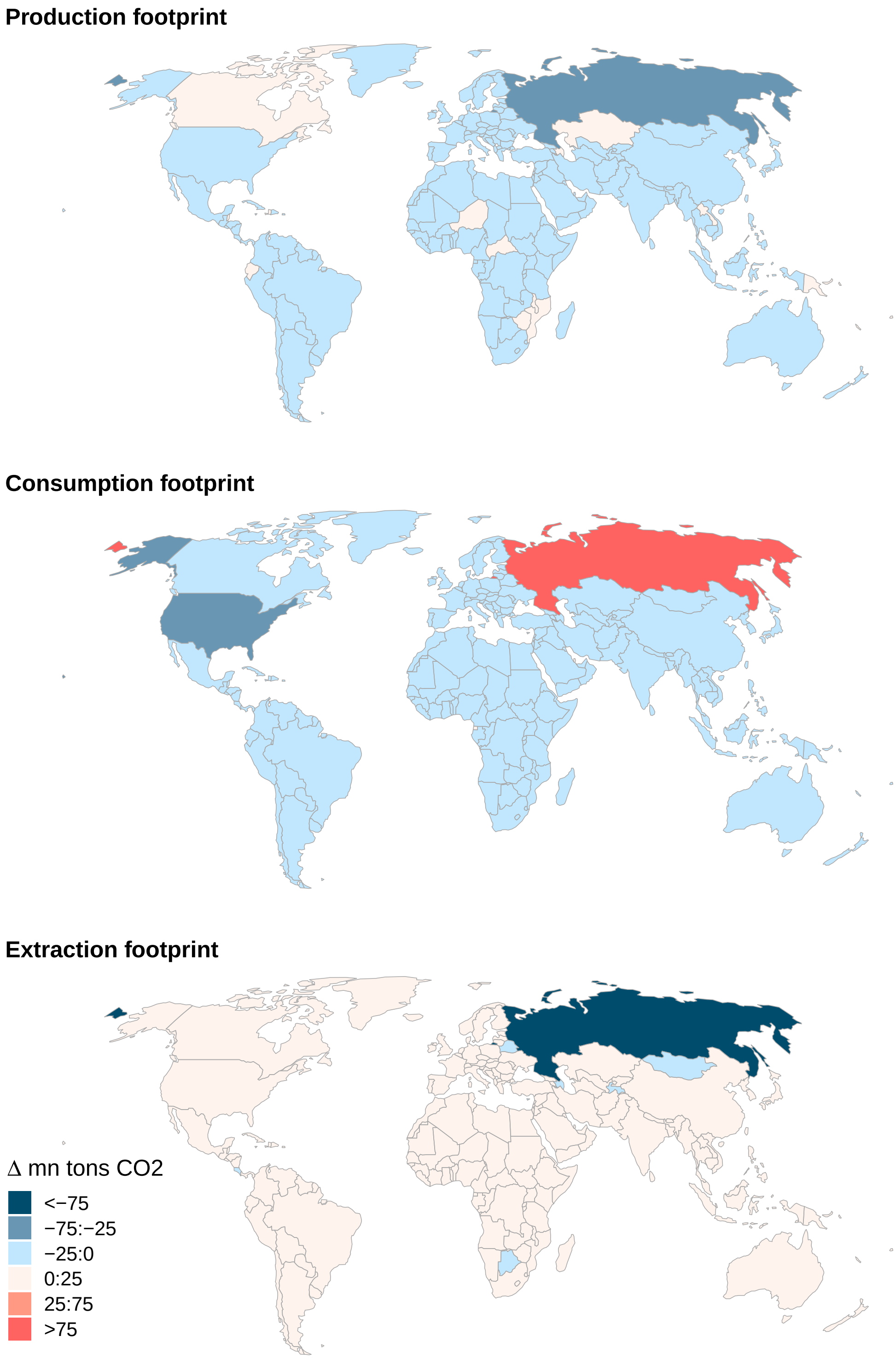


Figure C.5: Percentage change in carbon emissions, Russia balanced.



C.2.2 Tables

Table C.3: Countries' corresponding emission changes in mn tons CO2, each countries balanced individually

Country	Countries' footprint change			Global emission
	Production	Consumption	Extraction	change
		in mn tons CO2		
AFG	0.33	-9.79	2.49	-1.37
ALB	-0.17	-1.67	0.20	-0.81
ARE	-4.14	-24.88	14.03	-4.79
ARG	-0.26	-7.17	3.32	-2.37
ARM	-0.12	-1.80	0.00	-0.34
AUS	-5.16	22.95	-56.53	-26.25
AUT	0.13	4.47	-0.08	0.55
AZE	2.49	6.30	-11.70	-3.40
BEL	0.10	-26.00	0.04	-15.47
BEN	-1.92	-5.73	0.01	-3.37
BFA	-0.02	-0.41	0.00	-0.27
BGD	-0.65	-16.42	1.05	-7.55
BGR	0.01	0.15	-0.01	0.03
BHR	0.09	-0.52	0.21	0.05
BLR	-0.80	-4.74	0.20	-0.42
BOL	-0.49	-1.55	1.94	-0.39
BRA	0.21	18.25	-13.03	-3.53
BRN	0.06	0.27	-0.69	-0.24
BWA	0.04	0.92	-0.12	0.06
CAF	0.02	-0.07	0.00	-0.00
CAN	3.91	-12.87	20.32	1.76
CHE	0.05	0.91	-0.00	0.04
CHL	-0.11	5.87	-0.19	0.76
CHN	25.43	263.40	-74.90	17.43
CIV	0.03	0.25	-0.06	0.03
CMR	0.19	-1.45	1.49	0.13
COD	0.02	0.98	-0.20	0.52
COG	1.00	2.98	-3.05	-0.53
COL	-0.33	-4.98	13.10	2.63
COM	-0.12	-0.32	0.00	-0.20
CRI	0.04	0.22	0.00	0.04
CYP	-0.44	-1.69	-0.00	-0.32
CZE	1.48	19.60	-1.70	1.86
DEU	7.57	113.34	-6.71	9.12
DNK	0.23	-3.64	0.76	-1.84
DOM	-0.22	-0.84	0.00	-0.49
DZA	0.47	1.05	-2.17	-0.69
ECU	0.04	0.19	-0.29	-0.08
EGY	-6.31	-39.98	20.78	-5.13

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Table C.3 – *Continued from previous page*

