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ARTICLE

Trade and the environment, trade policies and environmental policies—How do they interact?

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Abstract

While international trade can offer gains from specialization 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 endeavor, 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 policies (such as trade agreements or tariffs) or environmental policies (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.

KEYWORDS
carbon border adjustment, carbon leakage, climate change, trade, trade policy

1 INTRODUCTION

Environmental degradation and anthropogenic climate change are among the greatest challenges the world is facing. They increasingly threaten economic welfare and, more broadly, human well-being. To mitigate their causes and to adapt to unavoidable changes, major economic investments and determination on the part of policymakers are required. In this endeavor, policy makers have started to move away from narrowly focused environmental or climate policies to broader strategies. These explicitly account for environmental but also social objectives in policy areas that previously focuses on purely 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 dates back at least to the 1970ies. It has received significant attention since then, both in the public arena as well as in the economics literature.

Trade is probably the most important driver of globalization. While it has increased global wealth significantly, trade is also closely interlinked with global environmental problems. Dating back to Grossman and Krueger (1993) and Copeland and 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 economies or sectors into "dirtier" versus "cleaner" industries or firms in different countries and thus their domestic pollution. More broadly, in an open economy, the pollution caused by the production of goods and services on the territory of a country generally differs from the pollution caused by the consumption of goods and services on the same territory (a country's pollution footprint). This wedge can be driven by different factors, environmental policy being one of them, trade policy another one. The third channel is the *technique effect*: 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. This channel can again be driven by a range of factors, including environmental and trade policy.

If one intends to address the effects of trade policies on environmental outcomes, it is necessary to understand how the latter are shaped by the mutual interaction of trade, economic outcomes, environmental policy, and trade policy. The aim of this paper is to provide a short but comprehensive and structured overview of the large literature that has contributed to answering different aspects of these complex interactions. It focuses on empirical and quantitative work that has emerged in the last 50 years with a strong focus on recent developments.

One way to look at this literature would be to structure it by methodological approaches. There are four main (non-exclusive) methodological approaches. The first approach is theoretical modeling, including trade models with or without firm heterogeneity, as well as game-theoretic approaches. This approach derives general findings and hypotheses and helps to understand relevant mechanisms such as the scale, technology and composition effects mentioned above. The second approach consists of descriptive data analysis. It is useful, for example, to derive emissions and environmental impacts embodied in trade but it can say little about drivers and causal effects. The third approach is empirical research. Naturally, it mostly focuses on ex-post analyses. Moreover, it is often limited by data availability and quality. The largest strand of literature related to the trade—environment nexus is based on a fourth approach, namely quantitative and numerical trade models enriched with environmental features. Applied quantitative models comprise partial equilibrium models for specific sectors and trade models capturing bilateral trade flows and international feedback effects. The latter include computable general equilibrium (CGE) models and structural gravity models which explicitly capture trade flows.

Such models can analyze counterfactual scenarios. That is, they can help shed light on the effects of latest policy measures not yet captured in the data and of future policy scenarios. They can also complement ex-post analysis with general equilibrium effects.

In the sequel, we regularly relate to these different approaches since they help to point to avenues for future research. However, we structure our review by the main research questions addressed in the literature. We believe that this gives a better picture of what we know about the linkages between environmental outcomes, trade, trade policy and environmental policy.

As the starting point for our review, Section 2 summarizes the descriptive literature on measuring environmental impacts embodied in trade. This motivates the more far-reaching question whether trade is good or bad for the environment, which is the focus of Section 3. Section 4 moves to the linkages between environmental policy, trade policy and environmental pollution asking how trade affects the effectiveness of environmental policy. In this context, it discusses how environmental policy can lead to the relocation of environmental impacts (carbon leakage) and emissions along value chains through trade. As a further topic of major interest, Section 5 discusses emissions caused by the transportation of goods across international borders. Section 6 concludes.

A large part of the overview focuses on carbon emissions, where the literature base is broadest. Our study draws 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 in these cases. 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 pay special attention to newer studies which introduce new methods or discuss additional major aspects of trade and the environment or can else be seen as pathbreaking.

2 | ENVIRONMENTAL IMPACTS EMBODIED IN INTERNATIONAL TRADE

Emission transfers or more broadly environmental impacts embodied in trade are important indicators of the relevance of trade for the environment. They are referred to, for example, as the carbon content of trade, the water content of trade, or the land content of trade. Such transfers represent a wedge between the environmental impact that is generated on the territory of a country (territorial impact or production-based impact) and the impact that is generated to produce the goods and services consumed in a country (water/land/carbon footprint or consumption-based impact). Besides production- and consumption-based impact assessment, for carbon emissions, one can calculate the emissions resulting from the burning of fossil fuels according to where the respective resources have been extracted (see, e.g., Kortum & Weisbach, 2021).

Related to this, there is a large and growing body of literature on descriptive data analysis[1] that started in the mid-1970s but gained importance in the early 2000s. One excellent example is the widely cited study by S. J. Davis and Caldeira (2010) who present a global consumption-based carbon inventory for the year 2004. These studies typically use a set of regional input-output tables linked through bilateral trade-flows and including input-related environmental impact variables to extract information on environmental impacts embodied in trade. Most studies use some type of multi-regional input-output (MIRO) analysis that can provide a consistent accounting framework to calculate a variety of different footprint indicators (Tukker, et al., 2018). These footprint indicators include different types of greenhouse gas emissions as well as water, land, and material use. Wiedmann et al. (2007) and Wiedmann (2009) provide early reviews of existing studies.

Many of the descriptive data analyses such as Chen et al. (2018), Peters (2008), Su and Ang (2011), Su et al. (2010) and the review by Wiedmann (2009) focus on methodological issues. Other studies deal with the developments in single countries including Italy, Japan, the Netherlands, Scotland, UK and the US (see Wiedmann, 2009 for an overview table) or a single year in multi-regional studies (e.g., Hertwich & Peters, 2009; Peters & Hertwich, 2008). Many studies focus on carbon emissions embodied in trade, but others include other greenhouse gases (e.g., Copeland et al., 2021; Hertwich & Peters, 2009) or water, land and material footprints (Steen-Olsen et al., 2012; Tukker et al., 2014).

In the context of this review, the multi-country analyses over time by Fan et al. (2016), Peters et al. (2011), Yamano and Guilhoto (2020), and Copeland et al. (2021) are most interesting. These four studies show that the amount of environmental impacts embodied in trade has grown substantially over the last decades. This is not surprising as international goods trade increased relative to global GDP by around 50% between 1995 and 2014 (see WTO, 2015). It reached an absolute all-time high at 5.6 trillion USD in the third quarter of 2021 (see UNCTAD, 2021).

Copeland et al. (2021) use data for carbon dioxide (CO_2) and Nitrogen Oxides (NO_x) from 1990 until 2009 showing that the shares of emissions embodied in international trade rose almost continuously over time for both types of emissions, reaching a peak in 2008 before falling 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 CO_2-emissions. Peters et al. (2011) also stress that non-energy-intensive manufacturing had a key role in international emission transfers since it accounted for a growing share of global CO_2-emissions trade (in 2008, around a third of total transfers). Copeland et al. (2021) report that in 2008 around 35% of global CO_2 emissions and 32% of NO_x emissions were embodied in traded goods and services. Generally, in their data, the share varies between a fourth to a third of global CO_2/NO_X emissions.

On a regional scale, the ranking of top emitters does not change significantly when moving from territorial emissions to carbon footprints (Fan et al., 2016), but this study as well as the data of the Global Carbon Project (www.globalcarbonatlas.org) show that industrialized and rich countries typically import CO_2 emissions (they have a higher footprint than territorial emissions) while emerging and developing countries as well as resource-abundant countries (Russia, South Africa, Venezuela, Australia, Qatar, Ukraine, Belarus) export emissions (they have a lower footprint than territorial emissions). Based on the data of the Global Carbon Project, in 2017, the top six net importers of CO_2 emissions were the US, Japan, Great Britain, Italy, France and Germany with the EU being the largest importer. The largest net exporters were China, India, Russia, South Africa and Kazakhstan. The EU 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 US has 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 different. The EU still is a large net importer of environmental impacts but the US and Australia, for example, have a lower water footprint than territorial water use.

An analysis by the OECD (Yamano & Guilhoto, 2020) shows that the gap between the net exports of CO_2 emissions from non-OECD countries and the net imports from OECD countries is continuously widening. Analyzing 14 countries, Fan et al. (2016) find four different categories of countries: In the first category, Russia and France show extreme differences between carbon footprints and territorial emissions. Germany, Spain, Great Britain, and Italy show a positive difference with a stable increasing trend. Australia, Canada, India, and Korea show a slight difference around zero and finally, China and Taiwan show a negative difference with an increasingly larger gap. 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 CO_2 in 1990 to 1.6 Gt CO_2 in 2008, which exceeds the Kyoto Protocol emission reductions*." Copeland et al. (2021) report growing net imports of pollution into rich countries not only for CO_2 but also (with a very similar pattern) for NO_X. They conclude that rich countries increasingly outsource pollution through international trade.

To summarize, the literature has found that the amount of emissions embodied in trade is significant and that the increasing gap between territorial emissions and emission footprints in rich countries hints at increased outsourcing of emissions.

Some papers go beyond simply describing emissions embodied in trade and analyze their drivers. Wu et al. (2022) summarize some relevant MIRO-based literature that mostly focuses on trade between China and different partners. Not surprisingly, the most eminent factors that have been identified to influence emissions embodied in trade are trade volume, development of carbon intensity of traded goods and trade structure. However, studies differ regarding the relative importance of these factors. The studies also include some analysis about which sectors are driving country-level results. Not related to carbon emissions, Debaere (2014) find that "*more water abundant countries tend to export more water-intensive products, and less water-abundant countries less water-intensive goods*."

