Carbon Taxes, Carbon Border Adjustments and the World Trade Organization

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Abstract

Can carbon taxes and associated carbon border adjustments (CBAs) respect existing agreements in international trade while significantly reducing pollution from carbon emissions? This paper answers this question in the context of a quantitative trade-and-emissions model for both non-cooperative (Nash) and cooperative (international negotiation with participation constraints) carbon tax setting. We find that a climate agreement that deviates from the usual design of uniform carbon taxes applied across its members and instead entertains the possibility of country-specific carbon taxes as a means of addressing participation constraints can achieve substantial reductions in worldwide emissions and offer a meaningful WTO-consistent alternative to the climate clubs described by Nordhaus (2015) that confront non-participants with the threat of WTO-inconsistent Nash tariff punishments. And we find that the design of CBAs permitted by the WTO can impact the degree of worldwide carbon reduction and welfare improvements in important ways. In particular, our findings suggest that optimal WTO rules on permissible CBAs will evolve with the evolving success of international cooperation over climate policy.

- Keywords: Climate change; Carbon taxes; Climate clubs; WTO; Carbon border Adjustments.

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1 Introduction

The harm from carbon emissions is global rather than local: the climate impact of an additional unit does not depend on where it is emitted. Furthermore, because countries trade with each other, carbon taxes in one location affect production and consumption in other locations. Both of these factors create international interdependency in outcomes from carbon taxes. However, the effective and incentive compatible design of carbon tax policies, whether accomplished unilaterally and non-cooperatively, or jointly and cooperatively in the context of a climate agreement, may come into tension with established international agreements on tariffs, agreements that address a separate international externality (Bagwell and Staiger, 1999). This paper analyzes the design of carbon tax policies and climate agreements in the context of the international trading system under the World Trade Organization (WTO).

Our approach uses a quantitative trade-and-emissions model based on Shapiro (2021) that includes carbon taxes and carbon border adjustments (CBAs). The model has intermediate goods, non-traded sectors, and heterogeneous emissions by country and sector pair. Throughout our analysis, we assume that countries respect their WTO tariff commitments.

We estimate the parameters of the model to match observed trade flows, observed relative value added by country, and observed relative price levels. We first use the estimated model to simulate Nash equilibria in carbon taxes under various CBA designs. We then calculate optimal climate agreements for carbon taxes under various assumptions about the design of the agreement, such as whether the carbon taxes specified in the agreement are uniform or country-specific and in the latter case whether CBAs are permitted, whether the agriculture sector is exempted from the carbon tax or not, whether international transfers are feasible, and whether the participation constraints imply that a single country has veto power over the agreement or not. We compare these outcomes to the benchmark climate agreement of a hypothetical global social planner.

Our central results are the following. First, we find that the gains from climate cooperation are substantial. Even when carbon taxes cannot for distributional/political economy reasons be applied to agricultural production, we find that the gains from climate cooperation relative to Nash outcomes are on the order of two and one half percent of worldwide welfare; in a world where carbon taxes apply also to agricultural production, we find that the gains from climate cooperation rise to roughly four percent of worldwide welfare.

Second, we find that unless large international transfers can be orchestrated by the climate agreement, participation constraints will substantially limit what a climate agreement can achieve in a world where countries respect their WTO tariff commitments, in line with the claims of Nordhaus (2015). In particular, if the climate agreement calls for all members to implement a uniform carbon tax, the costs imposed by participation constraints when international transfers are unavailable can range from one half of one percent to four percent of worldwide welfare depending on the form of the participation constraints. But we find that these costs can be almost entirely avoided if the climate agreement specifies country-specific carbon taxes as a means to address the participation constraints. Hence, according to our second finding, a climate agreement that deviates from the usual design of uniform carbon taxes applied across its members and instead entertains the possibility of country-specific carbon taxes as a means of addressing participation constraints can achieve substantial reductions in worldwide emissions and offer a meaningful WTO-consistent alternative to the climate clubs described by Nordhaus that confront non-participants with the threat of WTO-inconsistent Nash tariff punishments.

Third, we find that the design of CBAs permitted by the WTO can impact the degree of worldwide carbon reduction and welfare improvements in important ways. In particular, when cooperation over carbon taxes is not possible and Nash carbon taxes are below their cooperative levels, we find that permitting countries to implement a CBA that allows for some international cost-shifting can incentivize countries to choose higher Nash carbon taxes and lead to an increase in worldwide welfare of one half of one percentage point. But we find that when cooperation over carbon taxes is possible and carbon taxes are instead set at their cooperative levels, permitting countries to implement this cost-shifting version of a CBA would offer no benefit to the world. Taken together, these findings suggest that optimal WTO rules on permissible CBAs will evolve with the evolving success of international cooperation over climate policy. We also investigate the properties of an alternative CBA that takes the form of a non-discriminatory (MFN) tariff surcharge on imports of a product from all sources, set at a level that is calibrated to neutralize the carbon leakage that would otherwise be associated with a country's carbon taxes.

Finally, we find that when countries set their carbon taxes non-cooperatively, extending carbon taxes to agricultural production makes little difference to Nash outcomes. But under the climate agreements that we consider, applying carbon taxes to agricultural production raises worldwide welfare by roughly one and a half percentage points. An implication of this last finding is that efforts to extend carbon taxes to agricultural production will only have a substantial payoff in terms of worldwide welfare if countries have also succeeded in negotiating meaningful climate agreements.

There is a long literature that analyzes the interaction of carbon emissions, carbon taxes, and international trade including Elliott et al. (2010), Hémous (2016), Shapiro (2016), Copeland et al. (2022), Duan et al. (2021), Larch and Wanner (2017), Le Moigne et al. (2022), Farrokhi and Lashkaripour (2023), Martin (2023), Ma and Qin (2023), Kotlikoff et al. (2024), and Cruz and Rossi-Hansberg (2024). There is also a more specialized literature that examines the designs and effects of CBAs including Dong and Walley (2012), Fischer and Fox (2012), Keen and Kotsogiannis (2014), Fowlie et al. (2016), Kortum and Weisbach (2017), Campolmi et al. (2023), and Clausing et al. (2025). There is also a literature on international carbon agreements including Mattoo and Subramanian (2013), Hoekman and Mavroidis (2015), Harstad (2016), and Bourany (2025). Lastly, there is a literature on the design and implementation of rules of the WTO including Bagwell and Staiger (1999), Bagwell and Staiger (2002), Bagwell et al. (2021), and Staiger (2022). This paper lies at the nexus of these literatures. We examine the design of CBAs and international carbon agreements taking into account the globalized effects and localized costs of pollution and carbon taxes while still striving to respect international trade agreements under the auspices of the WTO.

The rest of the paper proceeds as follows. The next section reviews the logic of CBAs and previews the CBA designs on which our paper will focus. Section 3 presents our quantitative model. Sections 4 and 5 describe data sources and estimation of model parameters. Section 6 presents various benchmarks. Sections 7 and 8 present our Nash and cooperative results, respectively. Section 9 concludes. The Appendix includes a set of tables with detailed country-specific results not included in the main body of the paper.

2 Carbon Border Adjustments

In this section we provide an overview of the logic behind the design of a carbon border adjustment (CBA), and we preview the features of the specific CBAs that we will evaluate in the sections that follow. CBAs are a relevant consideration whenever *origin-based* carbon taxes – taxes on the production of carbon – are *not imposed uniformly* across all countries. This situation arises, for example, when a single country (or subset of countries) chooses to impose carbon taxes on its producers unilaterally. Alternatively, the situation could arise in the context of a social planner who cannot rely on international lump-sum transfers to offset the country-specific impacts of a uniform carbon tax on individual country welfares, and who then prefers to set country-specific carbon taxes (see Chichilnisky and Heal (1994) and Sandmo (2006)). Finally, the situation could arise in the context of a climate club where, as we describe below, country-specific carbon taxes are adopted to handle participation constraints. In the sections that follow we will consider the possibility of including CBAs in these situations. Here we provide motivation for the specific CBA designs on which we will focus.

2.1 A traditional carbon border adjustment

We will first consider a traditional CBA, the logic of which is most easily understood from a starting point where no country initially has a carbon tax in place. From this starting point, when one country unilaterally introduces a local carbon tax on production, it creates more favorable conditions of competition for foreign producers of carbon-intensive goods who wish to sell into (who wish to "access") its markets. This puts upward pressure on the world price of carbon-intensive goods and leads to "carbon leakage," an increase in the production of carbon-intensive goods in the rest of the world. By contrast, if the country were to adopt a carbon tax on consumption, it would trigger harmful market access consequences for higher emission foreign producers of carbon-intensive goods who wish to sell into its markets. This would put downward pressure on the world price of carbon-intensive goods and prevent carbon leakage, instead causing other countries to reduce their production of carbon-intensive goods and resulting in "negative carbon leakage."

While the carbon leakage problem associated with taxes on the production of carbon is widely emphasized as a shortcoming of the carbon-production-tax approach relative to taxes on carbon consumption, it is generally acknowledged that taxes on the production of carbon, which can be collected at a relatively small number of upstream sites, are substantially easier to administer than would be taxes on the consumption of carbon (Metcalf and Weisbach, 2009). But it is also understood that a tax on the production of carbon could be combined with a CBA that is set at the same level as the carbon production tax to, in effect, turn the carbon production tax into a carbon consumption tax, thereby addressing the carbon leakage problem that arises with a tax on the production of carbon alone. This is essentially what the EU's Carbon Border Adjustment Mechanism (CBAM), which complements the EU's Emissions Trading System (ETS – the EU's version of a tax on carbon production), is designed to accomplish, at least in principle.

CBAM entered into application in its transitional phase on October 1 2023, and it will begin its definitive regime on January 1 2026. Broadly speaking, under CBAM the producer of a dirty good produced outside the EU and destined for sale in the EU market must pay the same carbon tax on the carbon content of that good when the good crosses the EU border as it would have to pay had the good been produced within EU borders.[1] And by the same token, the producer of a dirty good produced within EU borders but destined for sale in *another* country would *not* have to pay the EU carbon tax, requiring that any collected EU

[1]CBAM allows foreign producers to claim credits for carbon taxes they pay in their own country as offsets to any carbon taxes they must pay to sell in the EU market. In the discussion here we ignore this feature by implicitly assuming that only the EU has a carbon tax on producers. In our quantitative work we will account for this feature.

carbon production tax would be rebated to the EU producer at the border, a feature that is under discussion as part of the proposed evolution of CBAM though not featured in the transitional phase and not included in the initial definitive regime that begins on January 1 2026. In this way, when combined with the EU tax on the carbon content of production, the EU's CBAM in principle converts EU carbon policy from a carbon tax imposed on EU producers to a carbon tax imposed on EU consumers.

When implementing a traditional CBA in combination with a tax on the production of carbon, a question arises as to whether the tax on the production of carbon and the CBA apply only to the direct carbon emissions associated with production, or rather to the direct-plus-indirect carbon emissions associated with production. In order to avoid double taxation, the tax on the production of carbon should apply only to the direct carbon emissions associated with production, a feature that is reflected in the EU's ETS.[2] On the other hand, for the traditional CBA to convert the carbon production tax to a carbon consumption tax, the CBA must tax the direct-plus-indirect carbon emissions associated with imports (assuming that the production of the imported product was not subject to any carbon taxes in the origin country), so that a dirty good produced outside the EU and destined for sale in the EU market is subject to the same carbon tax on the overall carbon content of that good when the good crosses the EU border as it would have to pay had the good been produced within EU borders. In the transitional phase of CBAM, the tax applies only to direct emissions, though there is also a requirement to report the indirect emissions. In the definitive regime of CBAM to begin January 1 2026, the reported indirect emissions will also be subject to the CBAM tax.

We will attempt to capture the key features of CBAM in the traditional CBA that we introduce into the model below.[3]

[2] For example, if the production of steel uses electricity directly as an input but also uses electricity indirectly because aluminum is required as an input to the production of steel and the production of aluminum itself uses electricity directly as an input, then taxing the direct-plus-indirect carbon emissions associated with steel production would subject steel producers to double taxation of the electricity embodied in their aluminum inputs: the price of their aluminum inputs would rise as a result of the tax on emissions in aluminum production, and then steel producers would also have to pay a tax themselves on the emissions associated with aluminum production.

