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Abstract
While international trade can offer gains from specialisation and access to a wider range of products, it is also closely interlinked with global environmental problems, above all, anthropogenic climate change. This survey provides a structured overview of the economic literature on the interaction between environmental outcomes, trade, environmental policy and trade policy. In this endeavour, it covers approaches reaching from descriptive data analysis based on Input-Output tables, over quantitative trade models and econometric studies to game-theoretic analyses. Addressed issues are in particular the emission content of trade and emissions along value chains, the relocation of dirty firms and environmental impacts abroad, impacts of specific trade polices (such as trade agreements or tariffs) or environmental policy (such as Border Carbon Adjustment), transportation emissions, as well as the role of firms. Across the different topics covered, the paper also tries to identify avenues for future research, with a particular focus on extending quantitative trade and environment models.

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1. Introduction

Environmental degradation and anthropogenic climate change are among the greatest challenges the world is facing and increasingly threatening economic welfare and, more broadly, human wellbeing. To mitigate their causes and to adapt to unavoidable changes, major economic investments and determination on the part of policy makers is required. In this endeavor, EU policy makers start moving away from a narrowly focused environmental or climate policy to broader strategies. These explicitly account for environmental but also social objectives in policy areas that previously centered around economic considerations. For example, the discussion on the role of central banks in mitigating climate change is relatively new. In contrast, the debate on the role of trade and trade policy and specifically trade agreements dates back at least to the 1970ies and has received significant attention both in the public arena (thinking, e.g., of protests at the international trade conference in Seattle in 1999 or the public debate about the transatlantic free trade agreement TTIP) as well as in the economic literature.

Trade is probably the most important driver of globalization and while it has no-doubt increased global wealth significantly, it is also closely interlinked with global environmental problems. Dating back to Grossman & Krueger (1993) and Copeland & Taylor (1994), economists describe three channels through which trade and associated macroeconomic changes may affect the environment. The first is the scale-effect: if trade scales up production, it also scales up related pollution. The second is the composition effect: Trade affects the composition of "dirtier" versus "cleaner" industries in different countries and thus their domestic pollution. More broadly, with trade, the pollution that is related to the production and provision of the goods and services consumed in a given country, which can either be produced domestically or be imported, is not equal to the pollution the country experiences on its own territory in the process of producing goods and services both for domestic consumption and exports. This wedge can be driven by different factors, environmental policy being one of them, trade-policy another one. The third channel is the technique channel: Trade can affect the pollution emitted per unit of output or per unit of value added within industries and thus the pollution intensity of production: the same amount of a given product is produced with more or less pollution. These channels can be driven by different factors, environmental policy obviously being one of them, trade-policy again another one.

If one intends to address environmental concerns in trade related policies, it is necessary to understand how environmental outcomes, trade, environmental policy and trade policy interact.

The aim of this DG TRADE Chief Economist Note is to provide a short but comprehensive and structured overview of the existing literature. It focuses on empirical and quantitative work that has emerged in the last 50 years with a strong focus on recent developments. A large part of the overview will focus on carbon emissions, where the literature base is broadest. Our study can draw on existing, often very extensive reviews and meta-studies of the literature on "trade and the environment". Given the very large and steadily increasing number of studies, we will point to these reviews whenever possible and will refrain from listing and reviewing every single study. Instead, the aim is rather to capture the main strands of literature and to discuss exemplary approaches and findings, including their merits and limits. We will try to point to potential gaps and avenues for future research to help EU policy makers make informed decisions.

The paper will proceed as follows. Motivated by Copeland et al. (2021), Section 2 presents some very general stylized facts about the linkages between trade and environmental outcomes, thereby putting the rest of the literature into perspective. Section 3 deals with measuring and modeling emissions and pollution along the value chain of international trade and Section 4 focuses specifically on the emissions of transportation, which is essential for the conduct of goods trade. Section 5 discusses the linkages of environmental policy, trade policy and environmental pollution while Section 6 turns from the aggregate to the firm-level. Section 7 concludes.

2. Stylized Facts

This chapter briefly describes relevant stylized facts about interactions of trade, trade policy and the environment, which help to put the following review of the literature into perspective.

2.1 Emissions embodied in trade and emission outsourcing

Emission transfers or more broadly environmental impacts embodied in trade (also denoted as water content of trade, land content of trade or carbon content of trade) are an important indicator for the relevance of trade for the environment. They represent the wedge between the environmental impact that is generated on the territory of a country (territorial impact or production-based impact) and the impacts that are generated to produce the goods and services consumed in a country (water/land/ carbon footprint or consumption based-impact). A third perspective besides production and consumption-based impact assessment has been added, e.g., by Kortum & Weisbach (2021): for carbon emissions it is also possible to calculate the emissions resulting from the burning of fossil fuels according to where the respective resources have been extracted.

Hand-in-hand with international goods trade which increased relative to global GDP by around 50% between 1995 and 2014 (see WTO (2015)) and reached an absolute all-time high at 5.6 trillion USD in the third quarter of 2021 (see UNCTAD (2021)), the amount of environmental impacts embodied in trade has grown, too. Copeland et al. (2021) use data for carbon dioxide (CO2) and Nitrogen Oxides (NOx) from 1990 until 2009 showing that the shares of emissions embodied in international trade for both types of emissions rose almost continuously over time, reaching a peak in 2008 before they fell in 2009 corresponding with a decline in global GDP and the ratio of international trade to GDP. This is also in line with data from Peters et al. (2011) for CO2-emissions. Peters et al. (2011) also stress that non–energy-intensive manufacturing had a key role in the emission transfers since it accounted for a growing share of, in 2008, 30% of global exported CO2-emissions. Copeland et al. (2021) report that in 2008 around 35% of global CO2 emissions and 32% of NOx emissions were embodied in traded goods and services. Generally, in their data, the share varies between a fourth to a third of global CO2 / NOX emissions.

On a regional scale, the data of the Global Carbon Project (www.globalcarbonatlas.org) show that industrialized and rich countries are typically implicitly importing carbon emissions (they have a higher footprint than territorial emissions) while emerging and developing countries but more generally resource rich countries (Russia, South Africa, Venezuela, Australia, Qatar, Ukraine, Belarus) export emissions (they have a lower footprint than territorial emissions). The top six net importers of CO2 emissions in 2017 were the USA, Japan, Great Britain, Italy, France and Germany with the EU as a whole being the largest importer. The largest net exporters were China, India, Russia, South Africa and Kazakhstan. The EU as a whole has continuously been the largest importer in this regard, and in parallel with its economic rise, China and India have become the largest exporters along with Russia. The USA have made a shift from the tenth largest exporter to the second largest importer between 1990 and 2017. The patterns for water and land-impact (Tukker et al., 2014) are somehow different, with the EU still being a large net exporter of environmental impacts but with the USA and Australia, for example, having a lower water footprint than territorial water use.

An analysis by the OECD (Yamano & Guilhoto, 2020) shows that for CO2 the gap between the net exports of CO2 emissions from non-OECD countries and the net imports from OECD countries is continuously widening. Peters et al. (2011) summarize that "[m]ost developed countries have increased their consumption-based emissions faster than their territorial emissions [..]. The net emission transfers via international trade from developing to developed countries increased from 0.4 Gt CO2 in 1990 to 1.6 Gt CO2 in 2008, which exceeds the Kyoto Protocol emission reductions." Copeland et al. (2021) in their review also report growing net imports of pollution into rich countries not only for CO2 but also with a very similar pattern for NOX and conclude that rich countries thus increasingly outsource pollution through the means of trade. Summarized, the amount of emissions embodied in trade is significant and an increasing gap between territorial emissions and emission footprints in rich countries hints at increased outsourcing of emissions. Analysis relating to environmental impacts embodied in trade is reviewed systematically in section 3.1. and analysis on trade policy as a driver of outsourcing is reviewed in section 3.2. Related to this section 4 reviews how trade agreements or more generally increased trade openness affect environmental indicators. Finally, also section 5 on the relocation of emission intensive production to countries with lower explicit or implicit emission prices or emission policies is closely related to the outsourcing of emissions.

Before turning to emissions from transport, it should be noted that the described imbalances do not imply that a world without trade would be the solution. Such a drastic change would lead to significant negative economic impacts but unclear effects on emissions, because assumingly a large part of these emissions would otherwise happen domestically and reduced productivity and related energy efficiency in the absence of international trade could even increase emissions. More generally, the presented data on emission transfers are only accounting measures and can say little about the effects of e.g. environmental or trade-polices on trade-flows and related emissions. For this one needs quantitative trade models that account for changes in prices and quantities resulting from policy scenarios. Findings resulting from such model-based analysis will be discussed especially in section 3.2 and chapter 5.

2.2 Emissions from Transportation

Up to this point, we have focused on international trade affecting emissions from production by shifting sectoral production patterns. More directly, trade also implies emissions from transportation. Even in cases, in which comparative advantage leads to emission-intensive production locating in countries with green production technologies, the additional transportation emissions can offset potential emission reductions. If the global division of labor already leads to emission-intensive activities shifting to relatively inefficient or low-regulated countries, the environmental harm is magnified by the additional transportation emissions. In a large data effort, Cristea et al. (2013) separate the emissions associated with production and with transportation of all traded goods. They find that, overall, one third of the emissions related to internationally traded goods stem from their shipping. Around this considerable level, they find large variation across both sectors and countries. While transportation accounts for only about 10 percent of the overall greenhouse gas (GHG) emissions of bulk agricultural exports (partly due to bulk transportation being about three times less emission intensive than container transportation and partly due to the high non- CO2 GHG emissions in agricultural production), transport is responsible for the clear majority of emissions (around 80 percent) of machinery exports. Almost as heterogeneously, transportation is responsible for only 14 percent of Chinese export emissions, but two thirds of the carbon emissions linked to US exports. The large differences are explained by differences in the weight-to-value ratios across products, distances travelled to deliver the good, and transportation modes (e.g., maritime transportation being less CO2-intensive than aviation per ton-km), as well as the varying emission intensities of the production processes (e.g. the US exports relatively more products with a lower weight-to-value ratio than China and Chinese production technology is more dirty on average). Note that the production emissions considered by Cristea et al. (2013) take into account all types of energy inputs (including electricity) and their respective associated emissions, but not the whole value chain, i.e. emissions due to the production of inputs other than electricity are not taken into account.