Recently, the development of global value chains and the associated international input-output linkages have found their way into structural gravity models of trade and the environment. Several studies shed light on aspects of trade-related emissions that have previously received less attention.[2] Caron and Fally (2022) combine a Ricardian gravity model that includes input-output linkages in production à la Caliendo and Parro (2015) with a more elaborate modeling of the energy sectors. They distinguish primary and secondary fossil fuels and explicitly incorporate natural resources. Additionally, they incorporate non-homothetic preferences. The authors investigate the emission effects of changing international consumption patterns and find that the shift toward less energy-intensive consumption at high-income levels becomes less pronounced once emissions along the whole value chain are accounted for. Thus, higher income levels alone will have less impact on emission savings than previously thought. Mahlkow and Wanner (2022) use a general equilibrium Ricardian trade model with global value chains and a gravity equation to consider the environmental implications of global trade imbalances. Their 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 US 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.

Summarizing, the presented data on emissions embodied in trade indicate that the wedge between territorial environmental impact and environmental footprints is gaining importance. The discussed studies show that MIRO-based analysis and quantitative models considering global value chains start to be used to obtain a more detailed view on emissions embodied in trade. These are shown to be driven by many factors including international consumption choices, trade structure and imbalances and the development of carbon intensities of traded goods. The existing studies shed light on aspects that have previously received less attention. However, the analysis so far is still fragmented, and the policy implications remain unclear. Also, there is a strong focus on methodological issues.

While we summarize a few additional studies related to the link between trade and climate policy and emissions in the following sections, we generally see scope for a more systematic and broader analysis of how emissions and other environmental impacts embodied in trade are shaped and how this knowledge could contribute to efficient and effective trade and environmental policies. Furthermore, considering the wedge between production and consumption emissions, the role of consumer preferences in shaping embodied emissions has so far received surprisingly little attention. The most promising avenue for future research is to use the increasingly accessible methodologies and data for improved analysis and modeling of the drivers of emissions and environmental impacts embodied in trade. This implies large potential for IO-table based quantitative trade models, in particular computable general equilibrium (CGE) and structural gravity models to focus more on emissions along global value chains and to assess their interaction with environmental and trade policy, a topic addressed in the next sections.

3 | IS INTERNATIONAL TRADE BAD FOR THE ENVIRONMENT?

The last section has shown that many environmental impacts are embodied in trade. Yet, this descriptive analysis is silent about the causal effects of policies and whether trade per se is good or bad for the environment.

3.1 | Effects of trade and trade liberalization on emissions

A 20-year-long tradition of studies has studied the effects of trade and trade liberalization on emissions by empirically relating broad trade openness measures to environmental outcomes. Two prominent examples of this literature are Antweiler et al. (2001) and Frankel and Rose (2005). Antweiler et al. (2001) find that international trade has only small effects on sulfur dioxide (SO_2) emissions through composition effects, but the trade-induced technique and scale effects imply that trade overall leads to a net reduction in SO_2. The estimations of Frankel and Rose (2005) do not allow to identify the mechanisms of the impact of trade on different measures of environmental quality (SO_2, N_2O, particulate matter, CO_2, 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* SO_2." 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 and Demena (2022) find that trade openness increases emissions. 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 CO_2 (a global pollutant) and SO_2 (a local pollutant), they can confirm the overall significant effect of trade on emissions only for CO_2.

Following the seminal contribution of Melitz (2003), a more recent literature has taken a disaggregate perspective. Using models with heterogeneous firms, it investigates how international trade is shaped by firms with heterogeneous productivities and how trade policies affect firms' behavior on domestic and foreign markets. As is evident from Cherniwchan et al. (2017)'s review article, (i) firm-level heterogeneity potentially plays an important role in determining the effects of trade on the environment, (ii) the trade and environment literature appears to lag the trade literature in shifting its focus toward studying firm-level behavior, and (iii) first contributions in this area have already uncovered important relationships. In the following, we briefly summarize the main theoretical findings, followed by results of econometric analysis and quantitative modeling.

Kreickemeier and 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 toward more efficient firms lowers emissions as these firms are also less pollution-intensive (a new so-called reallocation effect). Therefore, trade liberalization has an ambiguous overall effect on environmental outcomes, 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 vary only 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 intensities. Trade liberalization leads to a reallocation of production factors toward 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 so that their production is less emission-intensive. When trade liberalization allows them to grow, they find it optimal to invest even more into abatement. 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 and Ottaviano (2008) and stress that the resulting pro-competitive effect of trade liberalization reinforces the shift toward more productive and less pollution-intensive firms. The central ingredient in most theoretical frameworks investigating the role of firms for the trade-environment nexus 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 imply that only the most productive firms become exporters, they generate 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). The author 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. He finds that exporters pollute about 10% less than non-exporters, though with considerable heterogeneity across different types of pollutants and industries. Additionally, in a logit regression with the same sets of fixed effects, he finds that higher import competition drives small, relatively pollution-intensive firms out of the market.

Cui et al. (2016) and Cui and Qian (2017) also consider micro-level evidence for US producers. They investigate the effect of firms' exporting status on the emissions of local pollutants. Cui et al. (2016) find supporting evidence for exporters being cleaner, while Cui and Qian (2017) 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 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. Moreover, a higher wage level in the industry also increases exporters' relative pollution intensity.

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

Batrakova and Davies (2012) use data from the Irish Census of Industrial Production to assess the effect of being an exporter on pollution. They proxy pollution by firm-level energy use, since they do not have firm-level pollution data. They find that the effect of becoming an exporter 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.

Focusing on global rather than local pollution, Cole et al. (2013) were 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. Their results indicate that, at the firm-level, emissions are decreasing in the export share.

Richter and Schiersch (2017) combine four German administrative datasets to create a panel of German manufacturing firms for the period 2003–2011. They find that the carbon intensity decreases 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 and Ollivier (2021) consider the carbon intensity of exporting firms in a developing country context. Specifically, they use firm-level data on almost 8000 Indian firms for the period from 1995 to 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.

Using a panel of 1500 Swedish manufacturing firms from 2004 to 2011, Forslid et al. (2018) also find that exporting firms produce less carbon-intensively than non-exporters. The Swedish data set allows the authors to explicitly consider the abatement investment channel. They 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) do not find evidence that exporting has a significant effect on environmental innovation in Italy, while Girma and Hanley (2015) use data on UK firms 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 focuses on the export status of firms, there are some studies considering both the export- and the import side (see Cherniwchan, 2017, and Holladay, 2016, above). There are also a couple of studies focusing specifically on the import side. Gutiérrez and 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 from Swedish manufacturing firms, they find that intermediate input imports increase productivity and in turn lower emission intensity.

In summary, the theoretical and empirical literature gives strong evidence that international trade decreases the emission intensities of firms. Trade affects pollution of domestic firms through import competition. And it affects pollution of exporting firms through competition on international markets. Yet, we see a large potential for more empirical research using trade policy variation which is exogenous to the individual firm (cf., e.g., the study by Cherniwchan, 2017, discussed in the next subsection). This has the potential to mitigate endogeneity concerns due to firms' self-selection into exporting. Additionally, while the literature is largely in agreement that exporting firms are less emission-intensive, more research on the mechanisms that generate this outcome is needed. This will also help in feeding the empirical insights into quantitative models. Finally, empirical studies can say little about overall effects of trade, e.g. through scale effects. This is something quantitative trade models can do.

Shapiro and Walker (2018) incorporate Melitz-type heterogeneous firms with endogenous abatement into a quantitative general equilibrium framework to study the drivers of the decline in air pollution of US manufacturing firms (including carbon monoxide, NO_X, 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 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 extract the shocks to US and foreign competitiveness, to US expenditure shares, and to US environmental regulation from the data. They use their quantitative model to measure the effects of these shocks on US pollution, 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 observed decline of pollution. In contrast, changes linked to the international trade channel via competitiveness shocks are found to play only a small role.

Overall, accounting for firm-level heterogeneity in quantitative general equilibrium models remains the exception rather than the rule. While Shapiro and Walker (2018) take an important first step, their model has limitations, because it does not incorporate input-output linkages or model an energy market. We think that richer models that incorporate the empirical findings from the firm-level studies can enhance our understanding of the role firms play in shaping the effect of international trade on the environment in general equilibrium. Presently, the literature cannot yet offer a conclusive answer.

3.2 | Effects of trade agreements and specific trade policies

Up to this point, we focused our discussion on papers that consider the effects of trade, trade openness, and trade liberalization. We now discuss the literature that considers specific trade policies and trade policy patterns.

Shapiro (2021) considers sectoral patterns in both tariffs and non-tariff barriers to trade. 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. His finding reflects tariff escalation (i.e., the fact that tariffs tend to be higher for more downstream goods). Hence, it is due to the positioning in the value chain rather than the products' carbon intensity. Unintentionally, however, the combined pattern of sectoral trade policy differences and emission intensities leads to a substantial implicit carbon subsidy. Therefore, more symmetric trade policies for different industries along the value chain would lower global emissions.

A classic trade policy and one of the most studied policies in the empirical international trade literature, is the signing of regional trade agreements. Nemati et al. (2019) consider the effects of Mercosur, the North American Free Trade Agreement—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 high-income countries (US—Australia) and are able to lower per capita emissions if concluded between developing and emerging economies (Mercosur). NAFTA, an agreement between countries at very different development stages, appears to have increased greenhouse gas emissions. Specifically, they find that while NAFTA did not affect US and Canadian emissions, it led to an increase in Mexican emissions.

In a more disaggregated view, Cherniwchan (2017) considers the plant-level emission effects in the US for NAFTA. He estimates the effects of tariff changes both on the export and the import side on 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 effects of lower US tariffs and potentially resulting increased import competition from Mexico on US plants' emissions.

L. W. Davis and Kahn (2010) study 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-post and ex-ante assessments of individual trade agreements. In an ex-post evaluation study of the EU-Korea free trade agreement, based on the trade model of Aichele et al. (2016), the European Commission (2018) has found that trade creation between the relative clean partner countries and trade diversion away from earlier (dirtier) trade partners led to a small overall reduction in greenhouse gas emissions. In an ex-ante analysis of the African Continental Free Trade Agreement, Bengoa et al. (2021) use a CGE model to assess the environmental impact They find negligible changes in CO_2, but a substantial increase of about 20% in other greenhouse gas emissions and a decrease of the same magnitude in other pollutants. Tian et al. (2022) use a Caliendo and Parro (2015)-type quantitative trade model to estimate the future CO_2 effects of the Regional Comprehensive Economic Partnerships (RCEP) among the 10 countries of the Association of Southeast Asian Nations (ASEAN), China, Japan, South Korea, Australia, and New Zealand by modeling RCEP tariff reductions or elimination. Under complete tariff elimination among RCEP members global CO_2 emissions would increase by about 3% annually.