[3] The indirect emissions that will be included in the EU's CBAM calculation after January 1 2026 are restricted to the indirect use of electricity. In our analysis below, we will therefore consider two versions of our traditional CBA: a first version includes only direct emissions, as in the transitional phase of CBAM; a second version (to be included in the next draft of our paper) includes direct-plus-indirect emissions with the indirect emissions restricted to electricity use, as in the definitive regime of CBAM that begins on January 1 2026.

2.2 A leakage-neutralizing MFN carbon border adjustment

An implication of the discussion above is that, in effectively converting a tax on the production of carbon to a tax on the consumption of carbon, the EU's CBAM combines two goals: by preventing the world price of carbon-intensive goods from rising as a result of its carbon tax on EU producers, CBAM prevents carbon leakage; and in causing the world price of carbon-intensive goods to actually *fall*, CBAM penalizes trading partners whose production of dirty goods is particularly carbon-intensive by inducing especially large terms-of-trade declines for these trading partners.[4] The first goal seems broadly unobjectionable; the second goal may be laudable if it incentivizes EU trading partners to adopt greener technology, but it is also more controversial as it effectively harnesses CBAM for the purpose of unilaterally imposing on EU trading partners the reach of EU environmental policy. It is this second goal, and the associated feature that an EU trading partner using an especially carbon-intensive technology to produce dirty goods will face a higher CBAM tax to sell its goods in the EU market than a trading partner using a less-carbon-intensive technology to produce those goods, that has caused the design of CBAM to be met with strong resistance from Russia, China, India and other developing countries on the grounds that it amounts to a discriminatory tariff on EU trading partners.[5]

Motivated by this resistance, we will also consider a CBA design that strikes a middle ground between the positive carbon leakage associated with a tax on the production of carbon and the negative carbon leakage associated with a tax on the consumption of carbon. As we describe further below, such a CBA can be nondiscriminatory and, when combined with a tax on the production of carbon, is calibrated to essentially neutralize the leakage and lead neither to positive nor negative carbon leakage.[6] By designing the CBA to be an MFN surtax imposed on dirty-good imports, set at a market-access-preserving level that would hold world prices of carbon-intensive goods essentially unchanged when combined with the country's carbon tax (which is rebated on domestic production for export), this alternative CBA would prevent carbon leakage associated with the country's carbon tax without triggering harmful terms-of-trade consequences for any of its trading partners.

[4] These two goals were stated explicitly in an EU Council Press Release (March 15, 2022) announcing the adoption of CBAM: "The main objective of this environmental measure is to avoid carbon leakage. It will also encourage partner countries to establish carbon pricing policies to fight climate change."

[5] The EU disputes this characterization of its CBAM, claiming that it is in conformance with the WTO's MFN obligations, but other countries disagree. On May 12 2025 the Russian Federation initiated the first stage of a WTO dispute proceeding over this issue by filing a request for consultation with the EU over the WTO-legality of CBAM; on May 22 2025, the EU declined the Russian Federation's request, and the dispute has not yet proceeded beyond this initial phase.

[6] In considering such a CBA, we are following the logic of Bagwell and Staiger (2002) and especially Chapter 8 of Staiger (2022).

In distinguishing between the two goals of the EU CBAM and pursuing only the first, uncontroversial one, in principle this alternative CBA design would carry less risk than does CBAM of generating ill will among countries over climate policy at a moment when international cooperation is at a premium, at the same time that it would reduce the adverse distributional implications of the EU's carbon policies across the industrialized/developing country divide. An open question is how different the distributional impacts would be across these two CBA designs, and at what cost to the climate these gains might be achieved.

To investigate these and other questions, we will formalize in our model below a leakage-neutralizing CBA that conforms to MFN, and compare its performance to the traditional CBA described above.

2.3 A cost-shifting carbon border adjustment

A third and final CBA design feature that we consider is the removal from either of the CBAs described above of the rebate of carbon taxes paid on domestic production for export. In principle, the potential attractiveness of this feature would arise in a world where cooperation over carbon taxes is incomplete or nonexistent, and where as a result the carbon taxes applied by individual countries in the absence of CBAs is inefficiently low.

Allowing countries to introduce either of the CBAs described above with the rebate for exported production omitted would enhance the ability of each country to shift some of the costs of its carbon tax onto foreign exporters through terms-of-trade improvements, incentivizing countries to choose a higher unilateral carbon tax as a result. And in a world where carbon taxes are inefficiently low in the absence of CBAs, higher carbon taxes can lead to improvements in world welfare.[7] Weighing against these potential benefits is the possibility that the political support of exporters is necessary for a government to introduce a high carbon production tax.

More generally, according to the logic sketched above, the potential for any benefits from implementing such a cost-shifting CBA would presumably disappear if international cooperation over carbon taxes allowed those taxes to approach internationally efficient levels. Below we will investigate the performance of cost-shifting versions of the two forms of CBAs described above in the context of both noncooperative and cooperative carbon taxes.

[7] The logic of the second-best explains this claim. With climate agreements unavailable by assumption and carbon taxes therefore inefficiently low, it may make sense to help a country capture in the form of terms-of-trade improvements some of the positive climate benefits it creates for the rest of the world when it raises its carbon tax, with the rest of the world's worsening terms-of-trade then the mechanism by which payments are made for these climate benefits.

3 Model

Our model of the global economy is an Armington trade model with greenhouse gas emission that closely follows Shapiro (2021).

3.1 Demand, Costs, and Trade

Countries $i = 1, \dots, N$ produce goods in sectors $s = 1, \dots, S$ and trade in the global market subject to trade costs. The production and trade cost per unit of country j's imports of sector s produced in i are parameterized by ϕ_{ijs}, where

$$\phi_{ijs} = \tau_{ijs}(1 + t_{ijs})(c_{is} + K_{is} + CBA_{ijs}). \tag{1}$$

Trade costs depend on trade partner-sector specific iceberg-trade costs τ_{ijs} and tariffs t_{ijs}. Additionally, per-unit costs include the marginal production cost c_{is}, the carbon tax applied in the producing country K_{is}, and the carbon-border-adjustment between trading countries for that sector CBA_{ijs}. Since emissions are produced per unit of production, both the carbon tax and border adjustments are specific taxes.

Given productions costs, taxes, tariffs, trade frictions, and elasticity of substitution between goods from each country, $\sigma > 1$, the country-sector price index is

$$P_{js} = \left[\sum_i \phi_{ijs}^{(1-\sigma)} \right]^{1/(1-\sigma)}. \tag{2}$$

The unit cost of production for sector s in country i is Cobb-Douglas in labor and inputs from other sectors. Productivity parameter z_{is} scales production cost at the country-sector level. Parameters α_{iks} represent sector k's input share for production of s in country i:

$$c_{is} = z_{is} w_i^{1-\alpha_{is}} \prod_k P_{ik}^{\alpha_{iks}}. \tag{3}$$

With constant returns, the labor cost share is pinned down by the sum of input shares with $\alpha_{is} = \sum_k \alpha_{iks}$. The cost of each input is the country-sector price index P_{ik} specified in Equation 2.

The representative household in country j has Cobb-Douglas utility u_j over consumption aggregates in each sector. Household preferences are characterized by sectoral expenditure shares β_{js} and the elasticity of substitution, $\sigma > 1$, between country varieties which is constant across sectors:

$$u_j = \prod_s \Big[\Big(\sum_i q_{ijs}^{(\sigma-1)/\sigma} \Big)^{\sigma/(\sigma-1)} \Big]^{\beta_{js}}. \tag{4}$$

In our model, the numeraire is the US wage which we normalize to $w_{US} = 1$. Let $C_{ijs} = c_{is} + K_{is} + CBA_{ijs}$ be the total production and carbon costs before applying iceberg frictions and tariffs. The national income of country i includes total wages, tariff revenue, carbon tax revenue, CBA revenue, and lump-sum transfers:

$$Y_i = \underbrace{L_i w_i}_{\text{wages}} + \underbrace{\sum_{j,s} \frac{X_{jis} \cdot t_{jis}}{1 + t_{jis}}}_{\text{tariff rev.}} + \underbrace{\sum_{j,s} \frac{X_{ijs} \cdot K_{is}}{(1 + t_{ijs})C_{ijs}}}_{\text{carbon tax rev.}} + \underbrace{\sum_{i,s} \frac{X_{jis} \cdot CBA_{jis}}{(1 + t_{jis})C_{jis}}}_{\text{CBA rev.}} + \underbrace{F_i}_{\text{transfer}}. \tag{5}$$

International transfers are made between countries and are revenue neutral, $\sum_i F_i = 0$.

Expenditures X_{js} in country j on sector s include consumer spending on s and intermediate demand:

$$X_{js} = \beta_{js} Y_j + \sum_k \alpha_{jsk} \sum_j \frac{X_{ijs} \cdot c_{is}}{(1 + t_{ijs})C_{ijs}}. \tag{6}$$

International trade flows are characterized by the gravity equation:

$$X_{ijs} = \Big(\frac{\phi_{ijs}}{P_{js}} \Big)^{1-\sigma} X_{js} = \lambda_{ijs} X_{js}. \tag{7}$$

An equilibrium is a vector of wages $w = (1, w_2, \ldots, w_n)$ such that markets clear and representative households maximize utility given prices.

3.2 Carbon Emissions, Taxes, and Border-Adjustments

Each country-sector produces γ_{is} tons of carbon per unit of production. Total global emissions E are characterized by total production quantity scaled by the country-sector carbon intensity parameter:

$$E = \sum_i E_i = \sum_{j,s} \gamma_{is} \cdot \frac{X_{ijs}}{(1 + t_{ijs})C_{ijs}}. \tag{8}$$

Countries can implement carbon taxes to discourage emissions. When country i applies a tax of κ_i per ton of carbon, we allow countries to exempt sectors from the tax yielding the following sector-specific tax levied per unit:

$$K_{is} = \begin{cases} 0 & s \text{ is exempt} \\ \gamma_{is}\kappa_i & s \text{ is taxed.} \end{cases} \tag{9}$$

Below we detail the different kinds of CBAs for country j's imports of sector s from country i where κ_{is} is the carbon tax and γ_{is} is the direct emissions carbon intensity of sector s production in country i.

3.2.1 Traditional CBAs

The *Traditional CBA* is motivated by the CBAM mechanism and the classic theory behind carbon border adjustments. As discussed in section 2, the traditional CBA transforms a production tax on carbon into a consumption tax on carbon by including a carbon tax on all imports and by rebating the carbon tax on production that is exported. We also consider a version of the traditional CBA that does not rebate the carbon tax for exports, but does credit exporting countries for any carbon tax that they have placed on their exporters up to a maximum credit equal to the importing country's own carbon tax (i.e. there are no negative carbon border adjustments offered to any foreign exporters):

$$CBA_{ijs} = \gamma_{is}\kappa_{js} \text{ and } \underbrace{\kappa_{ijs} = 0 \text{ for } i \neq j}_{\text{tax rebate for exports}} \qquad \text{(“Traditional CBA”)}$$

$$CBA_{ijs} = \gamma_{is}\max\{\kappa_{js} - \kappa_{is}, 0\}. \qquad \text{(‘Traditional CBA w/o Export Rebate”)}$$

3.2.2 Leakage Neutralizing MFN CBAs

The *Leakage Neutralizing MFN CBA* is designed to appropriately adjust the price of imports to maintain domestic competitiveness with foreign producers in the presence of a carbon tax on domestic production. Given a carbon tax, each sector will face a tax proportional to the direct emissions from producing in that sector, γ_{is}. Since production uses other sectors as inputs, there is also an indirect increase in production cost according to the input-output matrix and emissions intensity of each sector. Recall α_{iks}, the cost share of sector k to produce s in country i. The CBA for a particular sector is designed to reflect the total (direct and indirect) carbon tax burden of production. Since emissions, carbon taxes, and

CBAs apply per unit, we use benchmark prices and costs to characterize the input quantities required to produce in each sector. Let c_{is}^0 and P_{is}^0 be the benchmark marginal cost and price of good s in country i. For a given sector, the total emissions tax burden is computed from the direct emissions of production plus the indirect carbon intensity of all input quantities. Some sectors (like agriculture) may be exempt from carbon taxes for political economy reasons. Let A_i be a matrix with components a_{iks} defined below:

$$\underbrace{a_{iks} = \frac{\alpha_{iks} c_{is}^0}{P_{ik}^0}}_{\text{quantity of } k \text{ required to produce } s \text{ in } i} \qquad \underbrace{\tilde{\gamma}_{is} = \begin{cases} \gamma_{is} & \text{if } \kappa_{is} > 0 \\ 0 & \text{if } \kappa_{is} = 0 \end{cases}}_{\text{taxed emissions intensity to produce } s \text{ in } i} \qquad \underbrace{e_{is} = (I - A_i)^{-1} \tilde{\gamma}_i}_{\text{total taxed emissions embodied in production of } s \text{ in } i}$$

The Leakage Neutralizing MFN (LNMFN) CBA applies each sector's total domestic tax burden to imports:

$$CBA_{ijs} = e_{js}\kappa_{js} \text{ and } \underbrace{\kappa_{ijs} = 0 \text{ for } i \neq j}_{\text{tax rebate for exports}} \qquad \text{("Leakage Neutralizing MFN CBA")}$$

$$CBA_{ijs} = e_{js}\kappa_{js}. \qquad \text{('LNMFN CBA w/o Export Rebate")}$$

3.3 Welfare and the Planner's Problem

In Section 3.1, we discussed the household objective function. Households do not internalize the social cost of carbon. Each country's social planner cares about GDP net of their country-specific linear cost to global emissions, δ_j. This yields the country-level welfare, W_j. The global social planner cares about all countries and sums country-welfare weighted by country j-specific welfare weights η_j:

$$W_j = \frac{Y_j}{P_j} - \delta_j E \qquad\qquad W^{global} = \sum_j \eta_j W_j.$$

The different objective functions at different levels of aggregation motivates our policy design problem. Households do not internalize externalities so countries turn to carbon taxes. Countries care about their own welfare and not the welfare of other countries. This can create non-cooperative policy equilibria that undercut the effectiveness of carbon taxes.

