Federica Cappelli, Davide Consoli, Valeria Costantini, Ilaria Fusacchia,
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INTERNATIONAL TRADE AND CLIMATE CHANGE
Part of the problem or part of the solution?

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International trade and climate change
Part of the problem or part of the solution?

by

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Executive summary

The relationship between trade and climate change is very complex and linkages occur in several directions. There are both direct and indirect mechanisms and the global characteristic of climate-related impacts and responsibilities improves such complexity within the political debate. To this purpose, a deep knowledge of linkages across sectors and regions as well as within different policy spaces is a requirement for assessment exercises of climate and/or trade-related policies.

The aim of this literature review is to present an overview of the different impacts and channels that should be addressed in policy evaluation from both a theoretical and practical point of view.

The analysis is divided in three parts. The first one (Sections 1-2-3) is dedicated to describing a taxonomy of the different impacts, linkages and transmission channels that could be traced both in a global or more local perspective.

The second part (Sections 4-5-6) investigates those quantitative models that are commonly used for economic analyses when the climate and trade-related aspects are jointly included. The description of practical cases studies as applications of the different models provides some guidelines for detecting the best computational solution according to the nature of the problem under investigation.

The third part presents some specific issues that are currently debated in policy negotiations, especially within the European Union, including the introduction of counterbalancing measures as a border tax adjustment (Section 7), the role of innovation trajectories and technology transfer (Section 8) and the most recent developments in the political analysis of the interactions between the rules settled by the international climate policy agenda as the Paris Agreement and the world trade policy framework represented by WTO rules (Section 9).

Given the vast literature today available on this topic, while considering the multiple linkages from a comprehensive perspective is needed to have a full picture of all potential impacts, it is of primary relevance the choice of the point from which the policy impact evaluation exercise should start, that in turn depends on the objectives of the policy itself. If a trade policy is under scrutiny, the quantitative analysis should start from the multilateral and/or bilateral economic relationships and then assessing the indirect impact on climate change. On the opposite, if the reduction of damages related to climate change is the primary policy goal, the effectiveness of mitigation or adaptation policies should be weighted by the relative economic impacts associated to trade linkages.

To this purpose, the document ends with four tables with different taxonomies of scientific contributions dealing with the climate and trade-related policy nexus with different quantitative methodologies and temporal perspectives, including ex-post and ex-ante analyses and also trade flows decomposition under a global value chain approach.

Acknowledgment

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1. Introduction

The relationship between trade and climate change is very complex since linkages run in multiple directions and both direct and indirect mechanisms are at work. A sort of mutual causal relation can be detected in the trade-climate nexus and this implies that each direction and effect type deserves to be investigated alone and than combined with the others. Accordingly, we analyse different channels, effects and empirical methods adopted in separate sections.

Since researchers never observe markets that are both closed and open at the same time, the fundamental challenge in this literature lies in assessing how local markets would behave under counterfactual scenarios in which they become more or less integrated with the rest of the world. In recent years, there have been significant improvements both in terms of the methodologies implemented and the data used. However, normative implications drawn from the empirical analyses are often blurred by the lack of acknowledgement that international trade is not desirable per se but is a means with others of achieving several possible economic and/or environmental goals. As a consequence, any recommendation about more or less trade liberalization ought to be derived from counterfactual comparisons with alternative scenarios while constantly focusing on the chosen goal.

Given the complexity of the topic and the peculiar point of view required to analyse each specific aspect of the nexus, the work is organised in different sections. Sections 2-5 adopt a general perspective and provide a broad picture of mechanisms and methods used for the investigation of the trade-climate change nexus. More in detail, Section 2 and 3 illustrate, in general terms, the mechanisms through which trade may worsen or mitigate climate change (Section 2) and on the opposite those through which climate change impacts trade (Section 3). Section 4 and 5 review the empirical results literature provides on mechanisms of both directions, by disentangling quantitative methods into ex-post (Section 4) and ex-ante (Section 5) analyses conducted on these issues. Going from general to particular, Sections 6-8 address three specific issues that are under the lens of the recent academic and policy debate. Section 6 investigates the role played by the higher complexity in global value chains in those mechanisms and causal loops generally addressed in previous sections. Section 7 focuses on the issue of carbon leakage and the main policy instrument designed to contrast it, namely carbon border tax adjustment, as a core element of the current debate on the interlinkages between climate change policies and international trade. Section 8 analyses the interrelations existing among trade, technology and climate change, focusing the attention on a specific element of the global value chain as a source of potential benefits related to knowledge transfer. Finally, Section 9 provides an overlook of the ongoing political debate.

2. The effects of trade on climate change

The volume of global trade has increased significantly over recent decades, as much as thirty-two times more than in 1950 (Tamiotti et al., 2009). This has wide-ranging impacts on GHG emissions which are responsible for climate change. To begin with, there are direct and indirect effects (Figure 1). The former relates strictly to the role of transportation in international trade of goods and associated impacts in terms of demand for energy and emissions.

With regard to the indirect effects in general, Grossman and Krueger (1993) make a distinction between the scale effect, i.e. changes in the scale of production and consumption activities, the composition effect, i.e. changes in the relative size of sectors, and the technique effect, i.e. changes in production techniques. The scale effect is crucial since a ceteris paribus assessment of the international trade impacts should be performed for the same scale of production/consumption. Even though the technique effect is often considered the main channel through which trade can mitigate climate change, it is worth recalling that in autarky the structure of the economy is likely to put more pressure on the environment than in free trade. Antweiler, Copeland and Taylor (2001) expand on the pioneering work by Grossman and Krueger (1993) to provide a systematic theoretical framework on the role of the three effects (scale, technique and composition) in shaping the relationship between trade and climate change. Their work will be illustrated in-depth in Section 4.

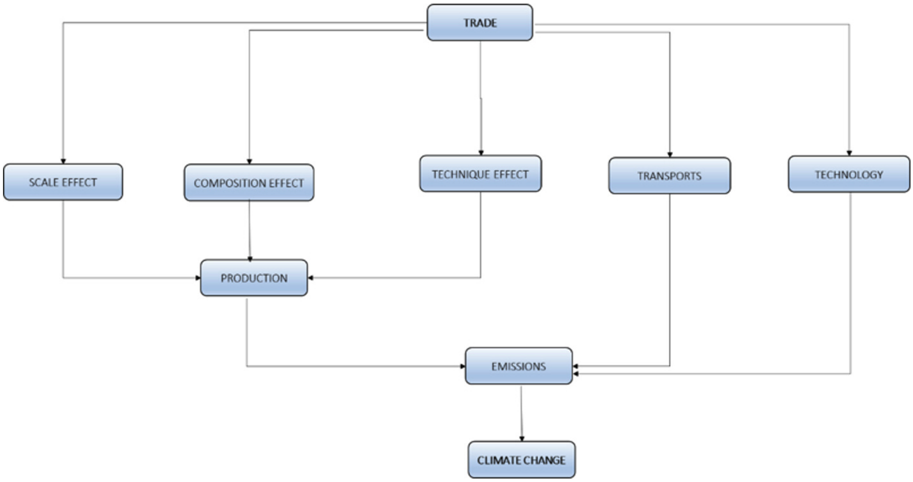

Figure 1 – *Direct and indirect impacts of trade on climate change*

In this vein, Cole and Elliott (2003) analyse the effect of trade openness on four environmental indicators, including CO_2 emissions, covering 32 developed and developing countries during the period 1975-1995. While obtaining mixed evidence across pollutants, they find that, overall, trade openness contributes to increasing emissions due to a large (positive) scale effect and only a small (negative) technique effect. The increase in production due to trade yields higher emissions insofar as clean technologies do not sufficiently counterbalance the increase in demand. However, it is worth mentioning that international trade is not the only possible factor boosting demand: to conclude that trade openness (rather than economic growth in general) contributes to increasing emissions, we need to show that the increase is larger than the one implied by alternative demand-boosting factors.

Other econometric studies confirm the empirical connection between higher emissions and trade openness (i.e. Managi, 2004; McCarney and Adamowicz, 2005) although the effects vary between developed and developing countries. For example, Managi et al. (2008) find that trade openness reduces CO_2 emissions in OECD countries because the negative technique and scale effects prevail over the positive composition effect but, at the same time, has an opposite effect on emissions in developing countries where scale and composition effects are both positive and dominate the technique effect.

On a more general level, trade (or trade opening) encourages knowledge transfer on production methods and design as well as the diffusion of innovation which fosters positive climate spillovers across countries, especially from developed countries to less developed ones. Such a transfer of technology and know-how generates positive spillovers for developing countries striving to counter climate change in the form of innovations developed in OECD countries and embodied in both intermediate and capital goods (Tamiotti et al., 2009).

Finally, some studies focus on the potential of trade as an adaptation strategy, especially in the agriculture sector which carries the burden in terms of negative impacts of climate change (Calzadilla et al., 2011a; Gouel and Laborde, 2018; Ouraich et al., 2018). Indeed, climate change can trigger a scarcity of certain goods and services in a country which may use trade as an adaptation strategy, importing what it needs from countries where these goods and services are still available.

Hence, while trade represents a valuable opportunity to contrast and respond to climate change, if not regulated properly the risk is an increase in CO_2 and other greenhouse gases emissions. This is especially true in the face of opposing effects of trade openness on emissions in developed and developing countries (Managi et al., 2008; Baek et al., 2009; Le et al., 2016). Accordingly, as both climate change and trade are global phenomena, regulations should take into account both importer and exporter countries.

- An increase in global exchange flows is responsible for an increase in GHG emissions if the scale effect overwhelms the technique effect and/or if the composition of the consumption basket is unbalanced towards dirty goods.
- Trade openness has opposing effects on emissions depending on the development level of the countries involved in trade relationships.
- Since climate change and trade are global phenomena, the regulatory framework must adopt a multilateral perspective.

3. The effects of climate change on trade

In line with Truong (2010), impacts of climate change on trade can be divided into physical ones (i.e., arising from climate damages) and policy ones (i.e., arising from the environmental policies implemented) as shown in Figure 2.

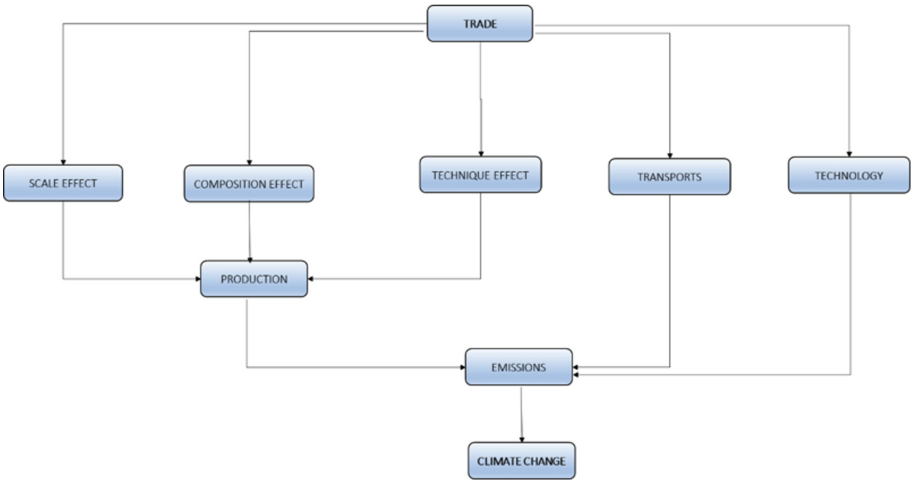

Figure 2 – *Direct and indirect impacts of climate change on trade*

As far as physical impacts are concerned, in addition to a reduction in agricultural productivity, resulting from changes in patterns and distribution of precipitations, the main effect is related to damage to trade infrastructures and transportation routes (Tamiotti et al., 2009; Dellink et al., 2017). For example, coastal infrastructure, bridges and distribution facilities are particularly vulnerable to extreme events (e.g., floods) and sea-level rise damage. Moreover, transportation routes in permafrost areas may be negatively affected by higher temperatures which would reduce the period of time that roads are accessible in winter. Consequently, disruptions to the supply, transport and distribution chains would increase the costs of international trade.

In addition to transportation costs, Dellink et al. (2017) identify three additional channels through which climate change can affect trade: changes in macroeconomic competitiveness (the macroeconomic channel); changes in comparative advantage at the sectoral level (the sectoral channel); and changes in policies. In particular, their ex-ante analysis using the CGE Env-Linkages Model shows that world exports may decrease by 1.8% in 2060, compared to the baseline scenario without climate damage while at the regional level, changes in trade patterns differ according to the vulnerability of each region to climate change, thus confirming the potential of trade as an adaptation strategy. In particular, in regions where the domestic production is highly affected by climate change, such as in India and Sub-Saharan Africa, exports contract more than imports whereas less vulnerable areas (e.g., Canada and Europe) see an increase in exports.