Overall, the literature on the effects of regional trade agreements demonstrates the heterogeneity of environmental effects across agreements, member countries, pollutants, and trade directions. It is thus far from a consensus on "the" environmental effect of trade agreements. In our view, there is a large potential for a systematic evaluation of the drivers of the observed heterogeneity.

Another strand of literature that has the potential to explain some of the heterogeneity in the environmental effects investigates the different designs of the agreements. Trade agreements increasingly include explicit environmental provisions. This has spurred corresponding empirical investigations. In a country-level analysis, Baghdadi et al. (2013) estimate whether countries that sign trade agreements containing more environmental provisions, do indeed pollute less. They find significant evidence for the provisions' effectiveness. On the bilateral level, Brandi et al. (2020) investigate whether environmental provisions affect the size and product patterns 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), 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 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 that consider general equilibrium adjustments. This is a promising area for future research.

4 | DOES TRADE HINDER THE EFFECTIVENESS OF ENVIRONMENTAL POLICY?

In this section, we turn to the questions how trade affects environmental policy outcomes and how trade policy can react to these effects.

4.1 | Production reallocation, pollution havens, and emission leakage

Research on the linkages between environmental policy and trade dates back at least to the mid-1970s and originally focused 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. It is 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 raise 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 producers in other countries to increase their production to sell resources while still possible (third channel or Green Paradox). 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 trade-driven production relocation and the fossil fuel market leakage, there are further channels through international technology spillovers (Gerlagh and Kuik, 2014) and reduced climate damages (Franks et al., 2022) but these are not trade-related and thus not in the focus of this paper.

Pollution haven effects in general are traditionally measured using econometric approaches surveyed by Jaffe et al. (1995) and later Brunnermeier and Levinson (2004) and Copeland and Taylor (2004). Brunnermeier and 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 and Taylor (2004, p. 48) conclude "*after controlling for other factors affecting trade and investment flows, more stringent environmental policy acts as a deterrent to dirty-good production.*" A prominent example of such studies is Levinson and Taylor (2008) who use US data on 130 manufacturing industries and analyze the impact of US environmental regulation on trade with Canada and Mexico. They 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. (2022) provide evidence for another case of a pollution haven effect due to the tightening of the US airborne lead standard which shifted battery recycling to Mexico and had negative health impacts for infants near the recycling plants.

More specifically, econometric studies of carbon leakage 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 and 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 and Felbermayr (2012, 2015) and Naegele and Zaklan (2019).

Aichele and 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 emissions 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. Using a panel of the carbon content of bilateral trade flows, Aichele and 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 with leakage, 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 and Zaklan (2019) also use a gravity equation for the CO_2 content of trade, to analyze how the European Emissions Trading Scheme (EU ETS) affects trade and carbon flows and find no evidence that the EU ETS caused carbon leakage.

On the sectoral level, Branger et al. (2017) 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) regressions and Prais-Winsten estimation 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 and 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 economic outcome variables can increase disproportionately. 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. Third, it is unclear if results for specific policies can be transferred to other sectors, regions and/or time periods. 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. In contrast, quantitative studies can analyze specific policies and to address potential reverse causality (e.g., net exporters of carbon have little interest in adopting climate policies). A key indicator assessed in many quantitative studies is the leakage rate, which measures the share of domestic emission reductions that is offset by emission increases abroad.

Often, 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 rate 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. This finding is strengthened by the study of Böhringer et al. (2017) that includes scenarios with different trade elasticities. Furthermore, a study by Balistreri et al. (2011) shows that incorporating the role of firms into CGE models makes a difference. They incorporate three different assumptions on the motivation for international trade in a small set of emission-intensive tradable sectors into the CGE model of Balistreri and Rutherford (2013). Specifically, they contrast the implications of neoclassical Heckscher-Ohlin-type relative endowment differences, Armington-type national product variation, and Melitz-type monopolistic competition frameworks with heterogeneous firms. 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 must be more intense than in the Armington framework. This has also implications for the stability of climate coalitions discussed in Section 4.2.

Sector-level studies are mostly based on partial equilibrium models; see World Bank (2015) for an overview; prominent studies include Demailly and Quirion (2006) and Fowlie et al. (2016). This work typically focuses on the most vulnerable sectors like cement, clinker, steel, aluminum, oil refining and electricity sectors and, among 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 and Quirion (2014) report statistically significantly 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 potential technology spillovers and thus tend to overestimate leakage (Gerlagh & Kuik, 2014).

In a theoretical contribution, H. Egger et al. (2021) study the role of firms in shaping the influence of international trade on 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 two-fold 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, that is, there is a negative leakage rate, driven by a shift toward labor inputs in the nonregulating country as wages decline due to reduced export opportunities.

What is to some degree striking is, that there are relatively few studies with quantitative trade models that analyze the implications of specific climate policies on emissions along value chains and the carbon content of trade as an important channel of carbon leakage. This is the case, even though such models could in principle rather easily do so. A few studies based on CGE models related to border carbon adjustment (BCA) are discussed in the following Section 4.2. which 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). Beyond BCA, Wu et al. (2022) use a CGE model with a carbon flow decomposition analysis to trace pathways of carbon leakage related to the targets of the Paris Agreement (the so-called Nationally Determined Contributions, NDCs). They find that the NDCs hardly change net trade of embodied emissions in most developed economies, but present some detailed results on how CO_2-emissions embodied in gross bilateral trade, CO_2-emissions related to domestic production, CO_2-emissions embodied in final consumptions and derived CO_2-emission leakage react to the implementation of the NDCs in different countries. For the EU, for example, the EU NDCs hardly affect CO_2-imports but induce both production-based and consumption-based CO_2-emissions to decline significantly. Meeting the European NDCs also implies a significant reduction of carbon outflow to other economies. In China, for another example, the global implementation of the NDCs implies a large decline in its CO_2-emissions embodied in net exports.

Overall, one can conclude that the relocation of environmental pollution as a result of environmental policy is supported by sufficient empirical and model-based evidence to be considered a real danger. To better understand these phenomena there are different areas for future research. Related to methodological approaches, one could learn more from incorporating firm-level dynamics into quantitative trade models. The study by Balistreri et al. (2011) shows that this can make a difference. Furthermore, the potential of quantitative trade models that have the capability for national carbon accounting along multiple dimensions could be used to assess a broader set of climate policies. 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 and how policies need to be designed to maximize welfare. More generally it remains important to systematically assess the effects of new discussed, planned or implemented polices both empirically and through quantitative trade models and to gain better understanding when relocation takes place and what is driving this. For example, there still is no study of the EU ETS reflecting the strong increases of carbon prices to 80€/tCO_2 or more since 2021. However, it is most relevant to better understand how to address environmental relocations. This is addressed in the following subsection.

4.2 | 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 to use import tariffs to target foreign pollution. Besides 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, for example, to multiple polluting goods (Hoel, 1996) or to tariffs on emissions embodied in trade that are shown to dominate tariffs based on the value of imports (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.*"

Again, a large strand of literature uses quantitative trade models to study carbon leakage. Among the instruments to address carbon leakage, BCA received most attention. Full BCA implies that the carbon content of imports is priced with the same carbon prices that are applied to domestic firms and that domestic firms are refunded for the carbon costs of their exported goods. This levels the playing field both on the domestic and the foreign market. Ghosh et al. (2012) or Lanzi et al. (2012) assess such full BCA. Other studies, such as Kuik and Hofkes (2010) and Winchester et al. (2011) include scenarios that only assess import tariffs without export rebates. 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 and Quirion (2014) estimate effects of BCA based on many Partial Equilibrium and CGE-model-based studies, also including 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 the reduction is between 1 and 15 percentage points. Yet, there are outliers where BCA generates negative leakage rates. Mathiesen and 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 countries with Kyoto commitments at the same level as the assumed 25 USD/tCO_2 domestic carbon tax and where the border tax is applied to the average emissions per unit of output in the countries without Kyoto commitments. 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 USD/tCO_2 in 2010 and rises to 40 USD/tCO_2 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 and Quirion (2014). Böhringer et al. (2017) stress that the negative leakage rate for BCA stems from the fact that energy market effects are not considered. 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 externalities 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 and 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 taxes. If these were implemented, global emissions would decrease by 0.5%.

Few studies (Böhringer, Carbone et al., 2012; Böhringer et al., 2017; Fischer & Fox, 2012; Lanzi et al., 2012; Monjon & Quirion, 2011) analyze further anti-leakage instruments such as output-based allocation 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. The evidence is that, among the explicit anti-leakage instruments, BCA is usually the most effective instrument to address leakage.

BCA also usually negatively affects the welfare of countries outside a climate coalition of countries jointly undertaking climate policy. This provides incentives for them to join the coalition. Such incentives are analyzed using stylized or parameterized game-theoretic models (reviewed by Al Khourdajie & Finus, 2020) and a few CGE models (Böhringer et al., 2016; Weitzel et al., 2012). Parametrized game-theoretic frameworks serve for illustrative purposes only (as in Al Khourdajie & Finus, 2020) or they are based on outcomes of larger numerical models. In the context of BCA this has been done with quantitative trade models (Farrokhi & Lashkaripour, 2021) and growth models (Nordhaus, 2015). 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 by Lessmann et al. (2009). The idea of a climate coalition or climate club stabilized by tariffs was pushed especially by the seminal paper of Nordhaus (2015).

The results of these studies are mixed. Al Khourdajie and 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 confirmed by the recent study of Farrokhi and 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 the 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 the US commit to be core members of the club. The second condition is that the tariff level is not bound 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 industrialized countries, but the remaining model-regions retaliate through implementing tariffs themselves. These key findings hold for different emission reduction 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 the major industrialized countries. 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 the 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 and Finus (2020) put it, that the underlying stability concept is seriously simplified and only the stability of the grand coalition and a group of industrialized countries is analyzed.