For this reason, countries may consider carbon-border adjustments that shield domestic producers from the burden of higher costs while facing global competition. The global social planner evaluates the effectiveness of different CBAs and other cooperative tax policies while incorporating every country's welfare. Under global policy, the country-level welfare will characterize distributional effects and the willingness-to-participate in global climate agreements.

4 Data

We create a cross-section of data on international trade and emissions in 2018 for 19 countries and 17 sectors. We focus on 2018 since it is the most recent year available across all of our datasets.

4.1 Trade Data

Our baseline trade data comes from the 2021 release of the 2018 OECD Inter-Country Input-Output (ICIO) tables. The ICIO provides bilateral trade, intermediate input use, final demand, and value-added measures for 67 regions and 45 industries. We aggregate these data into a final set of 19 countries (regions) and 17 sectors, as reported in Table 1.[8]

Bilateral trade flows are constructed by summing all intermediate exports and final goods exports recorded in the ICIO inter-country use and final demand matrices to our aggregated country-sector level. The ICIO intermediate input tables allow us to measure the value of inputs from each source sector to the producing output sector in each country. The ICIO final demand matrices allow us to construct expenditure shares in each sector for each country by combining final household consumption, government consumption, investment demand, inventory accumulation, and direct purchases. The ICIO labor compensation series reports the value of the labor input in each country's production across all sectors.

We supplement the ICIO data with the UNCTAD Trains data on population, tariffs, and price levels. Population will determine the labor force for each country and, combined with ICIO data, allow us to observe labor value added per capita. We compute average tariffs within our aggregated sector categories for each country in 2018.[9] UNCTAD also provides estimates of purchasing power parity (PPP). We aggregate UNCTAD PPP data from 2019 to our country definitions to observe price levels relative to the USA.

[8] We discuss aggregation of countries and sectors in the Appendix.

[9] For some countries, tariff data is not available for 2018 so we use the nearest year available.

4.2 Emissions Data

We follow the approach in Le Moigne et al. (2022) to construct country-sector emissions with three complementary datasets. Each dataset provides a distinct subset of global greenhouse gas emissions including carbon dioxide, methane, nitrous oxide, and fugitive emissions from direct fuel consumption, land use, and industrial processes. All sources of emissions are converted into CO_2-equivalent units using IPCC conversion coefficients. This produces a comprehensive dataset on annual production-based emissions across 19 countries and 17 sectors in 2018.

The OECD produces the Carbon Dioxide Emissions Embodied in International Trade Dataset (TECO2) that is based on the International Energy Agency's data on CO_2 emissions from fuel combustion. These data capture *direct* emissions from fossil-fuel use on-site for each sector. TECO2 excludes *indirect* emissions from electricity use that comes from purchased electricity produced offsite. Indirect emissions are included as direct emissions in the Energy sector. This dataset only provided CO_2 emissions from fuel combustion and we turn to the other two datasets to cover other sources.

The Food and Agriculture Organization of the United Nations (FAO) provides data on greenhouse gas emissions from agrifood systems. Emissions include methane, nitrous oxide, and carbon dioxide emissions in the Agricultural sector. We exclude emissions from fuel combustion since this is covered in the TECO2 data. Therefore, FAO provides non-energy agricultural emissions from livestock, rice cultivation, crop residue burning, fertilizer application, and manure management. The IPCC provides AR5 global warming potentials for methane and nitrous oxide that allow us to convert CO_2-equivalent tons of carbon. Emissions from this dataset will only contribute to the Agriculture sector.

The Emissions Database for Global Atmospheric Research (EDGAR) rounds out our data by providing emissions from industrial processes and fugitive emissions. These data include carbon dioxide, methane, nitrous oxide, and fugitive emissions which we convert to CO_2-equivalents. Emissions from production in this data come from non-fuel combustive activities like chemical reactions, ore reduction, metallurgical processes, flourinated-gases, and methane leakage. The sectors that include these kinds of emissions include: Chemicals, Electronics and Machinery, Energy, Metal, Nonmetallic Minerals, Other Mining, and Wood.

We combine TECO2, FAO, and EDGAR, to obtain total direct greenhouse emissions in CO_2-equivalent tons by country-sector. In Table 1 we report the share of global emissions by country and by sector. Emissions are highly concentrated across both countries and sectors. China accounts for over one-quarter of global production-based emissions, with the United States, European Union, and India compromising much of the remainder. We will highlight these four countries in our analysis. Across sectors, Energy and Agriculture emit contribute to over half of global emissions. Recall, however, that these numbers report direct emissions in that sector. Many of the other sectors indirectly emit by purchasing electricity from the Energy sector.

Country	Share of Emissions	Sector	Share of Emissions
China	28.03%	Energy	29.13%
Rest of World	14.94%	Agriculture	24.77%
USA	10.87%	Nonmetallic Minerals	9.32%
EU	8%	Metals	8.6%
India	7.06%	Transportation	7.28%
Rest of Asia	5.5%	Other Mining	6.16%
Russia	4.36%	Chemicals	3.97%
Brazil	3.47%	Other Services	3.47%
Indonesia	3.46%	Plastics	1.3%
Japan	2.46%	Wholesale and Retail	1.22%
Rest of Americas	1.94%	Construction	1.12%
Canada	1.71%	Other Manufacturing	1.1%
South Korea	1.49%	Wood	0.82%
Saudi Arabia	1.42%	Food	0.76%
Mexico	1.33%	Electronics and Machinery	0.48%
Africa	1.3%	Paper	0.32%
Australia	1.27%	Textile	0.17%
Turkey	0.95%		
Rest of Europe	0.44%		

Table 1: Country and Sector Share of Global Emissions

Notes: Table presents the share of annual global emissions contributed by each country and sector. Results are ordered by share.

5 Estimation

We estimate model parameters in two steps. First, we establish a baseline equilibrium by estimating trade costs, productivity, production, and taste parameters using OECD data on trade flows, production, and consumption. Second, we use the baseline equilibrium to estimate emissions intensity, emissions costs, and country welfare weights.

5.1 Estimation of Baseline Trade Model Parameters

We estimate baseline trade parameters by matching model predictions to three kinds of moments in the data: (1) trade flows, (2) price levels, and (3) trade deficits, similar to

Bagwell et al. (2021). First, we discuss the model parameters that we either assume or derive directly from the data separate from the main estimation procedure.

We set the elasticity of substitution to a standard value in the literature, $\sigma = 6$. Household preferences are characterized by consumption expenditure shares β_{is}, which are determined directly from sectoral expenditures and country income. Total country-sector production and input-output shares specify the production cost share parameters α_{iks}. We set wages, w_i, equal to the observed labor value added per capita in the data. This leaves the following three kinds of parameters: (1) iceberg trade costs $\boldsymbol{\tau}$, (2) productivity parameters $\mathbf{z}$, and (3) trade deficits $\mathbf{D}$. To reduce the number of parameters, we parameterize iceberg costs and productivity. We allow trade deficits to be determined freely.

Iceberg costs $\boldsymbol{\tau}$ for the traded sectors will depend on a bilateral component and a sectoral component. We normalize the bilateral component between US and Africa, $\tau_{US,AFR} = 0$:

$$\tau_{ijs} = \begin{cases} 1 & ; i = j \\ 1 + \exp\{\tau_{ij}^{\text{pair}} + \tau_s^{\text{sector}}\} & ; i \neq j. \end{cases} \tag{10}$$

Country sectoral productivity parameters $\mathbf{z}$ are allowed to flexibly vary across traded sectors and are constant within country for non-traded sectors. We normalize all US productivity parameters to 1:

$$z_{is} = \begin{cases} z_{is}^{\text{traded}} & ; s \text{ is traded} \\ z_i^{\text{nontraded}} & ; s \text{ is non-traded.} \end{cases} \tag{11}$$

Define the following moment-generating function

$$G(\boldsymbol{\tau}, \mathbf{z}, \mathbf{D}) = \begin{bmatrix} \lambda_{ijs} - \hat{\lambda}_{ijs}(\boldsymbol{\tau}, \mathbf{z}, \mathbf{D}) \\ P_j - \hat{P}_j(\boldsymbol{\tau}, \mathbf{z}, \mathbf{D}) \\ b_i - \hat{b}_i(\boldsymbol{\tau}, \mathbf{z}, \mathbf{D}) \end{bmatrix}, \tag{12}$$

where λ_{ijs} is the share of country j's expenditure on s that comes from country i, P_i is the country price level relative to the USA, and b_i is the deficit as a share of GDP. The hatted variables denote the trade equilibrium values of each object. We choose parameters by minimizing the weighted sum of the squared moments in G subject to market clearing constraints M:

$$\min_{\boldsymbol{\tau},\mathbf{z},\mathbf{D}} G(\boldsymbol{\tau},\mathbf{z},\mathbf{D})' W G(\boldsymbol{\tau},\mathbf{z},\mathbf{D}) \tag{13}$$

$$\text{s.t. } M(\mathbf{w},\boldsymbol{\tau},\mathbf{z},\mathbf{D}) = 0. \tag{14}$$

We weight each trade flow and price level equally and apply a weight of 10 to country deficit shares. This optimization problem recomputes the equilibrium for each choice of parameters. The constraint ensures that all market clearing conditions, $M(\mathbf{w},\boldsymbol{\tau},\mathbf{z},\mathbf{D})$, are satisfied at the wages we fixed to match the data.

5.2 Estimation of Emissions and Welfare Parameters

Emissions Intensity

The baseline model implies country-sector production quantities, Q_{is}. As described in Section 4.3, our data include estimates of country-sector total greenhouse emissions, E_{is}. We calibrate country i's carbon intensity from producing in sector s by the total emissions per quantity:

$$Q_{is} = \sum_{j,s} \frac{X_{ijs}}{(1+t_{ijs})C_{ijs}} \qquad \gamma_{is} = \frac{E_{is}}{Q_{is}}. \tag{15}$$

Carbon Cost Calibration

The Biden Administration's estimate of the global social cost of carbon is \$51/ton. Our model incorporates this cost with parameter δ_i, the country-specific constant marginal cost of emissions. We first calibrate the global social cost of carbon in our model by the sum of country-specific cost parameters:

$$\sum_i \delta_i = \$51 \cdot \frac{\sum_i Y_i/P_i}{\$14 \text{ trillion}} \qquad \delta_i = \frac{Y_i/P_i}{\sum_i Y_i/P_i} \cdot \sum_i \delta_i.$$

We translate our baseline model's global GDP into dollars estimates of global manufacturing GDP in 2020[10]. We then assume that the country-specific cost of carbon is proportional to the country's share of global GDP.

[10]See https://www.macrotrends.net/countries/WLD/world/manufacturing-output.