Country	Countries' footprint change			Global emission change
	Production	Consumption	Extraction	
	in mn tons CO2			
ESP	-0.11	8.62	-0.10	0.30
EST	0.06	-1.08	0.08	-0.31
ETH	-0.35	-12.99	0.13	-7.90
FIN	0.02	-0.14	0.01	-0.07
FRA	-0.40	-14.35	0.06	-9.78
GAB	0.10	0.74	-3.02	-1.15
GBR	-5.36	-52.15	8.87	-24.14
GEO	-0.95	-4.35	0.06	-1.62
GHA	-0.31	-2.34	2.60	-0.60
GIN	0.18	1.18	0.00	0.32
GNQ	0.18	1.91	-9.72	-3.38
GRC	0.39	-9.69	0.63	-3.44
GTM	-0.18	-1.76	0.06	-0.96
HKG	-0.19	-6.94	0.01	-2.40
HND	-0.35	-1.49	0.00	-0.85
HRV	-0.11	-1.33	0.08	-0.68
HTI	0.01	-0.09	0.00	-0.01
HUN	0.15	7.34	-0.31	0.73
IDN	4.06	29.70	-40.46	-10.71
IND	-6.48	-127.41	48.61	-15.13
IRL	5.51	24.89	0.00	1.89
IRN	-0.73	11.04	-18.11	-7.23
IRQ	10.36	25.19	-93.52	-31.70
ISR	-0.34	-4.80	0.36	-2.22
ITA	2.25	25.16	-0.41	2.40
JAM	-0.63	-3.77	0.01	-1.38
JOR	-4.21	-11.10	0.02	-5.47
JPN	0.17	6.10	-0.02	0.39
KAZ	-0.08	15.03	-22.44	-8.83
KEN	-0.60	-8.89	0.12	-3.79
KGZ	-3.32	-10.64	0.10	-4.61
KHM	-0.24	-0.84	0.00	-0.40
KOR	-8.16	68.09	-0.24	0.96
KWT	3.11	12.86	-32.86	-11.87
LAO	0.31	-0.34	0.36	-0.06
LBN	-3.56	-13.45	0.02	-5.53
LKA	-1.28	-5.50	0.01	-2.75
LTU	0.02	-2.11	0.01	-0.98
LUX	-0.24	-1.59	0.00	-1.06
LVA	-0.05	-2.48	0.01	-0.86
MAR	-2.18	-8.97	0.01	-4.72
MDG	0.00	0.02	-0.00	0.01
MEX	2.58	14.86	-4.17	1.26

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Table C.3 – *Continued from previous page*

Country	Countries' footprint change			Global emission change
	Production	Consumption	Extraction	
	in mn tons CO2			
MLI	0.05	-0.90	0.01	-0.63
MLT	-0.23	-2.70	0.00	-1.15
MNG	4.32	8.69	-7.67	0.38
MOZ	0.42	-3.54	3.66	-0.58
MUS	-0.31	-1.59	0.01	-0.72
MWI	0.07	-1.42	0.07	-0.47
MYS	8.27	45.46	-10.69	3.56
NAM	-0.13	-1.29	0.00	-0.47
NER	0.01	-0.23	0.05	-0.14
NGA	-0.86	-3.42	9.17	2.16
NIC	-0.15	-0.47	0.00	-0.28
NLD	0.64	-4.94	0.69	-2.30
NOR	-0.21	0.73	-3.15	-1.30
NPL	-1.12	-14.12	0.04	-6.23
NZL	-0.26	3.31	-0.68	-1.10
OMN	-0.80	-3.20	5.84	0.92
PAK	-19.56	-46.19	2.78	-25.46
PAN	3.47	-3.95	0.06	1.37
PER	1.13	6.18	-1.07	0.98
PHL	-5.15	-22.61	1.11	-10.55
POL	0.08	0.47	-0.05	0.07
PRI	-0.47	-2.14	0.00	-1.27
PRT	0.05	-1.49	0.00	-0.77
PRY	-0.64	-1.89	-0.00	-2.05
PSE	-0.85	-2.91	0.02	-1.80
QAT	-1.53	35.32	-136.36	-52.89
ROU	-0.35	-4.27	0.65	-2.14
RUS	-33.37	104.52	-248.51	-113.14
RWA	-0.05	-0.39	0.01	-0.31
SAU	0.49	56.64	-117.01	-45.58
SDN	-0.53	-2.82	0.62	-1.77
SEN	-0.87	-4.49	0.01	-2.40
SGP	1.71	-19.86	0.04	-7.18
SLV	-0.22	-1.60	0.00	-0.99
SRB	0.07	-1.92	0.25	-0.43
SVK	0.48	7.27	-0.02	1.55
SVN	0.09	-1.45	0.14	-0.63
SWE	-0.09	2.68	-0.01	-0.11
SWZ	0.01	0.08	-0.00	0.03
SYR	-4.23	-15.03	1.40	-4.22
TCD	0.06	0.49	-4.44	-1.76
TGO	-0.22	-2.58	0.00	-1.34
THA	3.20	33.73	-2.36	3.35

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Table C.3 – *Continued from previous page*

Country	Countries' footprint change			Global emission change
	Production	Consumption	Extraction	
	in mn tons CO2			
TJK	0.03	-3.11	0.21	-0.74
TTO	-1.05	1.44	-4.16	-1.63
TUN	-0.78	-2.96	0.35	-1.02
TUR	-5.34	-32.17	2.06	-12.58
TWN	-4.62	21.33	-0.04	-1.72
TZA	-0.15	-3.25	0.20	-1.66
UGA	-0.15	-2.27	0.01	-1.27
UKR	-0.39	-2.89	0.56	-0.50
URY	-0.00	0.21	-0.00	-0.01
USA	-26.78	-324.43	140.59	-78.49
UZB	-0.89	-4.98	4.34	-1.26
VEN	-1.09	5.35	-17.58	-7.02
VNM	-1.55	-6.15	0.17	-2.43
XAC	1.54	6.47	-28.41	-9.78
XCA	-0.01	-0.58	0.02	-0.17
XCB	-1.05	-8.82	0.50	-3.75
XEA	0.11	1.15	-0.43	-0.08
XEC	-0.54	-5.60	4.55	-0.39
XEE	-0.80	-2.90	0.01	-0.97
XEF	0.01	-0.17	0.00	-0.10
XER	0.58	-6.67	1.30	-1.62
XNA	2.13	10.19	-0.00	-1.79
XNF	3.14	6.81	-15.12	-4.22
XOC	1.46	-7.66	1.59	-1.32
XSA	-0.01	-0.06	0.00	-0.05
XSC	-0.27	-1.15	0.00	-0.43
XSE	-0.71	-4.47	13.29	0.72
XSM	-0.00	-0.02	0.00	-0.01
XSU	0.11	5.72	-17.75	-3.05
XTW	0.00	-0.01	0.00	-0.00
XWF	-0.66	-7.17	0.05	-2.29
XWS	-1.28	-5.37	-0.07	-2.48
ZAF	-4.95	28.96	-17.99	-7.60
ZMB	-0.28	1.02	-0.10	0.21
ZWE	0.45	-1.90	0.58	-0.02