Nordhaus (2015) combines game-theoretic analysis with quantitative modeling 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 10 USD/tCO_2, 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 12.5 USD/tCO_2. The rate increases for higher carbon prices and for a price of 100 USD/tCO_2 full participation is not achieved even with the highest tested tariff rate of 10%. Region-wise, Canada and the 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 only in 45 – 63% of cases. In 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.

Farrokhi and Lashkaripour (2021) use a quantitative multi-country, multi-industry general equilibrium framework with homogeneous firms modeled as in Krugman (1980) to characterize optimal policies that account for firm-level adjustments. The model is 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. 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. Beyond this, the role of firms in international trade 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 firm 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 narrower focus on trade and the environment here and refer the interested reader to the overview article by Cole et al. (2017).

Finally, motivated by Nordhaus' climate clubs, Barrett and 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*." Among 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.

Overall, the reviewed literature shows that BCA has some potential to reduce leakage rates but cannot completely prevent leakage. Still, BCA is most likely the most efficient anti-leakage instrument available. Its potential to induce broader climate cooperation is controversial, so we see further potential to bring together game-theoretic and quantitative trade models in the spirit of Nordhaus (2015) or Farrokhi and Lashkaripour (2021) or game-theoretic models and experimental research in the spirit of Barrett and Dannenberg (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, for example, models-based on the data set from the Global Trade Analysis Project, GTAP (www.gtap.agecon.purdue.edu) 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 following section) in greater detail. These improved models can then also be used to assess prevailing policies. One example is the US Inflation Reduction Act (IRA) (see, e.g., McKinsey, 2022), that implies large subsidies for clean energy technologies and raises the question, how leakage is affected if one world region (the EU) is relying on carbon pricing as their main climate policy instrument, while another (the US) is relying on subsidies. Furthermore, new policy plans such as the EU plan to implement a BCA provide the chance to learn more about how this instrument works in practice and to empirically test its effects.

5 | 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.

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. In a large data effort, they 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 variations across both sectors and countries. They also 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 led to higher emissions, but around a third of global trade flows lead to lower emissions. This is because production emission intensity in the exporting country is sufficiently lower than in the importing country so that saved emissions from production overcompensate additional emissions from transportation. The authors additionally investigate a set of counterfactual scenarios in a general equilibrium model). They find, among other things, that the future shift of economic activity toward China and India implies more bilateral trade between country pairs that are relatively far apart. As a result, transportation emissions increase more than the value of international trade.

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 sensitively 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 USD/tCO_2 carbon price on transportation emissions would bring down transport-associated emissions only by 7.7%. An increase of the carbon price to 80 USD/tCO_2 would cut 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 allows to quantify the changes in transportation emissions. Additionally, the model accounts for the effects of changing trade patterns on production locations for different types of goods and services. 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%, driven to similar extents by production and transportation emissions. Hence, trade not only implies higher emissions because goods are shipped longer distances, but also because it shifts pollution-intensive production toward countries with dirtier production technologies, even though the overall impact of trade on emissions remains rather low. The author also finds that even after considering 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 of 29 USD/tCO_2 on all international transportation, global welfare would be enhanced due to lower environmental costs, but effects are found to vary considerably: poor countries suffer more from the reduced gains from trade than they gain from lower emissions.

Klotz and Sharma (2023) also include transportation emissions into a quantitative trade and environment model. By incorporating input-output linkages in production following Caliendo and Parro (2015), they can also investigate the role of changes in global value chains in shaping transportation emissions from international trade. Lower trade costs make intermediate products cheaper and therefore lead to longer value chains, increasing both transportation emissions and the emission intensity in production. Accordingly, the authors find that a global elimination of all trade tariffs would increase global emissions by more than global GDP (1.8% vs. 0.5%). In line with the findings of Shapiro (2016), however, the authors find that trade impediments are generally not an efficient climate policy, as the implied mitigation costs of current tariffs are 550 USD/tCO_2 and therefore higher than usual estimates of the social cost of carbon. The authors additionally consider a range of trade liberalization schemes and find potential for gains from trade at low environmental costs if tariff reductions focus on downstream sectors close to final demand.

Lee et al. (2013) and Sheng et al. (2018) simulate a carbon tax of 30 and 18 USD/tCO_2, respectively, on transportation emissions in existing CGE models, 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% 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 tax gradually increasing to 75 USD/tCO_2, zero-emission vessels need to be available by 2030 and substitute ships leaving the fleet from 2030 onwards to achieve the IMO 50% reduction target for 2050 mentioned above.

The strand of literature on transportation emissions has clearly established that transportation emissions are a major part of how international trade affects the environment. Taking transportation technologies and modes as given, it also offers a good understanding of how trade policy changes shape trade patterns and in turn the associated transportation emissions. However, it 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, allowing, for example, for endogenous transportation mode choices or abatement innovation in the transportation sector. Recently, the international trade literature has moved toward 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 and Wanner (2022) briefly discussed in Section 2). Furthermore, changes in the fuel costs of international shipping have an additional indirect effect on shipping prices via changes in the negotiation power of ships that counteract the direct effect due to the fuel price change. This implies that a carbon price might reduce international shipping to a lesser extent than one would expect based on exogenous trade cost models. Ganapati et al. (2021) find that 80% 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%, 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 still in its infancy in many respects. However, important data efforts have demonstrated that a considerable share of trade-related emissions stems 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 a much more fine-grained picture of international transportation emissions. Additionally, quantitative trade and environment models have often treated these emissions with neglect and only considered them implicitly in the form of iceberg trade costs. We see large potential in more detailed modeling of transportation emissions, including but not limited to incorporating them into richer quantitative models and linking them to endogenous trade cost models.

6 | SUMMARY AND CONCLUSION

In this survey paper, 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 focuses on the emissions and partly also other environmental impacts embodied in trade and how they react to different policy measures including BCA (Section 4) and the emissions from transportation (Section 5). Covering the policy side, our central Sections 3 and 4 describe the analysis related to the phenomena of pollution havens and leakage of emissions and how trade and environmental policy measures can affect the relocation of environmental impacts as well as the cooperation in climate policy. Furthermore, we have reviewed the limited literature on specific trade agreements and trade policies and on transport emissions. The most relevant or exemplary papers are summarized in the table in the Appendix.

As mentioned already in the introduction, 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 from a different angle. We have seen, that the main four methodological approaches—theoretical modeling, descriptive data analysis, empirical research and quantitative and numerical models—have all been used to contribute to our understanding of the linkages between trade, environmental impacts, trade policy and environmental policy.

Theoretical modeling, including trade models with or without firm-heterogeneity as well as game-theoretic approaches, have allowed to derive general findings and hypotheses and help to understand relevant mechanisms such as scale, technology and composition effects or the possibilities of strategic tariff setting and stable coalition formation.

Descriptive data analysis has been extensively used to derive emissions and environmental impacts from extended input-output data. The related MIRO analysis is able to highlight important trends and the importance of trade in the global allocation of emissions but can say little about drivers and causal effects.

Empirical research is naturally mostly ex-post with a certain time-lag (as an example, empirical research on the EU ETS still mostly exists until the end of the second phase in 2012) since it relies on existing data and is also limited by data availability. Still, such analysis remains very important and is needed both to verify hypothesis and mechanisms derived from theoretical models as well as to build and parameterize numerical models. In this respect, there is also scope for stronger empirical validation in the many numerical models used. A large chance also lies in new types of (big) data that become available. For instance, Huang and Wang (2021) use data from social media to analyze the US-Chinese trade-war though to our knowledge not yet related to the trade-environment nexus. Given the increasing set of databases 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, 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 both for ex-post analysis but especially for ex-ante analysis of latest policy measures not yet captured in the data and future 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 and anti-leakage instruments. They are thus very flexible and can analyze a wide range of policies. More recently other types of CGE models have become popular. They are based on estimable gravity equations, that have the advantage to be more strongly grounded on empirically determined relationships rather than "guesstimated" functional forms of production functions, but they 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 talk about quantitative trade models of different complexities. Generally, CGE models are often criticized as black boxes, that make it hard to clarify mechanisms, but this is not necessarily different for empirical analysis. In terms of improved CGE modeling 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 CGE models is based on the Armington-assumption and only recently there is some research on how results change with **other 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 CGE models so that technique effects on carbon leakage cannot 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, CGE models can also be used for further **new types of policy analysis**.

- Even though many of the CGE 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 empiric literature, there is more potential to use CGE models for the analysis of **environmental provisions in trade agreements**.

Third, CGE 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 CGE against ex-post econometric estimates of policies to find out what models get right, what they miss, and why.

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ENDNOTES

[1] Though many of the papers cited in the following talk about "models", we prefer to refer to them as (elaborate) descriptive data analysis since they do not model the behavior of actors.

[2] Environmental gravity models previously focused either on final goods trade (Larch & Wanner, 2017, 2019; Shapiro & Walker, 2018) or simplified versions of intermediate goods trade (P. Egger & Nigai, 2015; Shapiro, 2016).

REFERENCES

Abman, R., Bastiaens, I., & Ruta, M. (2021). The effectiveness of environmental provisions in US trade agreements. *World Bank Policy Research Working Paper, 9601*.

Ackerberg, D. A., Caves, K., & Frazer, G. (2015). Identification properties of recent production function estimators. *Econometrica*, *83*(6), 2411–2451. https://doi.org/10.3982/ECTA13408

Afesorgbor, S. K., & Demena, B. A. (2022). Trade openness and environmental emissions: Evidence from a meta-analysis. *Environmental and Resource Economics*, *81*(2), 287–321. https://doi.org/10.1007/S10640-021-00627-0/TABLES/9

Aichele, R., & Felbermayr, G. (2012). Kyoto and the carbon footprint of nations. *Journal of Environmental Economics and Management*, *63*(3), 336–354. https://doi.org/10.1016/j.jeem.2011.10.005

Aichele, R., & Felbermayr, G. (2015). Kyoto and carbon leakage: An empirical analysis of the carbon content of bilateral trade. *Review of Economics and Statistics*, *97*(1), 104–115. https://doi.org/10.1162/REST

Aichele, R., Felbermayr, G., & Heiland, I. (2016). TTIP and intra-European trade: Boon or bane?, with R. Aichele and G. Felbermayr. *Jahrbücher für Nationalökonomie und Statistik /Journal of Economics and Statistics*, *236*(6), 639–664. https://doi.org/10.1515/jbnst-2015-1040

Akerman, A., Forslid, R., & Prane, O. (2021). Imports and the CO2 emissions of firms. *CEPR Discussion Paper*, 16090.