Country Welfare Weights

In some of our benchmarks, we allow the social planner to implement lump-sum transfers between countries. Given dispersion in country-price indices and for arbitrary welfare weights on individual countries, the social planner sometimes maximizes global welfare by transferring the entire income of certain countries. Global welfare maximizing transfers may be on the boundary.

To manage this pathological behavior, we calibrate the social planner's welfare weights on country welfare so that optimal global transfers are zero at baseline. Let $F^*(\eta)$ be the revenue-neutral vector of transfers that maximizes global welfare given the choice of welfare weights η:

$$F^*(\eta) = \underset{F \text{ s.t. } \sum_j F_j = 0}{\arg\max} \sum_j \eta_j W_j(F;\theta) \qquad\qquad F^*(\eta^0) = 0. \tag{16}$$

Country-welfare $W_j(F;\theta)$ is an equilibrium object that depends on transfers F and trade parameters θ. We estimated θ with no transfers, $F = 0$. Since transfers change the budget of each country, therefore changing the equilibrium wage vector, welfare $W_j(F;\theta)$ will differ from our baseline calibrated welfare. We resolve this and determine welfare weights by choosing weights η^0 so that zero transfers is optimal at baseline.

6 Trade Model Estimates and Benchmarks

6.1 Benchmark Results for Quantitative Trade Model

As benchmarks for the quantitative trade model, in Table 2 we present results from simulating autarky, zero tariffs free trade (while maintaining estimated iceberg costs), and frictionless trade (zero tariffs and iceberg costs). We summarize welfare with the percentage change in the sum of country welfare as well as the average per country percentage change in welfare. The benchmarks reported in Table 2 fall within the range of analogous results reported in the literature.

	Autarky	Zero Tariffs	Frictionless Trade
Total Relative Welfare	-4.46%	-0.17%	42.50%
Average Relative Welfare	-6.68%	-0.00%	71.41%
Relative Emissions	-2.22%	2.16%	61.64%

Table 2: Benchmarks for Quantitative Trade Model

Notes: "Relative" indicates percentage change relative to baseline outcomes.

6.2 The Global Social Planner Benchmark with Carbon

We now turn to carbon taxes for the benchmark of a global social planner. We assume that the planner faces no participation constraints, a property that will distinguish the planner's outcome from the "climate clubs" that we later consider. And we consider two scenarios. In a first scenario, the planner has access to international lump-sum income transfers and chooses a uniform carbon tax to apply to all countries of the world. Our second scenario assumes that international transfers are unavailable and considers two cases: in a first case, the planner continues to choose a uniform carbon tax to apply to all countries of the world; in a second case, we allow the planner to apply a different carbon tax to each country.[11] Each of these scenarios will serve as a useful benchmark against which the settings we consider in later sections can be judged.

Finally, here and throughout the paper we will entertain two possible cases with regard to the political economy of carbon taxes. Our first case assumes that countries can impose carbon taxes on all sectors without exception. This can be thought of as a world in which within-country political economy or distributional considerations in the context of carbon taxes have been overcome. Our second case assumes that countries are unable for political economy or distributional reasons to impose carbon taxes on agriculture. This can be thought of as reflecting the status quo political economy/distributional constraints on the setting of carbon taxes that most countries currently seem to face.

The quantitative results for the global planner are contained in Table 3. Here and throughout we present only worldwide aggregates and selected country variables in the tables included in the main sections of the paper; the Appendix includes tables with more complete country detail.

6.2.1 A Global Planner with Access to International Transfers

We start by assuming that the planner has access to international transfers, and that it chooses a uniform carbon tax to apply to all countries in addition to a set of international transfers. Column 1 of Table 3 presents the results when the planner faces no political economy/distributional constraints and can apply the carbon tax to all sectors without exception. In line with expectations, the planner sets the carbon tax faced by each country at a level of $51.46/ton, roughly equal to the calibrated marginal social cost of carbon of

[11] As we noted in section 2, this second case raises the possibility that the planner might wish to make use of CBAs as well. For brevity, we omit the results for the planner when it uses country-specific carbon taxes in tandem with CBAs, and restrict our analysis of CBAs to the noncooperative and climate club settings that we consider below.

Exemptions	None			Agriculture		
Tax	Uniform	Uniform	Ctry-Spec.	Uniform	Uniform	Ctry-Spec.
Transfers	Yes	No	No	Yes	No	No
Total Relative Welfare	5.20%	5.15%	5.16%	3.54%	3.53%	3.56%
Average Relative Welfare	0.93%	3.88%	3.88%	1.16%	2.84%	2.88%
Relative Emissions	-49.44%	-49.84%	-49.84%	-34.16%	-34.36%	-34.68%
Min. Carbon Tax	$51.46	$51.25	$45.81	$50.73	$50.97	$34.92
Average Carbon Tax	$51.46	$51.25	$51.05	$50.73	$50.97	$51.34
Max. Carbon Tax	$51.46	$51.25	$58.04	$50.73	$50.97	$64.12

Table 3: Social Planner Carbon Taxes

Notes: "Relative" indicates percentage change relative to baseline outcomes.

$51/ton.[12] The planner also makes use of international transfers (see Appendix Tables A4 and A5). Since our calibrated welfare weights ensure that the planner chooses zero transfers in the baseline without carbon taxes, the broad pattern of these transfers can be understood to reflect two basic forces: first, the carbon tax chosen by the planner will impact the welfare of countries differentially, and the planner can use international transfers to offset these distributional impacts when they are undesirable to the planner; and second, the planner's choice of carbon tax will alter price levels in each country differentially, and all else equal the planner finds it attractive to transfer income from high-price countries where the purchasing power of a unit of income is relatively low to low-price countries where the purchasing power is relatively high.

As column 1 of Table 3 reports, with its optimal carbon tax applied to all sectors and countries and its use of international transfers, the planner orchestrates a 49.44 percent reduction in worldwide emissions relative to baseline. Although the carbon tax is uniform across countries, the emissions reductions vary considerably across countries (see Appendix Tables A4 and A5), with emissions ranging from 85 percent of baseline for Rest-of-Europe to 20 per cent of baseline for Brazil. Total world welfare rises by 5.2 percent from baseline under the planner's interventions, but with substantial variation in the welfare effects across countries: the US, EU, Korea and Japan are the biggest gainers, with increases in welfare above baseline equal to 7 percent, 8 percent, 8 percent and 9 percent, respectively; and Africa is the biggest loser, with its welfare dropping by 30 percent from baseline.

In column 4 we present the results when the planner is subject to political economy/distributional constraints that prevent it from applying its uniform carbon tax to agricultural production. As a comparison of column 4 with column 1 reveals, exempting agriculture from carbon taxes

[12] We find the planner's carbon tax deviates slightly from the calibrated social cost of carbon, reflecting the planner's response to the presence of existing distortions (the baseline tariffs of each country).

costs the world roughly one and a half percentage points of welfare gains over baseline that the global planner could deliver if agricultural production were not exempt. The change in the uniform carbon tax implemented by the planner is small, but when this tax cannot be applied to agricultural production, the worldwide emissions reductions implemented by the planner falls by roughly 30 percent.

6.2.2 A Global Planner without Access to International Transfers

We next assume that the planner lacks access to international transfers. It is useful to consider two cases. We begin with the case where the planner continues to choose a uniform carbon tax to apply to all countries. We then consider the possibility of country-specific carbon taxes.

Column 2 of Table 3 presents the results when the planner lacks international transfers but continues to choose a uniform carbon tax to apply to all countries and all sectors. As a comparison of column 2 with column 1 confirms, the planner's choice of carbon tax is unaffected by the lack of transfers, as is the reduction of world-wide emissions and the increase in world-wide welfare relative to baseline. But the lack of transfers impacts substantially the welfare implications of the planner's intervention for specific countries (see Appendix Tables A4 and A5): all countries with the exception of Indonesia now gain relative to baseline in terms of welfare.

Choosing Country	USA	EU	China	India
Uniform Carbon Tax	$127.41	$126.39	$27.72	$24.03
Relative Emissions	-68.52%	-68.37%	-36.53%	-33.60%

Table 4: Unilaterally Optimal Uniform Carbon Tax by Country

Notes: "Relative" indicates percentage change relative to baseline outcomes.

To illustrate the differing incentives of various countries when it comes to carbon taxes and the tradeoffs that the global planner faces when choosing the carbon tax, we present in the four columns of Table 4 the results that would occur if the US, the EU, China or India respectively were given dictatorial power to set the uniform carbon tax for the world (and where international transfers naturally play no role). As the columns of Table 4 demonstrate, the US and the EU would choose to impose a level of carbon tax on the world ($127.41/ton and $126.39/ton, respectively) that is far higher than the $51/ton social cost of carbon and would reduce emissions by more than the global planner, while China and India would choose a carbon tax ($27.72/ton for China and $24.03/ton for India) that is considerably lower than the social cost of carbon and would reduce emissions by less than the global planner. These different incentives reflect the different burdens that each country carries when emissions are reduced with a uniform carbon tax relative to the benefits that each receives from the induced emissions reduction.

Returning to Table 3, column 5 presents the results when the planner faces political economy/distributional constraints that prevent it from applying its uniform carbon tax to agricultural production. As when the planner has access to international transfers, a comparison of columns 5 and 2 confirms that exempting agriculture from carbon taxes when the planner lacks international transfers costs the world roughly one and a half percentage points of welfare gains over baseline that the global planner could deliver if agricultural production were not exempt.

We next consider whether the planner might want to apply different carbon taxes to different countries if it lacks the ability to make international income transfers, a possibility that has been pointed out by Chichilnisky and Heal (1994) and Sandmo (2006). Column 3 of Table 3 presents the results when the planner can apply country-specific carbon taxes to all sectors including agricultural production, while column 6 presents the results when agricultural production is exempt from the carbon tax. The planner chooses to vary the carbon taxes imposed on each country (see Appendix Tables A4 and A5), for example (when it can tax agriculture) by raising the carbon tax on Brazil and Rest-of-Europe above the social cost of carbon to a level of $53.59/ton and $58.04/ton, respectively, while lowering the carbon tax on Korea below the social cost of carbon to a level of $45.81/ton. But as a comparison of columns 3 with 2 and columns 6 with 5 confirm, the cross-country variation in carbon taxes introduced by the planner has essentially no impact on total world welfare or worldwide emissions reductions relative to baseline.

Finally, it is notable that the planner imposes a higher carbon tax on China than it does on either the US or the EU, and India's carbon tax is also higher than the EU's (see Appendix Tables A4 and A5), despite the fact that, as noted in our earlier discussion and revealed in the columns of Table 3, China and India have a preference for lower carbon taxes than the US and the EU. This reflects the greater "bang for the buck" in terms of carbon reduction that the higher carbon taxes achieve in China and India relative to the US and EU, owing to the relatively high levels of carbon-intensity of dirty-good production in China and India.

7 Nash Carbon Taxes and WTO Rules on CBAs

In this section we simulate a Nash-carbon-tax world. We assume that existing carbon taxes do not reflect Nash choices, but are instead still in the process of adjusting to their Nash equilibrium levels. Hence, we do not require that our Nash carbon taxes match observed carbon taxes for our baseline year.[13] By comparing our results here to the results under the global social planner benchmark of the previous section, we can quantify the potential gains from cooperation over carbon taxes. At the same time, by quantifying the impacts of CBAs on Nash carbon taxes under the various forms that CBAs might reasonably take, we can shed light on whether WTO rules over CBAs could make an important contribution to the fight against climate change if cooperation over carbon taxes is not feasible, and we can evaluate the way in which these rules might best be designed in a world where countries maintain their cooperation over trade measures such as the rules governing CBAs but are unable to forge international agreements over the carbon tax itself.

As before, we present results both for the case when carbon taxes are applied to all sectors, and for the case when for political economy/distributional reasons agricultural production is exempt from carbon taxes.

Exemptions	None			Agriculture		
CBA	None	Trad.	Leakage Neutral	None	Trad.	Leakage Neutral
Total Relative Welfare	1.45%	1.50%	1.34%	1.20%	1.22%	1.07%
Average Relative Welfare	1.50%	1.48%	1.20%	1.26%	1.19%	0.95%
Relative Emissions	-9.58%	-10.11%	-10.22%	-8.01%	-8.23%	-8.33%
Average Carbon Tax	$3.97	$3.08	$4.97	$3.98	$3.83	$6.14
USA Carbon Tax	$9.99	$13.25	$14.61	$11.74	$13.96	$15.24
EU Carbon Tax	$9.92	$13.02	$9.67	$11.41	$14.69	$9.64
China Carbon Tax	$8.22	$8.57	$7.98	$8.23	$8.60	$8.05

Table 5: Nash Carbon Taxes

Notes: "Relative" indicates percentage change relative to baseline outcomes.