Table C.4: Countries' corresponding emission changes in mn tons CO2, all countries balanced simultanously

Country	Countries' footprint change		
	Production	Extraction	Consumption
	in mn tons CO2		
AFG	0.03	-10.26	2.51
ALB	-0.24	-1.69	0.26
ARE	-6.80	-28.01	28.41
ARG	-1.68	-9.09	5.17
ARM	-0.21	-1.97	0.00
AUS	-7.52	18.06	-35.95
AUT	-0.63	3.55	0.03
AZE	2.14	5.74	-10.50
BEL	-1.30	-27.72	0.08
BEN	-2.09	-5.92	0.01
BFA	-0.11	-0.53	0.00
BGD	-1.06	-17.38	0.98
BGR	-0.88	-0.33	0.04
BHR	-0.39	-0.60	0.15
BLR	-1.62	-5.69	0.18
BOL	-0.56	-1.68	3.82
BRA	-1.56	10.67	0.27
BRN	-0.03	0.20	0.18
BWA	0.10	0.69	-0.01
CAF	0.02	-0.07	0.00
CAN	2.74	-19.27	47.81
CHE	-0.57	-0.92	0.03
CHL	0.26	5.25	-0.17
CHN	-18.74	199.27	-23.64
CIV	-0.16	-0.06	0.06
CMR	-0.02	-1.60	1.87
COD	-0.04	0.87	-0.05
COG	0.93	2.95	-1.12
COL	-0.41	-5.65	18.47
COM	-0.13	-0.33	0.00
CRI	-0.09	-0.19	-0.00
CYP	-0.54	-1.77	0.00
CZE	1.31	18.89	-1.58
DEU	-1.23	93.22	-4.67
DNK	0.28	-4.16	1.54
DOM	-0.56	-1.41	0.00
DZA	-1.28	0.40	2.75
ECU	-0.07	-0.22	1.58
EGY	-9.49	-42.40	26.66
ESP	-5.22	4.13	-0.02

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Table C.4 – *Continued from previous page*

Country	Countries' footprint change		
	Production	Extraction	Consumption
	in mn tons CO2		
EST	-0.05	-1.42	0.16
ETH	-0.54	-13.36	0.14
FIN	-0.77	-1.92	0.07
FRA	-5.10	-20.19	0.15
GAB	0.06	0.73	-1.83
GBR	-8.32	-58.16	13.52
GEO	-1.13	-4.61	0.09
GHA	-0.31	-2.83	6.71
GIN	0.08	1.05	0.00
GNQ	0.15	1.88	-9.24
GRC	-1.39	-11.09	0.54
GTM	-0.41	-2.32	0.11
HKG	-0.82	-9.77	0.02
HND	-0.45	-1.77	0.00
HRV	-0.56	-1.23	0.17
HTI	0.01	-0.09	0.00
HUN	-0.64	6.80	-0.22
IDN	1.94	23.85	-28.75
IND	-31.32	-154.37	68.74
IRL	5.04	23.39	0.19
IRN	-4.20	8.77	-4.62
IRQ	8.96	23.14	-83.89
ISR	-1.79	-6.29	0.84
ITA	-3.72	18.05	-0.00
JAM	-0.81	-3.89	0.01
JOR	-4.61	-11.50	0.03
JPN	-7.38	-11.62	0.08
KAZ	1.20	12.95	-16.84
KEN	-1.11	-9.80	0.16
KGZ	-3.37	-10.80	0.11
KHM	-0.39	-1.15	0.00
KOR	-16.38	58.25	-0.16
KWT	2.06	12.77	-27.08
LAO	0.88	-0.41	0.94
LBN	-4.01	-13.85	0.03
LKA	-1.52	-5.83	0.01
LTU	-0.23	-2.60	0.01
LUX	-0.31	-1.80	0.01
LVA	-0.25	-2.86	0.01
MAR	-2.92	-9.91	0.01
MDG	-0.06	-0.12	0.00
MEX	-1.19	7.75	4.45
MLI	0.03	-0.99	0.01

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Table C.4 – *Continued from previous page*

Country	Countries' footprint change		
	Production	Extraction	Consumption
	in mn tons CO2		
MLT	-0.44	-2.81	0.00
MNG	4.22	8.43	-6.95
MOZ	0.42	-3.77	3.28
MUS	-0.34	-1.69	0.02
MWI	0.05	-1.47	0.07
MYS	6.93	42.58	-4.97
NAM	-0.10	-1.40	0.00
NER	0.01	-0.28	0.07
NGA	-1.89	-4.78	14.67
NIC	-0.22	-0.65	0.00
NLD	-2.94	-7.92	3.66
NOR	-0.50	0.30	12.03
NPL	-1.19	-14.17	0.04
NZL	-0.48	2.52	-0.43
OMN	-1.49	-3.67	10.64
PAK	-21.53	-49.36	3.39
PAN	2.20	-4.21	0.06
PER	1.06	5.52	-0.55
PHL	-6.01	-24.63	1.43
POL	-1.54	-2.55	1.61
PRI	-0.57	-2.43	0.00
PRT	-0.80	-2.16	0.01
PRY	-0.63	-1.94	-0.00
PSE	-0.97	-3.01	0.02
QAT	-1.64	35.23	-132.00
ROU	-0.94	-4.95	1.77
RUS	-37.58	102.61	-220.93
RWA	-0.09	-0.46	0.01
SAU	-1.47	54.85	-91.34
SDN	-0.67	-3.24	0.95
SEN	-1.03	-4.68	0.01
SGP	1.57	-21.92	0.09
SLV	-0.29	-1.84	0.00
SRB	-0.48	-2.24	0.24
SVK	0.08	6.60	-0.02
SVN	0.01	-1.51	0.14
SWE	-0.45	1.30	0.00
SWZ	0.00	-0.02	0.00
SYR	-4.86	-15.37	1.40
TCD	0.05	0.47	-3.98
TGO	-0.27	-2.71	0.00
THA	1.27	30.29	-1.13
TJK	-0.61	-3.21	-0.37

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Table C.4 – *Continued from previous page*