Al Khourdajie, A., & Finus, M. (2020). Measures to enhance the effectiveness of international climate agreements: The case of border carbon adjustments. *European Economic Review*, *124*, 103405. https://linkinghub.elsevier.com/retrieve/pii/S0014292120300374

Antimiani, A., Costantini, V., Kuik, O., & Paglialunga, E. (2016). Mitigation of adverse effects on competitiveness and leakage of unilateral EU climate policy: An assessment of policy instruments. *Ecological Economics*, *128*, 246–259. https://doi.org/10.1016/j.ecolecon.2016.05.003

Antweiler, W., Copeland, B. R., & Taylor, M. S. (2001). Is free trade good for the environment? *American Economic Review*, *91*(4), 877–908. https://doi.org/10.1257/aer.91.4.877

Arto, I., Rueda-Cantuche, J. M., & Peters, G. P. (2014). Comparing the GTAP-MRIO and WIOD databases for carbon footprint analysis. *Economic Systems Research*, *26*(3), 327–353. https://doi.org/10.1080/09535314.2014.939949

Baghdadi, L., Martinez-Zarzoso, I., & Zitouna, H. (2013). Are RTA agreements with environmental provisions reducing emissions? *Journal of International Economics*, *90*(2), 378–390. https://doi.org/10.1016/j.jinteco.2013.04.001

Balistreri, E. J., Hillberry, R. H., & Rutherford, T. F. (2011). Structural estimation and solution of international trade models with heterogeneous firms. *Journal of International Economics*, *83*(2), 95–108. https://doi.org/10.1016/j.jinteco.2011.01.001

Balistreri, E. J., & Rutherford, T. F. (2013). Computing general equilibrium theories of monopolistic competition and heterogeneous firms. *Handbook of Computable General Equilibrium Modeling*, *1*, 1513–1570. https://doi.org/10.1016/B978-0-444-59568-3.00023-7

Barrett, S., & Dannenberg, A. (2022). The decision to link trade agreements to the supply of global public goods. *Journal of the Association of Environmental and Resource Economists*, *9*(2), 273–305. https://doi.org/10.1086/716902

Barrows, G., & Ollivier, H. (2021). Foreign demand, developing country exports, and CO2 emissions: Firm-level evidence from India. *Journal of Development Economics*, *149*, 102587. https://doi.org/10.1016/J.JDEVECO.2020.102587

Batrakova, S., & Davies, R. B. (2012). Is there an environmental benefit to being an exporter? Evidence from firm-level data. *Review of World Economics*, *148*(3), 449–474. https://doi.org/10.1007/S10290-012-0125-2/TABLES/13

Bengoa, M., Mathur, S., Narayanan, B., & Norberg, H. C. (2021). Environmental effects of the african continental free trade agreement: A computable general equilibrium model approach. *Journal of African Trade*, *8*(2 (Special Issue)), 36–48. https://doi.org/10.2991/JAT.K.210719.001

Blyde, J. S., & Ramirez, M. A. (2021). Exporting and environmental performance: Where you export matters. *The Journal of International Trade & Economic Development*, *31*(5), 672–691. https://doi.org/10.1080/09638199.2021.2003424

Böhringer, C., Balistreri, E. J., & Rutherford, T. F. (2012). The role of border carbon adjustment in unilateral climate policy: Overview of an energy modeling forum study (EMF 29). *Energy Economics*, *34*(Supplement 2), S97–S110. https://doi.org/10.1016/j.eneco.2012.10.003

Böhringer, C., Bye, B., Fæhn, T., & Rosendahl, K. E. (2012). Alternative designs for tariffs on embodied carbon: A global cost-effectiveness analysis. *Energy Economics*, *34*, S143–S153. https://doi.org/10.1016/j.eneco.2012.08.020

Böhringer, C., Carbone, J. C., & Rutherford, T. F. (2012). Unilateral climate policy design: Efficiency and equity implications of alternative instruments to reduce carbon leakage. *Energy Economics*, *34*, S208–S217. https://doi.org/10.1016/j.eneco.2012.09.011

Böhringer, C., Carbone, J. C., & Rutherford, T. F. (2016). The strategic value of carbon tariffs. *American Economic Journal: Economic Policy*, *8*(1), 28–51. https://doi.org/10.1257/POL.20130327

Böhringer, C., Carbone, J. C., & Rutherford, T. F. (2018). Embodied carbon tariffs. *Scandinavian Journal of Economics*, *120*(1), 183–210. https://doi.org/10.1111/sjoe.12211

Böhringer, C., Rosendahl, K. E., & Storrøsten, H. B. (2017). Robust policies to mitigate carbon leakage. *Journal of Public Economics*, *149*, 35–46. https://doi.org/10.1016/j.jpubeco.2017.03.006

Brancaccio, G., Kalouptsidi, M., & Papageorgiou, T. (2020). Geography, transportation, and endogenous trade costs. *Econometrica*, *88*(2), 657–691. https://doi.org/10.3982/ECTA15455

Brandi, C., Schwab, J., Berger, A., & Morin, J. F. (2020). Do environmental provisions in trade agreements make exports from developing countries greener? *World Development*, *129*, 104899. https://doi.org/10.1016/J.WORLDDEV.2020.104899

Branger, F., & Quirion, P. (2014). Would border carbon adjustments prevent carbon leakage and heavy industry competitiveness losses? Insights from a meta-analysis of recent economic studies. *Ecological Economics*, *99*, 29–39. https://doi.org/10.1016/j.ecolecon.2013.12.010

Branger, F., Quirion, P., & Chevallier, J. (2017). Carbon leakage and competitiveness of cement and steel industries under the EU ETS: Much ado about nothing. *The Energy Journal*, *37*(3), 109–136. https://doi.org/10.5547/01956574.37.3.fbra

Brunnermeier, S. B., & Levinson, A. (2004). Examining the evidence on environmental regulations and industry location. *The Journal of Environment & Development*, *13*(1), 6–41. https://doi.org/10.1177/1070496503256500

Burniaux, J.-M., Chateau, J., & Duval, R. (2013). Is there a case for carbon-based border tax adjustment? An applied general equilibrium analysis. *Applied Economics*, *45*(16), 2231–2240. https://doi.org/10.1080/00036846.2012.659346

Cainelli, G., Mazzanti, M., & Montresor, S. (2012). Environmental innovations, local networks and internationalization. *Industry and Innovation*, *19*(8), 697–734. https://doi.org/10.1080/13662716.2012.739782

Caliendo, L., & Parro, F. (2015). Estimates of the trade and welfare effects of NAFTA. *Review of Economic Studies*, *82*(1), 1–44. https://doi.org/10.1093/restud/rdu035

Carbone, J. C., & Rivers, N. (2017). The impacts of unilateral climate policy on competitiveness: Evidence from computable general equilibrium models. *Review of Environmental Economics and Policy*, *11*(1), 24–42. https://doi.org/10.1093/reep/rew025

Caron, J., & Fally, T. (2022). Per capita income, consumption patterns, and CO_2 emissions. *Journal of the Association of Environmental and Resource Economists*, *9*(2), 235–271. https://doi.org/10.1086/716727

Chang, J., Cheng, Y., & Peng, S. (2022). Trade, emissions, and regulatory (non-)compliance: Implications of firm heterogeneity. *Review of International Economics*, *30*(1), 57–82. https://doi.org/10.1111/roie.12552

Chen, Z.-M., Ohshita, S., Lenzen, M., Wiedmann, T., Jiborn, M., Chen, B., Lester, L., Guan, D., Meng, J., Xu, S., Chen, G., Zheng, X., Xue, J., Alsaedi, A., Hayat, T., & Liu, Z. (2018). Consumption-based greenhouse gas emissions accounting with capital stock change highlights dynamics of fast-developing countries. *Nature Communications*, *9*(1), 3581. https://doi.org/10.1038/s41467-018-05905-y

Cherniwchan, J. (2017). Trade liberalization and the environment: Evidence from NAFTA and U.S. manufacturing. *Journal of International Economics*, *105*, 130–149. https://doi.org/10.1016/J.JINTECO.2017.01.005

Cherniwchan, J., Copeland, B. R., & Taylor, M. S. (2017). Trade and the environment: New methods, measurements, and results. *Annual Review of Economics*, *9*, 59–85. https://doi.org/10.1146/annurev-economics-063016-103756

Cole, M. A., Elliott, R. J. R., Okubo, T., & Zhou, Y. (2013). The carbon dioxide emissions of firms: A spatial analysis. *Journal of Environmental Economics and Management*, *65*(2), 290–309. https://doi.org/10.1016/J.JEEM.2012.07.002

Cole, M. A., Elliott, R. J. R., & Zhang, L. (2017). Foreign direct investment and the environment. *Annual Review of Environment and Resources*, *42*, 465–487. https://doi.org/10.1146/annurev-environ-102016-060916

Copeland, B. R. (1996). Pollution content tariffs, environmental rent shifting, and the control of cross-border pollution. *Journal of International Economics*, *40*(3–4), 459–476. https://doi.org/10.1016/0022-1996(95)01415-2

Copeland, B. R., & Taylor, M. S. (1994). North-South trade and the environment. *The Quarterly Journal of Economics*, *109*(3), 755–787. https://doi.org/10.2307/2118421

Copeland, B. R., & Taylor, M. S. (2004). Trade, growth, and the environment. *Journal of Economic Literature*, *42*(1), 7–71. https://doi.org/10.1257/002205104773558047

