

# **Trade and Climate Change: Global Value Chain and Policy Analysis**

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Für Mama.

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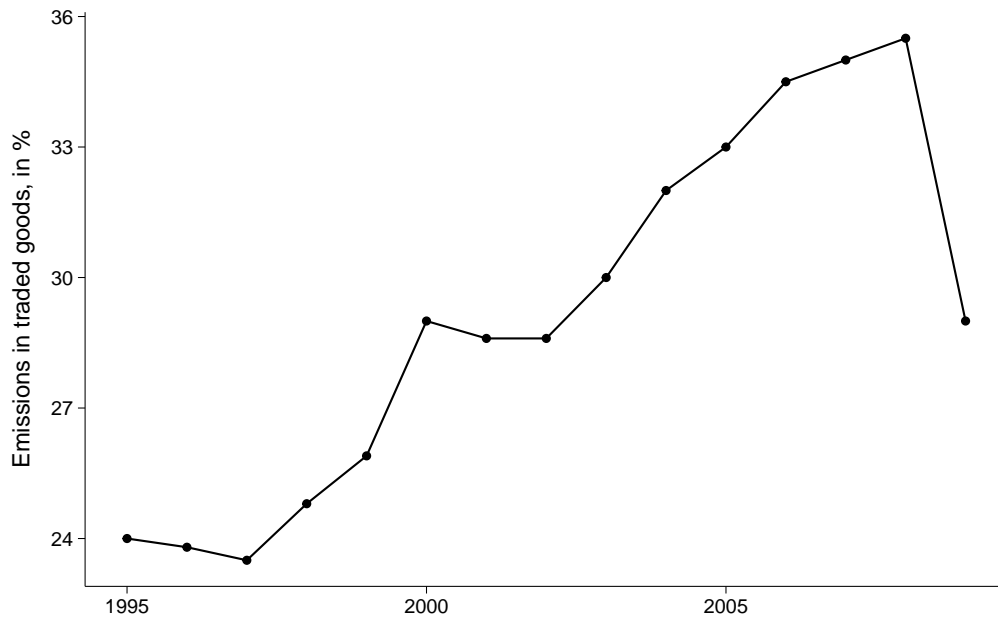
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# Introduction

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<sup>1</sup>. 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.

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<sup>1</sup>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<sup>2</sup> account

<sup>2</sup>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 CO<sub>2</sub> 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.<sup>3</sup> 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

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<sup>3</sup>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 multi-lateral 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.<sup>4</sup> 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.<sup>5</sup> 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

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<sup>4</sup>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.

<sup>5</sup>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<sup>6</sup> 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

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<sup>6</sup>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.<sup>7</sup> 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<sup>8</sup>. 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

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

<sup>8</sup>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*<sup>9</sup> – 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 extended 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

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<sup>9</sup>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.<sup>10</sup> 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

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<sup>10</sup>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 21<sup>st</sup> largest emitter of CO<sub>2</sub> 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.<sup>11</sup> 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 propagate through GVCs. In counterfactual scenarios, I derive the relative trade barrier liberalization required to offset climate change damages.

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<sup>11</sup>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  $9 \times 9$  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<sup>12</sup> 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

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<sup>12</sup>The RCPs are labeled after a possible range of radiative forcing values in the year 2100 (4.5, 6, and 8.5 W/m<sup>2</sup>, 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<sup>12</sup>

### Abstract

With ever-increasing political tensions between China and Russia on one side and the EU and the US on the other, it only seems a matter of time until protectionist policies cause a decoupling of global value chains. This paper uses a computable general equilibrium trade model calibrated with the latest version of the GTAP database to simulate the effect of such a decoupling - implemented by doubling non-tariff barriers - between the two blocks on trade and welfare. Imposing import barriers almost completely eliminates bilateral imports. In addition, changes in price

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<sup>1</sup>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.

<sup>2</sup>The chapter has been published as: 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, 75–108. The article is accessible via <https://doi.org/10.1007/s10663-022-09561-w>.

levels lead to higher imports and lower exports of the imposing country group from and to the rest of the world. The targeted country group increases exports to the rest of the world and reduces imports. Welfare falls in all countries involved, suggesting that governments should strive to cooperate rather than turn away from each other. By imposing a trade war on Russia, the political West could inflict severe damage on the Russian economy because of the latter's smaller relative economic size.

*JEL-Codes:* F11, F13, F14, F17

*Keywords:* Trade, non-tariff barriers, global value chains, quantitative trade model, China, Russia, European Union

## Chapter 2

# Macroeconomic Structural Change Likely Increases Inequality in India more than Climate Policy<sup>1</sup>

### Abstract

The decarbonization of India's economy will have different effects across income groups. As India is in the middle of the transformation process from an agriculture-based economy towards an industry- and service-based economy, called economic structural change, the extent of income distribution across households strongly depends also on the speed of economic transformation. While a number of recent studies have analyzed the distributional effects of carbon pricing, the specific role of structural change across sectors has not been in the focus of the related literature. Our study contrasts distributional effects from climate policy with distributional effects from structural change in India and asks how far carbon pricing supports or hinders structural change and development. We develop and apply a comprehensive model framework that combines economic growth and international trade dynamics related to structural change with detailed household income and expenditure data for India. Our study shows that changes in income and inequality due to carbon pricing vary with

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<sup>1</sup>The chapter has been published as: Leimbach, M., Huebler, M., Mahlkow, H., Montrone, L., Bukin, E., Felbermayr, G., Kalkuhl, M., Koch, J., Marcolino, M., Pothén, F. and Steckel, J.C. (2024). "Macroeconomic structural change likely increases inequality in India more than climate policy". *Environmental Research Letters*, 19(4), p.044070. The article is accessible via <https://www.doi.org/10.1088/1748-9326/ad34e9>.

changes in the sectoral structure of an economy. Our results indicate that carbon pricing tends to delay economic structural change by retarding the reallocation of economic activities from the agricultural sector to the manufacturing sector. Furthermore, the results emphasize that the increase in inequality due to structural change is substantially stronger than due to carbon pricing. Consequently, socially sensitive policies supporting the process of structural transformation appear to be more important for poor households than lowering climate policy ambitions.

*JEL-Codes:* F18, Q54, O13, D31

*Keywords:* Structural transformation, decarbonization, climate policy, income distribution

## Chapter 3

# The Carbon Footprint of Global Trade Imbalances<sup>1</sup>

### 3.1 Introduction

A quarter to a third of global CO<sub>2</sub> 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 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

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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](#)).<sup>2</sup>

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 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,

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<sup>2</sup>[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.



however, are found to be the surpluses of major fossil fuel exporters with their disproportionately large extraction footprints.

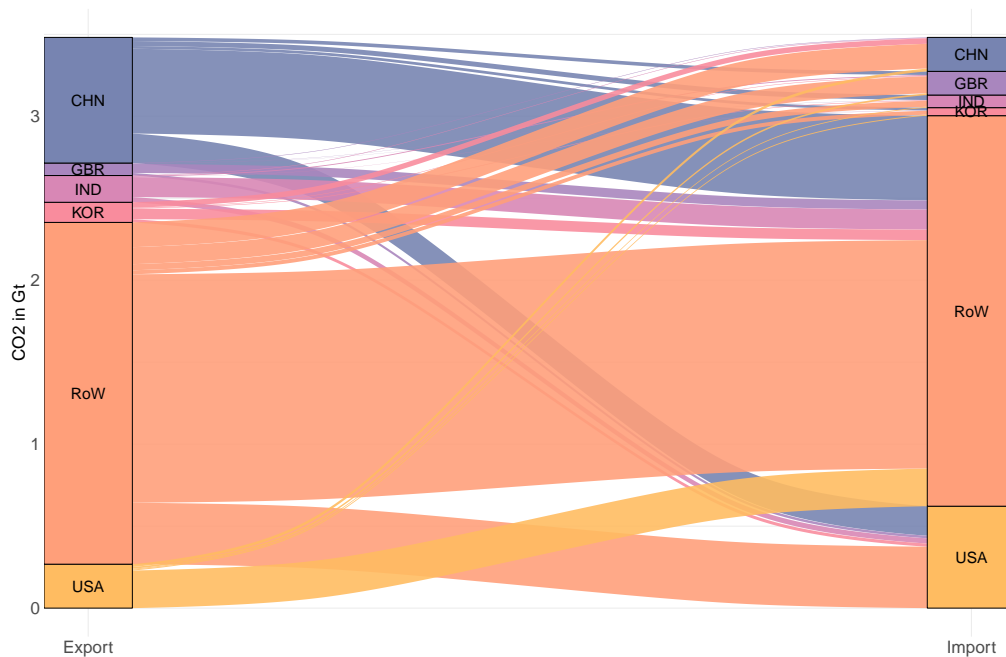
Our exercises come with one important disclaimer. Unlike a growing literature on the *sources* of trade imbalances (cf. e.g., [Reyes-Heroles, 2016](#); [Felbermayr and Yotov, 2021](#); [Cuñat and Zymek, 2023](#)), our paper purely examines the *consequences* of their removal, standing in the tradition 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

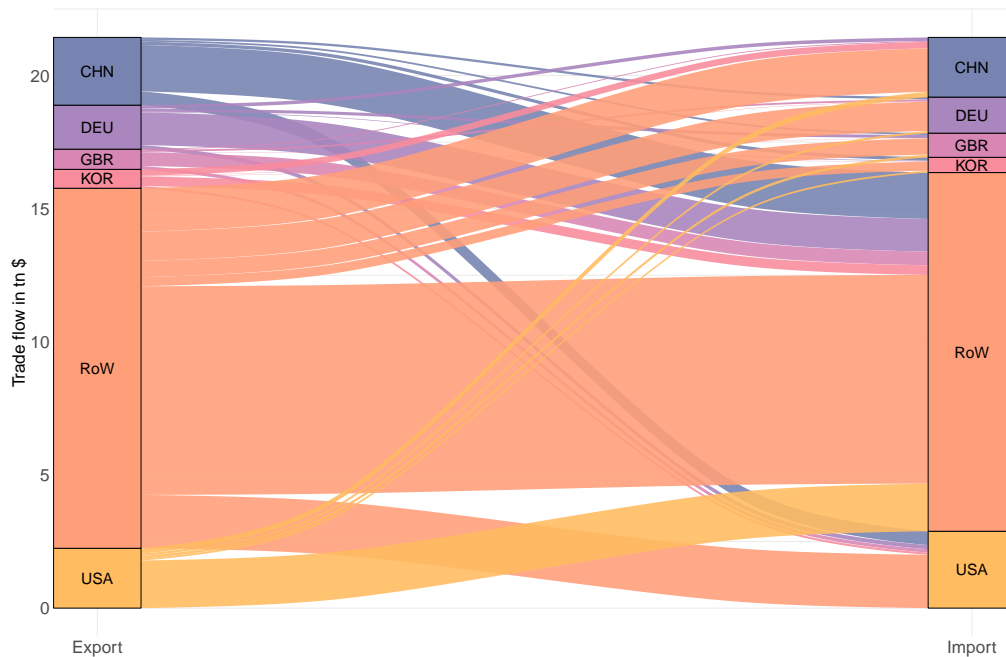
In this section, we take a look at the data and establish four stylized facts about value and embodied emission trade imbalances across countries and time. While not novel individually and in part very straightforward, the aim of this *collection* of stylized facts is to motivate that trade imbalances 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.