Country	Countries' footprint change		
	Production	Extraction	Consumption
	in mn tons CO2		
TTO	-1.44	1.28	-4.31
TUN	-1.25	-3.30	0.49
TUR	-10.86	-39.44	2.51
TWN	-7.21	17.66	-0.02
TZA	-0.40	-3.64	0.17
UGA	-0.30	-2.62	0.01
UKR	-1.61	-5.13	2.31
URY	-0.00	0.06	0.00
USA	-39.42	-343.08	155.86
UZB	-3.23	-6.54	11.26
VEN	-1.60	4.86	-12.19
VNM	-2.48	-8.70	1.79
XAC	1.18	6.18	-20.31
XCA	-0.02	-0.59	0.02
XCB	-1.19	-9.47	0.58
XEA	0.09	0.74	0.27
XEC	-0.70	-5.83	6.28
XEE	-0.97	-3.08	0.01
XEF	-0.03	-0.30	0.00
XER	0.42	-6.94	1.25
XNA	2.10	9.93	-0.00
XNF	2.42	6.35	-11.95
XOC	1.18	-7.99	1.94
XSA	-0.11	-0.07	0.00
XSC	-0.21	-1.16	0.00
XSE	-0.67	-4.71	21.62
XSM	-0.08	-0.13	0.02
XSU	-0.10	5.47	-11.57
XTW	-0.00	-0.01	0.00
XWF	-2.94	-7.49	0.06
XWS	-1.40	-5.53	-0.01
ZAF	-6.72	26.61	-24.07
ZMB	-0.28	0.79	-0.09
ZWE	0.52	-2.17	0.69

Appendix D

Climate Change Adaptation: Agricultural Productivity Shocks and Trade Policy Responses

D.1 Tables

Table D.1: GTAP 10 sectorlist and production values, scenario 1

Category	Code	Sector	Production in Bn. USD				
			Initial	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Ag. Products	b_t	Beverages & tobacco products	1274.5	1278.5	1278.7	1278.0	1277.4
	cmt	Bovine meat products	609.0	610.0	609.9	609.8	609.4
	ctl	Bovine cattle, sheep & goats, horses	430.3	431.7	431.3	431.0	430.3
	frs	Forestry	345.4	345.5	345.5	345.4	345.4
	fsh	Fishing	389.7	390.5	390.4	390.1	390.2
	mil	Dairy products	801.4	803.1	802.8	802.5	801.9
	oap	Animal products nec	737.4	739.8	739.2	738.4	737.7
	ofd	Food products nec	2929.2	2939.7	2935.0	2931.6	2924.5
	omt	Meat products nec	711.2	712.7	712.5	712.1	712.0
	pcr	Processed rice	391.3	399.7	398.8	394.9	394.5
	rmk	Raw milk	373.4	374.7	374.5	374.3	374.0
	sgr	Sugar	208.8	208.6	207.5	206.8	203.7
	vol	Vegetable oils & fats	460.2	463.6	462.3	461.5	457.7
	wol	Wool, silk-worm cocoons	39.9	40.0	40.1	40.0	39.9
Crops	c_b	Sugar cane, sugar beet	148.2	148.2	146.8	146.0	141.6
	gro	Cereal grains nec	382.1	387.9	386.1	384.0	383.8
	ocr	Crops nec	297.5	310.2	314.9	314.8	316.2
	osd	Oilseeds	340.2	343.4	341.2	340.5	334.5
	pdr	Paddy rice	313.7	324.6	322.9	317.7	316.2
	pfb	Plant-based fibers	101.0	102.3	101.1	99.6	99.4
	v_f	Vegetables, fruits, nuts	1385.7	1396.5	1381.1	1372.6	1355.3
	wht	Wheat	233.1	232.7	227.4	226.7	219.7
Fossils & Energy	coa	Coal	555.2	555.2	555.2	555.2	555.1
	ely	Electricity	2916.5	2916.4	2916.1	2916.1	2915.4
	gas	Gas	622.7	622.6	622.8	622.9	623.1
	gdt	Gas manufacture, distribution	289.5	289.5	289.5	289.5	289.6
	oil	Oil	2526.4	2526.2	2526.5	2526.8	2526.6
	p_c	Petroleum, coal products	4027.7	4027.4	4027.6	4027.9	4027.6
Manufacturing	bph	Basic pharmaceutical products	1115.7	1116.4	1116.3	1116.1	1115.9
	chm	Chemical products	4311.6	4314.0	4313.6	4313.1	4312.3
	eeq	Electrical equipment	2157.6	2157.9	2157.8	2157.8	2157.6
	ele	Computer, electronic & optical products	4678.7	4678.5	4678.4	4678.4	4677.8
	fmp	Metal products	2524.9	2525.0	2524.9	2524.7	2524.4
	i_s	Ferrous metals	3233.3	3233.6	3233.6	3233.4	3233.2
	lea	Leather products	491.2	491.6	491.6	491.5	491.4
	lum	Wood products	1012.9	1013.2	1013.3	1013.2	1013.2
	mvh	Motor vehicles & parts	4145.4	4145.9	4145.8	4145.5	4145.3
	nfm	Metals nec	2069.7	2069.2	2068.9	2068.8	2068.1
	nmm	Mineral products nec	2030.4	2030.8	2030.7	2030.6	2030.5
	ome	Machinery & equipment nec	4156.2	4156.8	4156.7	4156.6	4156.2
	omf	Manufactures nec	1817.6	1818.3	1818.5	1818.4	1818.5
	otn	Transport equipment nec	1312.6	1312.9	1312.8	1312.7	1312.7
	oxt	Other Extraction	1123.4	1123.7	1123.7	1123.7	1123.8
	ppp	Paper products, publishing	1788.3	1789.0	1789.2	1789.1	1789.2
	rpp	Rubber & plastic products	2240.7	2242.6	2242.9	2242.6	2242.9
	tex	Textiles	1617.8	1622.8	1622.6	1621.1	1621.6
	wap	Wearing apparel	1173.7	1175.2	1175.1	1174.7	1174.9
Services	afs	Accommodation, Food & service activities	3892.7	3896.0	3895.0	3894.0	3891.7
	atp	Air transport	959.8	959.9	959.9	959.9	959.9
	cmn	Communication	5741.3	5742.2	5742.3	5742.2	5742.4
	cns	Construction	12228.3	12231.1	12231.0	12230.3	12230.2
	dwe	Dwellings	5359.5	5359.5	5359.5	5359.5	5359.3
	edu	Education	4363.6	4364.0	4364.0	4363.9	4363.8
	hht	Human health & social work activities	7649.6	7651.6	7651.4	7651.0	7650.7
	ins	Insurance (formerly isr)	1825.2	1825.5	1825.5	1825.5	1825.5
	obs	Business services nec	8383.9	8386.0	8386.6	8386.6	8387.4
	ofi	Financial services nec	5788.8	5789.2	5789.1	5789.0	5788.8
	osg	Public Administration & defense	5834.8	5835.6	5835.5	5835.3	5835.1
	otp	Transport nec	4261.7	4262.5	4262.3	4262.1	4262.1
	ros	Recreational & other services	4329.7	4330.5	4330.4	4330.2	4329.6
	rsa	Real estate activities	3149.4	3149.6	3149.6	3149.6	3149.6
	trd	Trade	12022.2	12023.7	12023.6	12023.2	12022.7
	whs	Warehousing & support activities	1520.9	1521.5	1521.5	1521.4	1521.4