A further element of interest is the role of environmental policies where, as Chen and Woodland (2013) point out, different positions have been taken. On the one hand, advocates of the "Pollution haven hypothesis" claim that more trade openness would shift the production of pollution intensive goods to countries with less stringent environmental regulations. The counterargument is that environmental regulation can also improve the competitiveness of international markets. This intuition underlies the Porter Hypothesis (Porter and van der Linde, 1995), according to which strict environmental regulations provide domestic firms with incentives to invest more in research and development of new, cleaner technologies which would eventually increase their competitiveness. Furthermore, trade relations can also influence the stringency of individual countries' environmental regulations as in the case of the so-called "California effect" (Vogel, 1995) whereby environmental standards and regulation ratchet upwards towards the levels set in high-regulating trading partners (Perkins and Neumayer, 2012). At the same time trade impacts can mutually influence environmental policies as in the case of the carbon leakage effect that induces countries to adapt their domestic environmental policies to trade effects, as specifically analysed in Section 7.

Truong (2010) identifies two main approaches in the study of the relationship between trade and climate change. The first, the ex-post approach, is based on the use of econometric techniques on historical data whereas the second is based on the use of CGE models to generate ex-ante analyses that account for the multiplicity of linkages within a complex economy. While the former is more commonly employed to assess the impacts of trade on climate change, ex-ante CGE-based studies strive to analyse the effects of climate change on trade. The remainder of the document outlines the main contributions based on ex-post analysis in Section 4 and on the ex-ante modelling approach in Section 5.

A further relevant issue in the climate change-trade nexus is the embodied carbon associated with various stages of goods' manufacturing (from raw materials to distribution and final consumers). Without a global climate agreement, such an issue speaks to far-reaching consequences of unilateral abatement policies (e.g., options to avoid carbon leakage), impacts of environmental sustainability (e.g., concerning net importers of CO_2 emissions) and economic competitiveness, and whether international trade should be taken into account in climate negotiations.

Since productive processes become significantly fragmented and integrated at the global level, the assessment of emissions cannot rely on production-based or territorial emission accounting methods which measure emissions occurring within sovereign borders. As Wiebe and Yamano (2016) show, the use of global input-output inter-countries tables can significantly improve the measurement of trade embodied carbon that has been emitted anywhere in the world along GVCs. Emissions embodied in trade, that is, emissions generated by the production of traded goods and services, can be assessed by estimating the factor or value added content of trade. To this end, different theoretical models and accounting methods to decompose trade in terms of the quantity/value of embedded factor of productions can be employed (e.g., Foster-McGregor and Stehrer, 2013; Johnson and Noguera, 2012; Neary and Schweinberger, 1986; Trefler and Zhu, 2010).

- The physical impacts of climate change on international trade can strongly differentiate according to the specific sector and/or region under scrutiny
- Depending on potential benefits or lossess a sector/region might experience from climate change, the bargaining positions in climate negotiations are largely heterogeneous
- Depending on the relative position of each sector/region within the global trade network, there are large divergencies in emission patterns related to the embodied emissions associated to changes in the production system.

4. Empirical studies based on ex-post analysis

From an empirical perspective, ex-post studies have focused on both directions of the relationship between trade and climate change. For instance, some scholars (e.g. Grossman and Krueger, 1993; Antweiler, Copeland and Taylor, 2001; Cole and Elliott, 2003; Frankel and Rose, 2005; Baek et al., 2009; Le et al., 2016) have analysed the effect of trade on climate change, while others (e.g. Tobey, 2001; Ederington and Minier, 2003; Levinson and Taylor, 2008; Costantini and Mazzanti, 2012; Petrick and Wagner, 2014) have investigated the impacts of climate and environmental regulations on trade flows. The econometric techniques employed differ widely.

With regard to the effect of trade on climate change, Antweiler, Copeland and Taylor (2001) develop a theoretical framework whereby a fall in trade frictions brings about a scale effect, a technique effect and a trade-induced composition effect. Thus, in an economy consisting of two goods, one clean and one dirty, pollution depends on the pollution intensity of the dirty industry (technique effect), the relative importance of the dirty industry in the economy (composition effect), the overall size of the economy (scale effect), as well as the world prices of dirty goods and the government type. Taken individually, the scale effect increases pollution by simply scaling up production, keeping the mix of goods produced and the techniques employed constant. The technique effect, by inducing producers to switch to cleaner techniques of production, reduces pollution. The composition effect, in general, tends to increase pollution if the polluting (capital-intensive) industry devotes more resources to producing the dirty good. However, the direction of this effect differs widely depending on whether countries import or export the dirty good. The overall effect depends on which of the three effects prevails.[1]

From an empirical perspective, Antweiler, Copeland and Taylor (2001) use a panel database of 2,555 observations from 290 monitoring stations of SO_2 concentrations, located in 108 cities which represent 43 countries, in the period 1971-1996. The empirical model accounts for the endogeneity

[1] As already mentioned, this effect represents a (sort of) gross measure of the trade impact. The net impact of trade needs a (counterfactual) comparison with an alternative scenario without trade.

of pollution policy and allows a joint estimation of the three effects. The scale effect is measured as GDP per square kilometre[2] and has a positive effect on the elasticity of SO_2 concentrations, which ranges between 0.1 and 0.4. A one percentage point increase in the composition effect, given by the capital-to-labour ratio, induces a 1% increase in the pollution elasticity to an increase in trade intensity. The technique effect is measured as a one-period-lagged three-year moving average of per capita GNP and is estimated to decrease the elasticity of SO_2 concentrations to income by 0.9 to 1.5. As for the trade-induced composition effect, resulting from a fall in trade frictions, the coefficient is negative for the whole sample but the country-specific effect depends on comparative advantage (in terms of capital and labour intensity), thus reiterating the point that the relationship between income gains and policy responses is not straightforward. To distinguish between the effect among countries and detect effects such as the pollution haven hypothesis, openness to trade is conditional on countries' characteristics (thus, on comparative advantages), as well as the source of growth is decisive in evaluating the net effect of trade on pollution. In particular, in the case of neutral technological progress, pollution is reduced in all specifications because the negative technique effect always overwhelms the positive scale effect. On the other hand, economic growth driven by capital accumulation (prevailing composition effect) increases pollution concentration.

Similarly, Cole and Elliott (2003) estimate a panel econometric analysis with both fixed and random effects to detect the impacts of trade on four different pollutants: SO_2, CO_2, NO_x and BOD emissions. Unlike Antweiler, Copeland and Taylor (2001), their information on pollutants refers to national emissions as opposed to local concentrations, hence, both the technique and the scale effects are represented as GDP per capita. The two effects are then combined and, depending on the sign obtained, the prevailing effect can be discerned. In the case of SO_2 and BOD, the technique effect prevails over the scale effect (negative impact of GDP per capita on pollutant emissions), while for CO_2 and NO_x, the scale effect is predominant (positive impact of GDP per capita on pollutant emissions).

Building on Antweiler, Copeland and Taylor (2001)'s theoretical

[2] GDP per square kilometre is computed as the product between national real per capita GDP and population density by city.

framework, Le et al. (2016) employ a globally representative panel dataset to investigate whether trade openness increases or reduces pollutant emissions, measured as either a PM_{10} or CO_2 concentration. The main finding is that the overall net effect of trade openness on the environment depends on income levels and, thus, on the comparative advantage of countries in terms of capital and labour. Accordingly, for the global sample, trade openness is found to cause environmental degradation. However, when decomposing world countries according to their income level, the estimated effect of trade openness is positive for high-income countries and considerably negative for middle- and low-income countries. The reasoning is that capital-abundant (rich) countries export capital-intensive (polluting) goods, thus transferring the pollution burden of consumption to labour-abundant (poor) countries from which they import labour-intensive (clean) goods. These results are consistent with those of Baek et al. (2009) who estimate a Cointegrated Vector Autoregression (CVAR) to assess the direction of causality among trade openness, income and SO_2 emissions, without imposing a theoretical structure a priori. They find no empirical confirmation of reverse causality, whereas trade openness or income are usually the driving forces of SO_2 emissions. Their model empirically validates the Environmental Kuznets Curve (EKC) and, in line with Le et al. (2016), shows contrasting results for developed and developing (China excluded) countries. Accordingly, since environmental quality acts as a normal good, trade liberalization pushes economic growth, stimulating demand for clean technologies. However, the opposite result is found for those countries which have not reached the EKC turning point yet.

The analysis of Frankel and Rose (2005) also validates the EKC hypothesis empirically. They estimate a cross-country regression model to test the effect of trade on environmental quality (measured as SO_2, NO_2 and PM concentrations) for a given level of income per capita and allowing for the endogeneity of both trade and income. They employ geographical variables (such as physical and cultural distance between countries), taken from the gravity model, as instruments for trade. As for income, the instruments employed are lagged income, population size, rates of investment and human capital formation. There are three main findings. First, in line with the EKC hypothesis, the coefficient associated with the square of the GDP is negative for all of the three measures of environmental quality, denoting a mitigating effect of growth on pollution after a certain "income peak" is reached. Second, openness to trade has a positive effect on all measures of environmental quality, thus indicating a beneficial gains-from-trade effect which outweighs the adverse race-to-the-bottom effect. Finally, the evidence on the pollution haven hypothesis, measured as the interaction between trade openness and GDP, is mixed.

Turning to studies that focus on the opposite direction, namely the impact of climate change on international trade, Tobey (2001) empirically tests the hypothesis that stringent environmental regulations in the late 1960s and early 1970s caused a deviation in the trade patterns of the most polluting industries. Framed in the theoretical framework of the Heckscher-Ohlin model, extended to allow for non-homothetic preferences and scale economies, Tobey (2001) employs two different approaches to test the impact of environmental policies on trade patterns: I) the inclusion, among explanatory variables, of a qualitative variable, indicating the stringency of such policies; II) the analysis of the bias in the estimated error term when the variable representing environmental regulations is not included in the regression equation. In both cases, no evidence is found of any considerable effect of the stringency of environmental regulations on trade patterns.

These results are similar to those of Petrick and Wagner (2014) who estimate the causal impact of phase I and the first three years of phase II of the EU ETS on the competitiveness of Germany's manufacturing firms. Their analysis uses a panel database of about 50,000 German manufacturing plants with at least 20 employees between 2005 and 2010. Their approach combines differences-in-differences with semiparametric matching techniques. The results highlight that the reduction in emissions was very limited in the first phase of EU ETS but was substantial in the second phase. In the latter, abatement was due to an optimized use of firms' onsite generation of heat, while keeping a constant scale of production. Accordingly, German firms have not suffered a reduction in either gross output or exports, whereas the effect on employment has been insignificant in both statistical and economic terms.

Consistent results are found by Costantini and Mazzanti (2012) who empirically test the validation of the strong (Jaffe et al., 1995; Porter and van der Linde, 1995) and the narrowly strong (Jaffe and Palmer, 1997) versions of the Porter Hypothesis[3] on the export dynamics of the European Union from 1996 to 2007. Their analysis is based on a gravity model at the sectoral level, allowing for the possibility of differentiating sectors in terms of patterns of innovation and dynamic economic performances, while accounting for similarities across countries. Consistently, the picture provided in this study shows substantial differences across sectors. In particular, the strong version of the Porter Hypothesis appears to be especially convincing in the case of energy taxes applied to high and medium-low technology manufacturing sectors. In the former, the effects of energy taxes on export dynamics are even greater than those of global bilateral demand, similarities in the factor endowment and innovation capacity. In the latter, which are highly energy intensive with most of them included in the European Emission Trading Scheme, energy taxes have the greatest impact on sectors' competitiveness. Conversely, in medium-high and low technology sectors, neither energy taxes nor environmental regulations play a role. As for the narrowly strong Porter Hypothesis, energy taxes contribute to countries' international competitiveness in the green sector only when applied in combination with environmental R&D public expenditures. What is more, unlike the strong version of the Porter Hypothesis, here environmental regulation is much more effective than energy taxes and even more if considered in tandem with both total innovative efforts and innovative efforts in the green sectors. Finally, private and voluntary actions in terms of environmental regulations also play a significant role in fostering international competition and reinforcing the effect of public policies.

On the other hand, Levinson and Taylor (2008) and Ederington and Minier (2003) advocate the pollution haven hypothesis. The study by Levinson and Taylor (2008) investigates the link between environmental regulation and trade flows, with a specific focus on the pollution haven effect. Their analysis draws on a panel dataset on US imports from Mexico and Canada in 132 sectors. They ascribe the lack of agreement over the pollution haven hypothesis and the mixed evidence in the literature to three main misspecification issues in the econometric models estimated. The first issue concerns unobserved heterogeneity which leads to biased measurements of the variation in pollution abatement costs (PAC) which

[3] As defined at pag. 8.

is, hence, not only driven by differences in regulatory stringency, as it should be. To solve this problem, Levinson and Taylor (2008) include fixed effects in the empirical estimation. The second issue is related to the unobserved foreign pollution regulations, due to the correlation between the error term and PAC. Finally, the last issue is aggregation bias since the sectors are composed of a heterogeneous mix of industries. The last issue entails that an increase in production costs due to domestic pollution regulations favours some foreign industries relative to the most polluting domestic ones, resulting in an increase in imports and a reduction in domestic production. Since each industry's share of PAC is determined jointly with imports, the risk is that trying to quantify the effect of PAC on trade may unintentionally capture also the opposite effect. Levinson and Taylor (2008) address this and the previous issue through instrumental variables and demonstrate the validity of the pollution haven hypothesis, given that the relationship between industry PAC and imports into the USA from both Mexico and Canada is consistently positive and statistically significant. Ederington and Minier (2003) arrive at the same conclusion by analysing trade flows in US manufacturing industries between 1978 and 1992. The authors compare the OLS estimation (hence, with exogenous environmental regulation) with the estimation of a system of simultaneous equations for environmental regulation (hence, treated as endogenous) and net imports. In line with Levinson and Taylor (2008), they find that, when stringent environmental regulation (even in this case measured as PAC) is treated as an endogenous variable, it can be a significant source of comparative disadvantage.

