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Assessing different European Carbon Border Adjustment Mechanism implementations and their impact on trade partners

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The European Union (EU) will implement a Carbon Border Adjustment Mechanism (CBAM) to reach its climate mitigation targets while avoiding the relocation of its industries to countries with less stringent climate policies (carbon leakage). The exact implementation and possible future extensions of such an EU CBAM are still being debated. Here we apply a throughflow-based accounting method on detailed trade network data to assess the coverage of different implementation options. Using a stylized comprehensive EU CBAM as benchmark, we then quantify how an EU CBAM may affect the EU's trade partners by channeling the EU carbon price to other countries. We find that middle- and low-income countries for which the EU is an important export market would be disproportionally impacted even under conservative implementation options. We finally explore different international revenue recycling schemes to make the EU CBAM inclusive toward vulnerable countries and able to foster global climate cooperation.

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The European Union (EU) aims to reduce net greenhouse gas emissions by at least 55% by 2030, relative to 1990[1]. The reach of this ambitious goal relies largely on the reform and extension of the EU Emissions Trading System (ETS). Under an ETS, a limited volume of emission permits is auctioned or freely allocated to emitters and then traded on a dedicated market. The resulting emission price penalizes carbon-intensive production and incentivizes the adoption of low-carbon technologies[2]. However, higher costs for industries subject to an ETS may lead to a relocation of carbon-intensive industries to countries with less stringent climate policies[3]. In order to minimize such "carbon leakage", the EU ETS currently entails free allowances: a limited amount of emission permits allocated to sectors particularly exposed to carbon leakage (emission-intensive and trade-exposed sectors—EITE), to avoid competitiveness distortion for EU producers on both the domestic and export markets. However, free allowances are criticized for hindering the EU ETS by reducing the emission reduction ambition in EITE sectors and are incompatible with the EU target of net-zero emissions by 2050[4].

As part of the "Fit for 55" policy package, the EU will gradually replace the free allowances by a Carbon Border Adjustment Mechanism (CBAM)[1]. This CBAM will apply the price prevailing on emission allowances within the EU ETS to emissions released to produce commodities imported to the EU, unless a comparable emission price is already enforced in the exporting country. Export rebates are also currently discussed to refund allowance costs for products exported from the EU[5]. While a CBAM without export rebates would level the playing field within the EU domestic market only, export rebates would ensure that the competitiveness of EU production on the world market can be maintained.

Beyond producers and consumers within the EU, such an EU CBAM will affect other economic actors along international supply chains. Numerical analyses have shown that, even though the EU CBAM could in principle motivate emissions reduction abroad, key EU trade partners could as well retaliate with trade sanctions[5,6]. Understanding how the EU emission price is channeled to other countries is therefore crucial to increase acceptance of the CBAM by EU trade partners and to avoid repercussions on the global climate cooperation. Previous studies have analyzed the effect of an EU CBAM on the EU's major trade partners[5,7,8], but little is known about the exposure of middle- and low-income countries as they are usually modeled at a low level of detail. Yet, research at the sub-regional level has shown that the distributional effects of an EU CBAM might exhibit a broad variation depending on local conditions[7].

We contribute to this literature by developing an analytical framework that allows numerically assessing the emission coverage of different EU CBAM implementations and their effects on the EU's trade partners with a high spatial resolution. For that purpose, we use a throughflow-based accounting technique that allows us comprehensively tracking the CO_2 emissions caused by all the supply chains starting from, going through, and ending in the EU[9] and apply it on highly-detailed economic network data from 2016[10,11]. This approach enables estimating the pressure that an EU CBAM would impose on individual countries through direct and indirect trade dependencies, before any dynamic trade adjustments. Even though such trade adjustments might be changing the final effect of the CBAM, modelling them usually requires major assumptions on model parameters, a reduction of the regional resolution and a decrease in the tractability of the model. Here, by using simple assumptions, we complement such dynamic approaches by transparently estimating the drivers of these dynamic effects. Furthermore, we provide an assessment of the exposure of middle- and low-income countries to the EU CBAM that is missing in the current literature.