**Figure 3.1:** Bilateral flows of embodied CO<sub>2</sub> emissions in international trade, 2017.

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

Bilateral flows of embodied CO<sub>2</sub> 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 CO<sub>2</sub>. 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 CO<sub>2</sub>. As the US, Great Britain is also a net importer of embodied CO<sub>2</sub>, 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 imbalance patterns have been very persistent.<sup>3</sup> All individual countries

<sup>3</sup>See Figure C.1 in the Appendix C for a representation of the pattern in Figure 3.1

**Figure 3.2:** Bilateral trade flows, 2017.

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.

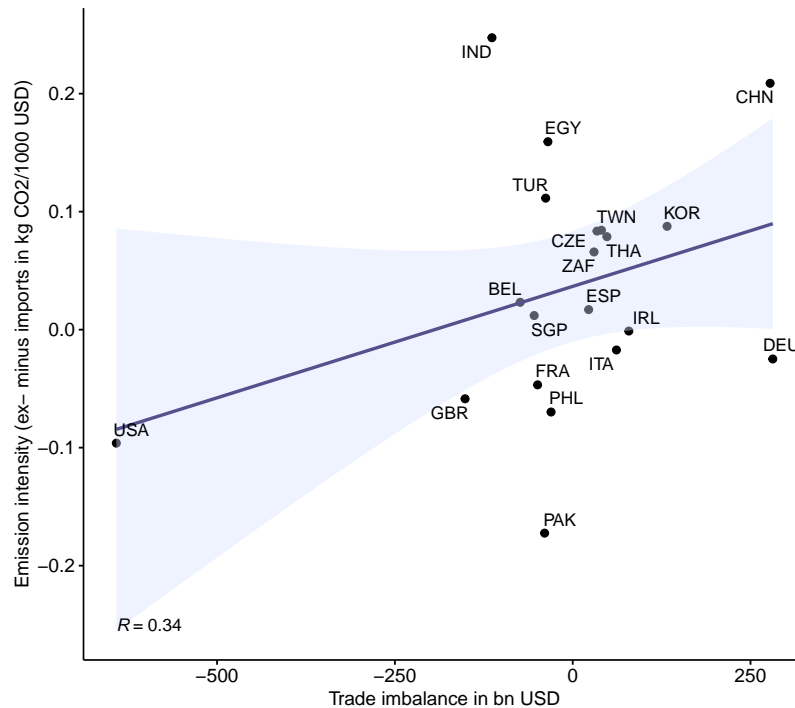
**Stylized Fact 2.** *Trade is highly and persistently asymmetric in value terms, too.*

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, 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

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since 2004 (the first base year of the GTAP 11 data base).

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

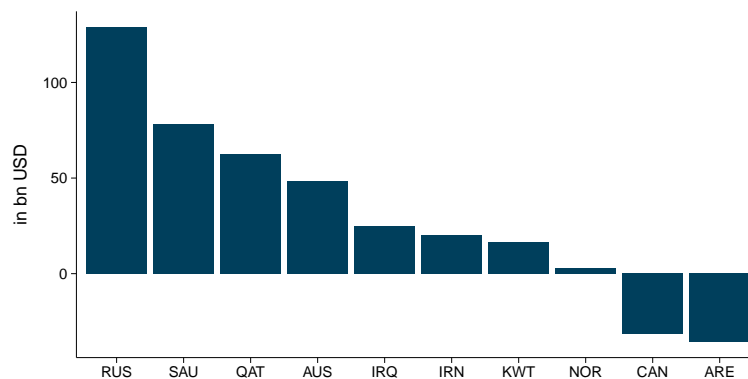


*Note:* Figure displays the 20 fossil fuel net-importers with the largest trade imbalances (Source: GTAP 11).

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.<sup>4</sup> 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.*

<sup>4</sup>See Figure C.2 in the Appendix C for a graphical representation.

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

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.<sup>5,6</sup> Countries supplying “dirty” 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

<sup>5</sup>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.

<sup>6</sup>Note that Figure 3.3 only shows countries that are net fossil fuel importers. As 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.

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 3.4 shows, this is exactly the case for many of the world's largest fossil fuel net-exporters.<sup>7</sup> Out of the top ten, eight countries have a trade surplus in 2017, which are partly huge in relation to these countries' overall GDPs.<sup>8</sup> 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 the framework by CP, the model is also closely related to [Shapiro \(2021\)](#), [Caron and Fally \(2022\)](#), and [Klotz and Sharma \(2023\)](#).

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

<sup>8</sup>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).

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  $\alpha$  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  $\gamma$ . 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  $\nu^{p^s}$  and  $\nu^s$ . 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:

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

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  $\gamma$ , 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<sup>9</sup>:

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

where  $d_n(\omega^j)$  are the demands for the specific varieties  $\omega^j$  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  $c_n^s a_n(\omega^s) \forall s \notin \mathcal{P}$ ,

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



where the cost of the input bundles are given by

$$c_n^o = \Upsilon_n^o [w_n]^{\gamma_n^{l,o}} \prod_{j \in \mathcal{J}} [P_n^j]^{\gamma_n^{j,o}} \quad \forall o \in \mathcal{O}, \quad (3.1)$$

$$c_n^p = \Upsilon_n^p [p_n^{r,p}]^{\gamma_n^{r,p}} [w_n]^{\gamma_n^{l,p}} \prod_{j \in \mathcal{J}} [P_n^j]^{\gamma_n^{j,p}} \quad \forall p \in \mathcal{P}, \quad (3.2)$$

$$c_n^s = \frac{P^{p^s}}{\nu_n^{p^s}} + (\nu_n^s)^{-1} \Upsilon_n^s [w_n]^{\gamma_n^{l,s}} \prod_{j \in \mathcal{J} \setminus \{p^s\}} [P_n^j]^{\gamma_n^{j,s}} \quad \forall s \in \mathcal{S} \setminus \mathcal{P}, \quad (3.3)$$

where  $\Upsilon_n^o = (\gamma_n^{l,o})^{-\gamma_n^{l,o}} \prod_{j \in \mathcal{J}} (\gamma_n^{j,o})^{-\gamma_n^{j,o}}$ ,  $\Upsilon_n^p = (\gamma_n^{r,p})^{-\gamma_n^{r,p}} (\gamma_n^{l,p})^{-\gamma_n^{l,p}} \prod_{j \in \mathcal{J}} (\gamma_n^{j,p})^{-\gamma_n^{j,p}}$ ,  $\Upsilon_n^s = (\gamma_n^{l,s})^{-\gamma_n^{l,s}} \prod_{j \in \mathcal{J} \setminus \{p^s\}} (\gamma_n^{j,s})^{-\gamma_n^{j,s}}$ ,  $w$  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  $\theta$  is a dispersion parameter (inversely) capturing the extent of comparative advantage differences within sectors.<sup>10</sup>

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

<sup>10</sup>Note that both EK and CP equivalently have countries draw productivities from a type-II extreme value (Frechet) distribution instead. We follow [Eaton and Kortum \(2012\)](#) here and use the original Ricardian technology measure of input requirements.

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.

### 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  $t_{ni}^j$ , 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

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

with  $A_{ni}^j = A_i^j / (t_{ni}^j c_i^j)$ . 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  $\omega$  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:

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

$\bar{A}$  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:

$$P_n^j = \exp \left( \int_0^\infty \ln(p) dF_n^j(p) \right) = \frac{\exp(-\varepsilon/\theta^j)}{\bar{A}_n^j}, \quad (3.4)$$

where  $\varepsilon = 0.5772 \dots$  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 ( $t_{ni}^j = \infty$ ) and the price hence simplifies to  $P_n^j = \exp(-\varepsilon/\theta^j)/A_{nn}^j$ .

Country  $n$ 's total spending on goods from sector  $j$  is  $X_n^j$ . 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<sup>11</sup>:

$$\pi_{ni}^j = \frac{X_{ni}^j}{X_n^j} = \left( \frac{A_{ni}^j}{A_n^j} \right)^{\theta^j}. \quad (3.5)$$

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<sub>2</sub>, 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:

$$X_n^j = \sum_{k \in \mathcal{J}} \gamma_n^{j,k} \sum_{i \in \mathcal{N}} X_i^k \pi_{in}^k + \alpha_n^j I_n, \quad (3.6)$$

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

<sup>11</sup>As described in EK, this share can be calculated as the probability that  $i$  has the lowest costs of delivering a good  $\omega$  to  $n$ :  $Pr[c_{ni}(\omega^j) \leq \min\{c_{ns}(\omega^j); s \neq i\}] = \int_0^\infty \prod_{s \neq i} [\exp(-(A_{ns}^j c)^{\theta^j})] d(\exp(-(A_{ni}^j c)^{\theta^j}))$ . 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  $(A_i^j/c_i^j)^\theta$ , substitute the expression into (3.5) and simplify using (3.4).

the resource prices) and the trade deficit ( $D_n$ ):

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

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

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

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  $A_n^j$ ,  $\theta^j$ ,  $\gamma_n^{l,o}$ ,  $\gamma_n^{j,o}$ ,  $\gamma_n^{r,p}$ ,  $\gamma_n^{l,p}$ ,  $\gamma_n^{j,p}$ ,  $\tilde{\gamma}_n^{l,s}$ ,  $\tilde{\gamma}_n^{j,s}$ ,  $\nu_n^{p,s}$  and  $\nu_n^{s,s}$ , 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  $\{w_n, p_n^r, P_n^j, \gamma_n^{l,s}, \gamma_n^{j,s}\}$  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,  $\{\hat{w}_n, \hat{p}_n^r, \hat{P}_n^j, \hat{\gamma}_n^{l,s}, \hat{\gamma}_n^{j,s}\}$  satisfy the following equilibrium conditions (3.9a)–(3.15b):

Cost changes of the input bundles:

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

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

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

Input cost share changes:

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

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

Price index change:

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

Bilateral trade share change:

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

Counterfactual total expenditure by country and sector:

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

Counterfactual final absorption:

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

Factor price changes:

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

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

Note that this second equilibrium definition has the advantage that there is no need to identify the level of the technology parameters  $A$  and  $\nu$  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.<sup>12</sup> 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

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

composite, either as an intermediate in production or in final consumption, weighted by the varying carbon intensities  $\iota^s$  of the different fossil fuel types. Classic national emissions (i.e. production footprints) are hence given by

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

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  $Y_n^{s^p} \equiv \sum_i \pi_{in} X_i^{s^p}$  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<sub>2</sub> 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:

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

where  $\cdot^s = [\gamma_1^{s,1}, \dots, \gamma_1^{s,J}, \gamma_2^{s,1}, \dots, \gamma_N^{s,J}]'$  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<sup>13</sup>),  $\mathbf{P}^s = [P_1^s, \dots, P_N^s]' \otimes \mathbf{i}_J$  collects secondary fossil fuel prices of all countries,  $\otimes$  denotes the Kronecker product,  $\mathbf{i}_J$  is a unit vector of length  $J$ ,  $\mathbf{A} = \begin{pmatrix} \mathbf{A}_{11} & \dots & \mathbf{A}_{N1} \\ \vdots & \ddots & \vdots \\ \mathbf{A}_{1N} & \dots & \mathbf{A}_{NN} \end{pmatrix}$  is

<sup>13</sup>Recall the discussion of gas inputs into the “gas distribution” sector above.

the global input coefficient matrix,  $\mathbf{A}_{in} = \begin{pmatrix} \gamma_i^{1,1} \pi_{in}^1 & \cdots & \gamma_i^{1,J} \pi_{in}^1 \\ \gamma_i^{J,1} \pi_{in}^J & \cdots & \gamma_i^{J,J} \pi_{in}^J \end{pmatrix}$  is a bilateral input coefficient matrix,  $_{n} = [\pi_{n1}^1, \dots, \pi_{n1}^J, \pi_{n2}^1, \dots, \pi_{nN}^J]'$  collects country  $n$ 's trade shares with all partners and in all sectors,  $_{n} = [\alpha_n^1, \dots, \alpha_n^J]'$  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 steel 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:

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

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  $\iota$  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 ( $\alpha$ ,  $\beta$ , and  $\gamma$ ), as well as bilateral trade shares ( $\pi$ ), 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 ( $\theta$ ) are taken from the online database of [Fontagné, Martin, and Orefice \(2018\)](#).<sup>14</sup> 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 ([Aguilar, Chepeliev, Corong, and van der Mensbrugghe, 2022](#)). The data supplies the model with all information that is needed from input-output tables ( $\alpha$ ,  $\beta$ ,  $\gamma$ ,  $\pi$ ,  $wL$ ,  $p^{r^p} R^p$ ,  $D$ ) for the year 2017.<sup>15</sup> We also calculate carbon intensities of different fossil fuel types ( $\iota$ ) 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

<sup>14</sup>Their GTAP 10 estimates are from October 2020 and can be found on their [website](#).