- Ex-post quantitative studies reveal that the overall net effect of trade openness on GHG emissions depends on the comparative advantage of countries in terms of capital and labour.
- Structural change might help reducing the negative environmental impact associated to a development process that is based on sustainability principles.
- The environmental regulatory framework might help such sustainable development process if a Porter-like effect is ensured by large investments in eco-innovation.

5. Empirical studies based on ex-ante analysis

In this section, we provide a short review on the main ex-ante models employed to analyse the relationship between trade and climate change, with a specific focus on GTAP, MIRAGE, ENV-Linkage and GEM-E3. The description of each model is also accompanied by a case study that works as an example of the model applied to the analysis of the issue at stake.

GTAP

The GTAP model is a multi-commodity and multi-region CGE model (Hertel, 1997; Hertel and Tsigas, 1999; 2000), used to perform an ex-ante analysis of trade patterns, production, consumption and intermediate use of commodities, with an economy-wide approach. In its standard version, the reference market is assumed to be perfectly competitive and exhibits perfectly constant returns to scale (Hertel and Tsigas, 1999). In such a market, consumers, as representatives of households, maximize their utility according to a non-homothetic constant difference of elasticities (CDE) implicit expenditure function whereas producers maximize profits subject to a CES production function. Domestic and foreign inputs are not substitutes, according to the Armington assumption which accounts for goods heterogeneity (Berrittella et al., 2007). In terms of production factors, capital and labour are perfectly mobile domestically, but immobile internationally, whereas land and natural resources are industry-specific (Berrittella et al., 2007). In the GTAP model, national income is allocated to aggregated private consumption, public consumption and savings, whereas expenditure shares are fixed and correspond to the level of utility of a Cobb-Douglas function. The standard version of the GTAP model can be integrated with new features that widen the array of applications (Corong et al., 2017). It also draws on a very rich database from which also other kinds of models can be gleaned. In its original formulation, the GTAP model was conceived to study the static effects of policy related to resource reallocations in a general equilibrium framework. Through the years, the model has undergone several improvements and refinements such as the incorporation of a welfare decomposition module (Huff and Hertel, 2001); a reformulation of the behaviour of final demand (McDougall, 2003); the disaggregation of the transportation sector by transport mode (Hertel et al., 2000); the inclusion of a representation of scale economies and imperfect competition (Francois, 1998); the development of a dynamic structure (Walmsley et al., 2000), and so on.

The GTAP model, version 7 has been used, among others, by Ouraich et al. (2018) to understand whether, with climate change, trade liberalization – tariff elimination in particular – may represent an effective adaptation policy in Turkey and Morocco. This study also provides a specific insight into the transmission channels through which trade liberalization of the agricultural sector can mitigate or reduce expected negative impacts of climate change (Ouraich et al., 2018). In this context, GTAP version 7 allows for the disaggregation of agricultural production and harvested areas by agro-ecological zones, defined in the study using FAO 2004 data for 159 crops types for each country. In terms of regional aggregation, the study adopted a structure based on 16 regions and considers Turkey and Morocco separately. The projection of the baseline scenario to 2050 is mainly based on productivity shocks of selected crop categories. The data employed to identify these shocks are taken from two main sources: the International Food Policy Research Institute Food Security CASE Maps database (IFPRI, 2010), generated with the IMPACT model, and the IMAGE model Version 2.2. (Ouraich et al., 2018). The main contributions of the study are related to the impacts on welfare gains resulting from trade liberalization. Even though the overall results reflect the theoretical expectations (i.e. global welfare gains from trade liberalization offsetting welfare losses due to climate change), disaggregated results focusing on the agricultural sector suggest that welfare losses in this sector cannot be neutralized by the gains achieved through trade liberalization (Ouraich et al., 2018). The study also shows that both Morocco and Turkey, due to the negative effects of climate change on agricultural productivity which then propagate to the whole economy, tend to increase their dependency on international trade (Ouraich et al., 2018).

GTAP-W and GTAP-E

In addition to the new features incorporated into the standard version of the GTAP model in recent years, several other parallel extended versions of the model have been created including GTAP-W and GTAP-E. The increasing interest in climate change mitigation and energy-environment interactions has led to the creation of GTAP-E. This model is aimed at studying the energy-environment-economy-trade interactions by taking into account the role of energy as both a factor of production and as the main source of GHG emissions (Burniaux and Truong, 2002; McDougall and Golub, 2009). For this purpose, the model differentiates and substitutes the energy inputs between renewable and fossil energy sources. It draws on an additional database for energy consumption and the related GHG emissions (Corong et al., 2017). Through the inclusion of additional equations, this model is also able to simulate the effects of several climate change policies as well as allow for trading emissions internationally.

GTAP-W, on the other hand, is explicitly designed to take into account the role of water as a factor of production in (irrigated) agriculture which, as such, presents substitution possibilities with other primary factors (Calzadilla et al., 2010; 2011a; 2011b). Like all CGE models, GTAP-W adopts a perfect competition paradigm to simulate adjustment processes. GTAP-W presents three main changes with respect to the standard version: I) the distinction between rainfed and irrigated water in the agricultural sector (Calzadilla et al., 2011a); II) energy factors separated from the intermediate inputs and inserted in a nested substitution level with capital; III) an extended model and database including CO_2 emissions related to energy consumption (Burniaux and Troung, 2002). Moreover, in terms of structural characteristics, the new GTAP-W is made up of 17 regions (as in the previous version by Berrittella et al., 2007) and 22 sectors (17 in the previous version), 7 of which are related to agriculture. However, the most relevant novelty concerns the production structure: in order to include water as a factor of production, the original land endowment in the value-added nest is differentiated between pasture land and land for rainfed and irrigated agriculture, in proportion to their contribution to total production. Irrigated agriculture differs from rainfed agriculture since irrigation, being costly, makes it more valuable: to account for this difference, irrigated agriculture is divided into value for land and value for irrigation (Calzadilla et al., 2011a).

An application of GTAP-W is provided by Calzadilla et al. (2011a) who investigate the effects of climate change and CO_2 fertilization on the agricultural sector, while explicitly taking into account the influence exerted by trade liberalization. The methodology consists in designing model experiments to represent future impacts of climate change on global agriculture, by comparing the 2000 baseline scenario – defined using the

IMPACT model – to two-time horizons, 2020 and 2050, in a Doha-like trade liberalization framework of the agricultural sector. Calzadilla et al. (2011a) include two main groups of variables: i) a forecast of changes in climatic variables (including temperatures, precipitations and river flows), taken from the Hadley Centre Global Environmental Model (HadGEM1); and ii) the average crop yield response of CERES, EPIC and AEZ crop models to increasing CO_2 concentrations in 2020 and 2050 for the IPCC SRES scenarios A1B and A2, as in Tubiello et al. (2006). Moreover, since the model includes the assumptions that climate change negatively impacts water endowments and soil moisture, the authors also define a land use scenario (Calzadilla et al., 2011a). The overall analysis is based on 16 different scenarios, obtained by the combination of two time periods (i.e. 2020 and 2050), two climate scenarios (namely, A1B and A2) and two trade liberalization scenarios (i.e. a 25% tariff reduction and a 50% tariff reduction). The main results of this study suggest that climate change is expected to impact global agricultural production negatively in both periods, but more harshly in the 2050 scenario where rainfed production shrinks, in addition to irrigated production. As for trade liberalization, the global effect appears to slightly reduce the negative impacts of climate change on global agricultural production. However, the effects of tariff reductions vary significantly at more disaggregated levels since they depend on several factors including location, crop typology and production costs. More importantly, trade liberalization would be effective in mitigating the negative effect of climate change by 2020, but in the long run, its effect in contrasting climate-related production losses is nil. The aggregated effects on welfare follow the same trend as agricultural production, positive in a first period, but negative over time. Conversely, food prices are projected to increase over time. Finally, trade liberalization is projected to reduce water use in water-scarce regions and increase it in water-abundant regions.

MIRAGE

MIRAGE is a multi-sector and multi-region CGE model able to assess the effects of trade policies in a climate change scenario. The details of the model are documented in Bchir et al. (2002); Decreux and Valin (2007); Fontagnè et al., (2013); and Bellora and Fourè (2019), among others. In the MIRAGE model, firms interact in Cournot-like oligopolistic competition. As pointed out in Bchir et al. (2002), three main novelties distinguish the

MIRAGE model from previous CGE models for trade analysis: I) explicit modelling of FDIs; II) the introduction of both horizontal (variety) and vertical (geographical origin) product differentiation; III) an accurate description of trade barriers, drawn on the *MAcMaps* database, also allowing for scenario building. With the exception of the data on trade barriers, the MIRAGE model draws on the GTAP 5 database. MIRAGE is a dynamic model, based on a sequential approach, which allows the number of firms in imperfectly competitive sectors to change in different periods. The basic model does not conceptualize any technological progress and the growth rate of all production factors is exogenous. The only exception is capital where accumulation depends on income changes and the net balance of FDIs. Besides, on the demand side, the representative household is considered as both household and government. The intra-temporal utility function of this agent is described by a Cobb-Douglas function whereas preferences follow an LES-CES function, allowing for demand to evolve in response to changes in the income level. On the supply side, the model conceives five production factors: two (namely, capital and natural resources) sector-specific and three (namely, skilled and unskilled labour and land) perfectly mobile across sectors, but immobile across countries (Bchir et al., 2002).

Ongoing work by Bellora and Fouré (2019) seeks to propose an empirical application of the MIRAGE-e model to understand the impact of different trade agreements under the constraint posed by the Nationally Determined Contributions prescribed by the Paris Agreement. This study also incorporates transport-related emissions, which are not covered by the Paris Agreement, by accounting for the different international transportation modes. They also account for five different greenhouse gases by drawing on the GTAP Non-CO_2 Emissions Data Base. In their model, every agent emits greenhouse gas emissions through their consumption of fossil energy goods (i.e. coal, crude oil, gas, refined petroleum), and firms' production processes. These emissions, which can be subject to border carbon tax adjustments when traded, can be mitigated thanks to the implementation of a carbon tax or a cap and trade mechanism (Bellora and Fouré, 2019). Finally, they separate trade of consumption goods from the trade of intermediates, hence accounting for global value chains.

ENV-Linkages

ENV-Linkages is an OECD recursive dynamic CGE model that can be used to analyse the economic consequences of climate impacts (Dellink et al., 2017), linking economic activities to energy and environmental issues (Chateau et al., 2014). In the ENV-Linkages model, production is defined under the assumption of perfect competition, with a technology characterized by constant returns to scale and multi-level production functions with constant elasticity of substitution. Total output is represented by the sum of two different production streams, namely old and new capital, whereas intermediate goods are given by the combination of domestic and foreign demand (Chateau et al., 2014). A representative consumer in each region, taking price as given, tends to optimally allocate their disposable income among the full set of commodities and savings. Also, in the ENV-Linkages model, CO_2 emissions are represented as the by-product of different fuels, while other greenhouse gases emissions (namely, methane, nitrous oxide, SF6, PCFs and HCFs) are linked to output (Dellink et al., 2017).

Dellink et al. (2017) provide a study of both direct (related to infrastructure and transport routes) and indirect (concerning changes in endowment and production) impacts of climate change on trade. As for the former, they develop a theoretical reconstruction of the mechanisms driving such impacts whereas the indirect effects are studied empirically using the OECD's ENV-Linkages model. The empirical analysis focuses on a single scenario which is considered as the most plausible according to a study by the OECD (2015). Their projections show that when both considering and neglecting the impacts of climate change, the absolute level of trade flows in the coming decades will grow. However, they found that, by altering the availability and distribution of natural and factor endowments, climate change indirectly affects trade patterns, modifying countries' comparative advantages and intensifying regional and sectoral disparities. Although climate change is projected to impact all regions and sectors, at a disaggregated level African and Asian regions will be impacted more harshly, as well as the agricultural sector. Nevertheless, in this context, some countries may benefit from climate impacts in terms of competitiveness. Indeed, a country's relative competitiveness, measured in the model by the Revealed Comparative Advantage (RCA) indicator, depends not only on its exposure to climate change and its level of specialization, but also on those of directly competing countries (Dellink et al., 2017).

GEM-3E

The development of the General Equilibrium Model for Economy-Energy-Environment (GEM-3E) is the result of collaboration between the European Commission, DG Research, the 5th Framework programme, national authorities and several European universities.

The GEM-3E is a recursive, macro-sectoral (31 sectors, in the world version), multi-regional (38 regions in the world version), dynamic CGE model, used to analyse the interplay between the economy and the environment and energy systems, as well as policy responses (Capros et al., 2013). The model is designed in such a way to comprehend a basic general equilibrium core which all other options (e.g. different market regimes, closure rules, policy options, and so on) can be added to without requiring a new calibration of the model, hence allowing for the greatest possible flexibility. Model calibration is based on the choice of a base year data set, drawing on a Social Accounting Matrix for each country or region. Both demand and supply are endogenous: with regard to the former, the flexibility of technical coefficients is guaranteed by the possibility of interchanging the mix of production which can be composed of both primary and intermediate inputs; as for the latter, the endogeneity of the demand is guaranteed by the possibility to change the consumption mix, consisting of durable and non-durable goods (Capros et al., 2013). The dynamism of the model is a recursive type and is driven by capital accumulation.