The structure of the paper is as follows. First, we assess the coverage of several implementations of an EU CBAM based on different assumptions of products and scopes coverage. Second, we use a hypothetical Comprehensive CBAM (CCBAM) that covers all emissions generated by producing imports to the EU as a benchmark for evaluating the multilateral effects of the EU CBAM: we explore conceptually through which channels carbon pricing within the EU affects its trade partners and empirically identify the countries that would likely be the most affected by an EU CCBAM. Third, we propose compensating schemes for an international recycling of the revenues of such an EU CCBAM to make it inclusive toward the most vulnerable countries. In the final section, we discuss the limitations of our approach, the robustness of our findings and their implications for policymaking.

Our results show that the coverage of the current EU CBAM proposal is relatively modest compared to the total emissions caused by all EU imports, and that this incomplete coverage might limit the efficiency of the EU CBAM. Even with conservative implementation options, we find that some low- and middle-income countries dependent on the EU for their exports would be disproportionally affected by the EU CBAM, as a large share of their domestic emissions would be covered by the EU emission price. Finally, the implementation of an inclusive international recycling of the EU CBAM fiscal revenue might increase the acceptability of the EU CBAM globally by mitigating its impacts on the most vulnerable countries, but its implementation will require balancing the conflicting interests of the EU trade partners.

Results

Comprehensiveness of the EU CBAM. The CBAM that will be introduced in 2023 will initially only apply to the direct emissions caused by the production of iron and steel, aluminum, cement, fertilizers, electricity and hydrogen imported into the EU[1]. Based on Multi-Regional Input-Output data for the year 2016[10,11], we estimate these emissions to be 83 Mt CO_2 (Fig. 1, "Scope 1 emissions", "Conservative coverage"), in absence of trade adjustments (see discussion). As per the current CBAM proposal, a further extension of the CBAM to a broader range of products (horizontal coverage) is already envisioned ("the coverage of the CBAM should reflect the activities covered by the EU ETS"[1]). Encompassing all the sectors currently covered by the EU ETS would increase the coverage of the EU CBAM to 179 Mt CO_2 ("Scope 1 emissions", "Ambitious coverage"). As electricity production is a major source of emissions globally, the planned EU CBAM should also cover indirect emissions from electricity use (Scope 2 emissions)[1]. Some downstream products derived from emission-intense commodities will likely be covered as well, as otherwise exporters to the EU could easily circumvent the EU CBAM by trading unregulated processed products instead of regulated raw materials. We estimate that including both scope 2 emissions and downstream products into the CBAM could enhance the volume of emissions covered by the EU CBAM to 328 Mt CO_2 or 490 Mt CO_2, depending on the horizontal coverage ("Scopes 1 and 2 and downstream product"s, "Conservative coverage" and "Ambitious coverage", respectively). Finally, an EU CBAM that would also cover the direct industrial emissions caused by EU imports in sectors not covered by the current EU ETS would amount to 504 Mt CO_2 when excluding downstream products ("Scope 1 emissions", "Comprehensive coverage") and to 932 Mt CO_2 when including these ("Scope 1 and 2 emissions and downstream products").