Building on the work by Cristea et al. (2013), Shapiro (2016) also compares emissions of international trade due to the production and transportation of the traded goods. Using different sea and land distances, as well as different data sources for modal shares, he finds an even larger share of transportation emissions, with the two emission types (production and transportation) contributing roughly equally to overall trade-related carbon emissions. These findings stress the importance of taking into account transportation when considering the effect of international trade on the environment. We come back to the emerging literature on transportation emissions in Section 6.

2.3 Empirical patterns across industries and firms

Until now, we have taken a bird's eye view on trade and emissions, though the transportation pollution discussion already hinted towards the importance of sectoral heterogeneity. Now, we want to take a brief look at more disaggregated patterns, considering the industry and firm level. First of all, Copeland et al. (2021) show that pollution-intensive industries (both in terms of CO2 and other, local, pollutants) are generally more trade-exposed. On average, the trade share in the dirtiest industries is about five times higher than in the cleanest industries. This pattern is partly driven by the distinction between manufacturing industries – that tend to be both more pollution-intensive and traded to a larger extent – and service industries with their low emission intensities and trade shares. Additionally, there are sectoral differences in trade policy related to the industries' position along the value chain that are reinforcing this pattern (see Shapiro (2021), also discussed in Section 3.2). In particular, relatively dirty industries tend to be more upstream, i.e. in a value chain position far from the final consumer. At the same time, tariffs tend to be higher for more downstream goods (due to tariff escalation). This combination makes dirtier industries face lower tariffs on average. At the firm-level, there is strong evidence that more productive firms produce less emission-intensively (see, e.g., Shapiro & Walker (2018)). This pattern is tightly connected to the role of trade; indeed, over the last two decades, firm-level heterogeneity in productivity has taken center-stage in both trade theory and empirics. Specifically, it is often large, highly productive (and hence on average less pollution-intensive) firms that tend to serve foreign markets. Additionally, sourcing inputs from abroad is conducive to productivity gains. We will come back to the different dimensions of the firm-level consideration in detail in Section 6.

3. International Trade and Emissions

3.1 Analyzing and calculating the emissions embodied in trade

A first way to analyze the relation between trade and environmental change is to use descriptive data analysis to identify the emissions or environmental impacts embodied in trade[1]. Tukker & Giljum et al. (2018) give an overview about the different approaches and argue "that global multiregional input-output (GMRIO) analysis[2] has the largest potential to provide a consistent accounting framework to calculate a variety of different footprint indicators." These footprint indicators (see below) include different types of greenhouse-gas emissions as well as water, land and material-use. Also, Wiedmann et al. (2007) provide evidence that the MRIO analysis which covers trade linkages on the intermediate input level is an appropriate methodological framework. There is by now a very large and still growing body of literature of related studies that started already in the mid-1970s but gained importance in the early 2000s and received broad attention with widely perceived studies like the one by Davis and Caldeira (2010) who present a global consumption-based CO2-inventory for the year 2004. Earlier reviews are provided by Wiedmann et al. (2007) and Wiedmann (2009). These studies describe and compare the existing approaches and their advantages and disadvantages and gather relevant information on model features (number of regions, data-base, approach) and the performed studies (years of analysis, environmental indicators, countries, etc.). Wiedmann (2009) also summarizes important results of 20 studies covering Italy, Japan, the Netherlands, Scotland, UK, US or multiple-countries. Generally, the focus in both reviews is on methodological

[1] Though many of the papers cited in the following talk about "models", we would rather call what they do descriptive data analysis since no assumptions on behavior of actors are made.

[2] GMRIO analysis uses a set of regional input-output tables linked through bilateral trade-flows and including environmental impact variables related to inputs (water use, emissions, etc.) to extract information on environmental impacts embodied in trade.

issues, but these papers highlight that there are numerous studies, both for single countries as well as in multi-country settings, pointing in the same direction of input-output relations.

A large share of multi-country studies especially on carbon emissions is based on MRIO tables provided by either the Global Trade Analysis Project (GTAP) or the World Input Output Database (WIOD)[3], which are compared by Arto et al. (2014), and then calculate carbon footprints themselves using associated emissions data. One important difference is that WIOD provides yearly data, while GTAP has data only for selected years. Furthermore, the Exiodatabase (see Stadler et al. (2018) and Merciai & Schmidt (2018)),[4] in its current version, provides monetary supply-use tables with physical extensions (from 1995 to the current edge) and a hybrid form where the supply-use tables are, as far as relevant, specified in mass or energy units. Data are available for 43 countries and 5 Rest of World regions and very notably not only for greenhouse gas emissions but also water, land and material use. The GTAP database is amongst others used by Peters and Hertwich (2008), Hertwich and Peters (2009) and Peters et al. (2011). For example, the WIOD database is used by Copeland et al. (2021), Fan et al. (2016) and Ward et al. (2019). Exiobase is used, i.a., by Tukker et al. (2016) and in several studies that are part of a special issue summarized in Tukker & Wood et al. (2018).[5]

Another relevant database that contains not only GMRIO tables but in addition derived carbon footprints is the EORA Global Supply Chain Database[6]. It provides domestic carbon footprints (currently for 1990 – 2018) as well as footprints embodied in trade at the sector level. A number of further databases provide carbon footprint data. The Global Carbon Project (www.globalcarbonatlas.org), currently contains data on territorial carbon emissions and carbon footprints for the period 1990 to 2018 and for 219 countries. These data are generated (see Friedlingstein et al., 2020) using the GMRIOs and emission data from GTAP.[7] Also, the "Trade in embodied CO2 (TECO2)" database of the OECD (https://www.oecd.org/sti/ind/carbondioxideemissionsembodiedininternationaltrade.htm) presents a set of indicators[8] to reveal patterns of CO2 emissions embodied in trade. They derive net exports of emissions by combining the OECD Inter-Country Input-Output (ICIO) Database and International Energy Agency (IEA) statistics on CO2 emissions from fuel combustion and provide data for some 60 countries plus diverse aggregates currently from 1995 to 2018.

Tukker & Giljum et al. (2018) compare the different data bases. They differ in time period, regional, sectoral and product detail, constant versus current prices, whether they cover only

[3] See https://www.gtap.agecon.purdue.edu/ and https://www.rug.nl/ggdc/valuechain/wiod/?lang=en respectively.

[4] https://www.exiobase.eu/index.php/about-exiobase.

[5] A long list of literature discussing technical issues of the data base but also with studies based on the database can be found here https://www.exiobase.eu/index.php/publications/list-of-journal-papers-references (accessed Feb 5th, 2022).

[6] https://worldmrio.com/.

[7] Since GTAP data are only available for individual years (1997, 2001, 2004, 2007, 2011, 2014) gross domestic product (GDP) and trade data are used to generate an annual time series.

[8] These indicators are: CO2 emissions based on production (i.e. emitted by countries), CO2 emissions embodied in domestic final demand (i.e. consumed by countries), net exports of CO2 emissions, per capita emissions; production and demand-based, country origin of emissions in final demand.

monetary or also physical units and footprint indicators. The differences are nicely summarized in their Table 2. Moran & Wood (2014) compare carbon footprints derived from Eora, WIOD, EXIOBASE, and GTAP-based OpenEU databases, and find that results for most major economies vary by less than 10% between MRIOs.

Table 1: Review of the main Global Multiregional Input-Output (GMRIO) databases in 2016

Database	*Countries*	*Detail (ixp)**	*Time*	*Extensions*	*Approach*
GTAP-MRIO	World (140)	57 × 57	1990, 1992, 1995, 1997, 2001, 2004, 2007, 2011	5 (GWP), land use (18 AEZ), energy volumes, migration	Trade data are balanced first. Trade is imposed on IOTS. IOTs are balanced with trade and macroeconomic data
ICIO	World (70)	34 × 34	1995–2011	Various	The harmonized OECD IOTs are used as a basis. The OECD bilateral trade database, which is consistent with the IOTS, is used for trade linking.
WIOD	World (40+RoW)	35 × 59	1995–2011, annually	Detailed socio-economic and environ-mental satellite accounts	SUTs are harmonized first. The use table is split in domestic and import use. Bilateral trade databases are created for goods and services using international statistics. Trade shares from this trade database are used to estimate the countries of origin of the import use. The Rest of World (RoW) is used to reconcile bilateral trade shares. Extensions are added.
Eora	World (around 190)	Variable (20 to 500)	1970–2013	Various	SUTs and IOTs are gathered in original formats and used to populate an initial estimate of all data points in the GMR SUT/IOT. A large set of hard and soft constraints are formulated. A routine then calculates the global MR SUT/IOT.
EXIOBASE V2	World (43+5) Rest of the world regions)	163 × 200	2007	26 emissions, 69 IEA energy carriers, water, land, over 40 resources	SUTs are detailed and harmonized. The use table is split in domestic and import use. Trade shares are used to estimate the countries of origin of imports, resulting in an implicit export of these countries. These implicit exports are confronted with the exports in the country SUT and with use of a balancing routine a balanced GMRIO is obtained.

Note: *i … number of industries; p … number of products. GWP … global warming potential; AEZ … agro-ecological zone; IEA … International Energy Agency.
Source: adapted from Tukker & Giljum et al. (2018), p. 493.

Many of the descriptive data analyses (i.e. Peters (2008), Su et al. (2010), Su & Ang (2011) or Chen et al. (2018)) focus on methodological issues. Others focus on the developments in single countries (see Wiedmann (2009) for an overview table) or focus on a single year in multi-regional studies (e.g., Peters & Hertwich (2008), Hertwich & Peters (2009)). Many studies focus on CO2 emissions embodied in trade, but some include other greenhouse gases (e.g., Hertwich & Peters (2009), Copeland et al. (2021)) or water, land and material footprints (Steen-Olson et al. (2012), Tukker et al. (2014)). Most interesting in the context of this review is the multi-country analysis over time (Copeland et al. (2021), Fan et al. (2016), Peters et al. (2011), Yamano & Guilhoto (2020)), whose main results have been summarized in section 2.