One of the strengths of this model that is worth mentioning is the inclusion of micro-economic policy mechanisms (for instance, the "employment dividends" of the carbon permits whose efficiency gains obtained by recycling revenues reduces the distortionary effects of taxes) consistent with the macro-economic structure, as well as institutional features. Furthermore, as highlighted by Capros et al. (2013), it is entirely written in a structural form, avoiding the need, also in the case of microeconomic behaviours, of reduced form equations. This model is particularly suited for energy and environmental policy since it allows for a high degree of flexibility when designing emission abatement measures, including different allocation schemes (e.g. grandfathering, auctioning, etc.), different policy instruments (standards, taxes, tradable permits), different levels of policy targeting (international, national, sectoral) and different greenhouse gases (CO_2, NO_x, SO_2, VOCs) etc. Emission reduction is achieved via three alternative mechanisms: I) end-of-pipe abatement; II) the substitution of fuels; III) a decrease in production. To test the effectiveness and impact (on both welfare and the environment) of a given policy, the model also allows for the simulation of counterfactual scenarios. The economic impact of such a policy is evaluated either through the impact on a consumer's welfare or the change in the equivalent variation of the consumer's welfare function. The impact on the environment is, on the other hand, given by the change in emissions and damages, whereas the cost-benefit analysis is represented by the change in the equivalent variation of global welfare, incorporating the environmental impact (Capros et al., 2013).

The GEM-3E model has been used by Kouvaritakis et al., (2003) for an assessment of the economic and environmental effects of EU energy tax policies in a computable general equilibrium framework. In particular, the authors project, for 2000-2010, the effect (at the European, national and sectoral level) of three policies: I) minimum energy tax rates; II) an environmental tax harmonization scenario; III) carbon tax. Minimum energy tax rates correspond to the pending proposal by the Spanish government and are to be applied to the final energy demand. Also, these tax rates should be applied in tandem with tax recycling, achievable through either a decrease, uniform across all sectors, in the social security contribution or a reduction in the public deficit, which loosens financial constraints in the private sector and reduces the interest rate. As represented in the model by Kouvaritakis et al. (2003), the burden of this policy differs widely among European countries where Scandinavian and Central European countries should only apply minor changes to the taxation already in place within their boundaries whereas countries like Ireland, Greece, Spain and Portugal should implement the greatest changes. At EU level, the impact of this policy is projected to be very small, although slightly positive in terms of GDP and welfare when recycling through social security contributions occurs. However, we must distinguish between the impacts at country level and sectoral level. At national level, the impact depends on the tax increase implemented. In countries where energy taxes are low, the recycling through social security contributions ensures positive effects, whereas in countries where energy taxes are already high, there is no possibility of recycling, but the decrease in the interest rate drives domestic demand without inducing higher energy costs. At the sectoral level, on the other hand, energy intensive sectors are the ones most affected by price increase.

The second policy evaluated by Kouvaritakis et al. (2003) is an environmentally friendly energy tax in which tax rates reflect the carbon content of each energy product. Two scenarios are implemented: one harmonized across all EU countries and one with enhanced cooperation where only agreeing countries (in this case, Norway, Sweden, Finland, Netherlands, Belgium, Luxembourg, Germany, Austria, France and Italy) take part, while the remaining ones apply minimum rates. In both scenarios, recycling operates via the reduction in social security contributions. In the harmonized scenario, CO_2 emissions are reduced by 2.6%, compared to the 12.7% imposed by the Kyoto target. All countries, apart from Greece and the Netherlands, have positive welfare gains and positive effects on employment and private consumption, achieved through tax recycling. In the scenario with enhanced cooperation, the policy impact is reduced only slightly and no significant difference is observable in the participating countries since they are also the ones with the lowest tax increase. Even in this case, energy-intensive sectors, especially the ones using coal, are the most affected.

Finally, Kouvaritakis et al. (2003) implement an emission allowance scheme for specific sectors defined by the Kyoto target (namely, electricity and heat generators, ferrous and non-ferrous ores and metals, non-metallic mineral products, metal products except machinery and transport equipment, paper and printing products) and a carbon tax for all other sectors (even in this case, recycled through a reduction of social security contributions). This scenario is the one presenting the highest impact, given that the carbon constraint is the strongest. In this case, the impact on both welfare and GDP is negative, but partly compensated by tax recycling. However, this scenario entails the greatest benefits in terms of employment and, accordingly, private consumption. Not surprisingly, countries where the environmental effort already in place was the highest are the ones selling allowances with a lower reduction target and lower carbon taxes.

Other models

In addition to the most widely-used computable general equilibrium models described above, other authors (e.g. Gouel and Laborde, 2018; Costinot et al., 2016; Dietz and Lanz, 2019; van Meij et al., 2018) have developed ex-ante models to study the relationship between climate change and international trade, mainly focusing on the agricultural sector.

Gouel and Laborde (2018) start with the assumption that climate change, by impacting crop productivity very differently depending on the countries' location, will also modify comparative advantages. Hence, their analysis aims to quantify the extent to which international trade and changes in production can help mitigate climate change impacts by taking into account the interactions with different adaptation policies in the agricultural sectors (what the authors call "margins of adjustment"). For this purpose, they develop a static quantitative general equilibrium trade model with spatially explicit land use. Accordingly, calibration and counterfactual simulations, encompassing 50 countries with 2011 as a base year, are based on gridded information at 5-arcmin resolution coming from crop science and concerning, among others, land resources, climate, land cover and potential yields for 35 crop typologies. The model developed by Gouel and Laborde (2018) is a refinement of the Armington quantitative trade model developed by Costinot et al. (2016), on which the modelling of acreage choice is based. Unlike the latter, in the model developed by Gouel and Laborde (2018), livestock plays a crucial role, supported by wide use of the land it requires through pastures and the demand for food which, with an elasticity that is higher than that of food demand, represents one of the margins of adjustment included in the model. Accordingly, their model considers three goods: crops, livestock and a non-agricultural good. To avoid regime changes and be allowed to express the model in relative terms, goods are imperfectly substitutable because of consumption habits in the country of origin. They also extend Costinot et al. (2016)'s model by considering all possible agricultural land uses and, accordingly, all types of crops shaping such uses of land. In this way, they also differentiate between the impacts of climate change on the agricultural sector according to the crop's sensitivity. However, unlike Costinot et al. (2016), here the land that can be converted into agricultural uses is constrained by the static nature of the model, hence preventing the conversion of forestry and protected areas (and, hence, neglecting deforestation as a possible margin of adjustment).

In the model proposed by Gouel and Laborde (2018), the parametrization of each margin of adjustment is independent of the others and is directly derived from the literature. On the demand side, parameters include the price elasticity of total agricultural demand, which is explicitly defined, and the elasticities of substitution between agricultural products for food and food demand. On the supply side, parameters include acreage elasticity and yield elasticity, while the adjustments between demand and supply are regulated by the trade elasticity. Also, for simplicity's sake, trade costs are of the iceberg type. As for the income elasticity of food demand, the quasi-linear preferences of the representative household make it consistent with the situation in developed countries, but underestimate the climate-induced reduction in food consumption in developing countries which are expected to follow the Engel's law. In terms of technology, agricultural goods are produced only with labour and present constant returns to scale, crops are produced through the combination of labour and land and livestock is produced by combining labour and food (Gouel and Laborde, 2018).

The authors simulate a counterfactual scenario to 2080 with shocks on crop yields gathered from crop science. The outcome provided is the result of the interaction among demand-side, supply-side and trade adjustments. In particular, shocks on crop yields induce supply-side adjustments, such as the relocation of production to more convenient areas and the climate-induced changes in local crop cultivability, which, in their turn, call for demand-side and trade adjustments. On an aggregate level, Gouel and Laborde (2018) find that climate change reduces global welfare by 1.72% but without trade adjustments, these losses amount to 76%. This is in open contrast with the one found by Costinot et al. (2016) who argued that only production adjustments are relevant to improve adaptation to climate change. Such a large difference is ascribable, according to the authors, to the fact that in Gouel and Laborde (2018) food demand and supply are inelastic, as resulting from the literature. In their model, supply-side adjustments, especially at the micro-scale, are considered to be the most important source of adaptation to climate change, but the distortionary effects they bring about need to be counterbalanced through international trade.

In another study focusing explicitly on adaptation mechanisms, Dietz and Lanz (2019) develop a dynamic structural economic model to understand how to satisfy world food demand in a context of climate change and economic and population growth. The novel structure of the model allows for the endogeneity of the factors shaping food demand and supply, namely fertility and technical change. With this model, created through a simulated method of moments procedure, Dietz and Lanz (2019) condition the evolution of macro-economy on past historical environmental and climatic data, by integrating reduced-form econometric models of the kind reviewed in Dell et al. (2014) and Carleton and Hsiang (2016) with a general equilibrium model.

The economy represented in this model is composed of two sectors, manufacturing and agriculture, both employing three inputs for production: capital, energy and land. Both sectors indirectly emit GHGs (namely, CO_2, methane and nitrous oxide) through the employment of (finite) fossil energy (which can be substituted with clean energy), but in the agriculture sector, GHGs are also directly emitted from production (methane and nitrous oxide) and land conversion (CO_2). In response to these emissions, climate change impacts the two sectors differently and has a biophysical impact on crop yields. The evolution of the state variable representing the atmospheric GHG concentration (which is also influenced by the manufacturing output) follows the carbon-cycle model proposed by Joos et al. (2013) and employed in the Fifth Assessment Report of the IPCC. In the model proposed by Dietz and Lanz (2019), two mechanisms of adaptation to climate change are possible: agricultural land conversion and innovation. Land resources are dynamic and can both be converted into agricultural land and gradually regress to the original state if not exploited whereas innovations, modelled as a discrete-time version of Aghion and Howitt (1992, 1998), are the engine pushing sectoral TFP.

An interesting representation in the Dietz and Lanz (2019) model concerns the population dynamic, which calls for a discussion of population ethics. Accordingly, fertility is endogenous and constrained, on the one hand, by a trade-off between child quantity and quality which is affected by the opportunity cost of time required to rear children and the increasing cost of education and on the other hand, by food production and, hence, by the impact climate change has on food production. It follows that the intertemporal utility function of a dynastic household head (who, in addition to his consumption, also decides on the number of children to give birth to and on their total utility) also captures the value of an additional human life as dependent on a critical level of consumption.

Dietz and Lanz (2019) adopt the structural economic model for three main purposes: i) counterfactual analysis without climate change; ii) *laissez-faire* projections for the 21st century with and without climate change; iii) an evaluation of the optimal climate policy from 2015 onwards. As for the period 1960-2015, the comparison between observed and estimated parameter values shows that the model can replicate data quite accurately in the long run. The only variables that show a sizeable divergence are clean and dirty energy use (with 13.6% and 6.0% average errors, respectively), denoting high variability. By running a counterfactual scenario in the absence of climate change, the authors estimated an 8.2% reduction in agricultural TFP and a 0.7% reduction in TFP in the rest of the economy in 2018. Even when taking these adaptation mechanisms into account, they estimate a 1.2% reduction (about $63 billion) in agricultural output due to climate change in 2018.

Laissez-faire projections show that both GDP and population are expected to increase but climate change poses a significant constraint on their growth. The amount of land converted is in line with the counterfactual scenario, whereas agricultural R&D effort is much higher in the *laissez-faire* scenario. Nonetheless, the 15% increase in the gross agricultural TFP by 2100 is not enough to compensate for climate damages since the net TFP is in any case lower in the counterfactual than in the *laissez-faire* scenario. Besides, in this scenario, GHG emissions are projected to increase over time, more than doubling between 2019 (15GtCeq) and 2100 (33GtCeq). Conversely, the Pigouvian tax that Dietz and Lanz (2019) test in the Optimal policy scenario proves to be effective in keeping GHG emissions constant over time. Indeed, by 2030, emissions are projected to fluctuate around 7.3GtCeq, resulting in a reduction of the atmospheric stock of GHGs of 40% and an increase to only 1.8° (hence, well below the mandated 2° above the pre-industrial level) in 2100. However, this achievement comes at the cost of a high (and increasing over time) optimal Pigouvian tax which should amount to $66/tCO_2$eq in 2020 (in 2010 US dollars) and $182/tCO_2$eq in 2100.