7.1 Nash Carbon Taxes in the Absence of CBAs

We begin by presenting the Nash carbon taxes in the absence of CBAs. Column 1 of Table 5 presents the results for the case when each country applies its carbon tax to all sectors.

As can be seen from column 1, for all countries, the Nash carbon taxes are set at a fraction of the level chosen by the global planner. In particular, while the planner sets the carbon tax roughly equal to the marginal social cost of carbon, $51/ton, in the Nash equilibrium the US and EU set their carbon taxes at $9.99/ton and $9.92/ton, respectively, China sets

[13] In the Conclusion we discuss briefly an alternative, where observed carbon taxes in our baseline year are assumed to reflect the Nash carbon taxes that arise in a world where governments place development/political weights on dirty good production, and where those weights would be calibrated so that the Nash carbon taxes match observed carbon taxes.

its carbon tax at \$8.22/ton, and the carbon taxes of many of the other countries are an order of magnitude smaller than that. The level of worldwide emissions that results with the implementation of Nash carbon taxes when all sectors are taxed is only 9.58 percent below baseline, far above the $49-50$ percent below baseline emissions that the global planner would implement. The welfare differences from the outcome under the global social planner are also substantial. Total world welfare rises by 1.45 percent relative to baseline when Nash carbon taxes are implemented and all sectors are taxed, a 4 percentage point reduction from the 5.2 percent welfare gains achieved for this case by the implementation of the carbon tax chosen by the planner.

Column 4 of Table 5 presents the results for the case when each country exempts its agricultural production from its carbon tax. Comparing across columns 4 and 1, there is a worldwide welfare cost to this exemption, but unlike for the case of the global planner, this cost is relatively small when countries are choosing Nash carbon taxes, much smaller than is the case for the global planner benchmark in Table 3. And as a comparison between column 4 across these two tables confirms, even in the case where agricultural production is exempt from carbon taxes, the global planner benchmark achieves world welfare levels that are two and a half percentage points above the Nash levels.

Hence, whether or not political economy/distributional considerations preclude the application of carbon taxes to agriculture, the welfare costs of implementing Nash carbon taxes relative to the choices of the global planner are large. In both cases, this cost is attributable to the small carbon taxes chosen by countries in the Nash equilibrium relative to the carbon tax chosen by the planner. Below we investigate the reasons for the large discrepancy between the carbon taxes chosen in these two settings.

7.2 Carbon Leakage and the Impact of CBAs

There are two reasons why the Nash carbon taxes reported in Table 5 are below the optimal carbon taxes chosen by the global planner. The first reason is that a country confers a positive climate externality on the rest of the world when it raises its carbon tax, a benefit that is internalized by the global planner but one that is not internalized when countries decide unilaterally whether to raise their carbon taxes. The second reason is the possibility of carbon leakage: when a country raises its carbon tax on the production of dirty goods, the world supply of dirty goods falls and the market-clearing world price of dirty goods must rise, inducing greater production of dirty goods in the rest of the world, thereby thwarting the country's unilateral efforts to reduce worldwide emissions, and discouraging the country from raising its carbon tax in the first place.

The first reason for the difference between the Nash carbon taxes and those that would be chosen by the planner can only be fully addressed through an international agreement over carbon taxes that allows countries to internalize the positive externalities of their carbon taxes. But the second reason can in principle be addressed with the introduction of CBAs, which by themselves do not require cooperation over carbon taxes.[14]

Country	EU			China		
CBA	None	Trad.	Leakage Neutral	None	Trad.	Leakage Neutral
Change in Own Emissions	-33.67	-25.07	-28.75	-341.12	-328.39	-330.80
Change in RoW Emissions	10.21	-17.79	4.82	9.06	-15.82	1.22
EU Carbon Tax	$1.03	$1.03	$1.03	$0.00	$0.00	$0.00
China Carbon Tax	$0.00	$0.00	$0.00	$1.03	$1.03	$1.03

Table 6: Carbon Leakage

Notes: All non-EU and non-China carbon taxes are set to zero. Own emissions refers to emissions in the EU in the first three columns, and emissions in China in the final three columns. RoW emissions refers to outside the EU in the first three columns and outside China in the final three columns.

In the first and fourth columns of Table 6, we illustrate the phenomenon of carbon leakage exhibited by the model for respectively the EU and China, for the case where carbon taxes are extended to apply to agricultural production (the case where agricultural production is exempt from carbon taxes is similar). For this table, we set all carbon taxes to zero and then raise the respective country's carbon tax by a small amount. And in the first and fourth columns the carbon-tax-imposing country does not apply a CBA. As these columns illustrate, the country's own emissions fall as it raises its carbon tax, but the emissions of countries in the rest of the world are also impacted, and for both the EU and China, on net the rest-of-world emissions rise. The associated carbon leakage causes worldwide emissions to fall by a fraction of the own-country emissions reductions (70 percent for the EU, 97 percent for China).

The second and fifth columns of Table 6 illustrate how a traditional CBA imposed by the EU and China can address the carbon leakage associated with their respective carbon taxes, and in fact results in negative carbon leakage. For both the EU and China, own emissions fall by less when a traditional CBA is included with the country's carbon tax, owing to the

[14] There is also a third potential reason for inefficiently low Nash carbon taxes that applies to dirty-good importing countries: if the tariffs of such countries are bound below their unilaterally optimal levels (e.g., as a result of WTO agreements), then these countries will have an additional unilateral incentive to keep their carbon taxes low as a way to maintain favorable terms of trade. However, for dirty-good exporting countries this same terms-of-trade concern would imply a reason to raise the carbon tax, so the overall bias of Nash carbon taxes induced by this third reason is ambiguous and we do not emphasize it here.

protection from import competition and the rebate of the carbon tax for exporters that the traditional CBA entails. At the same time, however, on net the rest-of-world emissions now also falls when a traditional CBA is included with the country's carbon tax (because the tax on dirty good consumption implied by the carbon production tax and the traditional CBA leads to a fall in the world price of dirty goods and a reduction in rest-of-world dirty good production), causing the worldwide emissions to fall by a multiple of the own-country emissions reductions (171 percent for the EU, 105 percent for China) and leading overall to greater worldwide emissions reductions than the same small carbon tax would generate in the absence of a CBA.

Finally, the third and sixth columns of Table 6 illustrate the impact of a leakage neutralizing MFN CBA on the degree of carbon leakage associated with a small carbon tax imposed by the EU and China, respectively. Again, for both the EU and China, own emissions fall by less when a leakage neutralizing MFN CBA is included with the country's carbon tax, owing to the protection from import competition and the rebate of the carbon tax for exporters that the leakage neutralizing MFN CBA entails. And as it is designed to do, the leakage neutralizing MFN CBA mitigates the carbon leakage caused by each country's carbon tax, but it does not cause carbon leakage to become negative as is the case under the traditional CBA.[15]

7.3 Nash Carbon Taxes in the Presence of CBAs

Motivated by our discussion above of the carbon leakage that results in the absence of CBAs, and of the way in which CBAs of various designs can address carbon leakage, we now present Nash carbon tax results when countries also impose CBAs.

We begin by considering the possibility that countries impose either traditional CBAs or leakage neutralizing MFN CBAs in tandem with their Nash choices of carbon taxes. The interpretation is that, while countries cannot achieve cooperation over carbon taxes, they can maintain cooperation over border tax measures, and we suppose first that such cooperation permits either traditional CBAs or leakage neutralizing MFN CBAs.

Columns 2 and 5 of Table 5, respectively, present the results for traditional CBAs when when agricultural production is subjected to carbon taxes and, alternatively, when agricul-

[15]Table 6 shows that the carbon leakage created by the EU's carbon tax under the leakage neutralizing MFN CBA is still substantial. The leakage neutralizing CBA is designed to face foreign exporters with the same increase in the cost of serving the domestic market that domestic producers of the same product experience as a result of the country's carbon taxes. This, however, does not guarantee that world prices won't change, since domestic demand in the country can change, and hence some leakage (in either direction) can in principle still occur as a result of general equilibrium effects. For this reason, a more accurate name for this CBA design might be "leakage mitigating," but as a simple reference that captures the essence of this CBA we prefer to use the name leakage neutralizing.

tural production is exempt from carbon taxes. Similarly, columns 3 and 6, respectively, present the results for leakage neutralizing CBAs when agricultural production is subjected to carbon taxes and, alternatively, when agricultural production is exempt. The main take-away from these columns is that, with regard to both worldwide welfare relative to baseline and worldwide emissions reductions relative to baseline, the introduction of CBAs has only minor impacts on Nash outcomes, whether these CBAs seek to simply neutralize carbon leakage (as in the leakage neutralizing MFN CBAs featured in columns 3 and 6 of Table 5) or seek to convert carbon taxes on production into carbon taxes on consumption and hence create negative carbon leakage (as in the traditional CBA featured in columns 2 and 5). This implies that the existence of carbon leakage is not the main reason for the large discrepancy between the Nash equilibrium outcomes and those chosen by the global planner.

It is also notable that, despite its elimination of the discriminatory features associated with the traditional CBA, the leakage neutralizing MFN CBA does not raise the Nash welfare of countries such as Indonesia and Mexico (see Appendix Table A3), even though these countries do face relatively higher tariffs under the traditional CBA than do countries with cleaner production such as the US and the EU. The reason for this finding can be traced to the property that, as described in section 2, the leakage neutralizing MFN CBA must by definition be applied to direct-plus-indirect emissions, while we have followed the practice in the transitional phase of the EU CBAM and applied the traditional CBA to direct emissions only. This implies that the leakage neutralizing MFN CBA tends to be quite a bit higher in absolute terms for all countries relative to the traditional CBA, and this feature ends up dominating the relative gains that countries like Indonesia and Mexico would enjoy with the elimination of discrimination implied by MFN.[16]

Finally, we noted in section 2 that eliminating the rebate of carbon taxes paid by producers who export their production would allow a country to shift a portion of the costs of its CBA onto trading partners through favorable terms-of-trade movements. In the current setting, allowing some international cost-shifting of carbon taxes could be advantageous, since as we have seen, the Nash carbon taxes in the absence of CBAs are far below the globally efficient level, in part because the rest of the world enjoys a positive climate externality whenever a country unilaterally raises its carbon tax.

It is therefore interesting to consider the attractiveness of the cost-shifting versions of

[16] As we noted in section 2, in the next draft of our paper we will also include a second version of the traditional CBA that is based on direct-plus-indirect emissions with the indirect emissions restricted to electricity use, as in the definitive regime of CBAM that begins on January 1 2026. Under this second version of the traditional CBA, the reason for the different average heights of the traditional and the leakage neutralizing CBA will no longer be present, and the elimination of discrimination implied by MFN may then dictate the relative attractiveness of the two CBA designs for countries with relatively carbon-intensive production.

the traditional CBA and the leakage neutralizing MFN CBA, where the rebate of carbon taxes paid by producers who export their production is omitted. In effect, the question we now ask is whether, in a world where cooperation over climate policy is impossible but where cooperation over border measures is still possible, could permitting some degree of international cost shifting in the context of carbon taxes be a second-best way to incentivize countries to raise carbon taxes toward the level that these countries would achieve if they had the ability to cooperate over carbon taxes directly?

Exemptions	None		Agriculture	
CBA, No Export Rebate	Trad.	Leakage Neutral	Trad.	Leakage Neutral
Total Relative Welfare	2.07%	1.41%	1.67%	1.12%
Average Relative Welfare	2.02%	1.26%	1.63%	0.99%
Relative Emissions	-14.12%	-10.99%	-11.49%	-8.91%
Average Carbon Tax	$7.45	$5.27	$9.50	$6.57
USA Carbon Tax	$15.51	$14.09	$17.15	$15.29
EU Carbon Tax	$16.03	$9.90	$19.17	$10.14
China Carbon Tax	$9.26	$7.86	$9.08	$7.96

Table 7: Nash Carbon Taxes with No Export Rebates

Notes: "Relative" indicates percentage change relative to baseline outcomes.