While methodologies can still be refined, the most promising avenue for future research is to use these increasingly accessible methodologies and data for improved analysis and modeling of the drivers of emissions and environmental impacts embodied in trade and their interlinkages with policy action. This is especially straight-forward with quantitative models that are already based on MRIOs such as Computable General Equilibrium (CGE) models. The limited existing literature in this respect related to different more specific topics is reviewed in the following sections.[9]

3.2 Modelling Emissions along global value chains

In principle, all IO-table based quantitative trade models are able to analyze emissions along global value chains for different policy scenarios but this is somehow surprisingly not yet frequently done. A few of the CGE-based studies related to border carbon adjustment (BCA) which are discussed in more detail in section 4.2. derive emissions embodied in trade along the entire value chain to model full BCA. Examples are the studies by Böhringer & Bye et al. (2012) and Böhringer et al. (2018). Very recently, Wu et al. (2022) use a GTAP-E based CGE model with a carbon flow decomposition analysis to trace paths of carbon leakage related to the NDC targets of the Paris Agreement. They find that the NDCs hardly change net trade of embodied emissions in most developed economies, but present some detailed results on how CO2 emissions embodied in gross bilateral trade, emissions related to domestic production, emissions embodied in final consumptions and derived emission leakage react to the implementation of the NDCs in different countries. For the EU, for example, CO2-imports are not much affected by its NDC, but its production-based and consumption-based CO2 emissions decline significantly. Reaching the European NDC also implies a significant reduction of carbon outflow to other economies.

Recently, the development of global value chains and the associated international input-output linkages have also found their way into other types of quantitative theory models of trade and the environment, which had previously focused on final goods trade (Larch & Wanner (2017), (2019); Shapiro & Walker (2018)) or simplified versions of intermediate goods trade (Egger & Nigai (2015); Shapiro (2016)). Shapiro (2021) incorporates multi-regional, multi-industry IO-linkages following Caliendo & Parro (2015) into his quantitative model which he uses to assess the environmental bias of current trade policies (see Section 4.3). As he focusses on global emission changes, he does not make use of the IO structure to track production and consumption emissions through the model. Caron & Fally (2022) combine a similar trade model structure with a more elaborate modelling of the energy sectors, distinguishing primary and secondary fossil fuels while explicitly incorporating natural resources, additionally adding non-homothetic preferences. They investigate the emission effects of changing international consumption patterns and find that the shift towards less energy-intensive consumption at high income levels becomes less pronounced once emissions along the whole value chain are taken into account. Mahlkow & Wanner (2022) also use a gravity-type global value chain general

[9] As a side note, there are also empirical studies on the connection between trade and environmental impacts. Daebare (2014) for example find that “more water abundant countries tend to export more water-intensive products, and less water-abundant countries less water-intensive goods”.

equilibrium Ricardian trade model to consider the environmental implications of global trade imbalances. They show how the model allows different kinds of carbon accounting, namely attributing emissions either to the country where they occur (production footprints), the country where the products associated with the emissions end up being consumed (consumption footprints), or the country where the fossil fuels originated from (supply or extraction footprints). They find that current global trade imbalances significantly contribute to global emissions as they allow large current account deficit countries such as the United States to maintain a particularly high consumption footprint and, most importantly, large fossil fuel exporters such as Qatar or Australia to sustain their huge extraction footprints.

To summarize, the discussed analysis show that quantitative models that take into account global value chains can be and have been used to obtain a more detailed view on the emission effects of trade policy and climate policy by additionally explicitly tracing emissions embodied in trade and can also shed light on aspects that have previously received less attention, such as the roles of consumption choices at different development stages or the role of trade imbalances.

Overall, we see large potential for IO-table based quantitative trade models (CGE / others) to focus more on emissions along global value chains and to assess their interaction with environmental and trade policy. In particular, the capability to do regional and national carbon accounting along multiple dimensions allows to broaden the set of climate policies considered. Traditionally, climate policy has a strong focus on reducing territorial emissions. A consideration of the whole global value chain allows an assessment of which policies succeed in reducing domestic production footprints without counteracting movements in the consumption and/or extraction footprints.

4. Emissions from Transportation

An obvious way in which international trade affects the environment is via the pollution and emissions associated with the transportation of goods across the globe. In line with the aforementioned insight by Cristea et al. (2013), namely that transportation accounts for about one third of total trade-related carbon emissions, the European Green Deal explicitly targets emissions from maritime emissions. Nevertheless, the economic literature on transportation emissions is surprisingly sparse.

Cristea et al. (2013) are the first to systematically attribute carbon emissions from international transportation to the respective origin and destination countries, as well as products. They use their newly gathered data for a partial equilibrium analysis in which they assess which trade flows are increasing or reducing overall emissions. In most cases, international trade and the associated transportation emissions lead to higher total emissions, but for around a third of global trade, the authors find that production emission intensity in the exporting country is sufficiently lower than in the importing country that saved emissions from production overcompensate additional emissions from transportation. They additionally investigate a set of counterfactual scenarios in a general equilibrium model (version 7 of the GTAP model) and find, among other things, that the differential projected growth rates across the world and the associated shift of economic activity towards China and India will lead to a much stronger increase in transportation emissions than in the value of international trade, as bilateral trade will shift towards country pairs that are relatively far apart.

Mundaca et al. (2021) provide an econometric analysis of how transportation emissions react to changes in bunker prices (i.e., international fuel prices for maritime or aviation activities). As these prices are determined on the world market, the authors have to rely solely on time variation in fuel prices to estimate the emission elasticity. They find that products with a low value-to-weight ratio react more sensibly to the price changes. In a partial equilibrium analysis, the authors then use their estimated elasticities to investigate a range of carbon pricing policies in international transportation. The authors find that the global implementation of a 40 Dollar carbon price on transportation emissions would bring down transport associated emissions only by a rather mild 7.7 percent. The authors therefore consider additional scenarios with more ambitious policy interventions, such as a step-wise increase of the carbon price to 80 Dollars per ton. They find that the latter would succeed in cutting emissions in half in comparison to business-as-usual by 2050, as targeted by the International Maritime Organization (IMO).

Shapiro (2016) incorporates transportation emissions into a quantitative trade model that allows the ex-ante simulation of different policy scenarios. He updates and adds to the data by Cristea et al. (2013) to calibrate a multi-sector structural gravity model. Running counterfactual scenarios in this framework first of all again allows to quantify the changes in transportation emissions. Additionally, the effects of changing trade patterns on production locations for different types of goods and services are taken into account. This allows to also quantify the induced changes in production emissions. To assess the overall effect of global trade on carbon emissions, the author considers an autarky scenario. He finds trade to increase global emissions by about a relatively low 5 percent, driven to similar extents by production and transportation emissions. Hence, trade implies higher emissions because goods are shipped longer distances and also because it shifts pollution-intensive production towards countries with dirtier production technologies, even though the overall impact of trade on emissions remains rather low in their estimates. The author also finds that even after taking into account the welfare costs of the emission increase, international trade still clearly fosters global welfare. Shapiro (2016) additionally considers counterfactual scenarios in which different sets of countries implement carbon taxes for different types of transportation. In the most ambitious scenario, in which all countries impose a carbon tax on all international transportation, global welfare would be enhanced due to lower environmental costs, but effects are found to vary considerably: poor countries actually suffer more from the reduced gains from trade than they gain from lower emissions.

Lee et al. (2013) and Sheng et al. (2018) simulate a carbon tax on transportation emissions in existing CGE models (GTAP-E and GTEM), both finding very moderate economic costs associated with such a globally coordinated policy initiative. In a case study focusing on Brazil, Schim van der Loeff et al. (2018) add to Cristea et al. (2013) and Shapiro (2016)'s data efforts to gain a detailed view of transportation emissions. Using shipping manifest data allows them to finely differentiate the emission intensity of shipping on a destination- and product-level. Overall, the authors find that Brazilian exports account for 3.2 percent of global international shipping emissions. Parry et al. (2022) discuss a specific policy proposal for an international carbon levy on maritime emissions and its practical implementation. They find that even with a global carbon levy in place that is gradually increased to 75 Dollars per ton of CO2, zero-emission vessels need to be available by 2030 and substitute ships leaving the fleet from 2030 onwards in order to achieve the IMO 50 percent reduction target for 2050 mentioned above.

This strand of the literature could benefit both from additional econometric analyses of the potential of transportation emission reductions and quantitative frameworks that model the transportation sector in greater detail and/or incorporate Shapiro (2016)'s approach into a more elaborate quantitative framework which features the input-output linkages of global value chains. Recently, the international trade literature has moved towards a more elaborate consideration of transportation and trade costs. For example, Brancaccio et al. (2020) develop a quantitative trade model with endogenous trade costs and Ganapati et al. (2021) study entrepôts and the role they play in endogenous transportation networks. Brancaccio et al. (2020) among others find that endogenous trade costs dampen the cost advantage of net exporters and therefore limit trade imbalances (with corresponding potential environmental implications along the lines of Mahlkow & Wanner (2022) discussed above) and that changes in the fuel costs of international shipping have an additional indirect effect on shipping prices via changes in the negotiation power that counteracts the direct effect due to the fuel price change (implying e.g. that a carbon price might reduce international shipping to a lesser extent than one would expect based on exogenous trade costs models). Ganapati et al. (2021) find that a large part (80 percent) of international shipping is done indirectly rather than right from the origin to the destination country – overwhelmingly so via one of the large trade entrepôts. This increases the transport distance of products by 30 percent, implying that the emissions associated with shipping the product from the initial starting to the final endpoint may be severely misjudged if it is calculated based on the direct distance between the two points. The understanding of transportation emissions could hence be further enhanced by combining quantitative trade and environment frameworks with features from these endogenous transportation cost models.

Overall, the literature on transportation emissions is surprisingly still in its infancy in many respects. However, important data efforts have demonstrated that a considerable share of trade-related emissions stem from the shipping rather than the production of internationally traded goods. As already exemplified for a single country in the Brazilian case, additional data can go further and deliver much more fine-grained picture of international transportation emissions. Additionally, quantitative trade and environment models have treated these emissions with neglect and often only considered them implicitly in the form of iceberg trade costs. We see large potential in a more detailed modelling of transportation emissions, including but not limited to incorporating them into richer quantitative models and linking them to endogenous trade cost models.