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Table D.1 – *Continued from previous page*

Category	Code	Sector	Production in Bn. USD				
			Initial	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
	wtp	Water transport	488.1	488.1	488.1	488.1	488.0
	wtr	Water	1416.7	1416.7	1416.7	1416.7	1416.6

Table D.2: GAEZ to GTAP concordance

GAEZ crop	Unit	GTAP sector
Sugarbeet	kg sugar/ha	c_b
Sugarcane	kg sugar/ha	
Barley	kg DW/ha	gro
Buckwheat	kg DW/ha	
Foxtail millet	kg DW/ha	
Highland maize	kg DW/ha	
Highland sorghum	kg DW/ha	
Lowland maize	kg DW/ha	
Lowland sorghum	kg DW/ha	
Maize	kg DW/ha	
Millet	kg DW/ha	
Oat	kg DW/ha	
Pearl millet	kg DW/ha	
Rye	kg DW/ha	
Silage maize	kg DW/ha	
Sorghum	kg DW/ha	
Spring barley	kg DW/ha	
Spring rye	kg DW/ha	
Temperate maize	kg DW/ha	
Temperate sorghum	kg DW/ha	
Winter barley	kg DW/ha	
Winter rye	kg DW/ha	
Cocoa	kg DW/ha	ocr
Cocoyam	kg DW/ha	
Coffee	kg DW/ha	
Coffee arabica	kg DW/ha	
Coffee robusta	kg DW/ha	
Greater yam	kg DW/ha	
Para rubber	kg DW/ha	
Tea	kg DW/ha	
Tobacco	kg DW/ha	
White yam	kg DW/ha	
Yam	kg DW/ha	
Yellow yam	kg DW/ha	
Coconut	kg DW/ha	osd
Groundnut	kg DW/ha	
Jatropha	kg DW/ha	
Rapeseed	kg DW/ha	
Soybean	kg DW/ha	

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Table D.2 – *Continued from previous page*

GAEZ crop	Unit	GTAP sector
Sunflower	kg DW/ha	
Dryland rice	kg DW/ha	pdr
Wetland rice	kg DW/ha	
Alfalfa	10kg DW/ha	pfb
Biomass highland sorghum	kg DW/ha	
Biomass lowland sorghum	kg DW/ha	
Biomass sorghum	kg DW/ha	
Biomass temperate sorghum	kg DW/ha	
Flax	kg DW/ha	
Grass	10kg DW/ha	
Miscanthus	10kg DW/ha	
Napier grass	10kg DW/ha	
Pasture legumes	10kg DW/ha	
Reed canary grass	10kg DW/ha	
Switchgrass	10kg DW/ha	
Banana	kg DW/ha	v_f
Cabbage	kg DW/ha	
Carrot	kg DW/ha	
Cassava	kg DW/ha	
Chickpea	kg DW/ha	
Citrus	kg DW/ha	
Cowpea	kg DW/ha	
Dry pea	kg DW/ha	
Gram	kg DW/ha	
Onion	kg DW/ha	
Phaseolus bean	kg DW/ha	
Pigeonpea	kg DW/ha	
Sweet potato	kg DW/ha	
Tomato	kg DW/ha	
White potato	kg DW/ha	
Spring wheat	kg DW/ha	wht
Wheat	kg DW/ha	
Winter wheat	kg DW/ha	

Table D.3: Scenario 1, trade flow changes in RCP 2.6, in percent.

	Δ Bilateral imports		Δ Internal trade		Δ Total exports	
	L	W	L	W	L	W
Ag. Products	0.99	-1.19	-0.41	0.54	-1.03	0.59
Crops	6.35	-5.79	-1.86	2.92	-5.33	3.24
Fossils & Energy	-0.43	0.60	0.03	-0.06	0.47	-0.11
Manufacturing	-0.21	0.52	0.25	0.01	0.48	-0.01
Services	-0.40	0.61	0.19	0.04	0.58	0.01

Table D.4: Scenario 1, trade flow changes in RCP 4.5, in percent.

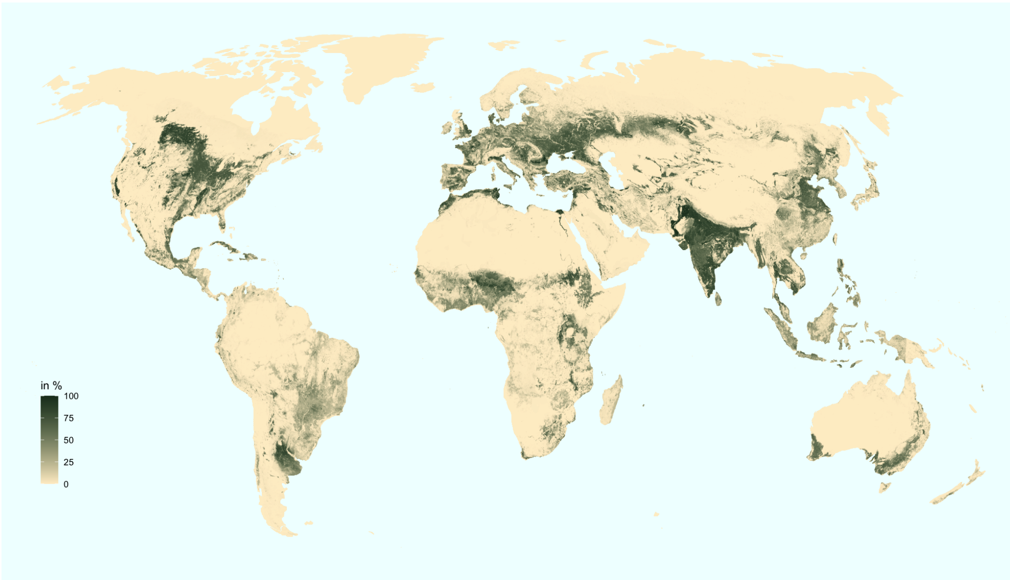
	Δ Bilateral imports		Δ Internal trade		Δ Total exports	
	L	W	L	W	L	W
Ag. Products	1.14	-2.02	-0.86	0.63	-1.61	0.72
Crops	7.70	-9.16	-3.58	4.70	-7.94	5.36
Fossils & Energy	-0.47	0.56	-0.29	-0.17	0.36	-0.22
Manufacturing	-0.27	0.53	0.28	-0.00	0.48	-0.05
Services	-0.51	0.90	0.40	0.04	0.84	-0.03

Table D.5: Scenario 1, trade flow changes in RCP 8.5, in percent.