Copeland, B., Shapiro, J., & Taylor, M. S. (2021). *Globalization and the Environment* (NBER Working Paper No. 28797). National Bureau of Economic Research, Inc. https://econpapers.repec.org/paper/nbrnberwo/28797.htm

Cristea, A., Hummels, D., Puzzello, L., & Avetisyan, M. (2013). Trade and the greenhouse gas emissions from international freight transport. *Journal of Environmental Economics and Management*, *65*(1), 153–173. https://doi.org/10.1016/j.jeem.2012.06.002

Cui, J., Lapan, H., & Moschini, G. C. (2016). Productivity, export, and environmental performance: Air pollutants in the United States. *American Journal of Agricultural Economics*, *98*(2), 447–467. https://doi.org/10.1093/AJAE/AAV066

Cui, J., & Qian, H. (2017). The effects of exports on facility environmental performance: Evidence from a matching approach. *The Journal of International Trade & Economic Development*, *26*(7), 759–776. https://doi.org/10.1080/09638199.2017.1303079

Davis, L. W., & Kahn, M. E. (2010). International trade in used vehicles: The environmental consequences of NAFTA. *American Economic Journal: Economic Policy*, *2*(4), 58–82. https://doi.org/10.1257/pol.2.4.58

Davis, S. J., & Caldeira, K. (2010). Consumption-based accounting of CO_2 emissions. *Proceedings of the National Academy of Sciences*, *107*(12), 5687–5692. https://doi.org/10.1073/pnas.0906974107

Debaere, P. (2014). The global economics of water: Is water a source of comparative advantage? *American Economic Journal: Applied Economics*, *6*(2), 32–48. https://doi.org/10.1257/app.6.2.32

Demailly, D., & Quirion, P. (2006). CO_2 abatement, competitiveness and leakage in the European cement industry under the EU ETS: Grandfathering versus output-based allocation. *Climate Policy*, *6*(1), 93–113. https://doi.org/10.1080/14693062.2006.9685590

Ederington, J., Levinson, A., & Minier, J. (2005). Footloose and pollution-free. *Review of Economics and Statistics*, *87*(1), 92–99. https://doi.org/10.1162/0034653053327658

Egger, H., Kreickemeier, U., & Richter, P. M. (2021). Environmental policy and firm selection in the open economy. *Journal of the Association of Environmental and Resource Economists*, *8*(4), 655–690. https://doi.org/10.1086/713040

Egger, P., & Nigai, S. (2015). Energy demand and trade in general equilibrium. *Environmental and Resource Economics*, *60*(2), 191–213. https://doi.org/10.1007/s10640-014-9764-1

European Commission, Directorate-General for Trade. (2018). Evaluation of the implementation of the free trade agreement between the EU and its Member States and the Republic of Korea: final report. Publications Office. https://data.europa.eu/doi/10.2781/897452

Fan, J.-L., Hou, Y.-B., Wang, Q., Wang, C., & Wei, Y.-M. (2016). Exploring the characteristics of production-based and consumption-based carbon emissions of major economies: A multiple-dimension comparison. *Applied Energy*, *184*, 790–799. https://doi.org/10.1016/j.apenergy.2016.06.076

Farrokhi, F., & Lashkaripour, A. (2021). *Can trade policy mitigate climate change?* 88.

Felbermayr, G., & Peterson, S. (2020). Economic assessment of carbon leakage and carbon border adjustment. *Briefing for the European Parliament*. https://doi.org/10.2861/577601

Fischer, C., & Fox, A. K. (2012). Comparing policies to combat emissions leakage: Border carbon adjustments versus rebates. *Journal of Environmental Economics and Management*, *64*(2), 199–216. https://doi.org/10.1016/j.jeem.2012.01.005

Forslid, R., Okubo, T., & Sanctuary, M. (2017). Trade liberalization, transboundary pollution, and market size. *Journal of the Association of Environmental and Resource Economists*, *4*(3), 927–957. https://doi.org/10.1086/693562

Forslid, R., Okubo, T., & Ulltveit-Moe, K. H. (2018). Why are firms that export cleaner? International trade, abatement and environmental emissions. *Journal of Environmental Economics and Management*, *91*, 166–183. https://doi.org/10.1016/J.JEEM.2018.07.006

Fowlie, M., Reguant, M., & Ryan, S. P. (2016). Market-based emissions regulation and industry dynamics. *Journal of Political Economy*, *124*(1), 249–302. https://doi.org/10.1086/684484

Frankel, J. A., & Rose, A. K. (2005). Is trade good or bad for the environment? Sorting out the causality. *The Review of Economics and Statistics*, *87*(1), 85–91. https://doi.org/10.1162/0034653053327577

Franks, M., Kalkuhl, M., & Lessmann, K. (2022). Optimal pricing for carbon dioxide removal under inter-regional leakage. *CEPA Discussion Paper*, *43*, Article 43.

Ganapati, S., Wong, W. F., & Ziv, O. (2021). Entrepot: Hubs, scale, and trade costs. *NBER Working Paper, 29015*.

Gerlagh, R., & Kuik, O. (2014). Spill or leak? Carbon leakage with international technology spillovers: A CGE analysis. *Energy Economics*, *45*, 381–388. https://doi.org/10.1016/J.ENECO.2014.07.017

Ghosh, M., Luo, D., Siddiqui, M. S., & Zhu, Y. (2012). Border tax adjustments in the climate policy context: CO2 versus broad-based GHG emission targeting. *Energy Economics*, *34*, S154–S167. https://doi.org/10.1016/j.eneco.2012.09.005

Girma, S., & Hanley, A. (2015). How green are exporters? *Scottish Journal of Political Economy*, *62*(3), 291–309. https://doi.org/10.1111/SJPE.12075

Grossman, G. M., & Krueger, A. B. (1993). Environmental impacts of a North American free trade agreement. In P. M. Garber (Ed.), *The U.S.-Mexico free trade agreement* (pp. 13–56). MIT Press.

Gutiérrez, E., & Teshima, K. (2018). Abatement expenditures, technology choice, and environmental performance: Evidence from firm responses to import competition in Mexico. *Journal of Development Economics*, *133*, 264–274. https://doi.org/10.1016/J.JDEVECO.2017.11.004

Hanley, A., Semrau, O., & Semrau, F. O. (2022). Stepping up to the mark? Firms' export activity and environmental innovation in 14 European countries. *Industry and Innovation*, *29*(5), 672–700. https://doi.org/10.1080/13662716.2021.2021865

Hertwich, E. G., & Peters, G. P. (2009). Carbon footprint of nations: A global, trade-linked analysis. *Environmental Science & Technology*, *43*(16), 6414–6420. https://doi.org/10.1021/es803496a

Hsiao, A. (2022). Coordination and commitment in international climate action: Evidence from palm oil. *Working Paper*, 51.

Hoel, M. (1996). Should a carbon tax be differentiated across sectors? *Journal of Public Economics*, *59*(1), 17–32. https://doi.org/10.1016/0047-2727(94)01490-6

Holladay, J. S. (2016). Exporters and the environment. *Canadian Journal of Economics/Revue Canadienne d'économique*, *49*(1), 147–172. https://doi.org/10.1111/CAJE.12193

Huang, Z. A., & Wang, R. (2021). Exploring China's digitalization of public diplomacy on Weibo and Twitter: A case study of the U.S.–China trade war. *International Journal of Communication*, *15*(0), 28.

Jaffe, A. B., Peterson, S. R., Portney, P. R., & Stavins, R. N. (1995). Environmental regulation and the competitiveness of U.S. manufacturing: What does the evidence tell us? *Journal of Economic Literature*, *33*(1), 132–163.

Klotz, R., & Sharma, R. (2023). Trade barriers and CO2. *Journal of International Economics*, *141*, 103726. https://doi.org/10.1016/j.jinteco.2023.103726

Kortum, S., & Weisbach, D. (2021). Optimal unilateral carbon policy. *Cowles Foundation Discussion Paper, 2659*.

Kreickemeier, U., & Richter, P. M. (2014). Trade and the environment: The role of firm heterogeneity. *Review of International Economics*, *22*(2), 209–225. https://doi.org/10.1111/roie.12092

Krugman, P. (1980). Scale economies, product differentiation, and the pattern of trade. *American Economic Review*, *70*(5), 950–959.

Kuik, O., & Hofkes, M. (2010). Border adjustment for European emissions trading: Competitiveness and carbon leakage. *Energy Policy*, *38*(4), 1741–1748. https://doi.org/10.1016/j.enpol.2009.11.048

Lanzi, E., Chateau, J., & Dellink, R. (2012). Alternative approaches for levelling carbon prices in a world with fragmented carbon markets. *Energy Economics*, *34*, S240–S250. https://doi.org/10.1016/j.eneco.2012.08.016

Larch, M., & Wanner, J. (2017). Carbon tariffs: An analysis of the trade, welfare, and emission effects. *Journal of International Economics*, *109*, 195–213. https://doi.org/10.1016/J.JINTECO.2017.09.003

Larch, M., & Wanner, J. (2019). The Consequences of Unilateral Withdrawals from the Paris Agreement. *CESifo Working Paper, 7804*.

Lee, T. C., Chang, Y. T., & Lee, P. T. W. (2013). Economy-wide impact analysis of a carbon tax on international container shipping. *Transportation Research Part A: Policy and Practice*, *58*, 87–102. https://doi.org/10.1016/J.TRA.2013.10.002

Lessmann, K., Marschinski, R., & Edenhofer, O. (2009). The effects of tariffs on coalition formation in a dynamic global warming game. *Economic Modelling*, *26*(3), 641–649.

Levinson, A. (2009). Technology, international trade, and pollution from US manufacturing. *American Economic Review*, *99*(5), 2177–2192. https://doi.org/10.1257/aer.99.5.2177

Levinson, A., & Taylor, M. S. (2008). Unmasking the pollution haven effect. *International Economic Review*, *49*(1), 223–254. https://doi.org/10.1111/j.1468-2354.2008.00478.x

Mahlkow, H., Felbermayr, G., & Peterson, S. (2021). *Der Effekt von klimapolitischen Maßnahmen auf CO2-Emissionen und CO2-Fußabdrücke (The Effect of Climate Policy Measures on Carbon Emissions and Carbon Footprints)* (Report on Behalf of the Bertelsmann Foundation).