5. Linkages between Environmental Policy, Trade Policy and Environmental Pollution

Research on the linkages between environmental policy, trade policy and environmental pollution dates back at least to the mid-1970s and focusses on the "pollution haven hypothesis".

This hypothesis predicts that countries with relatively weak environmental regulation attract pollution intensive production or that, vice versa, countries with relatively strong environmental regulation experience the relocation of pollution intensive industries and related trade flows. Emission leakage, that is the relocation of emission intensive production to countries with lower explicit or implicit emission prices or emission policies is a special case of the pollution haven hypothesis.

The phenomenon of leakage is a manifestation of the pollution haven effect and of particular relevance in the context of climate policy and carbon emissions. Theoretically, there are three main channels for leakage (Copeland et al. (2021). The first channel is related to competitiveness effects of environmental policy which directly or indirectly raises costs of polluting industries. Through shifting trade patterns, offshoring and foreign direct investment this can potentially cause production to relocate abroad. The other two channels exist mainly for climate policy, which reduces demand for fossil fuels and thus fossil fuel prices on international markets. In turn, this increases the demand for fossil fuels in countries without restrictions (second channel) and incentivizes counteracting reactions of the suppliers of fossil fuels that restrict supply, pushing up the price and encouraging producers in other countries to increase their production (third channel). Thus, trade is closely linked to pollution haven effects and emission leakage. Moreover, the more trade exposed a sector is, the stronger the first leakage channel.

In addition to the production relocation and the fossil fuel market leakage, there are further channels that have received less attention so far. Ambitious climate policy can lead to the development of clean technologies which can in turn spillover to countries that themselves do not undertake similar policy efforts, but nevertheless profit from the newly available technologies to reduce their fossil fuel input requirements. Gerlagh & Kuik (2014) include such a channel into a CGE model and show that this negative leakage channel can overturn the other leakage effects if international technological spillovers are sufficiently strong. In their theoretical discussion of carbon leakage in the context of carbon dioxide removal, Franks et al. (2022) stress yet another leakage channel, namely leakage via reduced climate damages. By lowering global emissions, climate policy put in place in one country lowers the extent and hence the detrimental effect of climate change on productivity in all countries, including countries that do not implement climate policies of their own. If these other countries' economies are less severely hit by climate change, their economies are larger than they would have been in the absence of climate policy and these countries therefore end up demanding larger amounts of fossil fuels for their larger production levels. This channel is so far absent from the quantitative trade and environment frameworks as these either abstract from climate damages altogether or capture them via a disutility component of emissions in consumer preferences.

Besides research related to the pollution haven argument, there is a 20-year long tradition of studies which empirically relate broad trade openness measures to environmental outcomes. Two prominent examples of this literature are Antweiler et al. (2001) and Frankel & Rose (2005). Antweiler et al. (2001) find that international trade has only small effects on SO2 through composition effects, but the trade-induced technique and scale effects imply a net reduction in SO2. The estimations of Frankel & Rose (2005) do not allow to identify the mechanisms of the impact of trade on different measures of environmental quality (SO2, N2O, particulate matter, CO2, deforestation, energy depletion, rural clean water access) but the authors conclude that "trade appears to have a beneficial effect on some measures of environmental quality, though not all, ceteris paribus. The effect is particularly beneficial for some measures of air pollution, such as SO2." Also, they find little evidence that trade has a detrimental effect overall and reject the hypothesis of an international race to the bottom driven by trade.

Yet, in their meta-study of 88 empirical studies published until 2018, Afesorgbor & Demena (2022) find that trade openness generally increases emissions and they stress the importance of making trade policies more compatible with sustainable environment policies by incorporating environmental decision-making into trade policy formulation. When separating their analysis for CO2 (a global pollutant) and SO2 (a local pollutant), they can confirm the overall significant effect of trade on emissions only for CO2.

In the following we will first discuss how to measure pollution haven effects and emission leakage and then how to possibly avoid emission leakage and more generally the role of trade policy to address emissions abroad. Finally, we will summarize a more recent literature on the effects of specific trade agreements and policies.

5.1 Measuring pollution haven effects and emission leakage

Pollution haven effects in general are traditionally measured using econometric approaches surveyed by Jaffe et al. (1995) and later Brunnermeier & Levinson (2004) and Copeland & Taylor (2004). Brunnermeier & Levinson (2004) conclude that *"[t]he early literature, based on cross-sectional analyses, typically concludes that environmental regulations have an insignificant effect on firm location decisions. However, recent studies that use panel data to control for unobserved heterogeneity, or instruments to control for endogeneity, find statistically significant pollution haven effects of reasonable magnitude. Furthermore, this distinction appears regardless of whether the studies look across countries, states, countries, or industries, or whether they examine plant locations, investment, or international trade patterns"*. In line with this, Copeland & Taylor ((2004), p 48) conclude that *"after controlling for other factors affecting trade and investment flows, more stringent environmental policy acts as a deterrent to dirty-good production"*. An example of such studies is Levinson & Taylor (2008) who use US data on 130 manufacturing industries and analyze the impact of US environmental regulation on trade with Canada and Mexico and find that sectors where abatement costs increase most see the largest increases in imports. Yet, again using US data, Ederington et al. (2005) show that it seems to be international mobility that affects international trade flows and that less pollution-intensive industries that are more labor-intensive and geographically "footloose" are more affected. Very recently Tanaka et al. (forthcoming) provide evidence for another case of a pollution haven effect as a result of the tightening of the US airborne lead standard which shifted battery recycling to Mexico and had negative health impacts for infants near the Mexican recycling plants. More specifically related to carbon leakage, econometric studies make use of data on the carbon content of trade. As discussed in section 2 such data already directly hint at increased outsourcing of emissions in rich countries. Supported by Peters & Hertwich (2008) who find that countries with emission reduction commitments under the Kyoto Protocol (Annex 1 countries) are net importers of emissions from countries that do not have such commitments (non-Annex 1 countries), this is potentially driven by climate policies. Examples of more sophisticated studies on the drivers of the carbon content of trade include Aichele & Felbermayr ((2012), (2015)) and Naegele & Zaklan (2019). Aichele & Felbermayr (2012) use a large panel of countries and an instrumental variables estimator to identify the causal effects of ratified and binding Kyoto commitments on carbon footprints and territorial emissions. While the Kyoto commitments reduced territorial emission by about 7%, they had no effect on carbon footprints and the ratio of imported emissions relative to territorial emissions increased by about 14 percentage points. This is consistent with carbon leakage effects as presented above.

Using a panel of the carbon content of bilateral trade flows, Aichele & Felbermayr (2015) make the role of international trade more explicit. They use a gravity equation, which accounts for domestic and imported intermediate inputs, and also deal with the non-random selection of countries into the Kyoto Protocol. Consistent again with leakage effects, they find that binding commitments have increased committed countries' embodied carbon imports from non-committed countries by around 8 % and the emission intensity of their imports by about 3 %. Naegele & Zaklan (2019) also use a gravity equation for the carbon dioxide content of trade, to analyze how the EU ETS affects trade and carbon flows, but find no evidence that the EU ETS caused carbon leakage.

Branger et al. (2017) do not use data on the carbon content of trade but estimate an equation linking imports of cement and steel to foreign and local demand (proxied by output indices) and the domestic carbon price derived from an analytical model. They use autoregressive integrated moving average (ARIMA) regression and Prais-Winsten estimations to analyze the impact of the EU-ETS on the cement and steel sector in the EU27, but find no evidence of carbon leakage. Verde (2020) provides a recent survey on the econometric evidence about the impact of the EU ETS on competitiveness and carbon leakage for which he reviews 35 studies and concludes that at least for the first two phases of the EU ETS until 2012 "there is no evidence of the EU ETS having had widespread negative or positive effects on the competitiveness of regulated firms, nor is there evidence of significant carbon leakage." They attribute this to "the combination of low-to-moderate carbon prices and generous free allocation, which to a varying degree has characterized the first two trading periods and a good part of Phase III".

Felbermayr & Peterson (2020) identify three general problems of econometric ex-post studies. First, the linear (logarithmic) approximations imply that the findings based on historical data can say little about the effects of more stringent policies since – especially in the presence of fixed costs – effects of climate policies on economics outcome variables can increase over proportionately. Second, to identify effects, the studies compare sectors, regions or industrial installations that are subject to different degrees of policy stringency and cannot capture the effects of measures that affect all units of observation. For example, findings of the effects of the EU-ETS on French manufacturing cannot be transferred to the German manufacturing sector or even the effects of the very different Californian Cap and Trade system on Californian industry. Third, it is unclear if results for specific policies can be transferred to other sectors, regions and/or time periods. In contrast, quantitative studies are able to analyze specific policies and to address potential reverse causality (e.g., net exporters of carbon have little interest to adopt climate policies). Applied quantitative models comprise partial equilibrium models for specific sectors and trade models capturing bilateral trade flows and international feedback effects. The latter include both CGE and structural gravity models.

A key indicator assessed in many studies is the leakage rate, which measures the share of domestic emission reductions that is offset by emission increases abroad.

Generally, leakage rates that are found in CGE studies are significantly higher than those implied by the empirical studies. To some degree this can be attributed to the fact that most empirical studies work with data from time periods in which climate policies have not yet been very stringent. Model-comparison studies (Böhringer & Balistreri et al. (2012)), meta-studies (Branger & Quirion (2014)) and recent reviews (Carbone & Rivers (2017)) show that the leakage rate in studies based on quantitative trade models typically varies between 5 and 30% with some outliers on both sides. Studies find that the leakage increases with the stringency of mitigation targets and decreases with the size of the coalition jointly undertaking climate policy (see Thube et al. (2021) for more details). Branger and Quirion (2014) investigate the role of model assumptions. They show that higher trade elasticities increase leakage, since the channels partly work through international trade. This finding is strengthened by the study of Böhringer et al. (2017) that includes scenarios with different trade elasticities.

Sector level studies are mostly based on partial equilibrium models; see World Bank (2015) for an overview; prominent studies include Demailly & Quirion (2006) and Fowlie et al. (2016). This work typically focuses on most vulnerable sectors like cement, clinker, steel, aluminum, oil refining and electricity sectors and, amongst other things for methodological reasons, finds higher leakage rates at least for some policy instruments. Sometimes leakage rates can even be over 100%. In contrast, Branger & Quirion (2014) report statistically significant higher leakage rates for CGE models than partial equilibrium models and suggest that this is the case since they cover the competitiveness channel and the predominating international fuel price channel, whereas partial equilibrium models typically only include the first one.