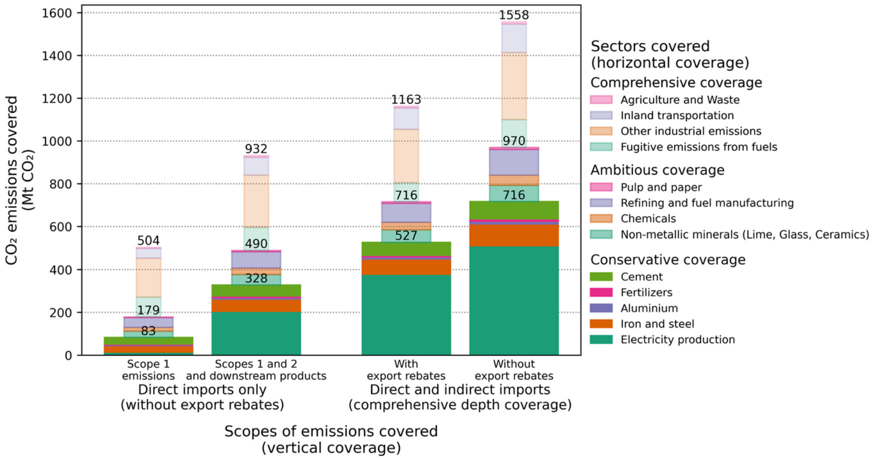

Fig. 1 CO_2 emissions covered by an EU CBAM under different implementation options. Bars show how much CO_2 emissions would be covered by an EU CBAM (assuming no trade adjustments), depending on the scope of emissions accounting (i.e., the number of layers in the supply chains included in emissions estimations - vertical coverage) and on the sectoral coverage (i.e., the sources of emissions covered by the EU CBAM — horizontal coverage). Four alternative vertical coverages are shown here. The option "Scope 1 emissions" only covers emissions directly caused by imports to the EU. Option "Scopes 1 and 2 and downstream products" also includes the emissions of the direct suppliers of exporters to the EU. These two implementation options are in line with the current EU CBAM proposal. By contrast, the "Direct and indirect imports" options account for all upstream emissions caused along the supply chains used to produce exports to the EU. In the setting "With export rebates", emissions caused by EU imports for producing goods that are further exported from the EU are excluded from the EU CBAM coverage. Estimated CO_2 emissions are detailed based on the process causing them (see Methods and Data). These processes are grouped into three horizontal coverage aggregates. The "Conservative coverage" category (dark, wide blocks) entails emissions that are explicitly addressed in the EU CBAM proposal. These provide a lower bound estimate of the emissions that would be covered by the current EU CBAM proposal. Sectors included in the "Ambitious coverage" category (half-transparent, medium width blocks) are processes covered by the current EU ETS which may eventually be covered by the EU CBAM as well. The sum of the emissions covered in the conservative and ambitious categories form together the upper bound of a sectoral coverage in line with current EU CBAM policy proposal. Adding light and thin blocks forms a "Comprehensive coverage" category, which would cover all sectors and all sources of emissions and hence corresponds to an extension of the CBAM to all industrial emissions. All data refer to 2016. International transportation-, land use- and final use-related emissions are not included here. Detailed data points are provided in Supplementary Table 1. Supplementary Table 2 details the processes covered in the different horizontal coverages.

A Comprehensive CBAM (CCBAM) that would address all imports to the EU ("Comprehensive coverage" on the horizontal dimension) and all indirect emissions caused by these imports ("Direct and indirect imports - Without export rebates") would cover 1 558 Mt of CO_2 through products imported to the EU. Even for the most conservative product coverage ("Conservative coverage"), a comprehensive scope of emissions already increases the volume of emissions priced nine fold (from 83 to 716 Gt CO_2 — "Direct and indirect imports - Without export rebates"). In particular, emissions from indirect electricity use increase sharply from 14 MtCO2 to 511 Mt CO2 (see Supplementary Table 1) when considering a deeper accounting scope: direct electricity imports to the EU represent only 3% of the total emissions from the electricity used to produce EU imports ("Direct and indirect imports - Without export rebates").

Failing to comprehensively price the upstream emissions caused by EU imports could decrease the competitiveness of some EU industries in the long term, as producers along the supply chains located in third countries would not bear the price of upstream emissions. As the announced EU CBAM would only cover a fraction of all emissions caused by products imported to the EU, it would only partially level the playing field between EU producers and their international competitors. In contrast, an EU CCBAM would thoroughly reconcile the EU abatement targets with competitiveness concerns. Even though such a CCBAM is still hypothetical due to administrative, technical, legal, and political reasons[5], it can serve as useful benchmark to evaluate the comprehensiveness of alternative CBAM implementations. In the remainder of the paper, we will focus on such an EU CCBAM and evaluate its impacts on the EU's trade partners. We assess the robustness of our findings with respect to more conservative implementation options in the discussion section.