Finally, van Meijl et al. (2018) run an interesting experiment by combining different ex-ante models to evaluate the mean emerging trend. The goal is to identify and evaluate potential economic consequences of climate change on the agricultural sector by 2050, under different scenarios of global emission mitigation efforts. From a methodological perspective, van Meijl et al. (2018) create a set of alternative scenarios taken from five different models, belonging to the categories of integrated assessment (IMAGE), partial equilibrium (CAPRI, GLOBIOM, MAgPIE) and computable general equilibrium (MAGNET), all harmonized according to standard model assumptions. Accordingly, the purpose of the authors is to cover the widest possible combination of socioeconomic (namely, SSP1, SSP2, SSP3) scenarios with two climate scenarios, one representing the 2-degree-mitigation policy (RCP2.6) and the other representing the no-mitigation policy (RCP6.0), while overcoming major shortcomings related to each modelling strategy. The five models differ widely in several aspects including the geographical scale of analysis, the level of disaggregation of the agricultural sector and the mechanisms of adaptation to climate change considered. In addition to CO_2 emissions, the simulation by van Meijl et al. (2018) also covers CH_4 and N_2O emissions related to agriculture and farming. Mitigation measures oriented towards these GHGs include bioenergy production, afforestation and reduced emissions from deforestation and forest degradation (van Meijl et al., 2018). In all scenarios, mitigation is achieved through a carbon price that, on the one hand, induces the adoption of more environmentally friendly technologies and systems of production and, on the other hand, reduces agricultural production and food consumption due to higher costs.

By and large, despite the many structural differences, the simulations by van Meijl et al. (2018) produce consistent results across SSP and RCP scenarios in the different models. Results show that negative impacts from climate change will be greater in the second half of the 21st century and are probably underestimated because of the omission in the models of the occurrence of extreme weather events. On average, despite the fact that each model pursues a different mitigation strategy, in the IMAGE, CAPRI, MAgPIE and MAGNET models, mitigation results in half methane emissions and a reduction of 40%-45% and 30% in CO_2 and N_2O emissions, respectively, and is roughly comparable across SSP scenarios. Conversely, in the GLOBIOM model, the emission reduction is much smaller and very different across SSP scenarios because mitigation is not driven by technological improvements but rather by changes in production systems and relocations. In the IMAGE, MAgPIE and MAGNET models, global agricultural production is the lowest in SSP1 and the highest in SSP3, suggesting that it is more influenced by population dynamics and dietary preferences than by GDP growth. On the other hand, projections from the CAPRI model show exactly the opposite, indicating GDP growth as the main driver of global agricultural production and depicting a more conservative dietary and waste change. Finally, in the GLOBIOM model, the latter factors are only marginally debated. On average, climate change impacts are projected to reduce global agricultural production by 0.5%-2.5%, with a slightly higher impact on RCP6.0. However, in all SSP scenarios tested by van Meijl et al. (2018), the reduction in global agricultural production – especially of rice and ruminant meat – appears to be larger when considering a mitigation strategy together with residual climate change (RCP2.6), compared to both a no-mitigation strategy and more severe climate change (RCP6.0). The same trend is found for global agricultural prices although the magnitude of the effect differs widely across the models. Cropland land use is projected to increase from SSP1 to SSP3 in IMAGE, MAgPIE, MAGNET and CAPRI as a result of the lower crop yields and the inelastic food demand induced by climate change, whereas in GLOBIOM, cropland land use decreases because climate change favours grassland for crops.

Results show that negative impacts from climate change will be greater in the second half of the 21st century and are probably underestimated because of the omission in the models of the occurrence of extreme weather events.

- Ex-ante analyses based on complex modelling frameworks are the best way to predict climate and economic impacts associated to a policy target that has an international dimension
- The best way to proceed in order to minimise biased results related to different model assumptions is to carry policy assessment with the help of different models
- Negative impacts on trade flows associated to climate change could be greater than expected in the second half of the 21st century due to the underestimation of extreme weather events in past modelling excercises

6. Empirical studies based on a GVC analysis

This section provides a brief review of the literature focusing on the quantitative results evaluating the level of embodied carbon flows in trade. The expansion of Global Value Chains (GVCs) over recent decades has significantly changed the nature and structure of international trade with significant repercussions on patterns of emissions. The main implication of fragmented and integrated productive processes at the global level is the huge increase of trade in intermediates, accounting for more than 50% of international trade in goods, with parts and components crossing several borders multiple times. This directly implies an increase in CO_2 emissions linked to trade since the production of consumable items requires more international transportation which is a high-carbon intensity sector. Meng et al. (2018) find that the environmental cost for generating one unit GDP through international trade is respectively 1.4 and 1.8 times higher than that through domestic production networks in 1995 and 2009.

International trade permits the geographic separation of consumers and emissions in the production of final goods. As a consequence, the emissions generated in one country are not necessarily the same as the emissions required for its consumption (Peters and Hertwich, 2008; Serrano and Dietzenbacher, 2010). Estimates of emissions based on domestic consumption have been used to complement production-based or territorial emission accounting methods (see, among others, Peters and Hertwich, 2008; Davis and Caldeira, 2010; Hasanov et al., 2018). While the latter measure emissions occurring in the production process within sovereign borders, consumption-based emissions accounting excludes emissions associated with exports and includes emissions generated in the production of imports. Both the contributions of exports to a country's territorial-based emissions and the contribution of imports to a country's consumption-based emissions have been found significant (Meng et al., 2018).

Three approaches based on environmentally extended input–output (IO) analysis are widely used to calculate embodied carbon in trade: the Single Region Input-Output (SRIO) with domestic technology assumption (DTA); the Bilateral Trade Input-Output (BTIO); and the Multi-Regional Input-Output (MRIO) models. Critical distinctions between the three models can be made with regards to the system boundary used (the way the imported intermediate goods are treated), the assumption about technology and model complexity. The SRIO model takes a single country and examines the emissions associated with its total consumption (also termed total demand, including household, government and capital investment), taking account of the embodied carbon in trade with the rest of the world (ROW). By aggregating the ROW as one region, it is generally assumed under this model that the same technology is applied to production, both home and abroad (the import substitution assumption). Embodied CO_2 for over 20 countries has been examined using SRIO models so far (as reviewed by Wiedmann, 2009). The BTIO model also considers emissions associated with the total consumption of one country, but decomposes trade by trading partner and applies differentiated emission factors, hence relaxing the import substitution assumption. Separately representing a handful of key trading partner countries using a BTIO model has been a popular quantification strategy. The MRIO model extends the IO analysis to a multi-regional level.

A key point is that in both SRIO and BTIO models, all imports are allocated to total consumption. In contrast, the MRIO model distinguishes between imports that are directed towards final consumption versus those directed towards intermediate consumption. The latter can be directed towards the production of goods for both domestic consumption and exports. Under the MRIO approach, the allocation of intermediate goods is endogenously determined to meet the final demand in each region. Thus, in theory at least, this model is capable of fully capturing the re-export of goods (also termed through-trade or feedback effects).

If countries were to use the same technologies and hence have the same emission intensities, the difference between production and consumption-based emissions would correspond to the trade balance position. Differences in technologies and emission intensities may lead to lower or higher overall emissions as a consequence of international trade. As a matter of fact, international outsourcing of production, or switching from domestic to international suppliers, may allow a reduction in emissions to be achieved at the country level, but the impact on global emissions may be negligible or even negative if imports use more GHG intensive production processes than the domestically produced goods that they displace (Ahmad and Wyckoff, 2003; Wiebe and Yamano, 2016). A proper estimation of emissions embodied in trade – that is, the emissions that occur during the production of traded goods and services – is then required to quantify emission transfers via international trade, identify whether and to what extent improvements in productivity and decoupling are due to national policies or to the outsourcing of production, and understand potential carbon leakage and associated competitiveness concerns (Wiebe and Yamano, 2016). More generally, a reallocation of emissions in each productive link of GVCs in different countries may provide a useful framework for informing the debate on environmental issues such as implications of international trade on the optimal policy for global pollutants (Peters and Hertwich, 2008), how to allocate the responsibility for emissions between producers and consumers (Cadarso et al., 2018) and improving understanding of the common but differentiated responsibilities between countries (Wiedmann, 2009).

Environmentally extended multi-region input-output (MRIO) methodologies allow a more accurate assessment of the emissions related to international trade. Miller and Blair (2009) provide an excellent overview and a thorough introduction to MRIO tables and models (see also Tukker and Dietzenbacher, 2013). The recent development of MRIO databases with global coverage has increased the potential of MRIO techniques for a consistent calculation of emissions in the complex framework of GVC-related trade.

The first empirical studies were published by the OECD. Ahmad and Wyckoff (2003) is an early attempt at computing the emissions embodied in trade using multi-regional input output (MRIO) analysis. Based on combustion-related CO_2 emissions, national IO tables and bilateral trade data for 24 OECD countries and 17 sectors, they estimate an environmentally extended world input-output table where the 'Rest of the world' is assumed to produce using the same technology (Leontief inverse) as Mexico and the same emissions coefficients as the US. Their results suggest relevant imbalances in the emission content of bilateral trade across countries. While this is the first systematic attempt to track emissions embodied in trade over global value chains beyond single-country studies, the coarse industry aggregation, the small number of countries included in the analysis and the strong assumptions limited the reliability of its results.

A truly global MRIO model was used, on the other hand, by Peters and Hertwich (2008) to estimate the CO_2 content of bilateral trade through data from GTAP version 6. Data refer to 87 world regions with a breakdown of 57 sectors for the year 2001. They provide estimates of emissions embodied in export and import as well as an estimate of carbon leakage.

More recently, the development of ad hoc world input output databases such as EXIOPOL (Tukker et al., 2009), the World Input Output Table Database (WIOD, Timmer et al., 2015), Exiobase (Stadler et al., 2018) and EORA (Lenzen et al., 2013) has allowed a more systematic assessment of the carbon content of bilateral trade flows accounting for global value chains. Based on the EXIOPOL database, which covers 43 countries and 129 sectors for the year 2000, Tukker et al. (2013) estimate that the share of greenhouse gas emissions embodied in trade over total greenhouse gas emissions is relatively low (between 10% and 20% of total).

Of the analysis based on WIOD data, the one by Arto et al. (2014a) is of particular interest since they compare the emission content of bilateral trade flows with the labour content of trade. Results for 40 countries, based on a 35-sector breakdown, suggest that as much as 24% of global greenhouse gas emissions and 20% of global employment are linked to international trade flows.

Arto et al. (2014c) provide a comparison between the two most commonly used databases in policy-related studies. e.g., the WIOD and GTAP-MRIO databases. They calculate the global CF of nations and find that four countries (USA, China, Russia and India) and three sectors (electricity, refining and inland transport industries) account for almost 50% of the differences.

Unlike EXIOPOL and GTAP, WIOD has a time series dimension (1995-2009) which evaluates the drivers of the emission content of trade through decomposition analysis. Xu and Dietzenbacher (2014) propose an interesting approach to decomposing emissions embodied in trade. Their contribution is to single out the pure trade component of changes in the global Leontief matrix (net of changes in the production function in terms of products mix) as well as the pure trade component of changes in final demand (net of changes in the consumption bundles).

Global MRIO databases span sector interrelationships across countries and link the consumption and production perspectives, thus providing a traceable link between the location of environmental impact and the processes that led to the impact fuelled by demand for goods and services elsewhere in the world. The identification of countries and sectors that contribute most to the carbon load of international trade is potentially relevant to the design of trade policies aimed at mitigating climate change (Wiedmann and Barrett, 2013). Hertwich (2020) estimates that the production of imports that enter export production now constitute 10% of global emissions. In industrialized countries, the declining domestic value added share in exports and the increasing share of exports in GDP have contributed to this development, whereas in emerging economies, the growth of GDP itself has been an important driving factor (Hertwich, 2020). By combining input-output modelling with trade gravity panel data analysis, Duarte et al. (2018) assess the determinants of CO_2 emissions embodied in trade and find a positive and negative income elasticity of CO_2 emissions for demand and supply, respectively, supporting the Pollution Haven Hypothesis, i.e., the notion that richer countries ‘externalize’ emissions and that the level of development is a determinant of carbon trade.

Even though a proper assessment of emissions embodied in international trade flows would require the use of multi-regional input-output databases, early studies based on single-country cases studies deserve a mention due to their policy relevance. Indeed, single-country studies were based on domestic input-output tables together with aggregate input-output tables for imported intermediate inputs and final products. While these studies do not consider heterogeneity in emission intensity and production technology across different importers and cannot consider feedbacks, they provide robust estimates on ‘avoided emissions’ due to international trade. These studies are based on the so-called Domestic Technology Assumption (DTA): imported commodities are assumed to be produced with the same combination of intermediate inputs (as described by the Leontief multipliers) and with the same environmental efficiency as domestically produced commodities. Serrano and Dietzenbacher (2010) explicitly consider the theoretical implications of DTA and provide evidence on the Spanish case for the years 1995 and 2000. A more recent contribution by Arto et al. (2014b) further develops the DTA approach by considering import in weights rather than in monetary value since they claim that the emission content of products is more strongly correlated with quantities than with monetary values.

Overall, the literature finds that, as volumes of trade increase, the amount of carbon dioxide emissions embodied in imports and exports increases, too. However, the levels remain highly uncertain for most countries and years. For example, estimates for emissions embodied in China's exports in 2005 range from 18% to 45% of their production emissions, whereas that embodied in China's imports in the same year range from 5% to 44% (Sato, 2014). Sources of uncertainty in estimations include both data limitations and methodological issues. The assumptions involved when using international trade in monetary terms, as well as the attribution of intermediate trade to intermediate and final consumption, are some of the key problems. As far as the first problem is concerned, MRIO tables rely on monetary data to approximate physical flows of goods. This assumes there is proportionality between monetary and physical flows. This necessitates multiple assumptions which induce additional layers of uncertainty, particularly in sectors in which product heterogeneity is important (Maurer and Degain, 2012). Quantitatively, the error associated with assuming there is proportionality between monetary and physical trade flows is significant – up to 40% for Australian energy and greenhouse gas multipliers (Lenzen, 1998). Regarding the second problem, to trace embodied carbon flows in trade, information is required on the spatial origin of intermediate and final imports. Furthermore, this information must be disaggregated by consuming sector (e.g. government, investment or industry sector). To construct multi-regional models, therefore, the inter-regional intermediate trade component must be estimated, based on known variables and analytical assumptions.