Mahlkow, H., & Wanner, J. (2022). The carbon footprint of global trade imbalances. *In Progress*.

Markusen, J. R. (1975). International externalities and optimal tax structures. *Journal of International Economics*, *5*(1), 15–29.

Mathiesen, L., & Maestad, O. (2004). Climate policy and the steel industry: Achieving global emission reductions by an incomplete climate agreement. *The Energy Journal*, *25*(4), 91–114.

McKibbin, W. J., Wilcoxen, P. J., Braathen, N. A., Tao, (Tom) H., & Levinson, A. (2008). The economic and environmental effects of border tax adjustments for climate policy [with comments]. *Brookings Trade Forum*, 1–34.

McKinsey. (2022). The inflation reduction: Here's what's in it. https://www.mckinsey.com/industries/public-sector/our-insights/the-inflation-reduction-act-heres-whats-in-it#/ (June 27, 2023)

Melitz, M. J. (2003). The impact of trade on intra-industry reallocations and aggregate industry productivity. *Econometrica*, *71*(6), 1695–1725.

Melitz, M. J., & Ottaviano, G. I. P. (2008). Market size, trade, and productivity. *Review of Economic Studies*, *75*(1), 295–316. https://doi.org/10.1111/j.1467-937X.2007.00463.x

Monjon, S., & Quirion, P. (2011). Addressing leakage in the EU ETS: Border adjustment or output-based allocation? *Ecological Economics*, *70*(11), 1957–1971. https://doi.org/10.1016/j.ecolecon.2011.04.020

Mundaca, G., Strand, J., & Young, I. R. (2021). Carbon pricing of international transport fuels: Impacts on carbon emissions and trade activity. *Journal of Environmental Economics and Management*, *110*, 102517. https://doi.org/10.1016/J.JEEM.2021.102517

Naegele, H., & Zaklan, A. (2019). Does the EU ETS cause carbon leakage in European manufacturing? *Journal of Environmental Economics and Management*, *93*, 125–147. https://doi.org/10.1016/j.jeem.2018.11.004

Nemati, M., Hu, W., & Reed, M. (2019). Are free trade agreements good for the environment? A panel data analysis. *Review of Development Economics*, *23*(1), 435–453. https://doi.org/10.1111/RODE.12554

Nordhaus, W. D. (2015). Climate clubs: Overcoming free-riding in international climate policy. *American Economic Review*, *105*(4), 1339–1370. https://doi.org/10.1257/aer.15000001

Parry, I., Heine, D., Kizzier, K., & Smith, T. (2022). A carbon levy for international maritime fuels. Review of Environmental Economics and Policy. https://doi.org/10.1086/717961

Peters, G. P. (2008). From production-based to consumption-based national emission inventories. *Ecological Economics*, *65*(1), 13–23. https://doi.org/10.1016/j.ecolecon.2007.10.014

Peters, G. P., & Hertwich, E. G. (2008). CO_2 embodied in international trade with implications for global climate policy. *Environmental Science & Technology*, *42*(5), 1401–1407. https://doi.org/10.1021/es072023k

Peters, G. P., Minx, J. C., Weber, C. L., & Edenhofer, O. (2011). Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the National Academy of Sciences*, *108*(21), 8903–8908. https://doi.org/10.1073/pnas.1006388108

Richter, P. M., Runkel, M., & Schmidt, R. C. (2021). Strategic environmental policy and the mobility of firms. *Journal of the Association of Environmental and Resource Economists*, *8*(5), 863–893. https://doi.org/10.1086/713562

Richter, P. M., & Schiersch, A. (2017). CO2 emission intensity and exporting: Evidence from firm-level data. *European Economic Review*, *98*, 373–391. https://doi.org/10.1016/j.euroecorev.2017.07.011

Schim van der Loeff, W., Godar, J., & Prakash, V. (2018). A spatially explicit data-driven approach to calculating commodity-specific shipping emissions per vessel. *Journal of Cleaner Production*, *205*, 895–908. https://doi.org/10.1016/J.JCLEPRO.2018.09.053

Shapiro, J. S. (2016). Trade costs, CO2, and the environment. *American Economic Journal: Economic Policy*, *8*(4), 220–254. https://doi.org/10.1257/pol.20150168

Shapiro, J. S. (2021). The environmental bias of trade policy. *Quarterly Journal of Economics*, *136*(2), 831–886.

Shapiro, J. S., & Walker, R. (2018). Why is pollution from U.S. manufacturing declining? The roles of environmental regulation, productivity, and trade. *American Economic Review*, *108*(12), 3814–3854.

Sheng, Y., Shi, X., & Su, B. (2018). Re-analyzing the economic impact of a global bunker emissions charge. *Energy Economics*, *74*, 107–119. https://doi.org/10.1016/j.eneco.2018.05.035

Steen-Olsen, K., Weinzettel, J., Cranston, G., Ercin, A. E., & Hertwich, E. G. (2012). Carbon, land, and water footprint accounts for the European Union: Consumption, production, and displacements through international trade. *Environmental Science & Technology*, *46*(20), 10883–10891. https://doi.org/10.1021/es301949t

Su, B., & Ang, B. W. (2011). Multi-region input–output analysis of CO2 emissions embodied in trade: The feedback effects. *Ecological Economics*, *71*, 42–53. https://doi.org/10.1016/j.ecolecon.2011.08.024

Su, B., Huang, H. C., Ang, B. W., & Zhou, P. (2010). Input–output analysis of CO2 emissions embodied in trade: The effects of sector aggregation. *Energy Economics*, *32*(1), 166–175. https://doi.org/10.1016/j.eneco.2009.07.010

Tanaka, S., Teshima, K., & Verhoogen, E. (2022). North-South displacement effects of environmental regulation: The case of battery recycling. *American Economic Review: Insights*, *4*(3), 271–288. https://doi.org/10.1257/aeri.20210201

Thube, S., Peterson, S., Nachtigall, D., & Ellis, J. (2021). The economic and environment benefits from international co-ordination on carbon pricing: A review of economic modelling studies*. *Environmental Research Letters*, *16*(11), 113002. https://doi.org/10.1088/1748-9326/ac2b61

Tian, K., Zhang, Y., Li, Y., Ming, X., Jiang, S., Duan, H., Yang, C., & Wang, S. (2022). Regional trade agreement burdens global carbon emissions mitigation. *Nature Communications*, *13*(1), 408. https://doi.org/10.1038/s41467-022-28004-5

Timmer, M. P., Dietzenbacher, E., Los, B., Stehrer, R., & de Vries, G. J. (2015). An illustrated user guide to the world input-output database: The case of global automotive production. *Review of International Economics*, *23*(3), 575–605. https://doi.org/10.1111/roie.12178

Tukker, A., Bulavskaya, T., Giljum, S., de Koning, A., Lutter, S., Simas, M., Stadler, K., & Wood, R. (2014). *The Global Resource Footprint of Nations. Carbon, water, land and materials embodied in trade and final consumption, calculated with EXIOBASE 2.1*. TNO.

Tukker, A., Giljum, S., & Wood, R. (2018). Recent progress in assessment of resource efficiency and environmental impacts embodied in trade: An introduction to this special issue: Recent progress in assessment of embodied impacts. *Journal of Industrial Ecology*, *22*(3), 489–501. https://doi.org/10.1111/jiec.12736

UNCTAD. (2021). Global Trade Update (November 2021). *Technical Report2*.

Verde, S. F. (2020). The impact of the EU emissions trading system on competitiveness and carbon leakage: The econometric evidence. *Journal of Economic Surveys*, *34*(2), 320–343. https://doi.org/10.1111/joes.12356

Weitzel, M., Hübler, M., & Peterson, S. (2012). Fair, optimal or detrimental? Environmental vs. strategic use of border carbon adjustment. *Energy Economics*, *34*, S198–S207. https://doi.org/10.1016/j.eneco.2012.08.023

Wiedmann, T. (2009). A review of recent multi-region input–output models used for consumption-based emission and resource accounting. *Ecological Economics*, *69*(2), 211–222. https://doi.org/10.1016/j.ecolecon.2009.08.026

Wiedmann, T., Lenzen, M., Turner, K., & Barrett, J. (2007). Examining the global environmental impact of regional consumption activities — Part 2: Review of input–output models for the assessment of environmental impacts embodied in trade. *Ecological Economics*, *61*(1), 15–26. https://doi.org/10.1016/j.ecolecon.2006.12.003

Winchester, N., Paltsev, S., & Reilly, J. M. (2011). Will border carbon adjustments work? *The B.E. Journal of Economic Analysis & Policy*, *11*(1), Article 7. https://doi.org/10.2202/1935-1682.2696

World Bank. (2015). *Carbon leakage: Theory, evidence and policy design*. The World Bank. https://doi.org/10.1596/K8516

WTO. (2015). International Trade Statistics 2015. *Technical Report*.