The first and third columns of Table 7, respectively, present the results for the cost-shifting version of the traditional CBA when agricultural production is covered by the carbon tax and alternatively when agricultural production is exempt, while the second and fourth columns present the analogous results for the cost-shifting version of the leakage neutralizing CBA. Comparing the results in Table 7 to the results in Table 5, the main takeaway is that, with regard to both worldwide welfare relative to baseline and worldwide emissions reductions relative to baseline, the removal of the rebate to exporters improves the outcomes under Nash carbon taxes by incentivizing countries to raise their carbon taxes, whether these CBAs seek to simply neutralize carbon leakage (as in the cost-shifting version of the leakage neutralizing MFN CBAs featured in columns 2 and 4 of Table 7) or seek to convert carbon taxes on production into carbon taxes on consumption and hence create negative carbon leakage (as in the cost-shifting version of the traditional CBA featured in columns 1 and 3 of Table 7).[17]

[17] Of course, it is also possible that the a country requires political support from its exporters for its carbon taxes, and that the promise of rebates is what keeps its exporters from revolting against the country's carbon taxes. Our model does not capture such political economy forces, and so our findings here must be viewed in the context of the appropriate caveats.

Taken together, the results of Tables 5 and 7 suggest that the best CBA design when countries cannot cooperate over carbon taxes is the cost-shifting version of the traditional CBA, that is, the traditional CBA without the rebate to exporters, mirroring the current design of the EU CBAM. According to the results in column 1 of Table 7 and comparing these with the results in column 2 of Table 5, when agricultural production is covered by carbon taxes, Nash worldwide welfare would be 2.07 percent above baseline when the cost-shifting CBA is used, still far below the welfare achieved by the global planner but more than one half a percentage point higher than when exporters receive the rebate. Similarly, when agricultural production is exempt from carbon taxes, a comparison of the results in column 3 of Table 7 with those in column 5 of Table 5 reveals that worldwide welfare would be 1.67 percent above baseline, about one half a percentage point higher than when exporters receive the rebate.

8 Cooperation over Carbon Taxes

In this section we consider what can be achieved with cooperation over carbon taxes. We refer to this cooperation as a climate club, and we focus on climate clubs with global participation. However, unlike the global social planner outcomes characterized in section 6.2, we assume that climate clubs face participation constraints. In addition to the participation constraint, the defining features of our climate clubs are the following: (i) whether international transfers are available, (ii) whether club members are assigned country-specific carbon taxes or rather a uniform carbon tax across members, and (iii) whether a CBA is included and, if so, its design.

We consider two forms that the participation constraints might take, each consistent with the assumption that club members cannot threaten to raise their tariffs against non-members above their WTO-bound levels (distinguishing our treatment of participation constraints from e.g., Nordhaus (2015)). A first participation constraint gives each potential club member veto power over the formation of the club. Hence, under the *veto participation constraint*, each club member must achieve at least as much welfare inside the club as it could achieve in the status quo where the club does not form. A second participation constraint takes a "free-rider" form: under the *free-rider participation constraint*, a club member must achieve at least as much welfare inside the club as it could achieve if it stayed out of the club and best-responded against the club's choices in its absence. We interpret these two participation constraints as together providing reasonable bounds on the possible (endogenous) participation constraints that might be considered. We will consider each in turn.[18]

8.1 A Climate Club with Veto Participation Constraints

We begin our investigation of climate clubs under the assumption that a viable climate club must meet a veto participation constraint for each member. We examine first what is achievable if the climate club restricts itself to a uniform carbon tax for all members, and then we turn to the possibility that the club specifies different carbon taxes for different members.

8.1.1 Uniform Carbon Taxes

Table 8 contains the results when the climate club must meet the participation constraint for all members with the choice of a uniform carbon tax. Column 1 presents the case where international transfers are available to the climate club and carbon taxes apply to all sectors without exception. As might be expected, comparing these results to column 1 in Table 3, it is apparent that when international transfers are available, the participation constraint makes no difference to the worldwide outcomes achievable by the climate club relative to those of the global planner, though the cross-country variation in welfare is compressed by the participation constraint for the climate club. The implied international transfers, however, are large (see Appendix Table A6) – with a number of countries paying or receiving transfers amounting to between 5 and 11 percent of their GDP – and arguably unattainable as a practical matter.

Exemptions	None		Agriculture	
Transfers	Yes	No	Yes	No
Total Relative Welfare	5.19%	4.71%	3.53%	3.35%
Average Relative Welfare	3.08%	4.03%	2.86%	2.92%
Relative Emissions	-49.48%	-37.95%	-34.20%	-28.08%
Uniform Carbon Tax	$51.46	$29.67	$50.66	$33.92

Table 8: Climate Club Uniform Carbon Taxes with Veto Participation Constraints

Notes: "Relative" indicates percentage change relative to baseline outcomes.

[18] Consideration might also be given to the case of climate clubs formed among a subset of countries. However, by allowing that club members may be assigned country-specific carbon taxes, we are able to effectively include this case by assigning a country its best-response carbon tax level. We choose to focus our analysis on the participation margin, in light of the emphasis of the Nordhaus-inspired literature on the use of tariff threats to induce participation. For simplicity we therefore assume that the climate club chooses carbon taxes (and transfers, if available) to maximize the same weighted objective function as our global planner would, but in the case of the climate club, subject to the participation constraints of its members.

As an alternative, column 2 of Table 8 therefore presents the results when international transfers are instead unavailable to the club. Now the impacts of the participation constraint are substantial (we find that Indonesia is the binding club member in equilibrium). To satisfy the participation constraint, the uniform carbon tax chosen by the climate club falls to $29.67/ton, far below the $51/ton social cost of carbon, and the club's ability to cut worldwide emissions is reduced from 49.48 percent below baseline when the club can make large international transfers to 37.95 percent below baseline when international transfers are infeasible, costing roughly one half of one percentage point of world welfare relative to the global planner benchmarks of Table 3.

Turning to the case where agricultural production is exempt from carbon taxes, the third and fourth columns of Table 8 show a similar pattern, indicating again that satisfying the participation constraint is costly to the worldwide outcomes achieved by the climate club if large international transfers are infeasible. And as with the benchmark outcomes of the global planer in Table 3 and different from the Nash carbon tax outcomes in Table 5, a comparison across the four columns of Table 8 confirms that extending carbon taxes to agricultural production makes a substantial difference to worldwide outcomes when carbon taxes are determined in a global climate club.

8.1.2 Country-Specific Carbon Taxes

We now turn to the possibility that the climate club has the ability to specify different carbon taxes for different members as a means of addressing participation constraints. To highlight the comparison with the uniform carbon tax analyzed above, where the implications of participation constraints are pronounced only when the club is unable to make large international transfers, we present results here only for the case where international transfers are unavailable. The results are contained in Tables 9 and 10.

While CBAs are now relevant in this context, we begin by discussing the results in the absence of CBAs. Column 1 of Table 9 contains the results when carbon taxes are applied to all sectors without exception, and where the climate club selects country-specific carbon taxes for each member and where countries do not impose CBAs. Comparing these results to those recorded in the first two columns of Table 8, it is evident that when international transfers are unavailable, country-specific carbon taxes become a valuable tool for dealing with participation constraints.

In particular, while the first two columns of Table 8 show that participation constraints impose a substantial cost in terms of worldwide welfare when international transfers are unavailable and the climate club is restricted to a uniform carbon tax for all members, the results reported in column 1 of Table 9 are essentially the same as those reported in

Exemptions	None			Agriculture		
CBA	None	Trad.	Leakage Neutral	None	Trad.	Leakage Neutral
Total Relative Welfare	5.15%	5.14%	3.57%	3.55%	3.54%	2.32%
Average Relative Welfare	4.04%	3.67%	2.47%	2.98%	2.70%	1.74%
Relative Emissions	-49.55%	-49.39%	-36.95%	-34.09%	-34.08%	-25.00%
Min. Carbon Tax	$37.29	$35.62	$0.00	$35.40	$32.00	$1.34
Average Carbon Tax	$50.47	$49.64	$27.51	$50.31	$51.23	$27.70
Max. Carbon Tax	$58.35	$55.87	$48.36	$65.55	$114.72	$92.90

Table 9: Climate Club Country-Specific Carbon Taxes with Veto Participation Constraints

Notes: "Relative" indicates percentage change relative to baseline outcomes.

column 1 of Table 8, indicating that the cost to worldwide welfare of satisfying participation constraints for a climate club that lacks the ability to make large international transfers can be avoided if the club can implement country-specific carbon taxes. Evidently, the use of country-specific carbon taxes allows the climate club to meet the participation constraints of its member countries without sacrificing its performance as measured by the worldwide emissions reductions and worldwide welfare increases that it is able to achieve, thereby preventing any shortfall in these metrics relative to the global planner benchmarks from Table 3.

Turning to the scenario where agricultural production is exempt from carbon taxes, our findings are similar. In particular, the results reported in column 4 of Table 9 are essentially the same as those reported in column 3 of Table 8, indicating again that the cost to worldwide welfare of satisfying participation constraints for a climate club that lacks the ability to make large international transfers can be avoided if the club can implement country-specific carbon taxes. And a comparison across the sets of columns in Table 9 indicates that, as with our global planner results and distinct from the Nash carbon tax setting, in the case of climate clubs, extending coverage of the carbon tax to agricultural production would yield significant improvements in worldwide emissions reductions and welfare increases.

As we noted, the presence of country-specific carbon taxes raises the possibility that CBAs might also be a desirable feature of the climate club. Focusing first on the case where carbon taxes apply to all sectors without exception, in columns 2 and 3 of Table 9 we allow club members to accompany their carbon taxes with, respectively, the addition of a traditional CBA for that country, and alternatively a leakage neutralizing CBA. As revealed by a comparison of columns 2 and 3 of Table 9 with column 1, the introduction of the traditional CBA induces some changes in the planner's carbon tax choice for individual countries and in the welfare of individual countries (see Appendix Table A7), but it has essentially no impact on total world welfare or world emissions reductions relative to baseline, and the introduction of the leakage neutral CBA substantially worsens the performance of the climate club. In columns 5 and 6 of Table 9 we present the analogous results for the case where agricultural production is exempt from carbon taxes, and the results there are similar to those in columns 2 and 3.

Finally, recall that in the context of our Nash carbon tax analysis, the cost-shifting versions of our traditional and leakage neutralizing CBAs, where the rebate to exporters is omitted, could be attractive. In particular, we found that implementing the cost-shifting version of the traditional CBA would increase worldwide welfare by more than one half a percentage point over the Nash outcome under the traditional CBA inclusive of the rebate to exporters. In Table 10 we report the results for the climate club when the cost-shifting versions of the traditional CBA and the leakage neutralizing CBA are implemented. The first two columns of Table 10 report the results for the case where carbon taxes apply to all sectors without exception, while the last two columns report the results for the case where agricultural production is exempt from carbon taxes. Apparently, as a comparison of the columns of Table 10 with the analogous columns of Table 9 reveal, when countries can cooperate over carbon taxes with the formation of climate clubs, the ability of each country to shift some of the costs of its carbon taxes onto trading partners is unimportant to the climate club, and the cost-shifting versions of CBAs now offer *no advantage* to the world.

Exemptions:	None		Agriculture	
CBA, No Export Rebate	Trad.	Leakage Neutral	Trad.	Leakage Neutral
Total Relative Welfare	5.14%	3.50%	3.54%	2.26%
Average Relative Welfare	4.04%	2.47%	2.95%	1.74%
Relative Emissions	-49.49%	-36.84%	-33.99%	-24.53%
Min. Carbon Tax	$35.13	$-0.00	$38.27	$1.07
Average Carbon Tax	$50.24	$25.29	$49.54	$23.73
Max. Carbon Tax	$52.22	$44.32	$70.50	$67.11

Table 10: Climate Club Country-Specific Carbon Taxes with Veto and No Rebate

Notes: "Relative" indicates percentage change relative to baseline outcomes.

More broadly, comparing our CBA results here with those of the Nash carbon tax setting of section 7, our findings suggest that optimal WTO rules on allowable CBAs will evolve with the evolving success of international cooperation over climate policy. Recall from our discussion in section 2 that during its transitional phase the EU's CBAM is based on direct emissions, while beginning with its definitive regime on January 1 2026 CBAM will be based on direct plus indirect emissions. Neither of these phases includes a rebate to exporters, but as we noted there is also discussion of introducing export rebates after the definitive regime for CBAM is in place. Our findings suggest that providing carbon tax rebates to exporters could have an unintended downside as long as countries continue to struggle over achieving effective international cooperation over climate policy.