To conclude, the inclusion of global value chains analysis seeks to move beyond the dichotomy producer vs consumer responsibility in the analysis of greenhouse gas emissions. Production-based accounting has been the basis for setting emission reduction targets (e.g. Kyoto Protocol) even though this criterion does not take into account the possibility of carbon leakage. At the other extreme, manufacturing-intensive countries stress that consumption-based emissions better reflect the responsibility of consumers as the ultimate beneficiaries of production activities and the corresponding emissions. At the same time, however, manufacturing-intensive countries also benefit from the value added generated by pollution-intensive steps in the global value chain. Based on these considerations, Gallego and Lenzen (2005) propose a framework in which the responsibility for production impacts is allocated to all agents (consumers, producers, workers, investors) in the global value chain "*in a way that reflects their contribution to the production process*" (p. 365). Further developments and applications of such a procedure for estimating shared responsibilities can be found in Lenzen et al. (2007), Liu and Fan (2017) and Dietzenbacher et al. (2020). Liu and Fan (2017), in particular, calculate the national/regional carbon emissions based on the value-added accounting approach as well as the amount of global carbon emissions embodied in value-added chains for the period 2000-2010 and find that CO_2 emissions caused by one country's economic growth are mostly emitted within its territory. However, GHG emissions associated with the production of imports that enter export production have risen rapidly since 1995, peaking in 2012.

- Differences in technologies and emission intensities may lead to lower or higher overall emissions as a consequence of international trade depending on the decomposition technique that is adopted
- An increase in trade volumes is generally associated to an intensification of carbon dioxide emissions, but the distribution along the global value chain is still uncertain due to lack of specific analyses
- The most equitable policy approach for the burden sharing of mitigation costs seems to allocate the responsibility for production impacts to all agents (consumers, producers, workers, investors) in the global value chain

7. Carbon leakage and border tax adjustment

The difficulties that have emerged during climate negotiations to reach (and comply with) a binding international treaty, also evidenced by the failure of almost all countries to be on track for the Paris Agreement, is often justified by concerns over the so-called carbon leakage. The issue that is often raised is that the implementation of domestic actions to reduce GHG emissions would induce an increase in emissions by non-acting countries. The result is the neutralization of the achievements of acting countries, aggravated by their loss of competitiveness in international markets. Tan et al. (2018) study the main channels through which carbon leakage occurs in the Hubei Pilot ETS, through a combined approach integrating computable general equilibrium with decomposition analysis. As suggested by IPCC (1996; 2001; 2007), they break carbon leakage down into three main channels: i) a competitiveness channel, resulting from the relocation of energy-intensive production in non-acting countries; ii) an energy channel, related to the higher consumption of fossil energy in non-acting countries in consequence of lower prices; iii) a demand channel, concerning the change in incomes and demand. They find that a curb in GHG emissions in the Hubei province increases emissions in the other Chinese provinces, the closer they are to Hubei. Furthermore, this carbon leakage effect is mainly driven by the competitiveness channel. However, the emission curb in Hubei is only partially compensated by carbon leakage effects in the other regions.

Nonetheless, studies aimed at quantifying the effects of carbon leakage produce contrasting results. As emphasized by Verde (2020), most ex-post studies find no statistically significant evidence of carbon leakage and losses of competitiveness brought about by EU ETS. For instance, Boutabba and Lardic (2017) estimate an ex-post rolling cointegration approach to detect the presence of carbon leakage caused by EU ETS. They find that, despite varying over time, carbon leakage and competitiveness losses in steel and cement sectors are only marginal. These findings are confirmed by Naegele and Zaklan (2019) who employ a panel data regression approach using input-output trade data taken from the GTAP. Reinaud (2008) reaches the same conclusion when analysing the EU ETS in the aluminium sector in the period 2005-2007. In her view, several reasons may justify these results, including the high incidence of long-term electricity contracts and the non-inclusion of aluminium smelter emissions within EU ETS in the period considered. On the other hand, most ex-ante studies mainly predict a strong presence of carbon leakage, ranging from 5% to 30% (e.g. Altamirano-Cabrera et al., 2010; Elliott et al., 2013; Carbone and Rivers, 2017).

To overcome the carbon leakage issue, several scholars and researchers have proposed the implementation of a Border Carbon Adjustment[4] (BCA) regime. However, although it has been discussed for years, no

[4] Sometimes referred to as Carbon Border Tax (CBT) or Border Tax Adjustment (BTA).

country has implemented a BCA to date. BCAs are mechanisms aimed at rebalancing emission controls across countries. They take the form of fees implemented by an importing country with a carbon pricing plan (e.g. a standard tax on carbon emissions or a cap-and-trade system) in place, on an exporter country that neglects the implementation of equivalent measures. Hence, such a measure would prevent environmental dumping behaviour and level the economic playing field through the application of a carbon tariff (or the participation to a cap-and-trade system) on "dirty" imports and rebates on "clean" exports. Indeed, the lack of regulation on carbon emissions is seen by Stiglitz (2006) as a tacit subsidy to firms that, by failing to internalize the emission externality, do not bear their full production cost. As reported by Condon and Ignaciuk (2014), the implementation of a BCA is usually motivated by three main reasons: i) the unfair loss of competitiveness of domestic industries; ii) carbon leakage; iii) a leverage effect (i.e. preference of some non-acting countries towards the uniformity of their domestic measures to those of acting countries, rather than the imposition of a BCA).

Evidence from ex-ante simulations shows that the effects in terms of competitiveness vary substantially depending on the GHGs considered (Ghosh et al., 2012) and country or region-specific factors, whereas carbon leakage rate decreases as the number of countries participating to emission curbing agreements increases (Böhringer et al., 2011). Several studies (among these, Mattoo et al., 2009; Burniaux et al., 2010) reveal that energy-intensive sectors incur in massive output losses due to the application of a carbon pricing plan (either a cap-and-trade mechanism or a carbon tax) which cannot be sufficiently offset by the implementation of a BCA regime. According to Burniaux et al. (2010), the losses are mostly ascribable to an increase in energy prices and consequently reduced consumption, and to a much smaller extent to competitiveness losses.

Kuik and Hofkes (2010) employ GTAP-E to assess the effects of the implementation of a BCA regime in the EU ETS for energy-intensive sectors. They simulate the effects of two different BCAs, one adopting the EU emission-coefficient and one adopting the foreign emission-coefficient. They find that none of the two options is effective in reducing carbon leakage. As for competitiveness, under EU ETS without a BCA regime, European energy-intensive firms lose market shares in both domestic and export markets. The implementation of a BCA regime increases the cost of imports, improving the competitiveness of EU firms in the domestic market substantially (especially when adopting foreign emission-coefficient). On the other hand, the loss of market shares in export markets due to EU ETS is slightly intensified by BCAs and the difference between the two coefficients is minimal.

By using the GTAP-E model, Antimiani et al. (2013) simulate different scenarios that aim to test which of the two main effects of the implementation of a BCA regime (i.e. carbon leakage or competitiveness preservation) prevails. Their findings, in line with those of Böhringer et al. (2012), reveal that the adoption of unilateral exogenous BCA policies has the sole effect of preserving the competitiveness of Annex I countries, generating minimum changes in the carbon leakage rate, but provoking huge losses to non-Annex countries. On the other hand, by adopting a unilateral endogenous BCA, the carbon leakage rate would be kept to a minimum, but at the cost of high welfare losses. A cooperative scenario with zero carbon leakage and non-Annex countries also allowed to trade emission proves to be the most efficient insofar as global emissions would be reduced by 6.54% and the equilibrium price of permits would drop substantially. In addition, this scenario presents the greatest global welfare gains and, accordingly, the lowest global cost of climate policy. Holmes et al. (2011) also offer the same advice and, considering the evidence for a BCA regime motivated by carbon leakage or competitiveness losses to be weak, advocate in favour of a global agreement on emission curbing and, were this option to fail, hope for bilateral or plurilateral mutual recognition frameworks as a second-best option.

Taking into account two hypothetical countries, Hect and Peters (2019) simulate a three-stage game with partial equilibrium structured as follows: in the first phase, they introduce a carbon pricing game, in the second phase a BCA regime and in the third phase an oligopolistic competition between firms. They find the application of a BCA regime to be effective in supporting a nationally determined environmental policy, with an improvement in the situation of the domestic producer, that is nonetheless accompanied by a strong worsening in the situation of the foreign country.

However, BCAs are not exempt from criticism. Some opposers of the implementation of a BCA regime claim that the adoption of a unilateral approach to tackle climate change may prevent the future achievement of multinational agreements (Houser et al., 2008; Dröge et al., 2009) since it is against the spirit of the UNFCCC (Eckersley, 2010). However, some authors (including Stiglitz, 2006; Helm et al., 2012; Mattoo and Subramanian, 2013) oppose this view by supporting the beneficial leverage effect and asserting that the application of BCAs can foster international cooperation on climate change. According to Mattoo and Subramanian (2013), such combined efforts may be achieved through more active participation of developing countries in global emissions curbing, supported by technology transfers by developed countries and the application of BCAs, where necessary. Technology transfers are also advocated by Bao et al. (2012) who, after simulating the effects of the application of a BCA by the United States and the European Union towards China's imports, consider the former to be a more effective tool in equalizing carbon emissions.

Other, and perhaps more important, critiques pertain to equity concerns related to the potential violation, through trade mechanisms, of the UNFCCC principle soliciting the adoption of Common But Differentiated Responsibilities (Eckersley, 2010). Indeed, the reason underlying the statement of this principle is to safeguard the economic development of the countries that are lagging and, then, the inconsistency of a level playing field. As observed by Mattoo et al. (2009), to avoid disruptive effects on trade and disproportionate impacts on developing countries in the implementation of a hypothetical BCA, a possibility is to adopt importer-country emission coefficients rather than exporter-country coefficients. Similarly, Eckersley (2010) argues that emissions should be computed based on shared producer and consumer responsibilities in order to ascribe to developed countries the amount of pollution caused by the relocation of energy-intensive industries to developing countries. However, given the practical and political difficulties in changing the UNFCCC system of accounting national emissions, he proposes to revisit the distinction of countries between Annex I and non-Annex I, dividing them in three groups: OECD countries, transition economies (what he calls "BASIC-plus") and developing countries. Only the former two groups should be subject to a BCA regime and the resulting revenues should be devoted to assisting (for instance, through technology transfer) BASIC-plus countries in their sustainable transition. In this way, consumer responsibility would be addressed through the price increase of imports and both the equity principles stated by the UNFCCC, as well as the nonarbitrariness imposed by the WTO, would be observed (Eckersley, 2010).

- Unilateral domestic mitigation actions might induce an increase in emissions by non-acting countries, with a resulting at least partial neutralization of the efforts in combacting climate change
- The border carbon adjustment advocated as a solution to carbon leakage might be less effective than an alternative solution based on technology transfer from developed to developing economies
- The border carbon adjustment solution arises severe concerns about equity in distribution of the mitigation burden as it may conflict with the UNFCCC principle soliciting the adoption of Common But Differentiated Responsibilities

8. Trade, technology and climate change

Another route that connects international trade and climate change is the creation and diffusion of environmental technologies – therein including climate change (CC) mitigation (see Dechezlepretre et al., 2011). Such a connection operates through two main channels, namely: I) the diffusion of environmental technologies embodied in traded products (embodied technical change); II) the trade-enabled international diffusion of (disembodied) knowledge (for instance through trademarks and patents).

The role of international trade as a vehicle for the diffusion of technological knowledge was first modelled by Coe and Helpman (1995) and, since then, has been investigated extensively through theoretical and empirical research.

Extensive empirical literature documents the relevance, drivers and impacts of environmentally sound technologies embodied in international trade flows. Costantini and Mazzanti (2012) estimate a gravity model of international trade in environmental goods and show that the environmental regulatory stringency and environmental knowledge stock of the exporting country trigger the export of environmental goods. Other studies focus on trade as an enabler of environmental technology transfer in projects related to the Clean Development Mechanism within the Kyoto Protocol. Dechezlepretre et al. (2008) analyse a sample of CDM projects to identify the drivers of technology transfer within CDM projects and find that higher trade openness correlates strongly with the likelihood of successful technology transfer. Similar results are found for Brazil, China, India and Mexico by Dechezlepretre et al. (2009). Lema and Lema (2013) broadly confirm these findings in a study on wind power, even though their empirical analysis highlights that international trade is less relevant for CDM projects in China and India than other countries.