	Δ Bilateral imports		Δ Internal trade		Δ Total exports	
	L	W	L	W	L	W
Ag. Products	1.79	-3.87	-2.35	0.78	-3.27	1.02
Crops	12.46	-14.14	-6.89	7.42	-12.21	8.94
Fossils & Energy	-0.71	0.90	-0.44	-0.36	0.45	-0.44
Manufacturing	-0.43	0.66	0.32	-0.03	0.58	-0.14
Services	-0.78	1.35	0.54	0.04	1.20	-0.12

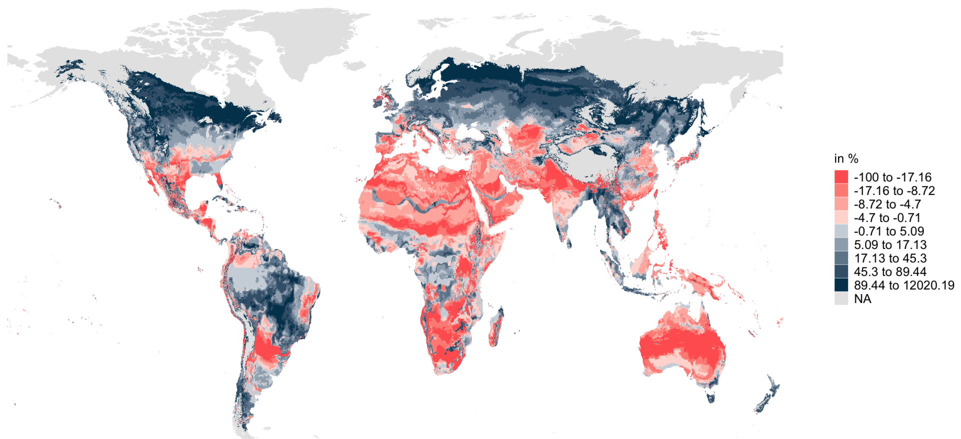
D.2 Figures

Figure D.1: Cropland share, 2014.



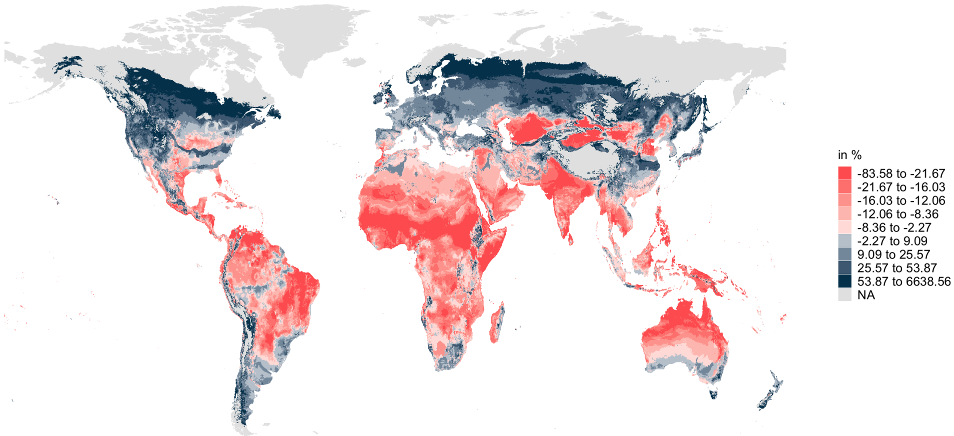
Note: Cropland share per grid cell in 2014 based on GAEZ, own calculation.

Figure D.2: *Cereal grains nec*, yield changes in 2071-2100 under RCP 6.0.



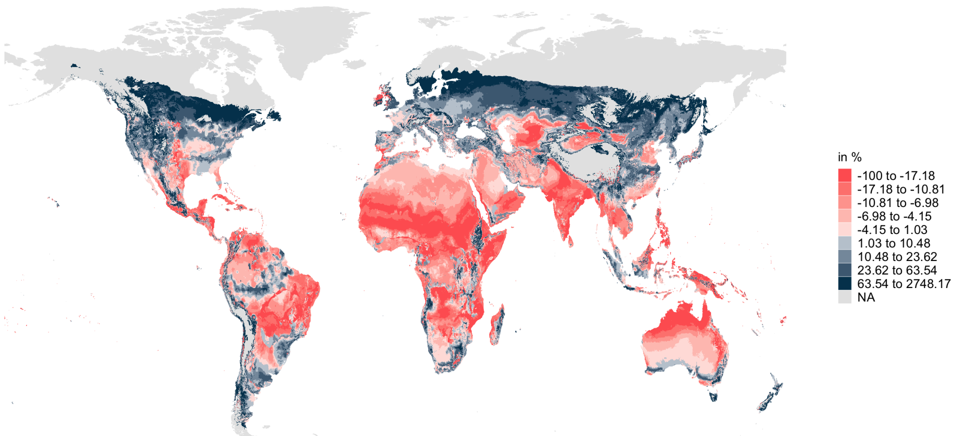
Note: GTAP sector *gro*, for mapping see Table D.2, based on GAEZ, own calculation.

Figure D.3: *Vegetables, fruits, nuts*, yield changes in 2071-2100 under RCP 6.0.



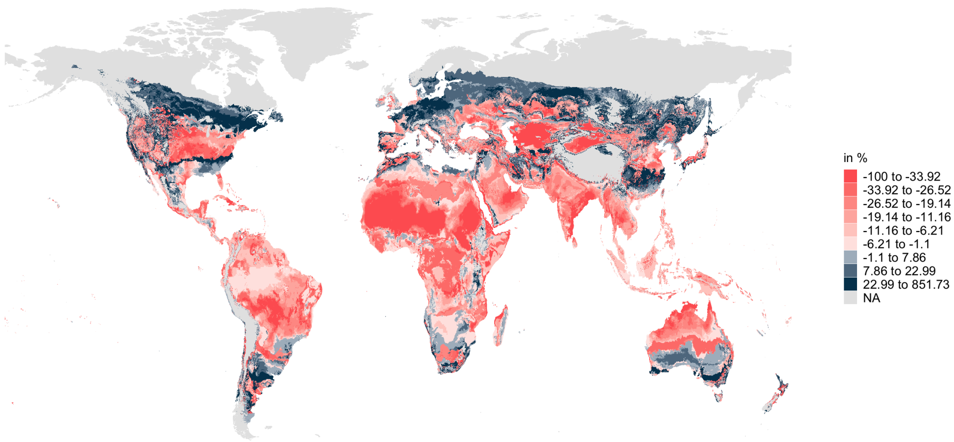
Note: GTAP sector *v_f*, for mapping see Table D.2, based on GAEZ, own calculation.