8.2 Alternative Participation Constraints

We now explore the extent to which our results change if we replace the veto participation constraint of the previous subsection with a free-rider participation constraint. Under the free-rider participation constraint, a club member must achieve at least as much welfare inside the club as it could achieve if it stayed out of the club and best-responded against the club's choices in its absence.

We focus on the no-transfer case, and we interpret this alternative participation constraint as illustrating the sensitivity of our findings in the previous subsection to the demands of the participation constraints faced by the climate club. For brevity, we present only the scenario where carbon taxes apply to all sectors, though our results are similar for the scenario where agricultural production is exempt from carbon taxes for political economy/distributional reasons. And we apply the free-rider participation constraint to a single country, maintaining every other country's participation constraint at its veto level. For illustrative purposes, we consider the possibility that the free-rider participation constraint applies to Indonesia, China, or the US, on the grounds that the veto participation constraint already binds in equilibrium for Indonesia, that China is large and its production is relatively carbon intensive, and that the US has withdrawn from the Paris Agreement. We therefore think of these three countries as spanning the most interesting possibilities.

A first result is immediate. If the climate club is restricted to selecting a uniform carbon tax for its members, the club cannot be viable when either Indonesia, China or the US is subject to a free-rider participation constraint and all other club members are subject to a veto participation constraint. This reinforces our results of the previous subsection that participation constraints will have a large and negative impact on the ability of a climate club to achieve worldwide objectives if (large) international transfers are infeasible and the climate club is restricted to a uniform carbon tax for all members.

If the climate club can select country-specific carbon taxes for its members, we find that applying the free-rider participation constraint to either Indonesia, China or the US does not materially alter our main finding from the previous subsection, namely that country-specific carbon taxes are an effective way to address the participation constraints of member countries without reducing the ability of the climate club to achieve its worldwide objectives. Table 11 present the results under country-specific carbon taxes when Indonesia, China or the US, respectively, is subject to a free-rider participation constraint.[19] As a comparison of these results to those reported in column 1 of Table 9 and the global planner benchmark results reported in Table 3 confirms, while the payoffs for individual countries are impacted in the expected way when one country has a free-rider participation constraint (see Appendix Table A8), the climate club with country-specific carbon taxes can continue to achieve most of what the global planner achieves in terms of worldwide outcomes.

Free-rider Country	Indonesia	China	USA
Total Relative Welfare	4.98%	4.90%	5.15%
Average Relative Welfare	4.10%	3.07%	4.04%
Relative Emissions	-49.73%	-47.39%	-49.55%
Average Club Carbon Tax	$55.94	$60.86	$50.51
Free-rider Country Carbon Tax	$8.02	$27.48	$49.67

Table 11: All-but-One Country Clubs and Best Response Participation Constraints

Notes: "Relative" indicates percentage change relative to baseline outcomes. The country that is free-riding is indicated in the table. We compute optimal country-specific taxes that satisfy the baseline veto constraint except for the free-rider country, whose constraint is their best response welfare under the Nash equilibrium with the All-but-One Club.

Overall, our results here indicate that in the absence of the ability to make large international transfers, if either Indonesia, China or the US were subject to a free-rider participation constraint while all other countries continued to be subject to a veto participation constraint, it would be even more critical for the climate club to select country-specific carbon taxes for its members than is the case when all countries are subject to veto participation constraints as in the previous subsection, since absent this feature a climate club would not be viable in the present setting and Nash payoffs would prevail.

9 Conclusion

Despite the externalities associated with the global effects of carbon pollution, reducing carbon emissions does not require blowing up the international trading system embodied in the WTO. Using an estimated quantitative trade-and-emissions model, we have shown that a climate agreement that deviates from the usual design of uniform carbon taxes applied across its members and instead entertains the possibility of country-specific carbon taxes as a

[19] To avoid taxonomies, we do not report results for the country-specific carbon tax case when CBAs are also introduced, but the results are similar to those we report in earlier sections of the paper.

means of addressing participation constraints can achieve substantial reductions in worldwide emissions and offer a meaningful WTO-consistent alternative to the climate clubs described by Nordhaus (2015) that confront non-participants with the threat of WTO-inconsistent Nash tariff punishments. And we have also shown that the design of CBAs permitted by the WTO can impact the degree of worldwide carbon reduction and welfare improvements in important ways, finding that optimal WTO rules on permissible CBAs will evolve with the evolving success of international cooperation over climate policy.

Our analysis could be extended in a number of potentially important ways. One direction would be to link tariff negotiations directly with the introduction of carbon taxes and their associated CBAs in a joint agreement. This may allow for more uniform carbon taxes while still inducing the participation of countries that are unilaterally less inclined toward carbon taxation. Our analysis also holds fixed the emissions intensity in each country and sector; but carbon agreements could have indirect effects on technological adaptation, and such agreements could allow countries to directly contract over technological adaptation or technology transfer. Further, as noted, we have assumed that existing carbon taxes are still in the process of adjusting to their Nash equilibrium levels, and hence we do not require that our Nash carbon taxes match observed carbon taxes for our baseline year. An alternative would be to assume that observed carbon taxes in our baseline year reflect the Nash carbon taxes that arise in a world where governments place development/political weights on dirty good production, and where those weights would be calibrated so that the Nash carbon taxes match observed carbon taxes; our analysis could then be carried out from the perspective of the implied government welfare functions. Lastly, our analysis maintains existing WTO commitments for all countries. To the extent that countries differ in the strength of their commitment to WTO rules, one could consider how carbon agreements might change if certain countries or coalitions of countries deviate from existing WTO commitments.

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A Appendix

A.1 Country Aggregation

We collapse 67 regions in the ICIO data into 13 countries and 6 regions: the EU, Africa, Rest of Asia, Rest of Americas, Rest of Europe, and Rest of World. Our definition of China includes both China and Hong Kong. For sparsity, we include United Kingdom with the 27 EU countries in our definition of the EU. For Africa, Rest of Asia, Rest of Americas, and Rest of Europe we report the countries in each category in Table A1. Rest of World remains as characterized by the OECD's ICIO data.

Region	Constituent Countries
Africa	Morocco, South Africa, Tunisia
Rest of Americas	Chile, Colombia, Costa Rica, Argentina, Peru
Rest of Asia	New Zealand, Brunei Darussalam, Cambodia, Kazakhstan, Lao People's Democratic Republic, Malaysia, Myanmar, Philippines, Singapore, Chinese Taipei, Thailand, Viet Nam
Rest of Europe	Iceland, Israel, Norway, Switzerland

Table A1: Country Groupings

Notes: Regions aggregate individual countries used in the analysis. Country names reflect raw classifications prior to aggregation.

A.2 Industry Aggregation

We turn 45 industries from the ICIO data into 17 sectors. First, we exclude the ICIO industry "Activities of households as employers" with industry code D97T98. We include "Mining support services" in "Mining, Energy" and "Other transport equipment" with "Motor Vehicles". After this first aggregation, we then combine industries as listed in Table A2.

Industry Aggregate	Constituent Raw Industries
Chemicals	Chemicals, Pharmaceuticals
Electronics and Machinery	Electronic, Electrical equipment, Machinery, Transport equipment
Food	Fishing, Food products
Metals	Basic metals, Fabricated metals
Nonmetallic Minerals	Coke, petroleum, Non-metallic minerals
Other Mining	Mining, energy, Mining, non-energy
Other Services	Water supply, Post, Tourism, Media, Telecom, IT, Finance, insurance, Real estate, R&D, Administration, Public Sector, Education, Health, Entertainment, Other service
Transportation	Land transport, Water transport, Air transport
Wholesale and Retail	Wholesale, retail, Warehousing

Table A2: Industry Aggregations

Notes: Each aggregate industry category pools the listed raw industries used in the underlying data sources.

Exemptions	None			Agriculture		
CBA	None	Trad.	Leakage Neutral	None	Trad.	Leakage Neutral
USA	1.50%	1.58%	1.64%	1.23%	1.28%	1.34%
Africa	1.59%	1.44%	1.43%	1.30%	1.08%	1.14%
Australia	1.54%	1.55%	1.20%	1.29%	1.29%	0.93%
Brazil	1.56%	1.50%	1.26%	1.31%	1.28%	1.01%
Canada	1.60%	1.40%	1.55%	1.33%	1.12%	1.27%
China	1.16%	1.24%	1.23%	0.91%	0.93%	0.94%
EU	1.51%	1.60%	1.55%	1.26%	1.32%	1.26%
Indonesia	1.50%	1.39%	0.93%	1.23%	1.13%	0.67%
India	1.56%	1.48%	1.24%	1.25%	1.17%	1.01%
Japan	1.50%	1.65%	1.54%	1.26%	1.36%	1.25%
South Korea	1.50%	1.70%	1.41%	1.25%	1.39%	1.12%
Mexico	1.54%	1.41%	0.77%	1.25%	1.08%	0.56%
Rest of World	1.45%	1.45%	0.33%	1.28%	1.31%	0.19%
Rest of Americas	1.57%	1.52%	0.95%	1.32%	1.26%	0.70%
Rest of Asia	1.47%	1.48%	1.56%	1.19%	1.17%	1.27%
Rest of Europe	1.46%	1.58%	1.25%	1.27%	1.34%	1.13%
Russia	1.57%	1.23%	0.88%	1.39%	0.92%	0.63%
Saudi Arabia	1.52%	1.28%	0.49%	1.35%	1.01%	0.22%
Turkey	1.44%	1.56%	1.67%	1.18%	1.18%	1.35%
Total	1.45%	1.50%	1.34%	1.20%	1.22%	1.07%

Table A3: Relative Welfare under Nash Carbon Taxes

Notes: "Relative" indicates percentage change relative to baseline outcomes.

Policy Regime	Uniform, With Transfers				Uniform, No Transfers			Country-Specific, No Transfers		
Country	Tax	Transfer Share	Relative Welfare	Relative Emissions	Tax	Relative Welfare	Relative Emissions	Tax	Relative Welfare	Relative Emissions
USA	$51.46	-0.08%	7.30%	-30.12%	$51.25	7.39%	-30.44%	$49.44	7.45%	-29.60%
Africa	$51.46	-48.73%	-29.54%	-61.76%	$51.25	2.37%	-64.41%	$50.69	2.54%	-64.03%
Australia	$51.46	-2.79%	2.94%	-48.02%	$51.25	5.74%	-48.79%	$49.95	5.84%	-48.11%
Brazil	$51.46	-7.89%	-6.26%	-80.12%	$51.25	1.13%	-81.23%	$53.59	0.93%	-81.93%
Canada	$51.46	-9.19%	-3.41%	-48.88%	$51.25	5.33%	-50.59%	$52.53	5.20%	-51.58%
China	$51.46	-3.58%	-1.11%	-52.97%	$51.25	2.66%	-52.99%	$51.62	2.61%	-53.24%
EU	$51.46	0.29%	7.80%	-23.41%	$51.25	7.54%	-23.38%	$49.31	7.59%	-22.45%
Indonesia	$51.46	3.93%	-0.21%	-68.71%	$51.25	-4.37%	-68.78%	$51.71	-4.53%	-69.22%
India	$51.46	-7.64%	-5.57%	-52.41%	$51.25	1.98%	-52.36%	$50.98	2.06%	-52.19%
Japan	$51.46	1.90%	9.36%	-27.50%	$51.25	7.19%	-27.35%	$48.04	7.28%	-25.97%
South Korea	$51.46	1.30%	7.76%	-39.55%	$51.25	6.79%	-38.45%	$45.81	7.08%	-35.52%
Mexico	$51.46	-6.84%	-1.06%	-44.13%	$51.25	5.37%	-45.55%	$50.24	5.48%	-44.91%
Rest of World	$51.46	12.81%	17.66%	-59.62%	$51.25	0.39%	-60.95%	$53.01	0.03%	-62.13%
Rest of Americas	$51.46	2.27%	6.86%	-55.67%	$51.25	4.14%	-55.32%	$52.97	3.92%	-56.49%
Rest of Asia	$51.46	1.50%	4.74%	-49.28%	$51.25	3.35%	-49.08%	$49.18	3.71%	-47.67%
Rest of Europe	$51.46	-1.28%	6.00%	-14.50%	$51.25	7.39%	-15.84%	$58.04	7.31%	-18.84%
Russia	$51.46	-6.41%	-5.32%	-58.83%	$51.25	0.33%	-59.96%	$52.37	0.08%	-60.64%
Saudi Arabia	$51.46	-2.75%	1.68%	-49.82%	$51.25	4.27%	-50.50%	$50.04	4.37%	-50.06%
Turkey	$51.46	-6.86%	-1.98%	-48.36%	$51.25	4.72%	-48.41%	$50.54	4.80%	-48.12%
Total			5.20%	-49.44%		5.15%	-49.84%		5.16%	-49.84%

Table A4: Global Social Planner Taxes - No Exemptions

Notes: "Relative" indicates percentage change relative to baseline outcomes.