Other studies also consider trade policy as an enabling (or limiting) factor for the cross-country diffusion of environmental technologies via trade. A series of works led by the OECD disentangle different aspects of trade liberalization negotiations of environmental goods. Steenblick (2005) highlights advocates listing environmental goods within broader product classes in the context of trade liberalization negotiations, as well as adopting "dual uses" of environmental goods. Tothova (2005) focuses on environmentally preferable products and negotiations of three specific product groups during the Doha Development Round and Johannesburg Plan of Implementation, suggesting opportunities for further removal of tariffs. A study by Steenblick (2006) shows that eliminating tariffs on biodiesel, solar-thermal water heaters and geothermal energy systems would benefit consumers of energy and particularly residents in rural areas in developing countries. Likewise, tariff removal would be advantageous for manufacturers both in OECD and developing countries due to increased trade in equipment. According to Hughes and Meckling (2017), the recent increase in import tariffs on Chinese PV panels approved by the US government points to a trade-off between industrial policy in support of the domestic manufacturing of environmentally-sound technologies and climate policy aimed at reducing abatement costs. They conclude that consensus on these import tariffs is rooted in the widespread perception of China's ascent in the international PV panel market. In this respect, Algieri et al. (2011) confirm that China is the world leader in PV production and export although Germany, Japan and the US still hold a comparative position.

Turning to the actual environmental impact of environmentally sound technologies embodied in trade flows, Carraro and De Cian (2013) provide empirical evidence of the significant role played by the importing of machinery and equipment as a driver of inputs (i.e. including energy) saving technical change. Costantini et al. (2017a) explicitly compute the environmental technology content of imported intermediate inputs using patent data and inter-sectoral input flows from the World InputOutput Database. Their results indicate a significant emission-saving (greenhouse gases, CO_2 alone, NOx and SOx) impact of environmental technologies embodied in imported intermediate inputs, thus revealing that technical change can be a source of improvement in environmental performance thanks to the upgrading process in the value chain.

Empirical evidence on the disembodied international flow of 'green' knowledge and the role of international trade as a medium for such flows is more sparse. A study on the magnitude and drivers of cross-country bilateral knowledge flows for selected energy technologies by Verdolini and Galeotti (2011) shows that, conditional on a series of other independent variables, two countries in the same trade block are more likely to enjoy knowledge flows. Using a similar approach Dechezlepretre et al. (2013) find that restrictions to trade and FDI are negatively related to cross-country knowledge flows for CC mitigation technologies, measured by patent citations. Wan et al. (2015) focus on trade-facilitated spillovers as a driver of cross-country convergence and estimate that trade flows account for as much as 30-40% of the unobserved variation in energy productivity in manufacturing across 16 EU countries. Wan et al. (2015) identify various mechanisms such as trade-induced knowledge spillovers, competition effects and specialization effects.

Finally, together with the role played by positive spillovers caused by technology embodied in trade, a new literature strand is focusing on international coordination between policy frameworks (especially related to environmental protection and sustainable energy transition) as a way of maximizing the adoption of development strategies oriented towards a sustainable pattern. It should be acknowledged that not only internal decisions and policy strategies adopted by individual countries, but also those adopted by other countries are likely to influence innovation and environmental performance. In this regard, empirical contributions have focused their attention on the existence of cross-country policy spillover effects that may positively influence eco-innovation dynamics through the export channel. On the one hand, foreign demand-pull policies may increase the potential market for new green technologies, thus positively influencing domestic investments in eco-innovation activities (Peters et al., 2012) driven by the potential dimension of foreign markets. On the other hand, technology-push foreign policies are expected to generate international knowledge spillovers that can benefit domestic technological capabilities (Dechezlepretre and Glachant, 2014) and consequently, domestic export competitiveness. Moreover, the role of host-country environmental policy stringency has been found to shape the decisions of top R&D performers on where they locate their environmental innovation activities, improving the environmental quality of traded goods (Marin and Zanfei, 2019).

These considerations can be fruitfully integrated within a policy mix framework of analysis as suggested by Costantini et al. (2017b) who showed that policy coordination between countries on policy mix design can represent a source of mutual advantages in terms of environmental policy effectiveness and increased export competitiveness performance.

- The diffusion of environmental technologies embodied in traded products can be a source of advantage in cooperative solutions with the aim of minimizing the abatement costs
- The existence of cross-country policy spillover effects that may positively influence eco-innovation dynamics through the export channel should be detected in order to inform the policy mix design process
- The diffusion of demand-pull policies in final destination countries can increase the market dimension for new green technologies, thus positively influencing domestic investments in eco-innovation activities

9. The ongoing political debate

The withdrawal – explicit or *de facto* – from the Paris Agreement (2015) of US, Australia and Brazil introduced important elements to the climate change and international trade political debate (The Economist Intelligence Unit, 2019). Moreover, according to the Climate Action Tracker (CAT), a monitoring group for governments' climate actions, some of the world's largest emitters of GHG lack the commitment to cope with climate needs, in particular in terms of Nationally Determined Contributions (NDC). NDCs are a core concept of the Paris Agreement, embody each country's policies and targets for climate change adaptation and mitigation and must be submitted to the UNFCCC every five years <https://www4.unfccc.int/sites/ndcstaging/Pages/Home.aspx>. Even though in January 2019 NDC submissions by 181 countries covered a total amount of 97% of global GHG emissions, <https://www4.unfccc.int/sites/ndcstaging/Pages/Home.aspx>, CAT considers the contributions of the world's largest emitters to be still too modest. Different examples supporting this statement can be found. EU Member States collective NDCs, which aim to reduce GHG emissions about 40% by 2030 compared with 1990 and boost renewable energy's shares of consumption to 32% (Eurostat, 2018), is rated "insufficient" by CAT which claims EU28 could reduce emissions by 62% <https://climateactiontracker.org/countries/eu/pledges-and-targets/>. Russia, which has signed but not ratified the Paris Agreement, is instead on the way to a growth in emissions (i.e. 18-25% by 2030) (The Economist Intelligence Unit, 2019). Another large emitter is China which has committed to increasing the share of non-fossil fuels in primary energy supply to 20% by 2030 and lowering GDP carbon-intensity by 60-65% compared with 2005 levels. Again, CAT rates such commitments as "highly insufficient", even though the country is actually about to achieve them <https://climateactiontracker.org/countries/china>.

Including international trade in this scenario introduces a crucial question: to what extent do trade agreements and WTO support Paris Agreement, NDCs and, more in general, climate goals? The analysis of the environmental impact of international trade dates back to the 1990s when trade agreements and climate policy have often been considered in opposition (The Economist Intelligence Unit, 2019). There are, indeed, two potentially crucial threats to environment: I) a globalization-induced increase in international trade intensifies cross-border pollution, II) technology advancements oversimplify and foster an intensive use of natural resources (de Melo et al., 2010). When NAFTA was signed, Grossman and Krueger (1991) identified the previously explained mechanisms through which trade agreements indirectly affect the environment (i.e. scale effect, composition effect, technique effect). Notwithstanding the potential climate-trade synergies detected by the model, the main outcome was that tariff reduction increases trade in carbon-intensive and environmentally damaging industries (Grossman and Krueger, 1991). Various climate conflicts, indeed, arose in that period, for instance, Canada's opposition to the EU effort of labelling tar sand as a "highly polluting" energy source and the US attack of the EU definition of renewables that restricted US exports of soybeans and biofuels. Considering these conflicts together with the fact that fundamental pillars of free trade often contrast with climate policy leads us to focus on the role of the WTO in this political debate.

The WTO started focusing on the climate-trade relationship in 1995, with the establishment of the Committee on Trade and Environment (CET), which, despite the number of studies produced, has brought very limited signs of progress to the debate, mainly due to the lack of a definition for "environmental goods" and the heterogeneity of the WTO members (The Economist Intelligence Unit, 2019). Moreover, in the case of country policies including trade restrictions for environmental reasons, both Paris Agreement and the WTO are ill-equipped to solve these controversies. It is not clear, for example, whether the WTO is entitled to take action when considering environmental subsidies as unfairly advantaging domestic firms over foreign ones <https://www.ipcc.ch/report/sixth-assessment-report-working-group-3>. However, even though the WTO has not ruled on any disputes related to the Paris Agreement, or multilateral environmental agreements, it has ruled on many trade-environment disputes. Among them, the most recent ones are the Canada Feed-in-Tariff dispute (2011) and the India Solar Cells dispute (2016).

First of all, it has played a key role in contemporary free-trade agreements such as the Korea-Australia Free Trade Agreement (KAFTA, 2014); the EU-Canada Comprehensive Economic Trade Agreement (CETA, 2016); the EU-Singapore Economic Partnership Agreement (2018); and the Comprehensive and Progressive Agreement for Trans-Pacific Partnership (CPATPP, 2018). In all these agreements, there are chapters dedicated to the environment and sustainable development. This represents a fundamental break with the past trend of opposition between climate and trade. However, the current form of trade agreements does not necessarily imply an increasing level of compliance with climate goals (Titievskaia, 2019). There is plenty of evidence in support of this statement. Above all, mixed agreements, like the EU-Mercosur Association Agreement, apply provisional applications to trade pillars (exclusive EU competence), while the application of political and cooperation pillars (pending or members' ratification) could even be avoided for a long time (Titievskaia, 2019). Second, there is the role of Trade and Sustainable Development chapters (TSD), which, together with competition and some specific trade provisions, are exempt from the general dispute settlement established and ruled by the WTO. TSD chapters, indeed, have separate procedures for disputes: first, a consultation request for the creation of a panel of experts; then, the monitoring activity by a TSD Committee to find a mutually acceptable solution, given the impossibility of applying punitive economic measures. The first case of such disputes is ongoing under the EU-Korea Free Trade Agreement (Titievskaia, 2019). Third, the weak legal status of environment-related provisions included in the agreements (The Economist Intelligence Unit, 2019) should be taken into account.

Another important issue concerns mitigation policies which see a juxtaposition between businessmen and environmentalists. The former perceive them as a threat to competitiveness whereas the latter fear the triumph of free trade instances over mitigation requirements (de Melo et al., 2010). Both of them call for solutions from the WTO. The competitiveness concerns of the private business sector find their theoretical basis in the asymmetric effect of climate change regulations on country economic performance depending on the structure of the economic systems, especially in the case on unilateral climate policies (James, 2009). Furthermore, companies based in countries that are more affected by the effects of mitigation policies may choose to relocate their production to countries without mandatory emission reduction standards (James, 2009). However, evidence shows that countries with relatively few environmental restrictions do not attract more investments. Furthermore, an analysis of the relationship between environmental standards and foreign direct investments by James (2009) finds that firms pay relatively scarce attention to the costs of satisfying environmental requirements when defining their investment strategy. Moreover, the same study demonstrates that carbon tariffs and other measures can be useful to convince developing countries to adopt similar standards, through which they are facilitated in accessing new markets (James, 2009). All in all, the fundamental difference between trade and climate change negotiation lies in the approach. Trade is bilateral, thus trade agreements can be enforced by a strategy of reciprocity, whereas mitigation policies require the involvement of a group of countries and reciprocity, in this case, is a very weak strategy.

All things considered, the most important contribution the WTO can make to the trade-climate change debate is a "climate waiver" (Bacchus, 2017). Such a waiver, according to Art. IX:3 and Art. IX:4 of the WTO Agreement, would allow the imposition of trade-restrictive measures in line with Paris Agreement and based on the amount of carbon used or emitted in specific productions. Thus, the WTO could be legally enforced when taking measures that, without the waiver, would even violate WTO rules (Bacchus, 2017). However, this should not be considered as permission for countries to adopt unjustifiable or arbitrary discriminatory measures since protectionism is dangerous for climate goals. For instance, protectionism prevents an easy flow of climate-friendly and cost-effective technologies. The possibility of a WTO climate waiver would be very important for all the trade agreements that incorporate trade-restrictive measures with environmental purposes, such as EU trade agreements (Titievsakaia, 2019). Currently, the EU is adopting these environmental measures, making them fall into the general exception category (Art XX-GATT). Thus, in theory, the EU can apply trade-restrictive measures that are in line with the Paris Agreement by successfully invoking the general exception principle (Titievskaia, 2019). However, the WTO requires strong causal linkages between the specific measure and the related environmental objective, thus measures addressing wide and complex phenomena – such as climate change – need more effort in order to be implemented. It has to be demonstrated, for example through quantitative projections, that the measure can make material contributions to a specific goal. It is exactly because of challenging situations of this kind that the EU, together with other countries, is calling for a WTO climate waiver (Titievskaia, 2019).

The active participation of the EU in the climate-trade political debate is also made evident by the fact that it is among the few countries and federations that are on their way to a "Green New Deal". In a European Commission communication of December 2019 – COM(2019) (European Commission, 2019) – the Commission set out the European Green Deal for EU which is an integral part of the Commission's strategy to achieve 2030 Sustainable Development Goals. Such a strategy consists of different steps, involving different topics and levels of action: I) increasing the EU's climate target for 2030 and 2050; II) allowing for a clean and secure energy supply; III) involving industry in a circular and sustainable economy; IV) implementing and improving energy efficiency; V) accelerating smart and sustainable mobility; VI) designing a healthy, secure, fair and environmentally-friendly food system; VII) safeguarding ecosystems and biodiversity; VIII) achieving "zero pollution". Moreover, the EU Green Deal refers to just and environmentally-friendly investments to finance the ecological transition (European Commission, 2019). With these points, the Green Deal sets the double goal of "reconciling economics with the planet" through complete decarbonization of the EU and, at the same time, defining "a new strategy for economic growth". If it succeeds, it will have a strong impact on the global economy by imposing rigid environmental standards to regulate trade within the EU market, the largest in the world. In particular, besides inspiring other countries to propose their own Green Deal, three hypothetical consequences have to be strictly monitored: first, countries that export their goods to the EU, such as China, for example, should mandatorily adapt to these standards; second, the possibility of introducing a tariff on the goods entering the EU market, according to their carbon footprint; and third, the possibility of including binding environmental clauses within EU trade agreements.