<sup>15</sup>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.

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.<sup>16</sup>

### 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,<sup>17</sup> 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.

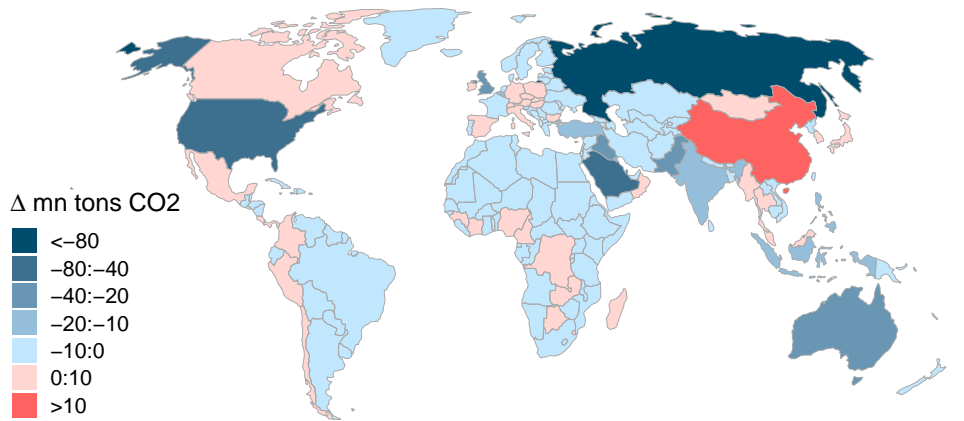
Figure 3.5 shows the change of global carbon emissions for all 160 counterfactuals. The value of each country represents the change in global carbon emission in the scenario where the respective country's imbalance is removed.<sup>18</sup> Generally and in line with our expectations based on the stylized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

<sup>16</sup>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.

<sup>17</sup>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.

<sup>18</sup>For the exact values of the change in global carbon emissions see Column (2) of Table C.3 in the Appendix C.

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



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 CO<sub>2</sub> emissions would go down by 78 Mt or 0.24 percent.<sup>19</sup> 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.<sup>20</sup>

<sup>19</sup>All emission quantities refer to CO<sub>2</sub> emissions only and to the model base year 2017.

<sup>20</sup>For a graphical representation of all countries' production, consumption, and extraction footprint changes in response to a US re-balancing, see Figure C.4 in the Appendix C.

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 running 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.<sup>21</sup>

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 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

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<sup>21</sup>For a graphical representation of all countries' production, consumption, and extraction footprint changes in response to a Russian re-balancing, see Figure C.5 in the Appendix C.

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.<sup>22</sup> 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:

$$\frac{\sum_n E'_n - E_n}{D_i} = \beta_0 + \beta_1 \frac{CF_i}{E_i} + \beta_2 \frac{EF_i}{E_i} + \varepsilon_i, \quad (3.19)$$

where  $E'_n$  refers to the counterfactual emissions in case country  $i$ 's trade 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.

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

<sup>22</sup>See Figure C.3 in the Appendix C for a graphical representation.

**Table 3.1:** Change in global emissions per rebalanced trade balance

	(1)	(2)
$CF/E$	162.879** (59.147)	-77.194* (32.100)
$EF/E$	-57.660*** (8.377)	96.363*** (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 CO<sub>2</sub> 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.

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 CO<sub>2</sub> per year. Is this a large effect? It is approximately equivalent to the total annual emissions of Spain — the number 21 emitter of CO<sub>2</sub> 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.<sup>23</sup> 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.

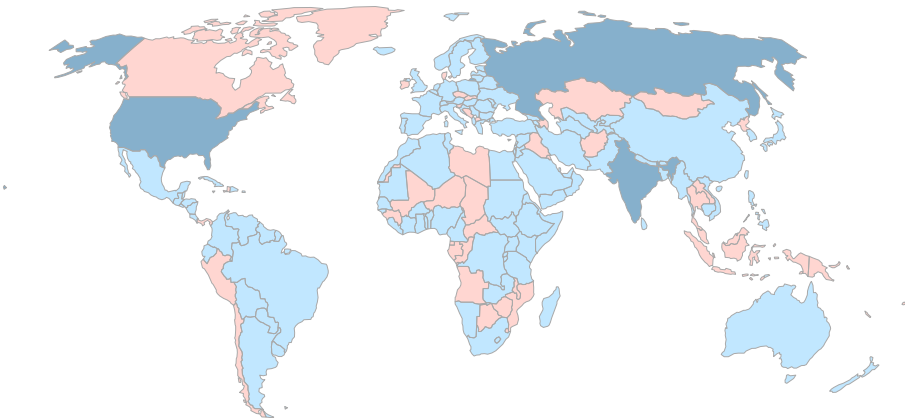
Second, the three footprints don't necessarily move in the same direction for the same country. The United States for example dramatically reduces its consumption footprint and also reduces, though much less strongly,

<sup>23</sup>For the exact values of change in carbon emissions and welfare see Table C.4 in the Appendix C.

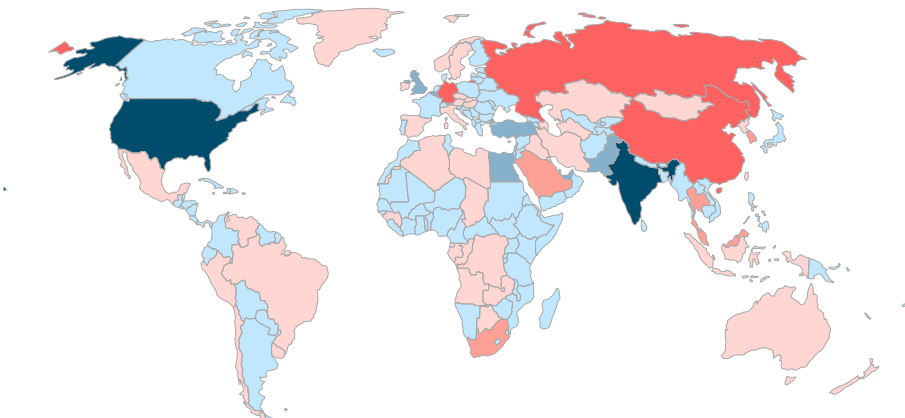


**Figure 3.6:** Percentage changes in carbon emissions, all countries balanced simultaneously.

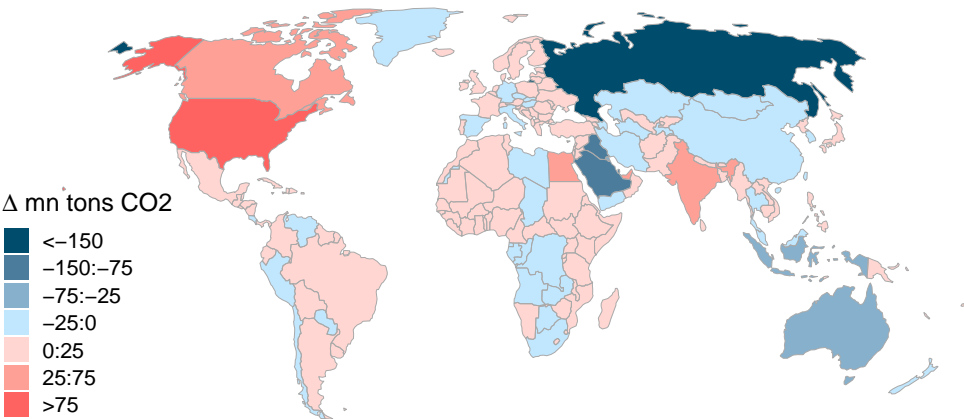
**Production footprint**



**Consumption footprint**



**Extraction footprint**





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 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<sup>1</sup>

### 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 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

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<sup>1</sup>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.

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 household 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 Quantitative 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).<sup>2</sup>

Using GAEZ, [Figure 4.1](#) shows gridded yield changes under future climate change for rice and wheat under RCP 6.0.<sup>3</sup> 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.

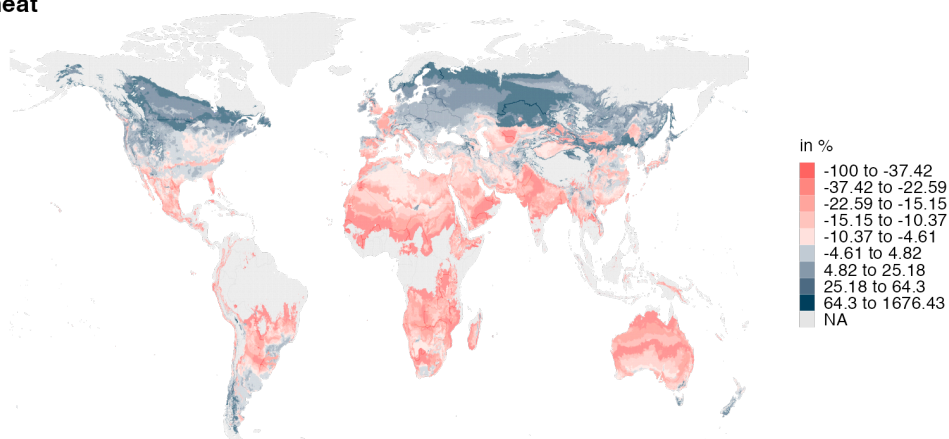
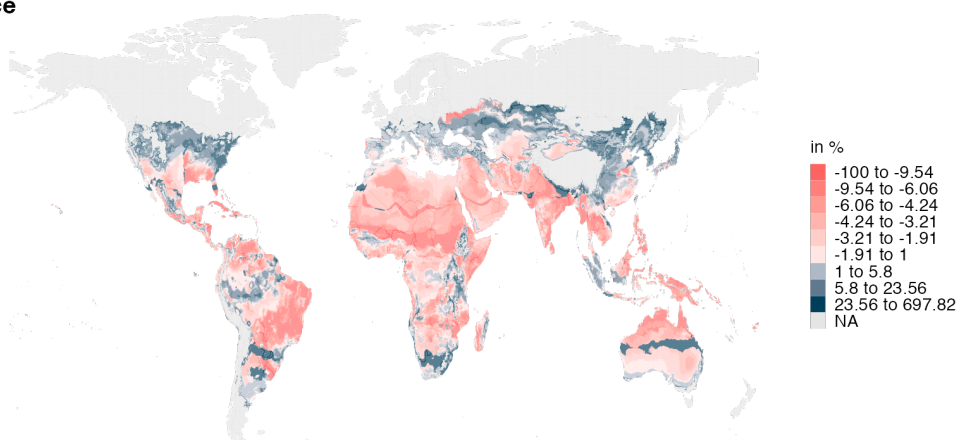
A potential adaptation strategy to mitigate negative climate change impacts is international trade. Trade can help countries diversify their economies and reduce their reliance on sectors that are vulnerable to climate change. Trade can also reduce risks associated with climate change by allowing a country to access a wider range of goods and services from different regions under heterogeneous climate change effects.<sup>4</sup> For example, if wheat yields in India will decrease substantially under climate change (see [Figure 4.1](#)), the country could import the quantity

<sup>2</sup>Climatic conditions are based on a time series of historical data of 1961-2010 and a 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.