Yet, both types of studies cannot capture the aforementioned potential technology spill-overs and thus tend to overestimate leakage (Gerlagh & Kuik (2014)).

5.2 Indirect Land- use changes as a special case of environmental leakage

After the promotion of biofuels became popular in the early 2000s, first authors pointed out that the early live cycle assessments of carbon emissions of biofuels relative to conventional fuels are incomplete since they do not account for indirect land-use effects. Indirect land-use effects (iLUC) are defined as the expansion of cropland in some foreign country in response to domestic biofuel policies and increased global demand for biofuels. If natural land covered by rainforests and grasslands is cleared to produce food crops that were diverted elsewhere for the production of biofuels, this releases greenhouse gas emissions. In the worst case this relocation effect more than offsets the direct greenhouse gas savings through biofuels. In addition, iLUC can have other significant social and environmental impacts, e.g., on biodiversity, water quality and food prices. In some sense iLUC effects are thus a special type of environmental leakage and the mechanism to transmit iLUC effects is mainly world market trade in agricultural products. In 2007, high corn prices and riots in Mexico in 2007 spurred an intensive debate about the trade-off between food versus fuel production. In 2008, two Science publications, (Fargione et al. (2008), Searchinger et al. (2008)) based on a carbon accounting approach and live-cycle emission assessment, respectively, received high attention in the media and in research. Both studies show that the overall greenhouse gas balance of many biofuels is negative. Fargione et al. (2008) calculate that converting rainforests, peatlands, savannas, or grasslands to produce food crop–based biofuels in Brazil, Southeast Asia, and the United States releases 17 to 420 times more CO2 than the annual greenhouse gas reductions that these biofuels would provide by displacing fossil fuels. They stress that only biofuels made from waste biomass or from biomass grown on degraded and abandoned agricultural lands planted with perennials can offer greenhouse gas savings. Searchinger et al. (2008) find that corn-based ethanol increases greenhouse gas emissions for 167 years and biofuels from switchgrass grown on U.S. corn lands increase emissions by 50%.

Besides carbon accounting and live-cycle assessments, a large strand of literature is based on partial or CGE models (see van der Werf & Peterson (2009) for an early comparison of approaches). For iLUC, international repercussions are decisive, so that CGE models are more adequate. While first global CGE studies (see Kretschmer & Peterson (2010)) had to rely on very rough approaches to account for land-heterogeneity, this changed with the release of the GTAP satellite data on agro-ecological-zones (AEZ) in 2005 (Lee (2005)) which was used in first studies a few years later. Kretschmer & Peterson (2010) give an overview about early papers on the effects of biofuel targets in the EU and the US on land-use change and food prices and the advantages and disadvantages of different land-use modeling approaches in CGE models. A broader and more recent review is given by Hertel et al. (2019). They screened 727 papers from which they selected 81 studies referenced in the review. They stress the development of grid-based modelling approaches and conclude that "*[b]y integrating local biophysical, economic, and institutional information into a global framework, complex gridded models—developed by large research institutes and teams of collaborators—represent the most suitable approach to explore both the global drivers of local LUCC, as well as the feedback from national and subnational interventions to the global level*". Their overview mostly focusses on the different approaches, but also reports findings related to trade and emphasize the role of international trade in mediating LUCC and leakage effect. Most relevant is the mentioned study by Schmitz et al. (2012) that claims to be the first trade study using spatially explicit mapping of land use patterns and greenhouse gas emissions. It analyses two different scenarios of increasingly liberal trade until 2045. Related to LUC they find that trade liberalization leads to deforestation, mainly in Latin America and that non-CO2 emissions will mostly shift to China due to comparative advantages in livestock production and rising livestock demand in the region. They conclude that "*[o]verall, further trade liberalisation leads to higher economic benefits at the expense of environment and climate, if no other regulations are put in place.*"

Related to future research Hertel et al. (2019) identify three main shortcomings of existing studies: they are not sufficiently interdisciplinary, most studies focus on global-to-local linkages and focus less on local-global linkages and the reliance on complex and proprietary frameworks maintained by large organizations that are thus not available for a broader use of diverse applicants.

Besides quantitative modelling, there is also econometric evidence on the effect of trade on land-use change, in particular on how international trade affects deforestation. For the specific example of the Brazilian Amazon, Faria & Almeida (2016) use panel and spatial econometric estimators for municipality-level data from 2000 to 2010 and find that higher trade openness leads to higher deforestation rates. Leblois et al. (2017) take a broader view and ask more generally what were the drivers of deforestation in developing countries since the start of the millennium. They start off by reviewing the existing literature, before moving on to an updated assessment of the drivers using satellite image data. Besides the well-established effects of higher overall levels of economic activity and of higher population density, they also find that agricultural trade is a major force contributing to deforestation in developing countries. This effect is found to be heterogenous and particularly pronounced in countries that so far still have a large forest coverage. Abman & Lundberg (2020) explicitly consider trade policy, rather than realized measures for trade openness. Particularly, they investigate how deforestation changes after the enactment of regional trade agreements. Using data on almost 200 countries from 2001 to 2012, they implement an event-study design that allows for dynamic effects for trade agreements on deforestation around the entry into force of the agreement. They find that three years after an agreement has been enacted, net deforestation is about a quarter higher than the pre-RTA average. Abman et al. (2021), see also section 5.4) re-assess the deforestation effect of regional trade agreements while taking into account differences in the design of the agreements. In particular, they show that appropriate environmental provisions in agreements mitigate the deforestation effect. Hsiao (2022) develops a dynamic empirical framework of the palm oil market based on micro-data and focusing on Indonesia and Malaysia to evaluate import tariffs as a substitute for domestic regulation. He finds that the proposed EU tariffs on palm oil imports are most effective when coordinated at least with other major importers like China and India and when governments commit to upholding the tariffs over a long period of time. Fully coordinated and long term committed tariffs could reduce carbon emissions by 39%. Unilateral EU import tariffs would reduce emission by only up to 6%. Yet, Malaysia and Indonesia are always negatively affected by tariffs. An export tax in these countries though reduces emissions by 39% as well and has positive financial implications for them.

5.3 Trade policies and alternatives to mitigate emission leakage and achieve optimal environmental policy

The broader question of the relation between trade policies and pollution or emissions abroad dates back to theoretical work of Markusen (1975). He shows that given that there is no pollution policy in a foreign country, the optimal domestic policy is to address domestic pollution through pollution policy and import tariffs to target foreign pollution. Beside the "usual" component to reduce import prices, a second component of the optimal tariff is intended to reduce foreign pollution. This work has been extended, e.g., to multiple polluting goods (Hoel (1996)) or to tariffs on emissions embodied in trade that are shown to dominate tariffs on import values (Copeland (1996)). Copeland et al. (2021) stress two main concerns derived from this literature: First *"If the export supply curve facing Home is very elastic, then Home's optimal tariff is low because it creates distortions at Home but does not have much of an effect on foreign* *pollution. […] And second, because the tariffs lead to a Foreign terms of trade deterioration, it redistributes income from Foreign to Home".*

A large strand of quantitative literature again focusses on addressing carbon leakage and is based on quantitative trade models. The instrument that has received most attention is border carbon adjustment (BCA) of which there are different forms. Full BCA implies that the carbon content of imports is priced at the same level of carbon prices that holds for domestic firms and that domestic firms get refunded for the carbon costs of their exported goods. This levels the playing field both on the domestic and the foreign market. Among the studies with BCA, Kuik & Hofkes (2010) and Winchester et al. (2011) include scenarios that only assess import tariffs while other studies (Ghosh et al. (2012), Lanzi et al. (2012)) include export rebates in addition. Furthermore, some scenarios include the full carbon content of trade (Ghosh et al. 2012), others only direct emissions and/or emissions from electricity use (Böhringer & Balistreri et al. (2012), Lanzi et al. (2012), Weitzel et al. (2012)). In their meta-analysis Branger & Quirion (2014) estimate effects of BCA based on a large number of Partial Equilibrium and CGE-model based studies, including also the multi-model-study described in Böhringer & Balistreri et al. (2012). They find that BCA would reduce the leakage rate on average by 6 percentage points and in most cases it is decreasing between 1 and 15 percentage points. Yet, there are outliers where BCA generate negative leakage rates. Mathiesen & Maestad (2004) use a partial model of the global steel market and find a negative leakage rate for a scenario where a border tax is introduced in the Annex B countries at the same level as the assumed 25$ domestic carbon tax and where the border tax is applied to the average emissions per unit of output in the non-Annex B countries. McKibbin et al. (2008) use an intertemporal general equilibrium model of the world economy to assess scenarios where either the US or the EU implements a carbon tax either with or without BCA. The implemented tax starts at 20$ in 2010 and rises to 40$ in 2040 and the BCA applies to the actual carbon content of imports. In both BCA scenarios leakage rates are negative. Neither of the papers provides an explanation for these findings.

Results of more recent studies (Antimiani et al. (2016), Böhringer et al. (2017), Larch & Wanner (2017), Mahlkow et. al. (2021) also fall in the range of results reported in Branger & Quirion (2014). Böhringer et al. (2017) stress that the negative leakage rate they find for BCA stems from the fact that energy market effects are not taken into account. Since policies can only target the trade channel of leakage, but cannot affect energy market effects, BCA is typically unable to completely offset leakage. Burniaux et al. (2013) thus find that BCA would be more effective in terms of reducing leakage for rather small coalitions which have less influence on global fossil fuel prices. Farrokhi and Lashkaripour (2021) use a multi-country, multi-industry, general equilibrium trade model featuring abatement technology, scale economies, and transboundary carbon externality to analyze the potential of strategically set BCA to affect pollution abroad. One core finding is that BCA can achieve only 1% of the CO_2 reduction attainable under globally first-best carbon taxes. Note, however, that the carbon border taxes considered by Farrokhi and Lashkaripour (2021) are optimal tariffs taking into account both terms of trade effects and the carbon externality, but are applied to all trading partners irrespective of the partners' climate policies. Another view is added by Larch & Wanner (2017) who use a structural gravity model to assess the indirect carbon taxes world-wide and then assume that carbon tariffs are implemented which account for bilateral differences in these implicit tariffs. If these would be implemented, global emissions would decrease by 0.5%.