Pricing locally, counting globally. An EU CCBAM covering all sectors and scopes in combination with a comprehensive carbon price on all EU domestic industrial emissions would cover a total of 3871 $MtCO_2$ (Fig. 2). About 60% of these emissions stem from domestic industrial production, while the remaining 40% would be priced via the EU CCBAM. Under such a CCBAM regime, exporters to the EU compete under an emission price (Fig. 2a, lower left corner): as the emissions they cause increase the price of their products, they have an incentive to reduce their emissions and those of their suppliers to gain competitiveness on the EU market. We call this incentive upstream pressure. Without export rebates, the price signal of the EU ETS is also channeled downstream along the supply chains, to non-EU consumers (Fig. 2a, lower right corner). However, such downstream pressure may have a negative effect on global carbon emissions, as it distorts the international competition in favor of producers not subjected to a carbon price (consumption leakage)[12]. The combination of a domestic carbon price, a CCBAM and export rebates hence conveys the upstream pressure while minimizing the potentially adverse downstream pressure.

Beyond the upstream and downstream pressures created by an EU CCBAM and a domestic carbon price, these policy instruments would also create a fiscal resource for the EU (Fig. 2b). Assuming a carbon price at 100€/t CO_2, the combination of a domestic carbon price and an EU CCBAM would yield between €293 billion (with export rebates) and €387 billion (without export rebates) per year to the EU budget, which