<sup>3</sup>Yield changes for other crops can be found in [Figures D.2 to D.7](#) in the [Appendix D](#).

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

Figure 4.1: Climate-induced yield changes.

**Wheat****Rice**

*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.

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.<sup>5</sup> On the other hand, besides the spatial correlation of climate change-induced productivity shocks (Dingel et al., 2019), foreign shocks spread to other countries through 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 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

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<sup>5</sup>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.

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  $\alpha_d^j$  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<sup>6</sup>. Each country is endowed with an exogenous quality-adjusted amount of land which is used across sectors

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<sup>6</sup>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”.<sup>7</sup>

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  $\gamma$ . 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:

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

with  $\beta_d^j + \eta_d^j + \sum_{k \in J} \gamma_d^{k,j} = 1$ .  $l_d$  is the labour input,  $\beta_d$  the labour input share,  $h_d$  the land input, and  $\eta_d$  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  $\Upsilon_d^j = (\beta_d^j)^{-\beta_d^j} (\eta_d^j)^{-\eta_d^j} \prod_{k \in J} (\gamma_d^{k,j})^{-\gamma_d^{k,j}}$ ,  $w$  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  $\omega^j$  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  $\omega^j$  from the lowest cost supplier such that

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

---

<sup>7</sup>Mobile in a sense that the production on each field can switch among sectors.

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  $\omega^j$  in  $n$  across all possible origin locations, i.e.

$$p_d^j = \min_o \{p_{od}^j\}. \quad (4.1)$$

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

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

### 4.2.3 International trade

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

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

where  $\phi_{od}^j$  denote generic bilateral sector-specific trade frictions.<sup>8</sup> These can take a variety of forms — e.g., tariffs, non-tariff barriers, export taxes. In that case we can specify

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

where  $\tau_{od}^j$  represent sector-specific ad-valorem tariffs,  $\kappa_{od}^j \geq 1$  iceberg trade costs, and  $\zeta_{od}^j$  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

<sup>8</sup>The “phiness” of trade à la [Baldwin et al. \(2003\)](#).

a Fréchet distribution.<sup>9</sup>

The price of the composite good is then given as

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

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

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

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 also be expressed as

$$\pi_{od}^j = \frac{\lambda_o^j (c_o^j \phi_{od}^j)^{-\theta^j}}{\sum_{h=1}^d \lambda_h^j (c_h^j \phi_{hd}^j)^{-\theta^j}} \quad (4.6)$$

#### 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

$$X_d^j = \sum_{k=1}^J (1 - \beta_d^k) \gamma_d^{j,k} \sum_{o=1}^d X_o^k \frac{\pi_{do}^k}{\tau_{do}^k \zeta_{do}^k} + \alpha_d^j I_d \quad (4.7)$$

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

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<sup>9</sup>The productivity distribution is characterized by a location parameter  $\lambda_o^j$  that varies by country and sector inducing *absolute* advantage, and a shape parameter  $\theta^j$  that varies by sector determining *comparative* advantage.  $\theta^j$  describes the elasticity of trade to trade costs

difference between imports and exports

$$D_d^j = \sum_{o=1}^d X_{od}^j - X_{do}^j \quad (4.8)$$

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

$$\sum_{j=1}^J \sum_{o=1}^d X_d^j \frac{\pi_{od}^j}{\tau_{od}^j \zeta_{od}^j} - D_d = \sum_{j=1}^J \sum_{o=1}^d X_o^j \frac{\pi_{do}^j}{\tau_{do}^j \zeta_{do}^j}. \quad (4.9)$$

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  $\hat{\phi}_{od}^j = \phi_{od}^{j'}/\phi_{od}^j$  — 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

$$\text{Input costs} \quad \hat{c}_d^j = \hat{w}_d^{\beta_d^j} \left[ \frac{\hat{r}_d}{\hat{A}_d^j} \right]^{\eta_d^j} \left( \prod_{k=1}^J [\hat{P}_d^k]^{\gamma_d^{k,j}} \right)^{1-\beta_d^j-\eta_d^j} \quad (4.10)$$

$$\text{Prices} \quad \hat{P}_d^j = \left( \sum_{o=1}^d \pi_{od}^j [\hat{\phi}_{od}^j \hat{c}_o^j]^{-1/\theta^j} \right)^{-\theta^j} \quad (4.11)$$

$$\text{Trade shares} \quad \pi_{od}^{j'} = \pi_{od}^j \left( \frac{\hat{c}_o^j}{\hat{P}_d^j} \hat{\phi}_{od}^j \right)^{-1/\theta^j} \quad (4.12)$$

$$\text{Expenditures} \quad X_d^{j'} = \sum_{k=1}^J (1 - \beta_d^k) \gamma_d^{j,k} \left( \sum_{o=1}^d \frac{\pi_{do}^{k'}}{\tau_{do}^{k'} \zeta_{do}^{k'}} X_o^{k'} \right) + \alpha_d^j I_d' \quad \text{with} \quad (4.13)$$

$$\text{Income} \quad I_d' = \hat{w}_d w_d L_d + \hat{r}_d r_d H_d$$

$$\text{Tariff revenue} \quad + \sum_{k=1}^J \sum_{o=1}^d (\tau_{od}^{k'} - 1) \left( \frac{\pi_{od}^{k'}}{\tau_{od}^{k'}} \right) X_d^{k'}$$

$$\text{Export tax revenue} \quad + \sum_{k=1}^J \sum_{o=1}^d (\zeta_{do}^{k'} - 1) \left( \frac{\pi_{do}^{k'}}{\tau_{do}^{k'} \zeta_{do}^{k'}} \right) X_o^{k'}$$

$$\text{Trade balance} \quad - D_d'$$

$$\text{Trade balance} \quad D_d = \sum_{j=1}^J \sum_{o=1}^d \frac{\pi_{od}^{j'}}{\tau_{od}^{j'} \zeta_{od}^{j'}} X_d^{j'} - \sum_{j=1}^J \sum_{o=1}^d \frac{\pi_{do}^{j'}}{\tau_{do}^{j'} \zeta_{do}^{j'}} X_o^{j'}. \quad (4.14)$$

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

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

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 (Aguilar 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.

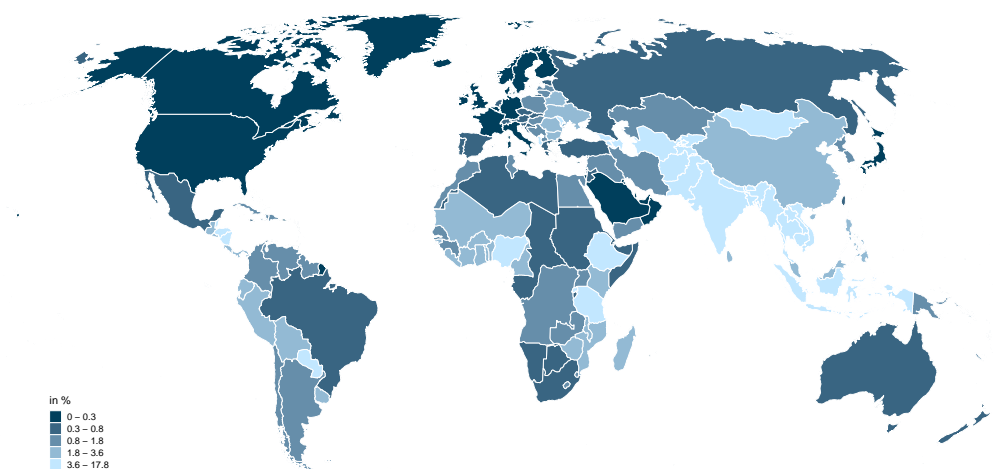
From GTAP, I derive all model parameters<sup>10</sup>, such as production factor shares of labour  $\beta$ , land  $\eta$ , intermediate input costs  $\gamma$ , trade shares  $\pi$ , consumption shares  $\alpha$ , tariffs  $\tau$ , export subsidies  $\zeta$ , labour income  $wL$ , and land rents  $rH$ .

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 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

<sup>10</sup>Despite the trade elasticities  $\theta^j$ , which I take from Fontagné et al. (2018), who use a gravity framework to estimate trade elasticities 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.

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<sup>11</sup>, 2.3 million grid cells on the earth's surface. Primarily, GAEZ is used by farmers and government agencies to assess the production *potential* for different crops in any given location on earth.

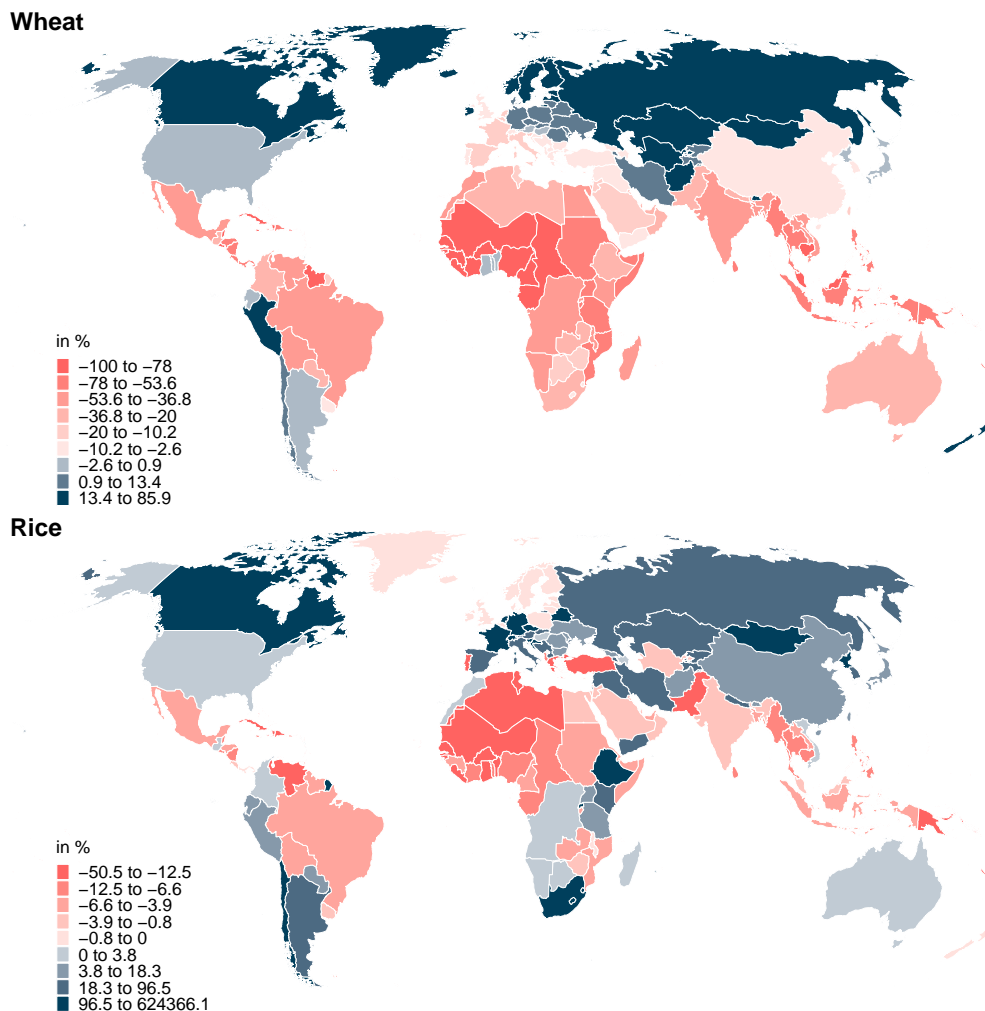
GAEZ productivity estimates are available for each cell, regardless a crop actually growing there. GAEZ uses state-of-the-art agronomic models, combining a vector of (i) attributes describing the growing characteristics in each cell, (ii) multiple parameters that govern how a given set of growing characteristics 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  $g \in \mathcal{G}_d \equiv [1, \dots, \mathcal{G}_d]$  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