Few studies (Böhringer & Carbone et al. (2012), Böhringer et al. (2017), Fischer & Fox (2012), Monjon & Quirion (2011), Lanzi et al. (2012)) analyze further anti-leakage instruments such as output based allocation (OBA) where the number of free permits in an emissions trading scheme depends on the level of economic output, industry exemptions of carbon pricing, offsets or consumption taxes that apply both to domestic and foreign firms which levels at least the domestic playing field. Altogether the evidence is that among the explicit anti-leakage instruments BCA is usually the most effective instruments to address leakage.

BCA also usually negatively effects the welfare of countries outside a climate coalition, providing incentives for them to join. Such incentives are analyzed using stylized and partly also parameterized game theoretic models, which are reviewed by Al Khourdajie & Finus (2020) and a few CGE models (Böhringer et al. (2016), Weitzel et al. (2012)). Parametrization of game-theoretic can either be rather ad-hoc and for illustrative purposes only (as in Al Khourdajie & Finus (2020)) or based on outcomes of larger numerical models. In the context of BCA this has been done with quantitative trade (Farrokhi & Lashkaripour (2021)) and growth (Nordhaus (2015)) models. There is also the idea that more general trade sanctions and in particular import tariffs can enforce cooperation in climate policies. Earlier literature on this is reviewed in Lessmann et al. (2009). The idea of a climate coalition or climate club stabilized by tariffs was pushed especially by Nordhaus (2015).

The results of these studies are mixed. Al Khourdajie & Finus (2020) conclude that BCA can act as a credible threat and has the potential to increase global cooperation in different specific settings and using different stability concepts for coalitions. This is somehow confirmed by the recent study of Farrokhi & Lashkaripour (2021) that parameterize a non-cooperative Nash outcome with their above- mentioned quantitative trade model. They find that strategically set tariffs can successfully deliver a globally first-best outcome. In the first-best, all countries tax carbon at its global marginal damage and global CO_2 emissions are reduced by 61%. One necessary condition for this solution to materialize is that both the EU and United States commit to be core members of the clubs. The second condition is that the tariff level is not bound to be linked to the carbon content of trade. Then, the club members can credibly threaten tariffs to all outsiders that are sufficiently high that any country prefers to incur the pain of domestic climate policy in order to avoid the larger pain of high trade barriers to important destination markets. Böhringer et al. (2016) find that carbon tariffs (based on direct emissions from the burning of fossil fuels in the production of imported goods as well as the indirect emissions embodied in the electricity inputs to that production process) induce China and Russia to join a coalition of Annex I countries but the remaining model-regions retaliate through implementing tariffs themselves. These key findings hold for different emission reductions targets of the coalition and different key parameters of the CGE model. Weitzel et al. (2012) find that no matter how high border taxes are India and Least Income countries never have an incentive to join a coalition that contains all Annex 1 countries except Russia. For China and Middle-Income countries the tax rates must be respectively 10 to 6.6 times larger than the carbon price in the coalition. Only Russia and the Energy Exporting model-regions have an incentive to join. Yet, international compensating transfers in form of additional emission allowances are found to be a more efficient instrument (regarding coalition welfare) to create a stable global (grand) coalition than BCA. A drawback of the two CGE papers is, as Al Khourdajie & Finus (2020) put it, that the underlying stability concept is seriously simplified and only the stability of the grand coalition and a group of Annex 1 countries is analyzed.

Nordhaus (2015) combines game theoretic analysis with quantitative modelling using his growth model DICE. In his study BCA only induces more ambitious climate policy outside the coalition for very low carbon prices and already for a price of above USD 10/tCO2, the climate club decreases to two regions. In line with Lessmann et al. (2009) broader trade tariffs would be more effective to induce cooperation. In Nordhaus (2015) even a tariff rate of 1% induces high participation for a carbon price of USD12.5t/CO2. The rate increases for higher carbon prices and for a price of USD 100/tCO2- full participation is not achieved even with the highest tested tariff rate of 10%. Region wise, Canada and EU participate in 83% of the analyzed 40 regimes while Japan, Latin America, Southeast Asia, sub-Saharan Africa and USA participate in 70% of coalitions. Russia, China, Brazil India, South Africa and Eurasia participate in only 45 – 63% of cases. In only 68% of regimes, we see all model-regions participating. The countries joining the coalition are those with low abatement costs, low carbon-intensity, high damages, and high trade shares.

Motivated by Nordhaus' climate clubs, Barret & Dannenberg (2022) combine an adjusted public goods game with a lab experiment "*to study the conditions under which the decision to link trade cooperation and the provision of a global public good can be expected to increase welfare*". Amongst other things, they show that linking trade agreements to emission reductions increases cooperation under multilateralism. Their policy recommendation is that trade measures should be integrated into a multilateral formal treaty and that countries should be discouraged from imposing them unilaterally.

Altogether, we see a potential for further research bringing together game-theoretic and quantitative trade models in the spirit of Nordhaus (2015) or Farrokhi & Lashkaripour (2021) or game-theoretic models and experimental research in the spirit of Barret & Danneberg (2022) to analyze how trade policy can or cannot help to improve cooperation on climate policy issues.

Related to quantitative trade models, there is still room for improvements in how these models capture trade costs. Typically, these are only captured in a stylized way as iceberg trade costs (in structural gravity models) or as margins (in classical quantitative trade models, e.g., GTAP-based models) without directly linking the costs of carbon prices to transport costs or capturing alternative modes of transport and accounting for speed of transport to capture the important role of transportation emissions (see section 4) in greater detail.

5.4 Effects of Trade Agreements and specific Trade Policies

Recently, the focus has shifted towards the evaluation of specific trade policies. Shapiro (2021) considers both tariffs and non-tariff barriers to trade on the sectoral and bilateral level. He identifies that both types of trade barriers are higher, the further downstream (i.e. closer to the final consumer) an industry is positioned in the value chain. At the same time, more upstream industries are more pollution-intensive. Therefore, currently implemented trade policies favor trade of relatively dirty products. These products' lower trade frictions are linked to tariff escalation and hence to the positioning in the value chain rather than to the products' carbon intensity. Unintentionally however, the combined pattern of sectoral trade policy differences and emission intensity differences leads to a substantial implicit carbon subsidy. More symmetric trade policies for different industries along the value chain would therefore lower global emissions. Other studies have investigated the effects of individual trade agreements. For example, Cherniwchan (2017), see also section 6, finds positive environmental effects of NAFTA at the US plant level. Nemati et al. (2019) use panel econometric methods to consider the effect of Mercosur, NAFTA, and the Australia-United States Free Trade Agreement on greenhouse gas emissions. They find that the agreements are not environmentally detrimental if concluded between only high-income countries (US-Australia) and are able to lower per capita emissions if concluded between only developing and emerging economies (Mercosur), but that NAFTA as an agreement including countries at very different development stages increases GHG emissions. Specifically, they find that while NAFTA did not affect US and Canadian emissions, it led to an increase in Mexican GHG emissions. Davis & Kahn (2010) use regression analysis to assess the effects of NAFTA on vehicle trade between the US and Mexico. They find that traded vehicles have higher emissions of local pollutants per mile than the average US vehicle, and lower emissions than the average Mexican vehicle. Overall however, NAFTA increases total lifetime emissions, primarily because of low vehicle retirement rates in Mexico. Other studies have used quantitative models to undertake ex-ante assessments of individual trade agreements. For instance, Bengoa et al. (2021) use a CGE model to assess the environmental impact of the African Continental Free Trade Agreement. They find negligible changes in CO2, but a substantial increase of about 20 % in other GHG emissions and a decrease of the same magnitude in other pollutants. Tian et al. (2022) use a Caliendo-Parro (2015)-type quantitative trade model to ex-ante estimate the CO2 effects of the Regional Comprehensive Economic Partnerships (RCEP) among the ten countries of ASEAN (Association of Southeast Asian Nations), China, Japan, South Korea, Australia, and New Zealand by modelling RCEP tariff reductions or elimination. Under complete tariff elimination among RCEP members global CO2 emissions would increase by about 3.1% annually.

Another strand of literature assesses patterns in the environmental effects across different trade agreements according to the design of the agreements. Since explicit inclusion of environmental provisions has increasingly been used in trade agreements this has spurred corresponding empirical investigations. Baghdadi et al. (2013) estimate at the country-level whether countries that sign trade agreement containing more environmental provisions, pollute less and find significant evidence for the provisions' effectiveness. On the bilateral level, Brandi et al. (2020) investigate whether environmental provisions affect the amount and the product pattern of bilateral trade flows. Estimating gravity specifications, they find that the provisions lower pollution-intensive exports from developing countries, while fostering green exports. On the agreement level, Abman et al. (2021), see also section 5.3, find that while the entry into force of regional trade agreements tends to lead to more deforestation, this effect is offset if the trade agreement contains environmental provisions on forest protection and/or biodiversity.

Overall, the (mostly still young) literature on environmental provisions in trade agreements has already generated interesting empirical patterns using econometric methods, but these estimates have so far not been used to inform policy scenarios in quantitative models. We see potential for a more thorough understanding of the effects of such provisions with quantitative modelling that takes into account general equilibrium adjustments.

6. Firm-level considerations

Ever since the seminal contribution on trade with heterogeneous firms by Melitz (2003), the question how international trade is shaped by the role of firms has taken center stage in both theoretical and empirical trade research. As is evident from Cherniwchan et al. (2017)'s review article, (i) firms potentially play an important role in determining the effect of trade on the environment, too, (ii) the trade and environment literature is to a certain extent lagging behind the trade literature in shifting its focus towards studying the firm level, and (iii) first contributions in this area have already uncovered important relationships. In the following, we first summarize main theoretical findings, followed by econometric analysis and finally quantitative modeling.