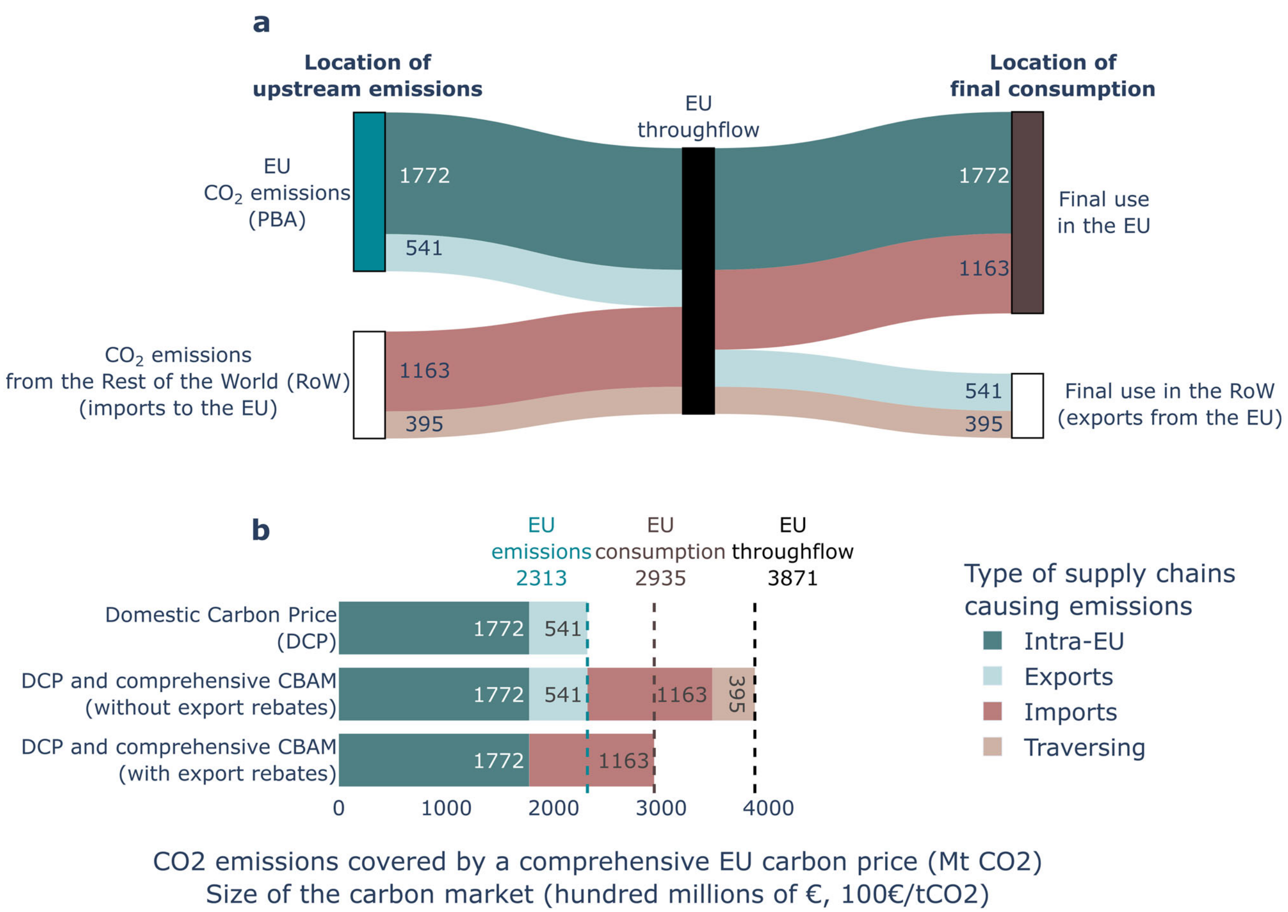

Fig. 2 Multilateral effects of comprehensive carbon pricing options in the EU. Panel **a** shows the upstream CO_2 emissions released along the supply chains involving the EU (central black bar). These emissions occur either in the EU (blue bar, upper left) or in the rest of the world (white bar, bottom left). The final product of these supply chains is used either in the EU (brown bar, upper right) or in the rest of the world (white bar, bottom right). The flows' thickness is proportional to the volume of upstream CO_2 emissions caused. Panel **b** describes the type of the supply chains covered by different comprehensive carbon pricing options and the size of the carbon market created, assuming an illustrative carbon price of 100€ per tCO_2. A Domestic Carbon Price (DCP) would cover all emissions generated within the EU, both for producing goods consumed in the EU (Intra-EU supply chains, dark green) and for producing goods consumed abroad (exports, light green). A comprehensive CBAM without export rebates would cover imported emissions as well (dark and light red), no matter whether these imports ultimately serve final users in the EU (Imports, dark red) or are used to produce goods further reexported outside of the EU (traversing supply chains, light red). Export rebates would exclude exported as well as traversing supply chains from the carbon pricing. We consider no free allocations here, as these are supposed to be phased out while the EU CBAM gets implemented. The comprehensive coverage analyzed here corresponds to a comprehensive sectoral coverage and a comprehensive depth coverage (see Fig. 1). We do not consider potential trade adjustments here.

corresponds to about 660€ per year and 870€ per year per EU citizen, respectively[13]. Even though our analysis likely overestimates the revenue of an EU CBAM (see the discussion section below), the existence of such fiscal revenue could create an incentive for non-EU countries to implement their own carbon pricing scheme — at least on their exports — to get the fiscal revenue otherwise captured by the EU.

This incentive would apply more intensively to countries releasing a large share of their emissions to supply the EU final consumers, as a substantial portion of their domestic CO_2 emissions would be covered by an EU CCBAM (relative upstream pressure, Fig. 3). According to our analysis, this is the case for many middle- and low-income countries, in particular in North and Sub-Saharan Africa. As the exports from these countries are largely directed to the EU and poorly diversified (Supplementary Fig. 1), these economies would have limited options to dampen the upstream pressure caused by an EU CCBAM. Furthermore, most of these countries have minor historical emission responsibilities while simultaneously being at the front line of climate change impacts[14–16]. An EU CCBAM that would put high pressure on such countries would oppose the fundamental principle of "shared but differentiated responsibilities" of the United Nations Framework Convention on Climate Change, which states that those countries should be supported in their transition to a low-carbon economy[17].

Building a climate coalition. The implementation of a comprehensive and inclusive EU CCBAM could therefore include compensating measures to acknowledge the differentiated responsibilities of the EU's trade partners in the climate crisis. One avenue to alleviate the upstream pressure caused by a comprehensive EU CCBAM on the most vulnerable countries is to exempt them, either indirectly by limiting the coverage of the EU CCBAM to a selected set of industrial commodities which are not essential for these countries, or directly by exempting the imports from these countries from the EU CCBAM. However, restricting the EU CCBAM to a range of industries secondary to these countries would create a substantial entry cost to these sectors, which may hinder their development in low- and middle-