<sup>11</sup>Owing to the curvature of the earth, grid cells at different latitudes cover different areas.

as a “baseline” to calculate yield changes under future climate conditions.

**Figure 4.3:** Productivity changes under RCP 6.0.



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.<sup>12</sup> The only difference to the “baseline”

<sup>12</sup>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



estimates, instead of past weather realizations GAEZ uses predicted future daily stream of weather from 2071 to 2100 to estimate future crop yields  $A_g^c$ .

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

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

where  $c \in \mathcal{J}_c \equiv [1, \dots, \mathcal{J}_c]$ .<sup>13</sup> 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 leveled out in the aggregate,  $\hat{A}_d^j$  would be one.<sup>14</sup> 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<sup>15</sup> which goes beyond the scope of this paper.

Figure 4.3 shows the values of  $\hat{A}_d^j$  for  $j = \text{wheat}$ <sup>16</sup> 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

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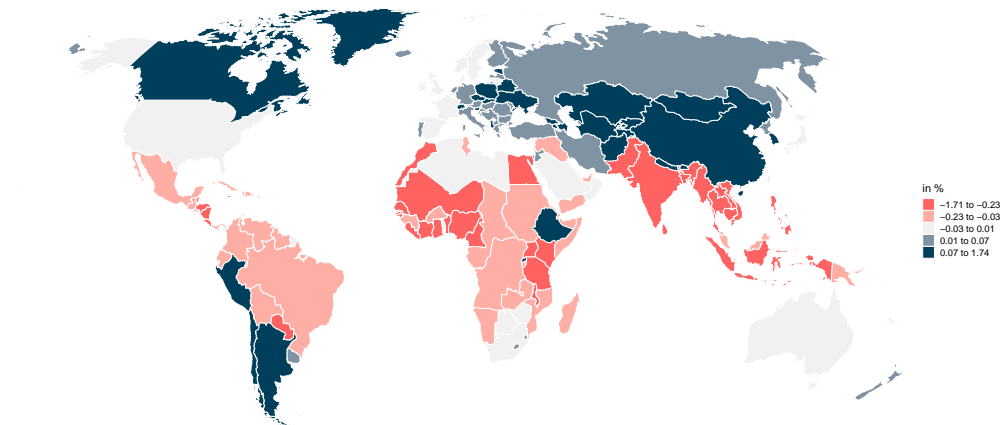
(ppm) of CO<sub>2</sub>-equivalent by the year 2100. RCP 4.5: This scenario represents a moderate reduction in greenhouse gas emissions, resulting in atmospheric concentrations of around 640 ppm CO<sub>2</sub>-equivalent by 2100. RCP 6.0: This scenario represents a stabilization of greenhouse gas concentrations at around 710 ppm CO<sub>2</sub>-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 CO<sub>2</sub>-equivalent by 2100.

<sup>13</sup>For a sector-crop concordance see Table D.2.

<sup>14</sup>Even though this consideration is highly unlikely given the narrow sector-crop matching.

<sup>15</sup>To model land use change properly, dynamic feedback loops with market prices and emissions are required, see e.g. Dominguez-Iino (2022).

<sup>16</sup>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.

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.

## 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),

**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
<i>N</i>	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.

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 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.<sup>17</sup> 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.

	$\Delta$ Bilateral imports		$\Delta$ Internal trade		$\Delta$ 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 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

<sup>17</sup>See Table D.3, D.4, and D.5 in the Appendix D for other RCPs.

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.

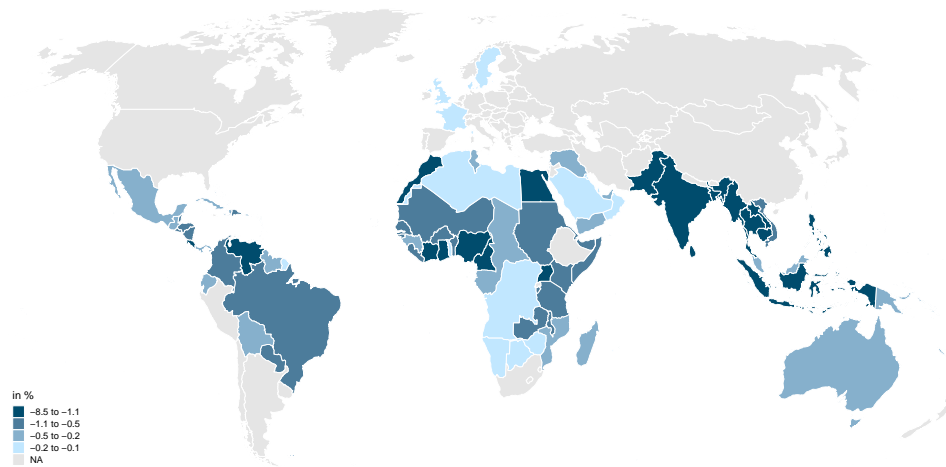
	(1)	(2)	(3)	(4)
Import share	0.004+ (0.002)	0.012*** (0.003)	0.012*** (0.003)	0.004 (0.004)
$\Delta$ Productivity	0.003** (0.001)	0.018*** (0.005)	0.015** (0.005)	0.015** (0.005)
Trade exposure			0.005+ (0.003)	0.004 (0.003)
Agriculture share				-0.047*** (0.013)
Num.Obs.	141	74	74	74
Adj. R2	0.128	0.321	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 in Scenario 1. With increasing greenhouse gas concentrations and more

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

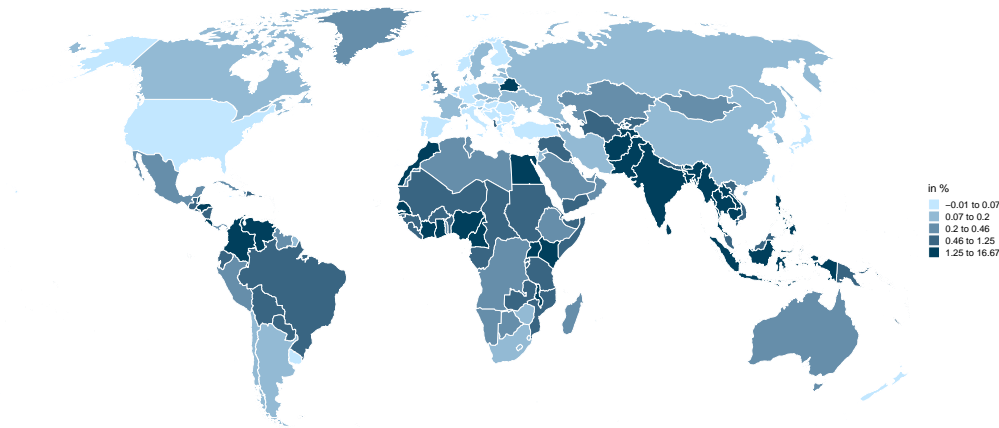
*Note:* NTB change necessary to compensate climate-induced welfare losses (Scenario 1) per country. NA values indicate countries that gain welfare in Scenario 1.

severe yield losses, necessary NTB reductions also have to get bigger.<sup>18</sup> 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 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

<sup>18</sup>Compare Figure D.11, D.12, and D.13 in the Appendix for other RCPs.

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

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 barriers. 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<sup>1</sup>

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<sup>1</sup>The chapter has been published as: 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, 75–108. The article is accessible via <https://doi.org/10.1007/s10663-022-09561-w>.

## Appendix B

### Macroeconomic Structural Change Likely Increases Inequality in India more than Climate Policy<sup>1</sup>

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<sup>1</sup>The chapter has been published as: Leimbach, M., Huebler, M., Mahlkow, H., Montrone, L., Bukin, E., Felbermayr, G., Kalkuhl, M., Koch, J., Marcolino, M., Pothén, F. and Steckel, J.C. (2024). “Macroeconomic structural change likely increases inequality in India more than climate policy”. *Environmental Research Letters*, 19(4), p.044070. The article is accessible via <https://www.doi.org/10.1088/1748-9326/ad34e9>.



## **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 in mn USD	Value added
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
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

*Continued on next page*

Table C.1 – Continued from previous page

GTAP code	Country	Trade imbalance in mn USD	Value added
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
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

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Table C.1 – Continued from previous page

GTAP code	Country	Trade imbalance in mn USD	Value added
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
SIV	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
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

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Table C.1 – Continued from previous page

GTAP code	Country	Trade imbalance in mn USD	Value added
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
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

Continued on next page

Table C.2 – Continued from previous page

GTAP code	Emission footprint in mn tons CO2		
	Production	Extraction	Consumption
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
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

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Table C.2 – Continued from previous page

GTAP code	Emission footprint in mn tons CO2		
	Production	Extraction	Consumption
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
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
SIV	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

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Table C.2 – *Continued from previous page*

GTAP code	Emission footprint in mn tons CO2		
	Production	Extraction	Consumption
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
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.