Kreickemeier & Richter (2014) are the first to consider a Melitz-type trade and environment setting. In their theoretical framework, trade liberalization affects emissions in two ways: the increase in overall production leads to an increase in emissions (a scale effect) and the reallocation of production towards more efficient firms lowers emissions as these firms are also less pollution-intensive (a new so-called reallocation effect), with an ambiguous overall effect depending on the exact relative pollution intensities of firms with different productivity levels. Cherniwchan et al. (2017) additionally incorporate endogenous abatement by firms and show that the environmentally beneficial reallocation effect may be reinforced by rising abatement investments of those firms that gain from trade liberalization. Forslid et al. (2018) model emission intensities to only vary between heterogenous firms because of varying abatement investments. More productive firms are larger and invest more in abatement technologies as they have more to gain from lowering their emission intensity. Trade liberalization leads to a reallocation of production factors towards larger firms that are sufficiently productive to pay the fixed exporting costs. On the one hand, this leads to higher production and hence higher emissions. On the other hand, these firms invest more in abatement and are hence producing less emission-intensively and their growth in response to the trade liberalization makes an even higher level of abatement investment worthwhile for them. In the symmetric two-country setting and under the assumptions of a Pareto distribution and a specific functional form for the relationship between abatement investment and emission intensity, the scale effect and the additional abatement effort due to trade liberalization exactly cancel each other. Chang et al. (2022) consider a framework with heterogeneous firms and endogenous markups following Melitz & Ottaviano (2008) and stress that the resulting pro-competitive effect of trade liberalization reinforces the shift towards more productive and less pollution-intensive firms. Rather than the effect of trade policy on the environment, Egger et al. (2021) study how international trade influences the effectiveness of environmental policy. In a setting with two asymmetric countries with heterogeneous firms, the regulating country's emissions are – unsurprisingly – lowered by an increase in the emission tax. This decrease is driven by a scale effect and a twofold technique effect: each firm produces less pollution-intensively due to the higher emission price and the least productive (i.e. dirtiest firms) are driven out of the market as their profits can no longer cover their fixed costs. The reduction is less strong in the open economy as the export opportunity dampens the market size reduction effect of the tax. Interestingly, emissions in the nonregulating country are also found to decrease, i.e. there is a negative leakage rate, driven by a shift towards labor inputs in the non-regulating country as wages decline due to reduced export opportunities.

The role of firms in international trade also affects how environmental policy is strategically set, in particular if firms are allowed to endogenously choose their production location. Forslid et al. (2017) and Richter et al. (2021) consider homogenous firms models with trade and mobile firms and show that firm mobility induces tax competition that drives down environmental taxes compared to the global social optimum. In considering firms' decisions where to produce, these last two contributions are related to the literature on the interplay of FDI and the environment. For brevity, we retain a more narrow focus on trade and the environment here and refer the interested reader to the overview article by Cole et al. (2017).

Key in most theoretical frameworks investigating the role of firms in international trade on environmental outcome is that more productive firms are less emission intensive. In some models, this is incorporated as an assumption, in others it is the endogenous outcome of firm-level abatement decisions. As these models at the same time imply that only the most productive firms become exporters, there is the empirically testable implication that exporters are cleaner in the sense that they emit less per unit produced.

The empirical literature in this area has been pioneered by Holladay (2016) who uses US data from the National Establishment Times Series and the Environmental Protection Agency (EPA)'s Risk-Screening Environmental Indicators (RSEI) to estimate how exporting status affects toxic releases at the plant level. In a regression with industry, state, and time fixed effects and controlling for size differences, he finds that exporters pollute about 10 percent less than non-exporters, though with considerable heterogeneity across different types of pollutants and particularly across industries. Additionally considering import competition in a logit regression with the same sets of fixed effects, he finds that higher competition drives small, relatively pollution-intensive firms out of the market.

Cui et al. (2016) and Cui & Qian (2017) also consider micro-level evidence for the exporting status on the emission of local pollutants by US producers. Cui et al. (2016) use a two-step regression procedure and find supporting evidence for exporters being cleaner, while Cui & Qian (2017) use a matching estimator and find a similar pattern in some sectors, but also estimate that in some sectors exporters produce more pollution-intensively. They link the sectoral heterogeneity to a number of industry characteristics, finding e.g. that a higher overall level of abatement capital expenditure widens the gap between exporters and non-exporters, while fiercer import competition makes the emission intensity of exporter and non-exporters more similar and a higher wage level in the industry also increases exporters' relative pollution intensity.

Blyde & Ramirez (2021) additionally investigate whether the export destination matters for the effect on pollution and, using Chilean data, find that the richer the destination market, the stronger the pollution reduction effect of exporting.

Batrakova & Davies (2012) use data from the Irish Census of Industrial Production to assess the effect of being an exporter on firm-level energy use, which is used as a proxy for pollution due to a lack of firm-level pollution data. Using both quantile regressions and a difference-in-differences propensity score matching estimator, they find that the effect of becoming an exporter on energy use depends on the prior level of energy intensity: relatively "clean" producers increase their energy use when exporting as the export decision mainly entails a scale effect on their produced quantities, while energy use goes down for relatively "dirty" (i.e. previously energy-intensive) producers, as the scale effect is overcompensated by a technique effect due to cleaner production technologies that become worthwhile because of the exporting opportunity.

Cherniwchan (2017) considers the plant-level emission effects in the US for one specific trade liberalization episode, namely NAFTA (see also Section 4). He combines particulate matter and sulfur dioxide emission data from the EPA's Toxic Release Inventory (TRI) and employment and sales data from the National Establishment Times Series (NETS) with sector-level tariff and trade data. In a regression with plant, industry-year, and state-year fixed effects, he estimates the effects of tariff changes both on the ex- and the import side on the different types of pollution, using the tariff changes induced by the entry into force of NAFTA as identifying variation. He finds robust evidence that Mexican tariff cuts and the resulting increased exporting opportunities for US plants lower pollution in these US plants. On the other hand, there is no clear and significant pattern for the effect of lower US tariffs and potentially resulting increased import competition from Mexico on US plants' emissions.

In terms of global rather than local pollution, Cole et al. (2013) are the first to empirically consider the effect of exporting on carbon intensity. Using a cross-section of Japanese firms in 2006, the authors assess a wide range of determinants of firm-level carbon emissions, including the share of output that is exported. Both a simple OLS regression and different spatial error models indicate that firm-level emissions are decreasing in this export share.

Richter & Schiersch (2017) combine four German administrative datasets to create a firm-level panel for German manufacturing in the period 2003-2011. They use a structural econometric approach from the productivity literature following Ackerberg et al. (2015) to control for unobserved productivity and find that the carbon intensity is decreasing in the export intensity. As their approach controls for productivity differences, this finding is in support of endogenously higher abatement investments by exporters rather than a purely exogenous link between productivity and emission intensity.

Barrows & Ollivier (2021) also consider the carbon intensity of exporting firms, but in a developing country context. Specifically, they use firm-level data on almost 8000 Indian firms for the period from 1995-2011 and investigate how these firms react to foreign import demand shocks. They find that firms' emissions go up due to a scale effect, but this increase is mitigated by about 50 % due to a counteracting decrease in emission intensity.

Rodrigue et al. (2022) and Rodrigue et al. (forthcoming) investigate how the emissions of Chinese manufacturing firms were affected by China's WTO accession in 2001. Using firm-level emissions data from the Ministry of Ecology and the Environment, annual manufacturing surveys, and customs records, Rodrigue et al. (forthcoming) find evidence for Chinese exporters being less emission-intensive than non-exporters – and increasingly so after the WTO accession. While endogenous abatement levels play a part in explaining this pattern, exporters are found to primarily be cleaner due to differences in product scope, investment in new capital, and the import of abatement equipment from abroad. Rodrigue et al. (2022) decompose Chinese SO2 emission changes after the WTO accession into scale, composition, and technique effects. They show that standard decompositions that are based on theoretical underpinnings with perfect competition or constant markups are heavily biased because they do not take into account changes in the competitive environment and hence in markups. Based on mapped firm level emission, production survey, and balance sheet data, the authors find that considering emission intensities based on costs rather than on revenues (and hence independent of markup changes) cuts the technique effect in half.

Using a panel of 1500 Swedish manufacturing firms from 2004-2011, Forslid et al. (2018) also find that exporting firms produce less carbon-intensively than non-exporters. This finding is robust to including sector and year fixed effects into the regression, but not to firm fixed effects, potentially due to many smaller firms repeatedly switching in and out of exporting. The Swedish data set allows the authors to explicitly consider the abatement investment channel and they indeed find that exporting firms invest significantly more in cleaner technologies. In considering the mechanism behind the firm-level technique effect that leads to lower emission intensity for exporters, Forslid et al. (2018) can be connected to the literature on exporting and environmental innovation. Considering firm-level data from individual countries, Cainelli et al. (2012) run Probit regressions for a range of environmental innovation variables in Italy and do not find evidence that exporting has a significant effect, while Girma & Hanley (2015) use data on UK firms and an instrumental variable identification strategy and do find a positive effect. These positive effects are confirmed in a sample of firms from 14 European countries by Hanley et al. (2022), who additionally distinguish process- and product-based environmental innovations and show that the positive effect is entirely driven by process-based innovation and is particularly strong for firms that export to markets with stringent environmental policies in place. While – in line with the Melitz-type theoretical focus - most of the empirical firm-level literature focusses on the export status of firms, there are some studies considering both the ex- and import side (see Cherniwchan (2017), and Holladay (2016), above) and there is also a couple of studies focusing specifically on the import side. Gutiérrez & Teshima (2018) analyze Mexican plant-level reactions to increased import competition and find that firms react with increased energy efficiency and lower emissions. Akerman et al. (2021) consider a different import dimension, namely the import of intermediate goods. Using data for Swedish manufacturing firms, they find that intermediate input imports increase the productivity and in turn lower the emission intensity.

While the empirical literature has generated many interesting insights over the last years, we see large potential for more empirical research using trade policy variation which is exogenous to the individual firm, as done, e.g., by Cherniwchan (2017). This has the potential to mitigate endogeneity concerns otherwise faced due to firms' self-selection into exporting.