Wu, L., Zhou, Y., & Qian, H. (2022). Global actions under the Paris agreement: Tracing the carbon leakage flow and pursuing countermeasures. *Energy Economics*, *106*, 105804. https://doi.org/10.1016/j.eneco.2021.105804

Yamano, N., & Guilhoto, J. (2020). *CO2 emissions embodied in international trade and domestic final demand: Methodology and results using the OECD Inter-Country Input-Output Database*. OECD. https://doi.org/10.1787/8f2963b8-en

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APPENDIX: OVERVIEW LITERATURE REVIEW

	Focus of the paper	*Independent* variables (effect of what aspects of trade/trade policy on the environment/climate)	*Dependent* variables (effect of trade/trade policy on what aspects among the environment/climate)	Methodology used	Datase/database used	Remark
Aichele and Felbermayr (2012)	Causal effects of ratified and binding Kyoto commitments on carbon footprints and territorial emissions	Kyoto commitments	Carbon footprints and territorial emissions	Panel data approach with instrumental variables estimator	xx	
Aichele and Felbermayr (2015)	Causal effects of ratified and binding Kyoto commitments on carbon content of bilateral trade	Kyoto commitments	Carbon content of bilateral trade flows	Gravity estimation	xx	Nägele and Zaklan (2019) have comparable approach for EU ETS
Antweiler et al. (2001)	Is free trade good for the environment	Trade intensity (trade rel. to GDP)	SO2-Emissions	Cross-country time series random and fixed effects	Cross-country data	Exemplary study
Böhringer, Balistreri et al. (2012)	The effects of BCA on carbon leakage	Climate Policy (BCA vs. No BCA)	Emissions, leakage rate	CGE modeling	Mostly GTAP	Cross-model comparison study and exemplary for a large set of CGE-based studies
Branger and Quirion (2014)	Determinants of carbon leakage and effects of BCA on leakage	BCA, model characteristics	Emissions, leakage rate, welfare	Meta-analysis of existing PE and CGE studies	Diverse for underlying models	Meta-analysis

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	Focus of the paper	***Independent*** **variables (effect of what aspects of trade/trade policy on the environment/climate)**	***Dependent*** **variables (effect of trade/trade policy on what aspects among the environment/climate)**	Methodology used	Datase/database used	Remark
Brunnermeier and Levinson (2004)	Survey on empirical research related to pollution haven hypothesis (firm relocation due to environmental action)	Different environmental policy/spending variables	Mostly plant locations	Different empirical approaches including cross-section conditional logit and panel data approaches	Diverse	Survey article
Caron and Fally (2022)	Can income-driven differences in consumption patterns explain the environmental Kuznets Curve for emission intensity?	Positive income shock (via TFP shock)	Emission (intensity)	Structural gravity model	GTAP, IEA's "Extended Energy Balances," gravity variables from CEPII	Incorporates non-homothetic preferences, therefore of particular interest in the context of developing countries
Cherniwchan (2017)	What were the plant-level pollution effects of export opportunities and import competition for US firms induced by NAFTA?	tariff changes due to NAFTA	Pollution (particulate matter, sulfur dioxide)	Fixed effects regressions	US EPA's Toxic Release Inventory (TRI), National Establishment Times Series (NETS), plus tariff and trade data	Strength of the empirical approach: focus on liberalization policy rather than on firms' export status is more plausibly exogenous

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	Focus of the paper	*Independent* variables (effect of what aspects of trade/trade policy on the environment/climate)	*Dependent* variables (effect of trade/trade policy on what aspects among the environment/climate)	Methodology used	Datase/database used	Remark
Copeland (1996)	Optimal unilateral policy for a country that imports a good from a neighboring country and is harmed by pollution generated during the production of that good	Import tariffs on polluting good foreign pollution quota	National welfare/ pollution	Analytical model	N.a.	
Copeland and Taylor (1994)	Linkages between national income, pollution, and international trade. Isolating the scale, composition, and technique effects	Trade liberalization; growth in south or north, transfers	Worldwide pollution	Analytical north-south model	N.A.	
Cristea et al. (2013)	Which part of the emissions associated with international trade stems from transportation?	International trade and transportation	GHG emissions	Descriptive analysis, statistical decomposition, CGE modeling	GTAP 7, US Imports and Exports of Merchandise, Eurostats Trade, ALADI trade database, Transborder Surface Freight Data, "Ship Emissions Study" (National Technical University of Athens Laboratory for Maritime Transport), Air Transport Association of America	

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	Focus of the paper	*Independent* variables (effect of what aspects of trade/trade policy on the environment/climate)	*Dependent* variables (effect of trade/trade policy on what aspects among the environment/climate)	Methodology used	Datase/database used	Remark
S. J. Davis and Caldeira (2010)	Global consumption-based CO_2 inventory	Trade in goods and services	Carbon footprints	MRIO-analysis	GTAP	
Farrokhi and Lashkaripour (2021)	Assessment of BCA with respect to incentivizing climate coalitions and with respect to optimal 2nd best policy	BCA	Cooperation, emissions	non-cooperative Nash model parameterized with a quantitative trade model	WIOD plus additional sources	Features a firm-level component including increasing returns to scale and a flexible abatement technology, but firms are homogeneous
Fischer and Fox (2012)	Effectiveness of different anti-leakage policies	Border tariff on imports, border rebate for exports, full BCA, output-based rebating	CO_2-Emissions & Leakage rate	Analytic model + CGE model	GTAP	
Fowlie et al. (2016)	Static and dynamic implications of alternative market-based policies limiting greenhouse gas emissions in the US cement industry	Market based climate policies	Emissions, leakage, welfare	PE modeling for cement sector	Diverse	Exemplary study
Frankel and Rose (2005)	Is trade good or bad for the environment	Trade intensity (trade rel. to GDP)	NO_2, SO2, CO_2 emissions, particular matter, deforestation, energy depletion	Cross-country time series with an instrumental approach	Cross-country data	Exemplary study

(Continues)

	Focus of the paper	*Independent* variables (effect of what aspects of trade/trade policy on the environment/climate)	*Dependent* variables (effect of trade/trade policy on what aspects among the environment/climate)	Methodology used	Datase/database used	Remark
Gerlagh and Kuik (2014)	Can technology spillovers overturn the leakage effects of unilateral climate policy?	Unilateral EU climate policy (reduction by 20 %)	Output, trade flows, leakage	CGE Modeling (extension of GTAP-E)	GTAP + Patent data	Calibration of the technology spillover is rather rudimentary, simulations are more of a demonstration of the channel
Hsiao (2022)	Emission reductions of import tariffs on palm oil imports from Malaysia and Indonesia	Import tariffs / Export tariffs	Emission of palm oil production	Dynamic empirical framework of the palm oil market	Diverse micro-data	
Al Khourdajie and Finus (2018)	Whether and under which conditions BCA can mitigate free-riding and reduce carbon leakage	BCA	Cooperation, emissions	Strategic game-theoretic trade model	n.a.	
Kortum and Weisbach (2021)	What is the optimal unilateral climate policy mix?	Energy extraction and consumption taxes, tariffs on energy and goods imports, export subsidies	National welfare and emissions	Analytic model + calibrated quantification	OECD TECO2 Database, International Energy Agency World Energy Statistics Database	
Larch and Wanner (2017)	Effects of the emission reduction pledges made by the Annex I countries in the Copenhagen Accord	Carbon tariffs	Trade, welfare, and carbon emissions	Structural gravity model	GTAP8 + additonal data	Incorporates the decomposition of scale, composition and technique effects into a quantitative model

(Continues)

	Focus of the paper	*Independent* variables (effect of what aspects of trade/trade policy on the environment/climate)	*Dependent* variables (effect of trade/trade policy on what aspects among the environment/climate)	Methodology used	Datase/database used	Remark
Levinson (2009)	Drivers of air pollution from US manufacturing (scale, composition and technique effects)	Import of polluting goods	Pollution levels	Decomposition analysis	EPA data on pollution BEA I-O tables	
Levinson and Taylor (2008)	Effects of US environmental regulation on trade with Canada and Mexico	Pollution Abatement Costs of US Manufacturing	Net imports from Canada and Mexico to US	Fixed effects estimations + 2SLS with an instrumental approach	US Data for 130 manufacturing industries from 1977 to 1986	
Nordhaus (2015)	Stable coalitions that agree on carbon price and are held together by trade tariffs / BCA	trade in goods and services	Number of coalition members, emissions, carbon price	Game-theoretic model parameterized with the IAM DICE	Data sources of DICE	
Peters et al. (2011)	Development of carbon emissions embodied in trade over time	Trade in goods and services	Carbon emissions embodied in trade	MRIO-analysis	GTAP	Exemplarily for a large set of related studies
Fan et al. (2016)	Development and drivers of carbon emissions embodied in trade	Trade in goods and services	Carbon emissions embodied in trade	MRIO-analysis	WIOD	
Steen-Olsen et al. (2012)	Carbon, land and water footprint of major EU countries in 2004	Trade in goods and services	Carbon emissions, water use and land use embodied in trade	MRIO-analysis	GTAP + additional water and land-data	

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	Focus of the paper	*Independent* variables (effect of what aspects of trade/trade policy on the environment/climate)	*Dependent* variables (effect of trade/trade policy on what aspects among the environment/climate)	Methodology used	Datase/database used	Remark
Shapiro and Walker (2018)	Explanation for the decline in US manufacturing emissions since 1990	International trade and domestic environmental regulation	Emissions (CO, NOX, PM, SO2, VOCs)	Statistical decomposition of emission changes and Melitz-type structural gravity model	US Census Bureau's Annual Survey of Manufactures (ASM), Pollution Abatement Costs and Expenditures (PACE), US EPA's National Emissions Inventory (NEI), plus production and trade data	
Shapiro (2016)	Is trade still welfare-enhancing once we take into account the emissions from transportation?	Carbon pricing in international transportation	Trade, welfare, carbon emissions from production and transportation	Structural gravity model	History Database of the Global Environment, Environmental Systems Research Institute (ESRI), US Imports of Merchandise, Australian Bureau of Statistics, GTAP	Novel part in the model: explicit introduction of transportation emissions; price for this: rather simple quantitative model otherwise (e.g., fixed sectoral emission intensities)

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	Focus of the paper	***Independent* variables (effect of what aspects of trade/trade policy on the environment/climate)**	***Dependent* variables (effect of trade/trade policy on what aspects among the environment/climate)**	**Methodology used**	**Datase/database used**	**Remark**
Shapiro (2021)	Is there an unintended environmental bias in currently implemented trade policies related to upstream industries being dirtier and facing lower trade barriers?	Industry-level tariffs and non-tariff barriers	Carbon emissions	Fixed effects regressions, IV regressions, structural gravity model	Exiobase, Market Access Map (Macmap) database, Census Bureau's Imports of Merchandise, World Bank's World Integrated Trade Solutions (WITS),	Quantitative model features input-output linkages and would hence allow consideration of global value chain emissions, but focus on global emission changes
Verde (2020)	Literature survey on effects of EU ETS on competitiveness and carbon leakage	EU ETS	Competitive performance/carbon leakage/investment leakage/stock return	different empirical approaches: Time series / Panel data / DiD/ MFM	Diverse firm and sector-level data sets	Contains table similar to this for a set of studies