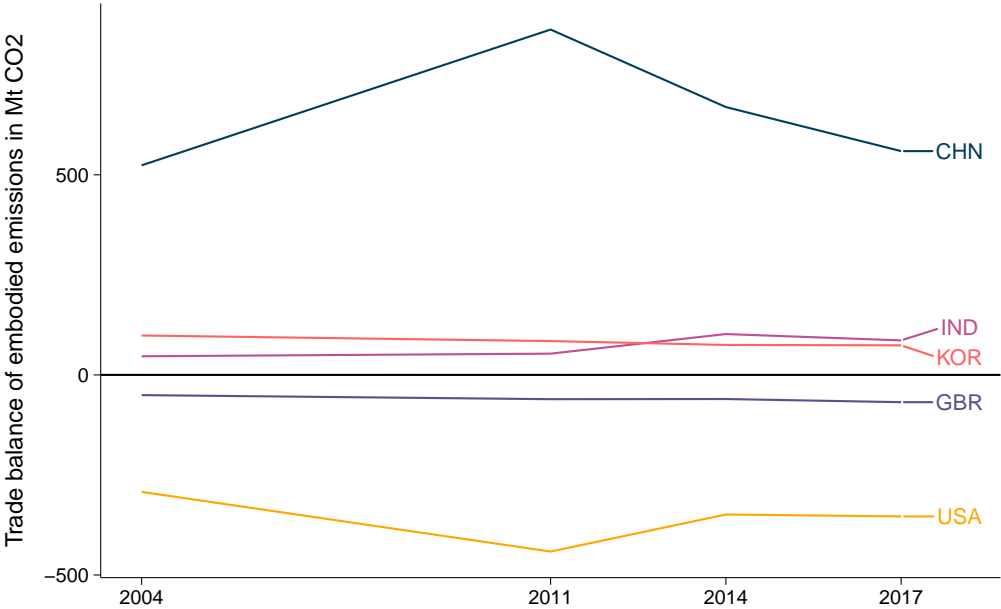
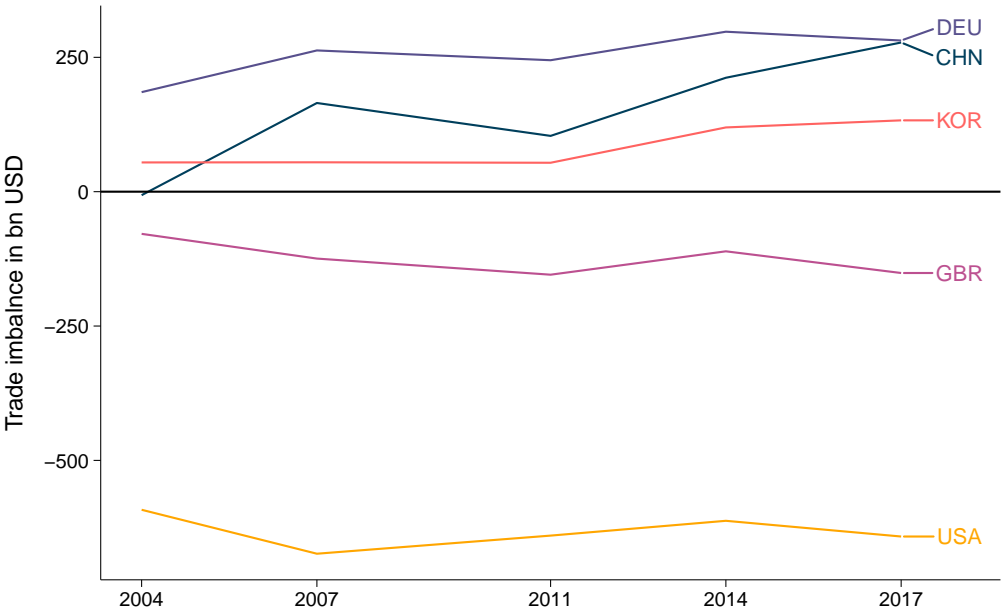


Figure C.2: Trade imbalance, by year.



## 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.

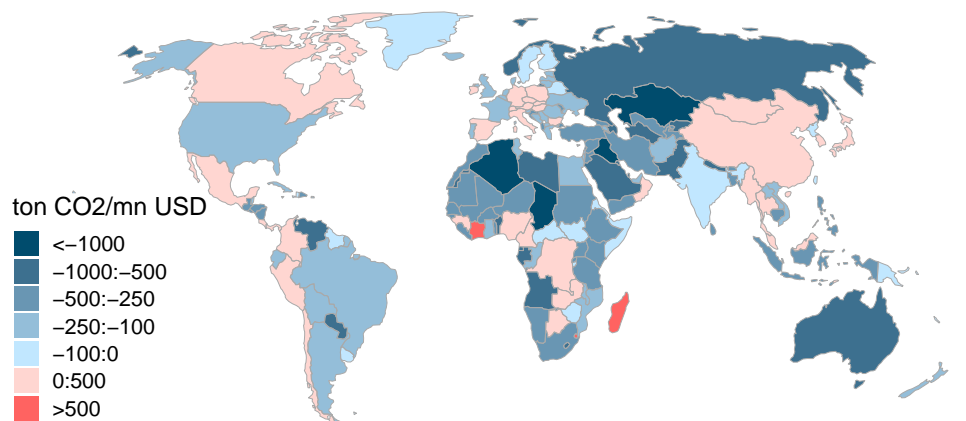
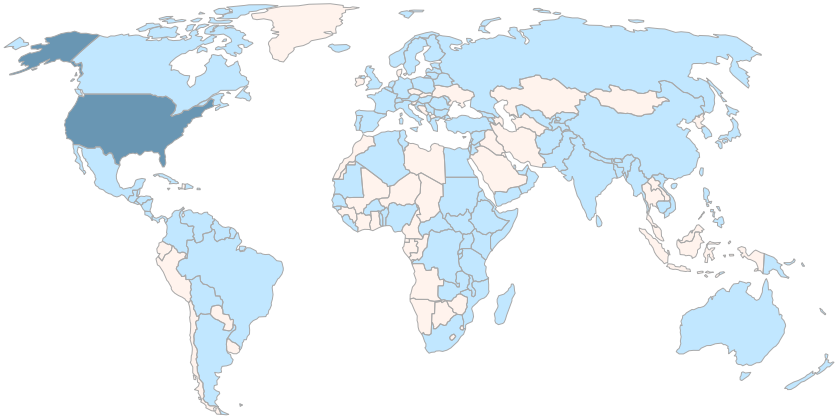
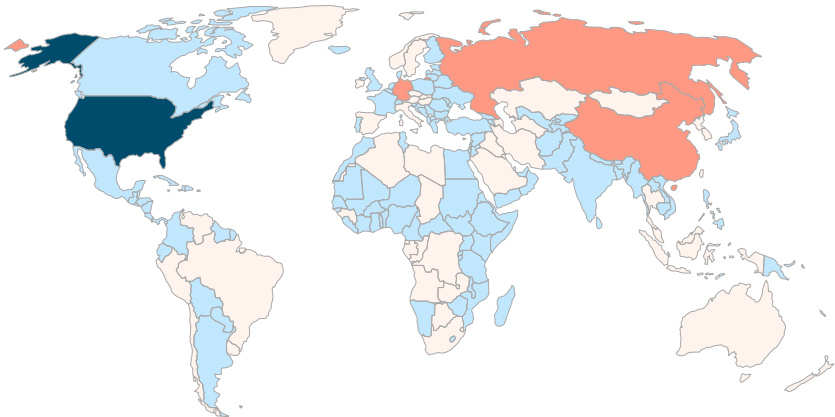


Figure C.4: Percentage change in carbon emissions, USA balanced.

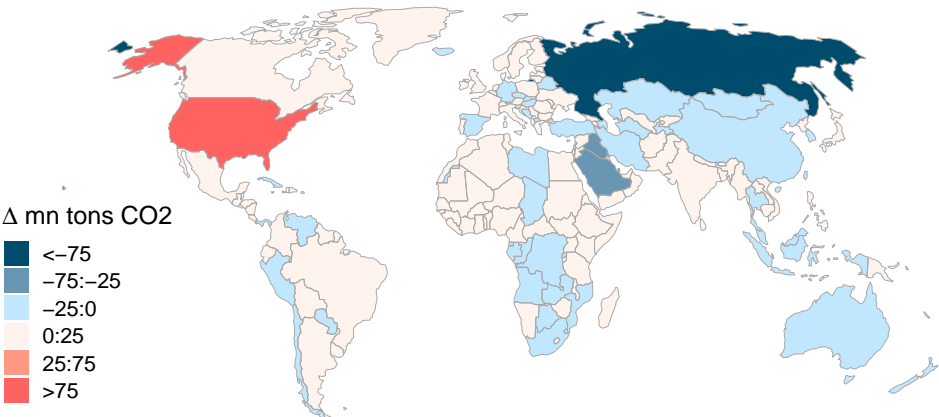
Production footprint



Consumption footprint



Extraction footprint

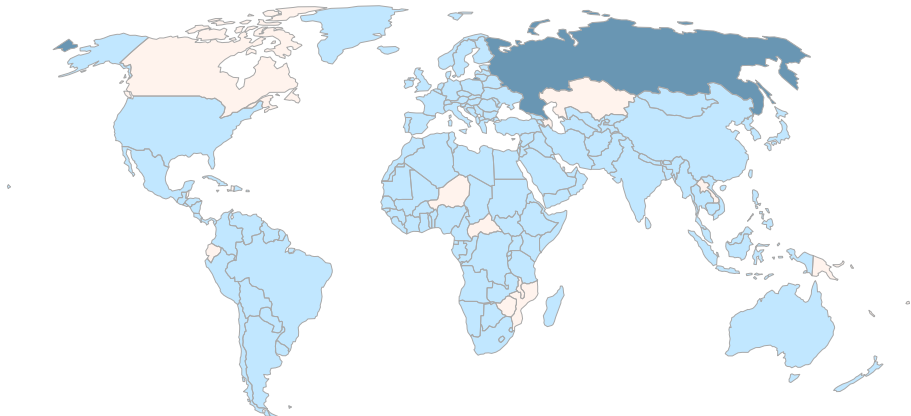


$\Delta$  mn tons CO<sub>2</sub>

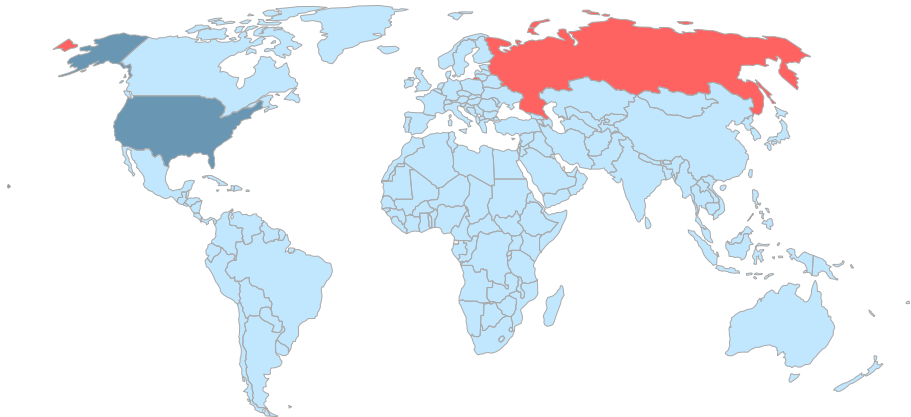
- <-75
- 75:-25
- 25:0
- 0:25
- 25:75
- >75