Most quantitative trade and environment frameworks do not explicitly model the role of firms. An early exception is Balistreri et al. (2011) who incorporate three different assumptions on the motivation for international trade in a small set of emission-intensive tradable sectors into the computable general equilibrium model of Balistreri & Rutherford (2013). Specifically, they contrast the implications of neoclassical Heckscher-Ohlin-type relative endowment differences, Armington-type domestic product variation, and Melitz-type monopolistic competition with heterogeneous firms trade frameworks for the effects of sub-global climate policy initiatives. Standard policy intuition rooted in neoclassical trade theory implies that non-coalition countries experience welfare gains due to lower energy prices and higher prices for their sales of energy-intensive products. In Armington-setups, which are extremely common in CGE settings, these welfare-enhancing effects are counteracted by a strong terms-of-trade shift in favor of the coalition countries. Trade adjustments and hence carbon leakage rates are found to be much stronger in the Heckscher-Ohlin and Melitz settings. To achieve the same overall emission reduction, abatement has to be more intense than in the Armington framework, implying higher welfare costs for the coalition countries. For non-coalition countries, modelling trade according to Melitz rather than Armington, turns around the overall welfare effect, i.e. generating welfare gains for outside countries in the Melitz setting.

Shapiro & Walker (2018) incorporate Melitz-type heterogeneous firms with endogenous abatement into a quantitative general equilibrium framework to study the drivers of the decline in US manufacturing air pollution emissions (including carbon monoxide, nitrogen oxide, and particulate matter) between 1990 and 2008. Using a statistical decomposition of pollution changes akin to Levinson (2009), but disaggregated to the product rather than only industry level, they show that (i) based on the change of the overall scale of production, pollution should have increased rather than declined, (ii) changes in the composition of the product mix cannot explain the observed pollution pattern either, and (iii) technique effects (i.e. changes in how production is done, rather than what or how much is produced) are responsible for the observed strong decline. To bring their Melitz-type quantitative trade and environment model to the data, the authors combine industry-level data from the OECD STAN database and the WIOD database (Timmer et al. (2015)) with much more detailed firm-level data from the United States, including from the US Census Bureau's Annual Survey of Manufactures and the US EPA and Census Bureau's Pollution Abatement Costs and Expenditures survey. They back out from the data the shocks to US and foreign competitiveness, to US expenditure shares, and to US environmental regulation. To disentangle the effects of these shocks on how US pollution has changed in the investigation period, they use their quantitative model, separately introducing each of these shocks while keeping the other factors at their 1990 levels. Regulatory changes in the US are found to be by far the most important driver of the pollution decline. Changes linked to the international trade channel via competitiveness shocks are found to play only a small role in explaining the observed US pollution trends.

Farrokhi & Lashkaripour (2021) model firm-level abatement decisions in a similar and actually more general way than Shapiro & Walker (2018). The firms, however, are modelled as homogenous firms as in Krugman (1980). In the resulting flexible multi-country, multi-industry model, the authors cannot only simulate the effects of exogenous policy scenarios, but are able to characterize optimal policies that account for firm-level adjustments. Focusing on carbon emissions, they show that the optimal unilateral policy can be implemented with a combination of a carbon tax and industry-specific production subsidies, import taxes, and export subsidies. Compared to the globally optimal policy mix, carbon taxes are set too low as they only internalize the part of the climate costs that is incurred by the specific country. Compared to a setting without a carbon externality, border taxes contain not only a terms of trade driven component, but a second carbon border tax component that aims at lowering carbon emissions abroad. The model is calibrated to trade, production, and emission data from the WIOD database and used to assess the feasibility of Nordhaus (2015)'s climate club proposal, as well as the potential of optimally set carbon tariffs to reduce global emissions. As discussed in section 5.2, they find that a climate club based on EU and US core participation can achieve global cooperation while optimally set carbon tariffs achieve only a very small fraction of the optimal reduction.

Shapiro & Walker (2018) and Farrokhi & Lashkaripour (2021) have different relative strengths in considering heterogenous vs. homogeneous firms, incorporating firm-level vs. purely aggregated data in the calibration, considering exogenously given vs. optimal policies, forcing abatement into a specific functional relationship resulting in a Cobb-Douglas production function vs. allowing for a generalization of Copeland & Taylor (2004)'s abatement mechanism, and aggregating the non-US data into one rest of the world vs. implementing a truly multi-country model. Additional insights on how firms in international trade shape environmental outcomes and how they affect policy choices could be obtained by combining some of the best features of these two worlds. Both frameworks share the limitation that firms' abatement decisions are not linked via an energy market. This rules out the fossil fuel market leakage channel that at least in the context of carbon emissions is likely to play an important rule. Incorporating this leakage channel into quantitative trade and environment models with firms could therefore be an important avenue for future research. Further, relating to the very brief mention of FDI and multinational production above, we want to point to the to this date complete lack of quantitative general equilibrium frameworks that bring together international trade, multinational production via FDI, and environmental outcomes. Furthermore, it would also be helpful to know how different trade-specifications, including Melitz-type approaches, affect general outcomes, something which has so far only be analyzed for a few specific scenarios.

7. Summary and Conclusion

In this DG TRADE Chief Economist Note, we have reviewed a large and dynamic literature analyzing different aspects of the nexus between trade, trade policy, environmental outcomes and environmental policy. A large share of this literature is related to carbon emissions and climate change. The literature on emissions or environmental impacts focusses on the emissions embodied in trade and partly also other environmental impacts (chapter 3) and the emissions resulting from transportation (chapter 4). Covering the policy side, our central chapter 5 describes the analysis related to the phenomena of pollution havens and leakage of emissions and other environmental impacts including land use change and how trade and environmental policy measures can affect the relocation of environmental impacts as well as the cooperation in climate policy, including through border carbon adjustment (BCA). Furthermore, we have reviewed the limited literature on specific trade agreements and trade policies. Finally, chapter 6 has described the research on the role of firms played in the described nexus.

Another way to look at the literature is to structure it by methodological approaches, which might be helpful to approach the scope for future research. Very broadly, there are four methodological approaches, which can also be combined to some degree.

The first approach is theoretical modeling, including trade models with or without firm-heterogeneity as well as game-theoretic approaches. This allows to derive general findings and hypotheses and helps to understand relevant mechanisms such as scale, technology and composition effects or the possibilities of strategic tariff setting and stable coalition formation.

However, this survey has been focused on quantitative analysis. The first general approach in this respect is descriptive data analysis. This approach has been extensively used to derive emissions and environmental impacts from extended input-output data. While the related multi-regional-input-output (MRIO) analysis is able to highlight important trends and the importance of trade in the global allocation of emissions, it can say very little about drivers and causal effects.

The second approach is econometric / empirical research. It can naturally be mostly ex-post with a certain time-lag (as an example, empirical research on the EU ETS still mostly exists until the end of Phase 2 in 2012), since it relies on existing data and is limited by data availability. Still, such analysis remains important and is needed both to verify hypotheses and mechanisms derived from theoretical models as well as to build and parameterize numerical models. In this respect, there is also scope for a stronger empirical validation in the many numerical models used. A large chance also lies in new types of (big) data that become available. Modelling land-use effects of trade already relies on detailed geographical data. For instance, data from social media are used to analyze the US-Chinese trade-war (Huang & Wang (2021)) though to our knowledge not yet related to the trade environment nexus. Given the increasing set of data bases including panel data on different types of environmental impacts embodied in trade we also see a potential for further empirical studies exploring their drivers including trade openness, trade policy and environmental policies.

The largest strand of literature related to the trade – environment nexus is based on different types of quantitative and numerical models. In particular, computable general equilibrium (CGE) models and structural gravity models explicitly capture trade flows and can analyze counterfactual scenarios. This implies that these types of models can be used also for ex-post analysis but are especially useful for ex-ante analysis of latest of future policy measures not yet captured in the data and policy scenarios. Traditionally, and pushed strongly by the development of the GTAP data set and the associated GTAP model, Armington-type multi-regional, multi-sectoral CGE models have been used to assess topics like leakage effects, anti-leakage instruments and indirect land-use effects of environmental and trade policies. They are thus very flexible in terms of policy shocks modelled and can analyze a wide range of policies. More recently, quantitative trade and environment models based on estimable gravity equations have become popular. They have the advantage of being more strongly grounded on empirically determined relationships rather than functional forms of production functions, but, as a downside, often are less detailed. At the same time as mathematical approaches and data sources converge, the distinction between "classical" CGE models and newer approaches becomes increasingly blurred and one should rather consider them as quantitative trade models of different complexities. In terms of improved quantitative modelling we see a number of promising avenues for future research.

First, **model features** and **model approaches** could be improved in different respects:

- The larger share of quantitative models is based on the Armington-assumption, with Ricardian models being the second, growing group. and only recently there is some research on how results change with **different trade specifications**, including Melitz-type approaches. More research in this direction would be helpful.
- Despite the importance of **transport and trade costs**, these are typically only captured in a very stylized way (as iceberg trade costs or margins) without directly linking the costs of carbon prices to transport costs, capturing alternative modes of transport or accounting for speed of transport. Here, both data and conceptual work needs to be undertaken to allow for a more disaggregated analysis in this respect. One avenue could be to combine quantitative trade and environment frameworks with features from endogenous transportation cost models.
- Also, **technological change** is mostly exogenous or only roughly calibrated in quantitative trade and environment models so that technique effects on carbon leakage cannot or only partially be captured.
- Related to **land-use changes**, there is room for more focus **on local-global interactions** and the development of more accessible open-access model frameworks that can be tested and used by the broader research community
- There are not yet models that account **for firm level abatement** decisions AND capture **energy market general equilibrium effects**. There is also a lack of frameworks that bring together international trade, multinational production via FDI, and environmental outcomes.

Second, quantitative models can also be used for furthering **new types of policy analysis**.

- Even though many of the quantitative models are based on detailed IO-Tables and are already well equipped to **analyze emissions along global value chains** and their reaction to policy scenarios, this is rarely done. Also, the policy scenarios themselves could focus more on which policies succeed in reducing domestic production footprints without counteracting movements in the consumption and/or extraction footprints.
- Inspired by a still young empirical literature, there is more potential to use CGE models for the analysis of **environmental provisions in trade agreements**.

Third, quantitative models (together with experimental research) can be increasingly used to parameterize game-theoretic models to analyze the strategic importance of trade policy in coalition formation in the context of public environmental goods.

One final road for research might be to compare ex ante predictions of numerical quantitative models results against ex post econometric estimates of policies to find out what models get right, what they miss, and why.

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