Figure D.4: *Oilseeds*, yield changes in 2071-2100 under RCP 6.0.



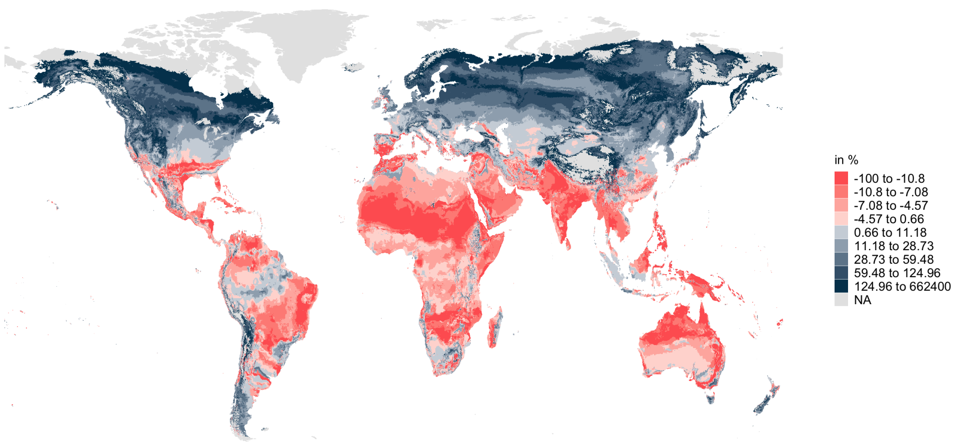
Note: GTAP sector *osd*, for mapping see Table D.2, based on GAEZ, own calculation.

Figure D.5: *Sugar cane, sugar beet*, yield changes in 2071-2100 under RCP 6.0.



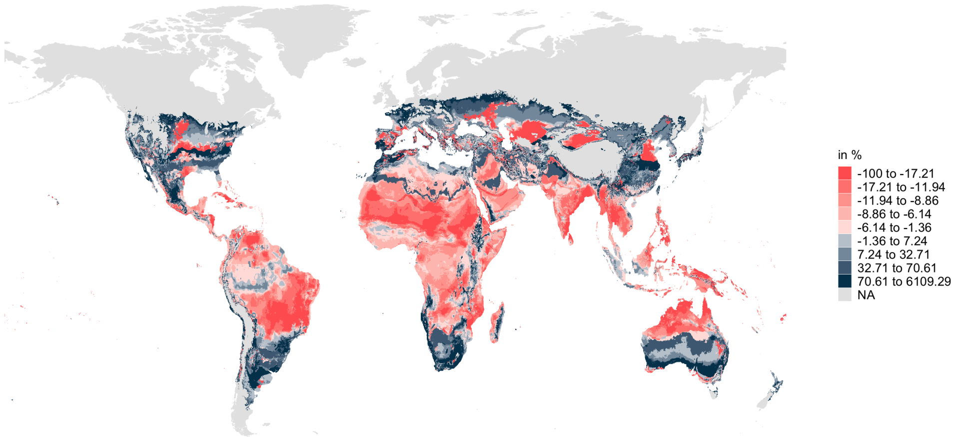
Note: GTAP sector *c_b*, for mapping see Table D.2, based on GAEZ, own calculation.

Figure D.6: *Plant-based fibers*, yield changes in 2071-2100 under RCP 6.0.



Note: GTAP sector *pfb* for mapping see Table D.2, based on GAEZ, own calculation.

Figure D.7: *Crops nec*, yield changes in 2071-2100 under RCP 6.0.



Note: GTAP sector *ocr*, for mapping see Table D.2, based on GAEZ, own calculation.

Figure D.8: Welfare change in scenario 1 under RCP 2.6.

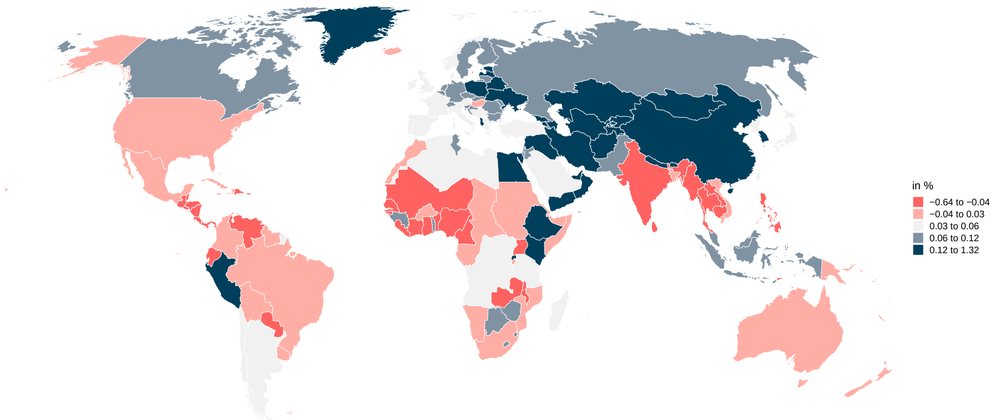


Figure D.9: Welfare change in scenario 1 under RCP 4.5.

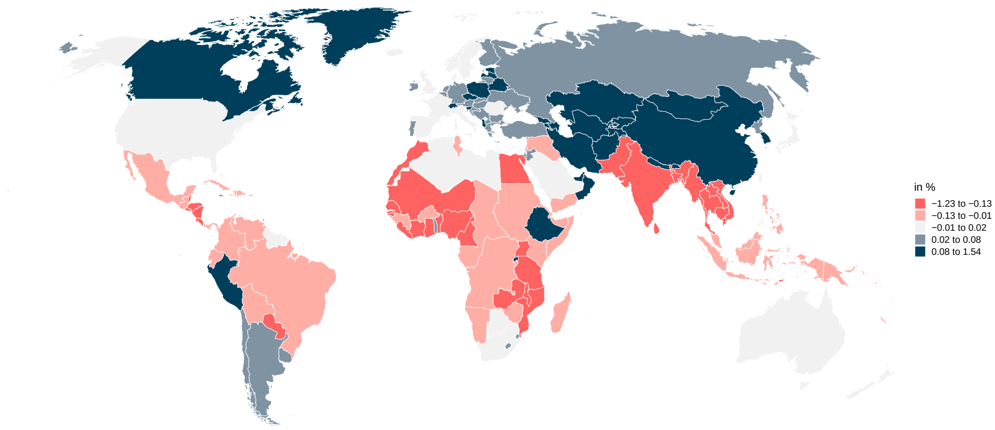


Figure D.10: Welfare change in scenario 1 under RCP 8.5.