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

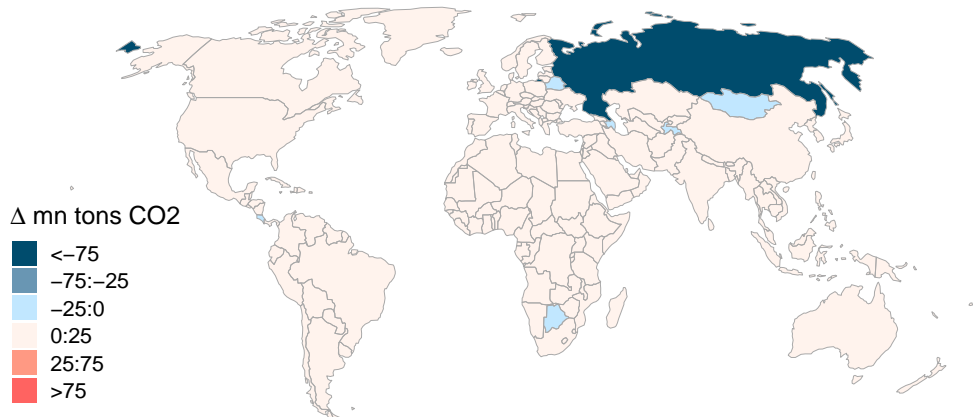
Production footprint



Consumption footprint



Extraction footprint



## C.2.2 Tables

**Table C.3:** Countries' corresponding emission changes in mn tons CO<sub>2</sub>, each countries balanced individually

Country	Countries' footprint change			Global emission change
	Production	Consumption	Extraction	
	in mn tons CO <sub>2</sub>			
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
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

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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			
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
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

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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			
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
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

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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			
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 simultaneously

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

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Table C.4 – *Continued from previous page*

Country	Countries' footprint change		
	Production	Extraction	Consumption
	in mn tons CO2		
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
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

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Table C.4 – *Continued from previous page*

Country	Countries' footprint change		
	Production	Extraction	Consumption
	in mn tons CO2		
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
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
SIV	-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
	sgf	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
	pdn	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
	ext	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
Services	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
	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
	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	ocr
Winter rye	kg DW/ha	
Cocoa	kg DW/ha	
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	osd
Yam	kg DW/ha	
Yellow yam	kg DW/ha	
Coconut	kg DW/ha	
Groundnut	kg DW/ha	
Jatropha	kg DW/ha	
Rapeseed	kg DW/ha	pdr
Soybean	kg DW/ha	
Sunflower	kg DW/ha	pfb
Dryland rice	kg DW/ha	
Wetland rice	kg DW/ha	
Alfalfa	10kg DW/ha	
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	

*Continued on next page*

Table D.2 – Continued from previous page

GAEZ crop	Unit	GTAP sector
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.

	$\Delta$ Bilateral imports		$\Delta$ Internal trade		$\Delta$ 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

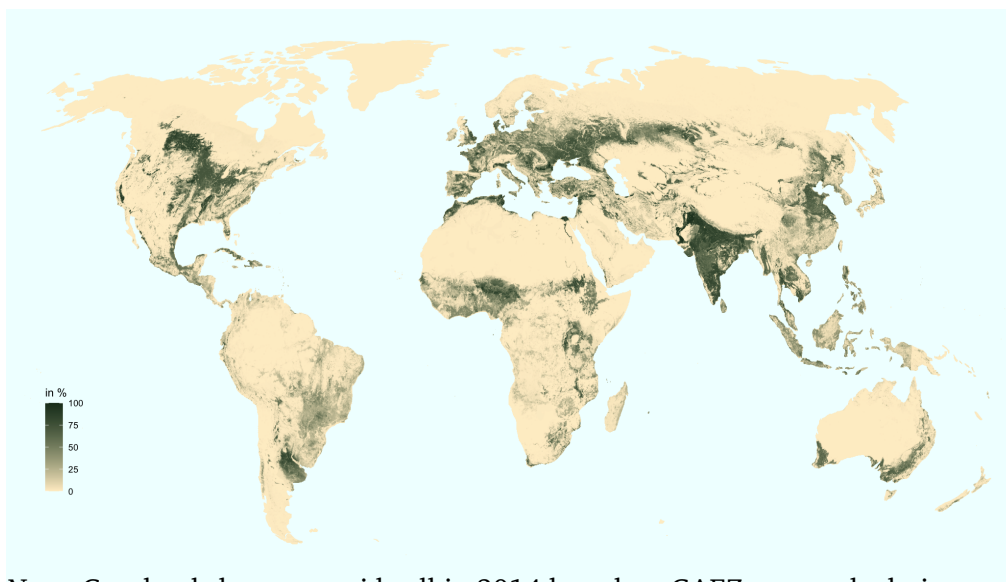
Table D.4: Scenario 1, trade flow changes in RCP 4.5, in percent.

	$\Delta$ Bilateral imports		$\Delta$ Internal trade		$\Delta$ 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.

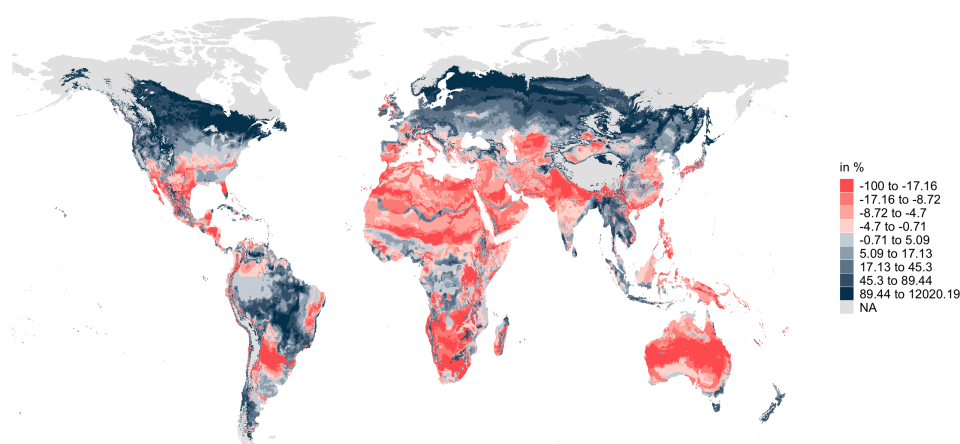
	$\Delta$ Bilateral imports		$\Delta$ Internal trade		$\Delta$ Total exports	
	L	W	L	W	L	W
Ag. Products	1.79	-3.87	-2.35	0.78	-3.27	1.02
Crops	12.46	-14.14	-6.89	7.42	-12.21	8.94
Fossils & Energy	-0.71	0.90	-0.44	-0.36	0.45	-0.44
Manufacturing	-0.43	0.66	0.32	-0.03	0.58	-0.14
Services	-0.78	1.35	0.54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

## D.2 Figures

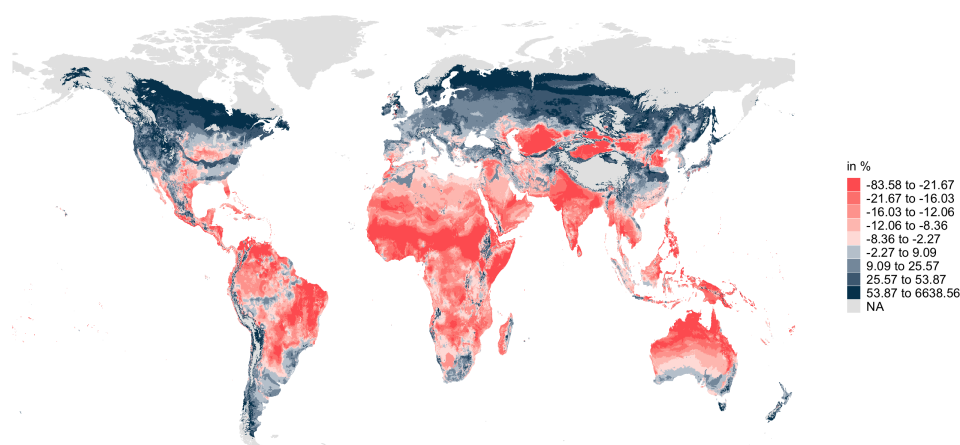
**Figure D.1:** Cropland share, 2014.

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

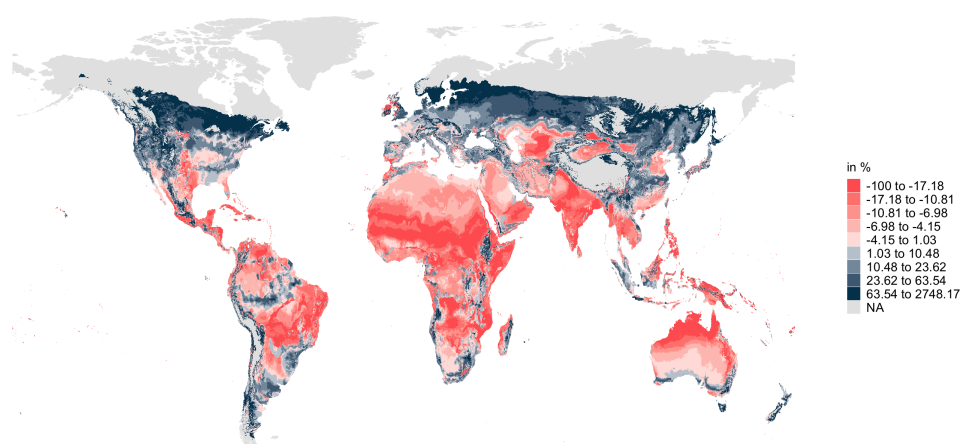


**Figure D.2:** *Cereal grains nec*, yield changes in 2071-2100 under RCP 6.0.

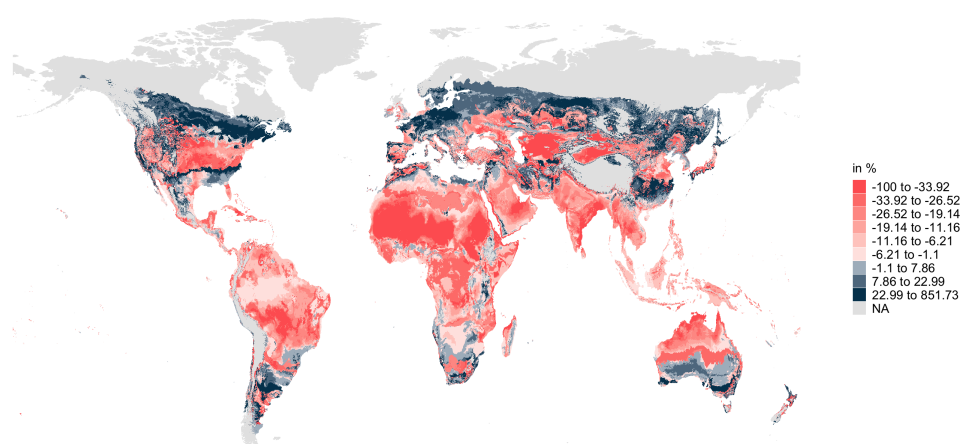
*Note:* GTAP sector *gro*, for mapping see Table D.2, based on GAEZ, own calculation.

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

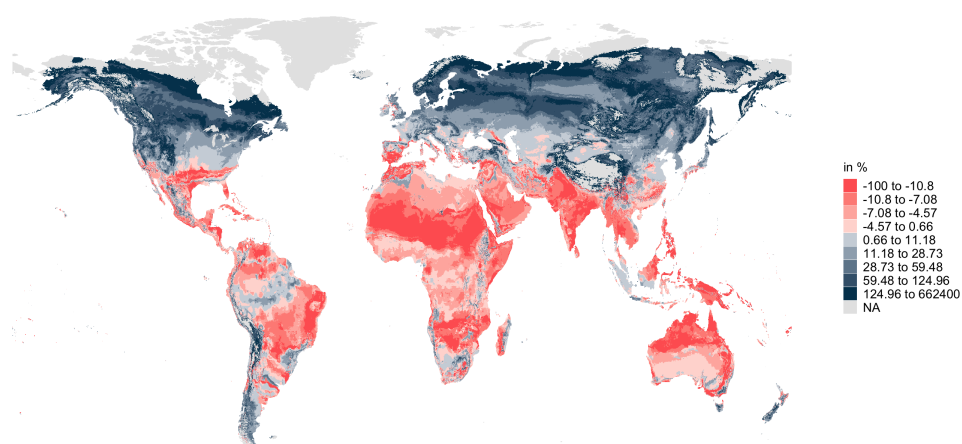
*Note:* GTAP sector *vf*, for mapping see Table D.2, based on GAEZ, own calculation.