Table 1

Taxonomy of contributions on climate change and trade based on historical analysis

Article	Linkage	Methodology	Additional details
ETS system			
Branger et al. (2016)	Impact of the EU ETS net imports on the competitiveness of the cement and steel industries.	Time-series regression techniques.	Effects are not statistically significant.
Boutabba & Lardic (2017)	Impact of the EU ETS net imports on the competitiveness of the cement and steel industries.	Rolling cointegration approach which accounts for multiple structural changes.	Effects on net imports that are positive and statistically significant for some subperiods.
Costantini & Mazzanti (2012)	The effect of the EU ETS is captured by a binary variable for the years 2005-2007, the period corresponding to Phase I.	Sector-level gravity model of international trade for manufacturing exports from 15 EU countries to 145 importing countries, in 1996-2007.	Estimated coefficients indicate that the EU ETS increased exports of medium-low technology sectors which roughly correspond to those covered by the EU ETS: thus, an outcome consistent with the Porter Hypothesis.
Naegele and Zaklan (2017)	Investigation whether the EU ETS caused carbon leakage in European manufacturing sectors, as measured by changes in sector-level international trade flows and related carbon movements. Sector-level trade flows in embodied carbon and value are computed using detailed trade and input-output data (from the Global Trade Analysis Project) for the years 2004, 2007 and 2011.	Two models are estimated, namely for net imports and bilateral flows (thus allowing for intra-industry trade) and four alternative measures of environmental stringency are considered to represent the EU ETS.	Since no significant effects are found, the authors conclude that, during its first two phases, the EU ETS did not have a systematic impact on flows of trade or embodied CO_2 emissions.

Petrick and Wagner (2014)	Estimation of the impact of the EU ETS on CO_2 emissions and CO_2 intensity, as well as on employment, gross output (sales) and the exports of regulated manufacturing firms in Germany.	The DiD approach is applied to firm-level panel data obtained from the national production census, covering over 90% of the EU ETS installations operated by manufacturing firms and located in Germany. About 400 regulated firms are in the estimation samples.	In the reference model, the effects on employment are not statistically significant, while positive effects on the value of both sales and exports are identified for the first three years in Phase II (i.e., 2008-2010). The positive effects are non-robust, however, since they become statistically insignificant in most of the alternative estimations performed.
Trade openness and trade policy			
Antweiler, Copeland and Taylor (2001)	Estimation of the impact of trade on SO_2 concentration.	Econometric panel analysis with endogenous environmental policy.	The scale and the composition effects are positive, while the technique effect is negative. The sign of the trade-induced composition effect depends on countries' comparative advantages.
Baek et al. (2009)	Investigation of the presence and direction of causality among trade openness, income and SO_2 emissions without knowing the theoretical structure a priori.	Cointegrated Vector Autoregression (CVAR).	No reverse causality; trade and income are the driving forces of SO_2 emissions. Empirical validation of the EKC.

Cole & Elliott (2003)	Effect of trade openness on the environment.	Econometric analysis.	
Frankel & Rose (2005)	Estimation of the effect of trade on environmental quality (PM10, SO_2 and CO_2 concentrations) for a given level of income.	Cross-country regression model with instrumental variables.	Empirical validation of the EKC. Negative effect of trade openness on all measures of environmental quality.
Grossman & Krueger (1993)	Empirical analysis of the relationship between trade and environment in terms of scale, composition and technique effects.	Econometric analysis.	North America and Mexico.
Le et al. (2016)	Estimation of the effect of trade openness on PM10 and CO_2 emissions.	Econometric panel analysis.	For the global sample, trade openness causes environmental degradation, but the effects are diverse if conditioned on income.
Managi et al. (2008)	Impact of trade openness on environmental quality.	Econometric panel analysis.	SO_2 and CO_2 emissions of 88 countries from 1973 to 2000; BOD emissions of 83 countries from 1980 to 2000.
Managi (2004)	Impact of trade on the environment: whether free trade is harmful or beneficial to the environment.	Econometric panel analysis.	63 developed and developing countries over 1960-1999.
McCarney & Adamowicz (2005)	Effects of openness on organic water pollutant (BOD) and carbon dioxide (CO_2) emissions.	Econometric panel analysis.	The dataset for CO_2 is ?made 143 for the period 1970-2000; The dataset for BOD includes 119 countries for the period 1980-1995.

Environmental regulation			
Perkins & Neumayer (2012)	Analysis of the “California effect”.	Econometric panel analysis.	Automotive sector.
Tobey (2001)	Estimation of the effect of stringent environmental regulation of trade patterns in the USA.	Cross-sector regression model.	No considerable effect of the stringency of environmental policy on trade patterns.
Levinson & Taylor (2008)	Estimation of the link between environmental regulation and trade flows with a specific focus on the pollution haven effect.	Econometric panel analysis with fixed effects and instrumental variables.	Empirical validation of the pollution haven hypothesis.
Ederington & Minier (2003)	Estimation of the link between environmental regulation and trade flows.	System of simultaneous equations.	Empirical validation of the pollution haven hypothesis.

Table 2

Taxonomy of contributions on climate change and trade based on ex-ante analysis

Article	Linkage	Methodology	Additional details
CGE models			
Bellora & Foure (2019)	Impacts of trade on climate change.	MIRAGE CGE Model.	Interactions between climate change policy and free trade agreement (Simulation of trade agreements, taking into account the constraints imposed by NDCs in the Paris Agreement).
Calzadilla et al. (2011a)	Impacts of climate change and CO_2 fertilization on global agriculture and its interactions with trade liberalization.	GTAP-W Model.	Agriculture.
Dellink et al. (2017)	Impacts of climate change on trade considering both direct and indirect effects.	ENV-Linkages CGE model	Direct effects: infrastructure and transport routes; Indirect effect: economic impacts from changes in endowments and production.
Kouvaritakis et al. (2003)	Assessment of economic and environmental effects of EU energy tax policies.	GEM-E3 CGE model.	Climate Change Policy and Global Trade.
Ouraich et al. (2018)	Impacts of climate change at the country level by taking into account its implications for international markets.	GTAP CGE Model.	Agriculture in Morocco and Turkey.
Truong (2010)	Impacts of Trade on Climate Change: Scale, Composition, Technique and Direct Effects; Impacts of Climate Change on Trade: Productivity changes, Changes in Comparative Advantages.	CGE Models: GTAP, ORANI-G.	Review of Analytical Tools.

van Meijl et al. (2018)	Evaluation of the potential economic consequences of climate change in the agricultural sector by 2050, under different scenarios of global emission mitigation efforts.	Models: IMAGE, CAPRI, GLOBIOM, MAgPIE, MAGNET.	The global impact of climate change on agricultural production by mid-century is negative but small. The magnitude of price changes is different between models due to methodological differences.
Other models			
Costinot et. al. (2016)	Role of international trade in adapting to climate change, with particular emphasis on acreages changes and large adaptation efforts through demand and supply.	Armington quantitative trade model for land use/acreage modelling.	New approach to land use modelling.
Dietz S., Lanz B. (2019)	Quantification of the capacity to meet food demand under conditions of climate change, economic and population growth.	Structural global economic model. Inclusion of several features, including an explicit agriculture sector, endogenous fertility, directed technical change and fossil/renewable energy.	Adaptation takes place through R&D and agricultural land expansion. Simulation of optimal GHG taxes which allow future temperatures to be kept well below 2°C.
Gouel & Laborde (2018)	Role of international trade in attenuating the effects of climate change, focusing on the role of production and trade adjustments as margins of adaptation.	Quantitative general equilibrium trade model.	Agriculture.
Tubiello et al. (2006)	Analysis of crop responses to elevated CO_2 under a variety of experimental modelling.	Variety of experimental crop models.	Agriculture and crop modelling.

Table 3

Taxonomy of contributions on climate change and trade based on a GVC approach

Article	Linkage	Methodology	Additional details
Carbon footprint			
Arto et al. (2014c)	Comparison of carbon footprint estimates in GTAP-MRIO and WIOD.	EE-MRIO and SDA.	About 50% of the differences are attributable to US, China, Russia and India; about 50% of the differences are attributable to the electricity, refining and inland transport industries.
Tukker et al. (2013)	Calculation of the environmental footprint of EU consumption (in terms of carbon, land, water and material) using EXIOPOL data.	EE MR SUT.	EU policies focus mainly on energy and carbon footprints. We show that the EU land, water, and material footprint abroad is much more relevant and should be prioritized in the EU's environmental product and trade policies.
Dellink et al. (2017)	Impacts of climate change on trade considering both direct and indirect effects.	ENV-Linkages CGE model.	Direct effects: infrastructure and transport routes; Indirect effect: economic impacts from changes in endowments and production.
Emissions embodied in trade			
Arto et al. (2014a)	Comparison between emissions and jobs embodied in international trade with WIOD data.	EE-MRIO.	24% of GHG emissions and 20% of employment are linked to trade.

Hertwich (2020)	Calculation of emissions embodied in trade with EXIOBASE data.	EE-MRIO.	4.4 Gt CO_2eq. was associated with the production of products imported for export production.
Peters and Hertwich (2008)	Calculation of carbon emissions embodied in trade using GTAP data.	EE-MRIO.	Globally there are over 5.3 Gt of CO_2 embodied in trade and that Annex B countries are net importers of CO_2 emissions.
Drivers and other analysis about emissions embodied in trade			
Duarte et al. (2018)	Gravity model on emissions embodied in trade using data from WIOD.	Regression analysis and EE-MRIO.	As economies grow, they tend to externalize CO_2 emissions. Results support the Pollution Haven Hypothesis (PHH) and the role that technologies play in reducing global emissions.
Gallego & Lenzen (2005)	Proposal of a methodology for the allocation of shared producer and consumer responsibility for emissions embodied in trade.	Theoretical approach based on EE-MRIO.	Their approach enables the division of responsibility into mutually exclusive and collectively exhaustive portions that are assigned to the different economic sectors and become consistently smaller as one moves away from the location of the impact within the supply or demand chain system.

Liu & Fan (2017)	Value-added-based accounting of CO_2 emissions method to account for anthropogenic CO_2 emissions within the context of the economic benefit principle based on OECD I-O tables, OECD-STAN data and OECD Bilateral Trade Database.	EE-MRIO.	CO_2 emissions caused by one country's economic growth are mostly emitted within its territory.
Meng et al. (2018)	Definition and assessment of backward and forward linkages in terms of emissions in global value chains.	EE-MRIO.	The environmental cost for generating one unit GDP through international trade is respectively 1.4 and 1.8 times higher than that generated through domestic production networks in 1995 and 2009.
Xu & Dietzenbacher (2014)	Structural decomposition analysis of emissions embodied in international trade based on WIOD data.	SDA and EE-MRIO.	Imports increasingly embodied more emissions than exports in many developed countries. Exports increasingly embodied more emissions than imports in many emerging countries.

Table 4

Taxonomy of contributions on trade, environment and technological change

Article	Linkage	Methodology	Additional details
Trade, technology and climate change			
Costantini & Mazzanti (2012)	Drivers of export of environmental goods.	Econometric estimation of a gravity model.	Environmental regulation in exporting countries drives export of environmental goods.
Dechezlepretre et al. (2008)	Analysis of the technology transfer content of CDM projects.	Cross-section econometric analysis.	Trade openness of the target country increases the likelihood of technology transfer within CDM projects.
Carraro & De Cian (2013)	Structural estimation of factor-augmenting technical change and assessment of the drivers.	Constrained system estimation, FGLS estimator.	Import of machinery and equipment is an important driver of inputs saving technical change.
Costantini et al. (2017)	Estimation of the effect of patents embodied in intermediate inputs on sector-level emissions.	Panel data econometrics.	Environmental technology embodied in imported inputs contributes to reducing sector-level CO_2 and greenhouse gas emissions.
Verdolini & Galeotti (2011)	Quantification of cross-country knowledge spillovers for energy technology and assessment of the drivers.	Panel data econometrics.	Two countries belonging to the same trade block are more likely to have knowledge flows.
Wan et al. (2015)	Assessment of the role played by trade in facilitating the convergence in cross-country energy productivity.	Panel data econometrics.	About 30-40% of the unobserved variation in energy productivity is explained by trade.

Dechezlepretre et al. (2013)	Evaluation of the drivers of knowledge flows regarding climate change mitigation technologies in terms of patent citations.	Panel data econometrics.	Restrictions to trade and FDI are negatively related with cross-country knowledge flows for CC mitigation technologies.

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The relation between international trade and climate change is extremely complex since multiple interlinkages are at work. Direct and indirect mechanisms characterize a mutual relation between these two global dimensions bringing severe threats to the stability of the international institutional framework. To this purpose, a deep knowledge of all linkages across sectors, regions and different policy settings is a prerequisite for better informing evaluation assessment of climate and trade policy proposals. This book presents a literature review on this topic with the specific aim of guiding the readers through the multiple quantitative methodologies developed and adopted by the international scientific community to design policy impact evaluation exercises.

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