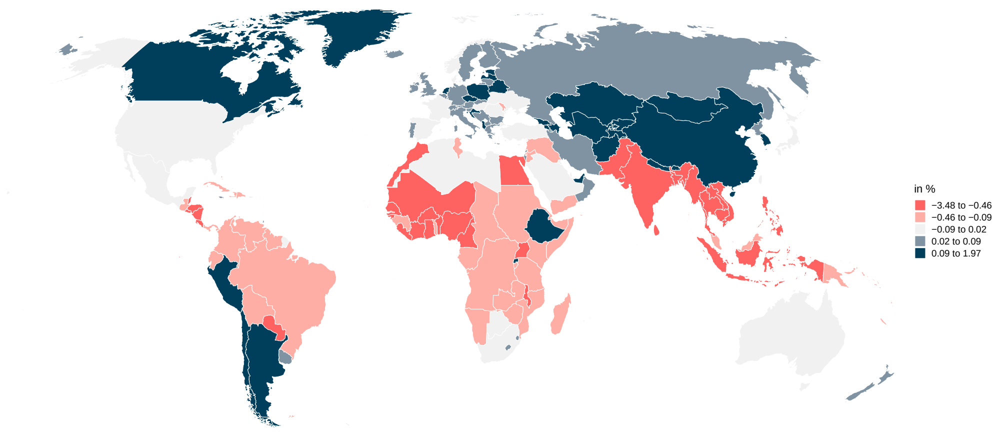


Figure D.11: NTB changes in scenario 2 under RCP 2.6.

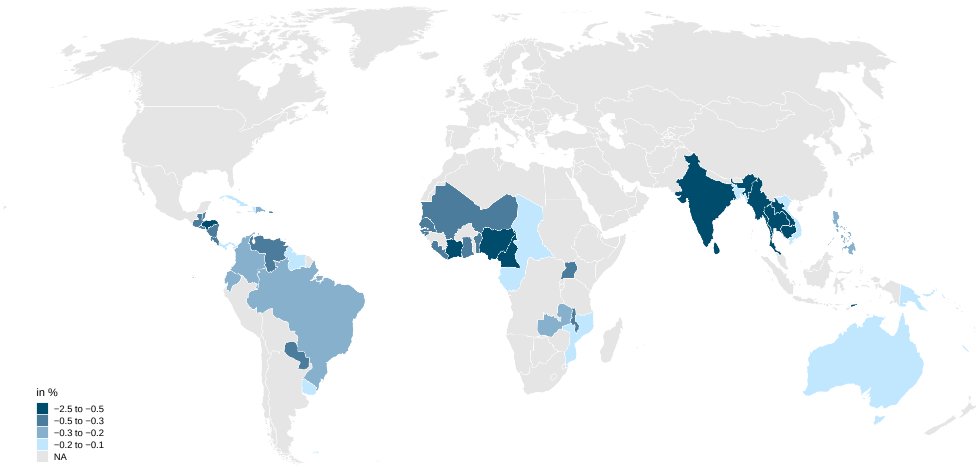


Figure D.12: NTB changes in Scenario 2 under RCP 4.5.

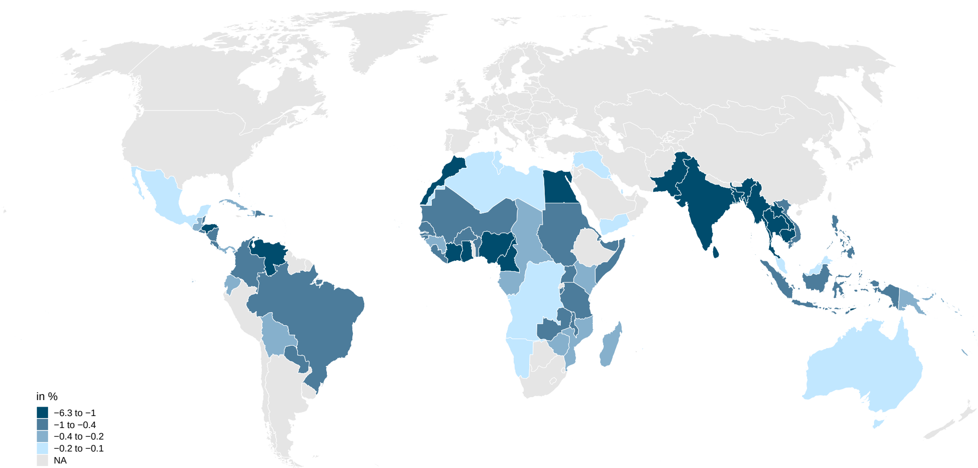
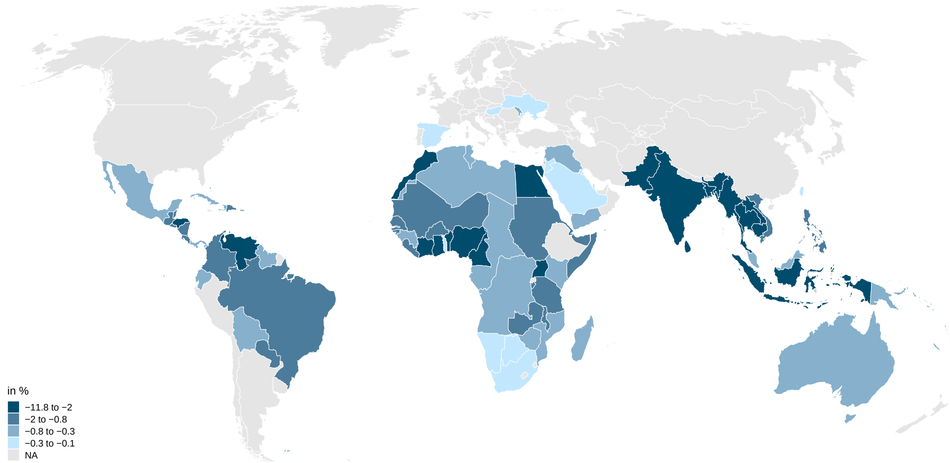


Figure D.13: NTB changes in scenario 2 under RCP 8.5.



Erklarung zum selbständigen Verfassen der Arbeit:

Ich erkläre hiermit, dass ich meine Doktorarbeit "Trade and Climate Change: Global Value Chain and Policy Analysis" selbstständig und ohne fremde Hilfe angefertigt habe und dass ich als Koautor maßgeblich zu den weiteren Fachartikeln beigetragen habe. Alle von anderen Autoren wörtlich ubernommenen Stellen, wie auch die sich an die Gedanken anderer Autoren eng anlehnenden Ausführungen der aufgeführten Beiträge wurden besonders gekennzeichnet und die Quellen nach den mir angegebenen Richtlinien zitiert.

Datum	**Unterschrift**
19.01.2024	