Policy Regime	Uniform, With Transfers				Uniform, No Transfers			Country-Specific, No Transfers		
Country	Tax	Transfer Share	Relative Welfare	Relative Emissions	Tax	Relative Welfare	Relative Emissions	Tax	Relative Welfare	Relative Emissions
USA	$50.73	0.40%	5.36%	-27.74%	$50.97	4.94%	-27.67%	$54.26	4.92%	-28.66%
Africa	$50.73	-44.13%	-31.53%	-60.16%	$50.97	-1.23%	-61.91%	$59.06	-2.11%	-64.06%
Australia	$50.73	-0.36%	4.04%	-29.81%	$50.97	4.42%	-29.98%	$52.50	4.44%	-30.37%
Brazil	$50.73	0.85%	5.75%	-10.42%	$50.97	4.76%	-10.03%	$64.12	4.32%	-11.43%
Canada	$50.73	-3.61%	0.46%	-24.73%	$50.97	4.18%	-26.55%	$54.98	4.02%	-27.83%
China	$50.73	-1.90%	-1.89%	-51.59%	$50.97	0.13%	-51.72%	$54.35	-0.30%	-53.34%
EU	$50.73	0.79%	6.08%	-18.85%	$50.97	5.21%	-18.63%	$51.31	5.25%	-18.62%
Indonesia	$50.73	4.05%	5.52%	-18.80%	$50.97	0.88%	-18.48%	$36.10	2.80%	-16.04%
India	$50.73	-5.48%	-6.16%	-43.12%	$50.97	-0.60%	-43.29%	$51.43	-0.62%	-43.46%
Japan	$50.73	1.67%	6.73%	-27.53%	$50.97	4.79%	-27.43%	$49.63	4.87%	-26.76%
South Korea	$50.73	2.88%	7.29%	-39.37%	$50.97	4.13%	-38.91%	$45.66	4.45%	-35.98%
Mexico	$50.73	-4.78%	-1.73%	-34.94%	$50.97	3.09%	-35.94%	$53.95	2.96%	-37.03%
Rest of World	$50.73	3.53%	7.87%	-15.02%	$50.97	3.59%	-15.68%	$34.92	4.54%	-13.82%
Rest of Americas	$50.73	0.69%	5.60%	-10.90%	$50.97	4.79%	-10.83%	$42.76	5.18%	-9.62%
Rest of Asia	$50.73	-0.91%	1.02%	-33.81%	$50.97	2.06%	-33.88%	$49.41	2.24%	-33.20%
Rest of Europe	$50.73	0.66%	6.15%	-13.54%	$50.97	5.38%	-13.26%	$56.54	5.37%	-14.91%
Russia	$50.73	-5.90%	-6.00%	-52.34%	$50.97	-0.51%	-53.16%	$54.59	-1.08%	-54.72%
Saudi Arabia	$50.73	0.58%	3.04%	-49.51%	$50.97	2.42%	-49.53%	$57.13	2.06%	-51.60%
Turkey	$50.73	2.58%	4.49%	-47.89%	$50.97	1.57%	-48.00%	$52.82	1.46%	-48.88%
Total			3.54%	-34.16%		3.53%	-34.36%		3.56%	-34.68%

Table A5: Global Social Planner Taxes - Agriculture Exempt

Notes: "Relative" indicates percentage change relative to baseline outcomes.

Exemptions	None			Agriculture		
Transfers	Yes		No	Yes		No
Uniform Tax	$51.46		$29.67	$50.66		$33.92
Country	Transfer Share	Relative Welfare	Relative Welfare	Transfer Share	Relative Welfare	Relative Welfare
USA	-0.64%	6.68%	5.85%	0.02%	4.94%	4.19%
Africa	-2.93%	-0.00%	2.88%	1.09%	0.00%	0.00%
Australia	-3.83%	1.96%	5.04%	-1.04%	3.32%	3.88%
Brazil	-1.16%	-0.00%	1.81%	0.37%	5.17%	4.14%
Canada	-5.35%	-0.00%	5.01%	-3.88%	0.17%	3.90%
China	-2.47%	-0.00%	3.46%	-0.13%	0.00%	1.33%
EU	-0.53%	6.88%	5.92%	0.01%	5.21%	4.37%
Indonesia	4.11%	-0.00%	0.00%	3.17%	4.47%	1.81%
India	-1.88%	-0.00%	3.33%	0.53%	0.00%	0.83%
Japan	0.95%	8.20%	5.70%	0.70%	5.56%	4.11%
South Korea	-0.16%	6.21%	5.56%	1.30%	5.57%	3.76%
Mexico	-5.68%	-0.00%	5.01%	-2.99%	0.00%	3.16%
Rest of World	10.82%	14.55%	2.22%	0.54%	4.20%	3.27%
Rest of Americas	1.09%	5.47%	4.37%	0.14%	4.95%	4.19%
Rest of Asia	-0.28%	2.85%	4.12%	-1.94%	-0.00%	2.55%
Rest of Europe	-1.94%	5.27%	5.76%	0.20%	5.59%	4.46%
Russia	-0.65%	-0.00%	2.45%	0.47%	0.00%	1.04%
Saudi Arabia	-4.01%	0.49%	3.87%	-0.14%	2.27%	2.42%
Turkey	-4.70%	-0.00%	4.26%	1.21%	2.90%	2.08%
Total		5.19%	4.71%		3.53%	3.35%

Table A6: Climate Club Uniform Carbon Taxes with Veto Participation Constraints

Notes: "Relative" indicates percentage change relative to baseline outcomes.

Exemptions	None						Agriculture			
CBA	None		Trad.		Leakage Neutral		None		Trad.	
Country	Tax	Relative Welfare	Tax	Relative Welfare	Tax	Relative Welfare	Tax	Relative Welfare	Tax	Relative Welfare
USA	$49.67	7.39%	$49.32	7.46%	$33.85	5.46%	$55.17	4.79%	$51.92	5.00%
Africa	$50.91	2.44%	$52.88	0.67%	$30.43	0.00%	$41.63	-0.00%	$37.33	-0.00%
Australia	$50.15	5.76%	$51.16	5.17%	$40.05	2.98%	$53.23	4.29%	$55.84	3.81%
Brazil	$53.84	0.86%	$55.87	1.18%	$46.41	0.00%	$65.55	4.16%	$114.72	2.63%
Canada	$52.81	5.13%	$54.51	4.77%	$29.12	4.37%	$56.04	3.85%	$64.53	3.10%
China	$51.86	2.51%	$52.41	2.66%	$43.37	1.16%	$51.45	0.00%	$53.96	-0.00%
EU	$49.50	7.54%	$48.64	7.71%	$9.50	5.63%	$51.92	5.13%	$50.08	5.35%
Indonesia	$37.29	-0.00%	$35.62	-0.00%	$27.18	0.00%	$36.58	2.63%	$38.47	1.97%
India	$51.19	1.93%	$53.86	-0.00%	$33.83	0.00%	$46.60	-0.00%	$44.48	0.00%
Japan	$48.17	7.22%	$47.82	7.56%	$14.23	5.19%	$50.20	4.75%	$48.73	5.12%
South Korea	$45.93	7.02%	$46.83	7.39%	$1.59	4.80%	$46.23	4.29%	$46.72	4.73%
Mexico	$50.48	5.40%	$51.48	4.47%	$33.74	2.48%	$54.85	2.79%	$54.03	2.26%
Rest of World	$52.85	-0.00%	$52.22	0.25%	$27.55	0.00%	$35.40	4.39%	$39.98	3.85%
Rest of Americas	$53.25	3.83%	$53.60	3.50%	$48.36	1.04%	$43.46	5.05%	$50.57	4.27%
Rest of Asia	$49.09	3.56%	$49.82	3.24%	$20.19	3.66%	$50.21	2.05%	$51.03	1.98%
Rest of Europe	$58.35	7.25%	$44.30	7.64%	$-0.00	5.13%	$57.62	5.24%	$48.08	5.49%
Russia	$52.48	-0.00%	$40.57	-0.00%	$32.58	0.00%	$47.81	0.00%	$32.00	0.00%
Saudi Arabia	$50.23	4.29%	$52.27	0.90%	$35.80	-0.00%	$58.16	1.87%	$39.26	0.00%
Turkey	$50.81	4.72%	$50.03	5.08%	$14.93	5.09%	$53.82	1.28%	$51.70	1.67%
Total		5.15%		5.14%		3.57%		3.55%		3.54%

Table A7: Climate Club Country-Specific Carbon Taxes with Veto Participation Constraints

Notes: "Relative" indicates percentage change relative to baseline outcomes.

Free-rider Country	Indonesia			China			USA		
Country	Tax	Relative Welfare	Relative Emissions	Tax	Relative Welfare	Relative Emissions	Tax	Relative Welfare	Relative Emissions
USA	$55.32	7.28%	-31.84%	$63.09	6.65%	-34.81%	$49.67	7.39%	-29.73%
Africa	$56.26	1.63%	-66.34%	$63.64	-0.00%	-69.23%	$50.90	2.44%	-64.17%
Australia	$56.49	5.36%	-51.45%	$65.62	4.35%	-55.73%	$50.15	5.76%	-48.29%
Brazil	$59.08	0.46%	-83.01%	$59.16	-0.00%	-83.02%	$53.85	0.86%	-82.00%
Canada	$58.58	4.68%	-54.34%	$67.30	3.53%	-58.04%	$52.81	5.13%	-51.75%
China	$56.93	1.85%	-55.63%	$27.48	5.49%	-37.04%	$51.86	2.51%	-53.39%
EU	$54.64	7.46%	-24.54%	$62.89	6.82%	-28.15%	$49.50	7.54%	-22.57%
Indonesia	$8.02	7.88%	-11.66%	$36.61	-0.00%	-56.35%	$37.29	0.00%	-57.70%
India	$56.43	0.93%	-55.05%	$59.39	-0.00%	-56.59%	$51.19	1.93%	-52.37%
Japan	$52.09	7.17%	-27.41%	$60.06	6.48%	-31.58%	$48.17	7.22%	-26.07%
South Korea	$49.00	6.95%	-36.73%	$55.09	6.02%	-41.44%	$45.92	7.02%	-35.61%
Mexico	$56.05	4.91%	-48.16%	$64.76	3.71%	-53.03%	$50.48	5.40%	-45.10%
Rest of World	$53.52	0.00%	-61.96%	$52.08	-0.00%	-60.71%	$52.85	0.00%	-62.03%
Rest of Americas	$59.05	3.23%	-59.47%	$70.43	1.45%	-64.77%	$53.25	3.83%	-56.66%
Rest of Asia	$55.38	2.45%	-52.39%	$64.03	0.73%	-57.04%	$49.09	3.56%	-47.98%
Rest of Europe	$64.78	7.18%	-20.83%	$73.41	6.59%	-23.41%	$58.35	7.25%	-18.97%
Russia	$53.01	0.00%	-60.75%	$51.30	-0.00%	-59.77%	$52.48	0.00%	-60.71%
Saudi Arabia	$54.37	4.03%	-51.50%	$62.61	3.02%	-54.15%	$50.22	4.29%	-50.15%
Turkey	$55.89	4.38%	-50.14%	$64.08	3.43%	-53.32%	$50.81	4.72%	-48.24%
Total		4.98%	-49.73%		4.90%	-47.39%		5.15%	-49.55%

Table A8: Optimal Country-Specific Taxes with Free Rider Constraint

Notes: "Relative" indicates percentage change relative to baseline outcomes.