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

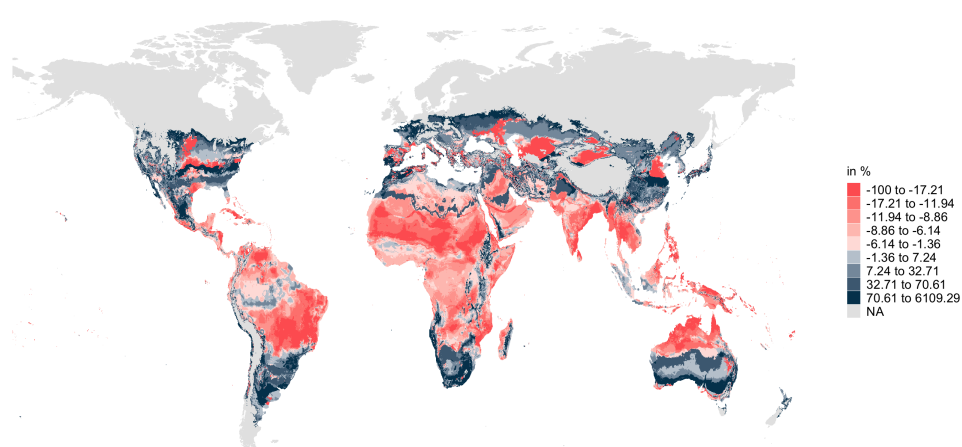
Note: GTAP sector *osd*, for mapping see Table D.2, based on GAEZ, own calculation.

**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 *pf* 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.

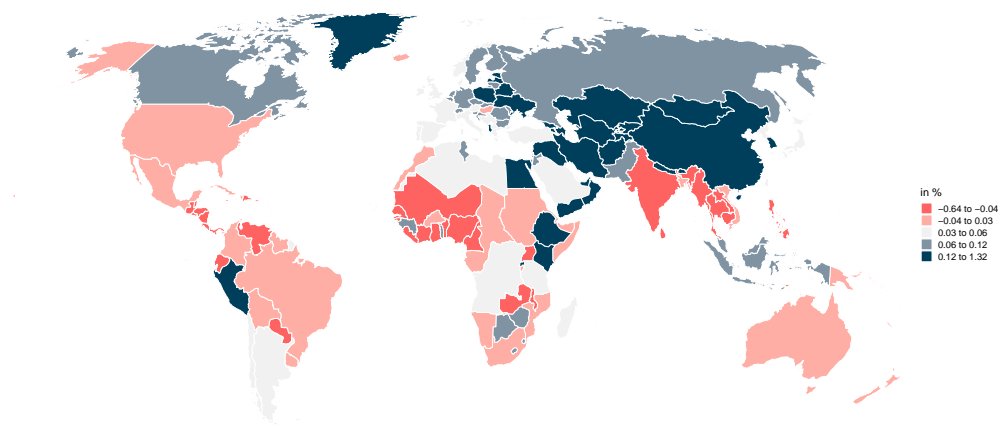
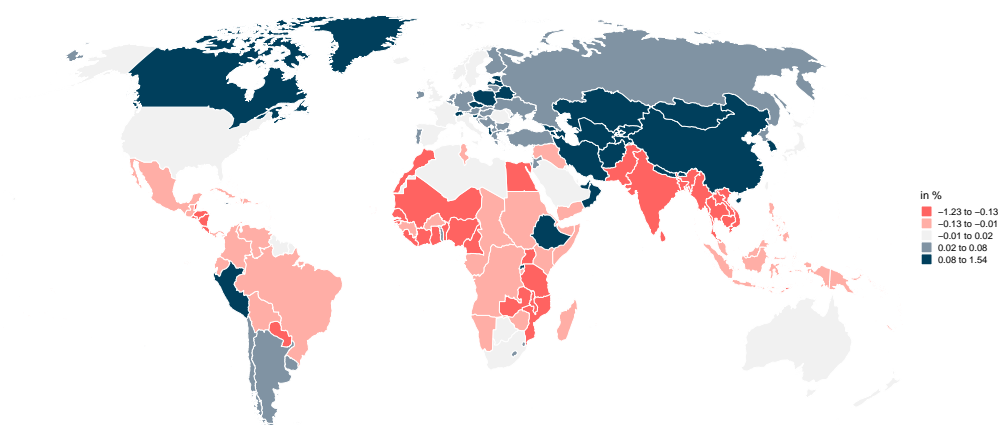
**Figure D.8:** Welfare change in scenario 1 under RCP 2.6.**Figure D.9:** Welfare change in scenario 1 under RCP 4.5.

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

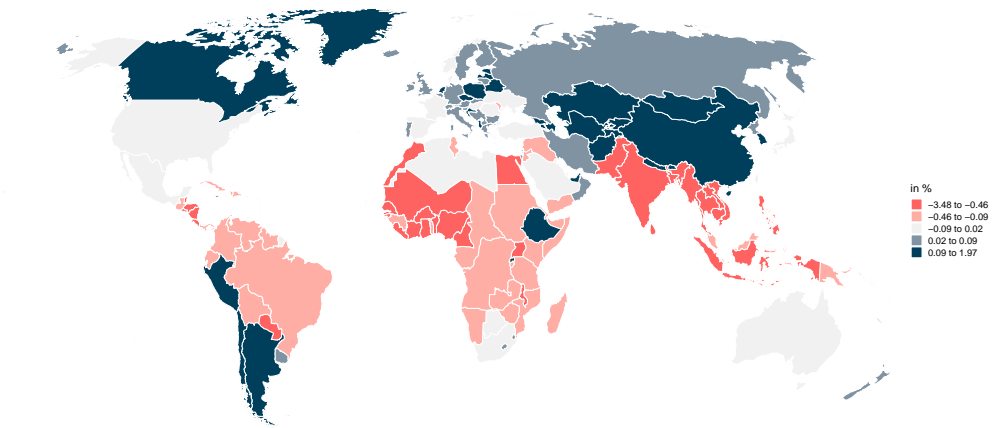


Figure D.11: NTB changes in scenario 2 under RCP 2.6.

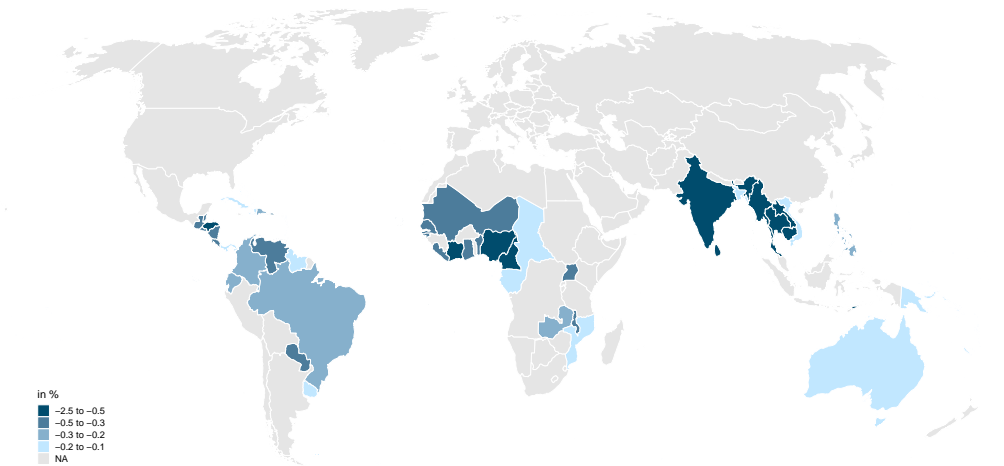


Figure D.12: NTB changes in Scenario 2 under RCP 4.5.

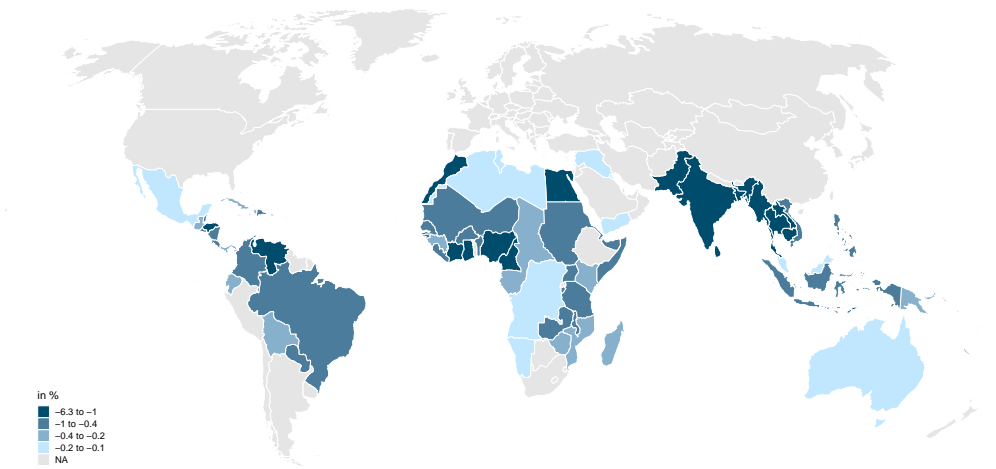
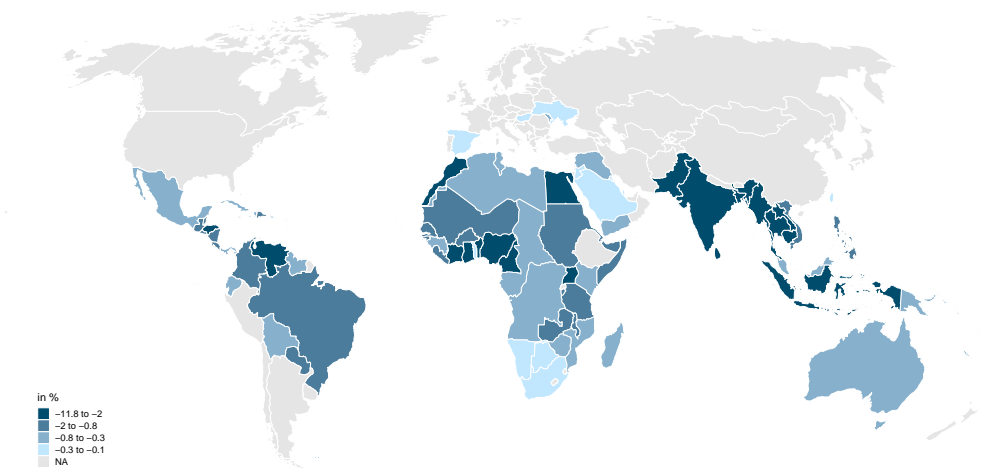


Figure D.13: NTB changes in scenario 2 under RCP 8.5.





## **Erklärung 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 übernommenen 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