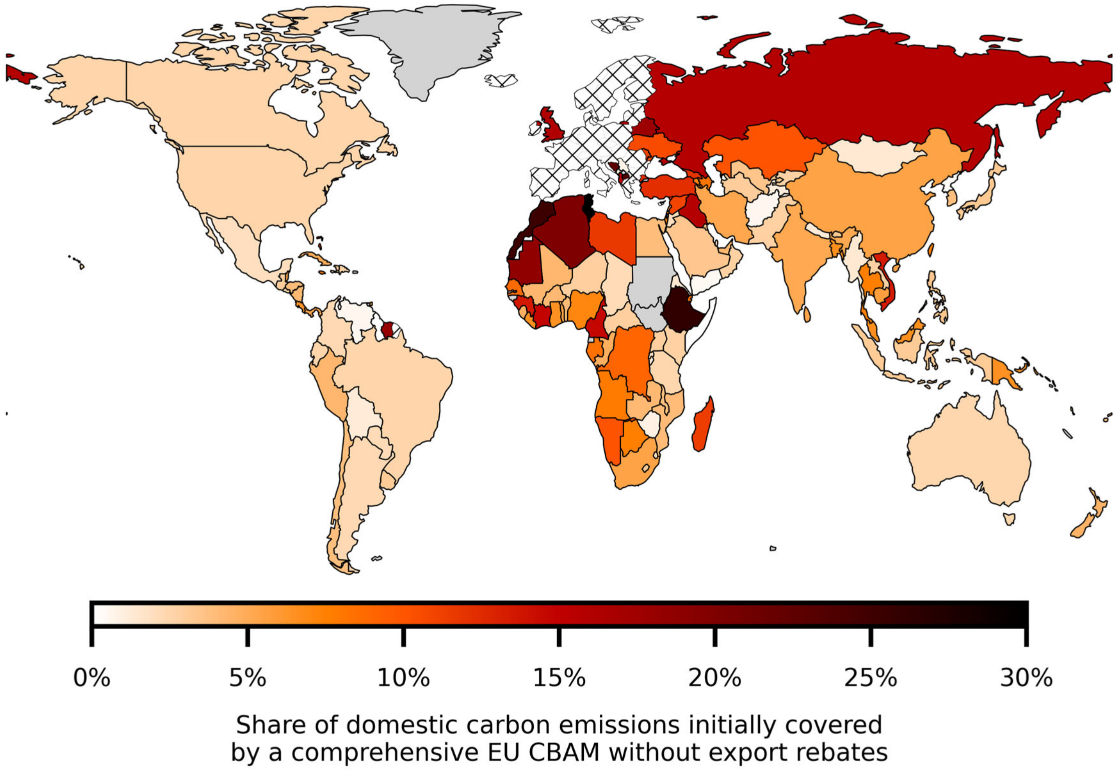

Fig. 3 Relative upstream pressure induced by a comprehensive EU CBAM without export rebates. The relative upstream pressure is defined as the share of CO_2 emissions caused to supply the final demand in the EU, as a percentage of domestic carbon emissions. Grey indicates lack of data, hatchings indicates member countries of the EU ETS. The relative upstream pressure does not consider possible trade adjustments.

income countries. In turn, exempting some countries from the EU CCBAM could give an incentive to these countries to develop emission-intense industries, hence creating "pollution havens" and harmful lock-in effects[18]. An alternative, but less discussed avenue is an international recycling of the EU CCBAM revenues (Fig. 4). As for the double dividend yielded by a coherent recycling of the revenue of a domestic carbon price[19], the inclusive recycling of the revenues of the EU CCBAM could likely benefit global climate cooperation, both by increasing the acceptability of the EU climate policy within non-EU countries and by helping the most vulnerable countries to access low-carbon technologies or to adapt to a changing climate.

Implementing an inclusive recycling scheme of an EU CCBAM revenue would require balancing the conflicting interests of the EU trade partners. In absence of revenue recycling, fossil fuel exporters such as Russia, Algeria or Saudi Arabia would be strongly affected by an EU CCBAM on a per capita basis (Fig. 4a). Refunding countries proportionally to the upstream pressure they experience would hence implicitly favor fossil fuel exporting countries (Fig. 4b), compared to the absence of a recycling scheme (Fig. 4a). Such option might ease the implementation of the EU CCBAM by saving the interest of major trade partners and limit the likelihood of trade retaliations[6]. However, it is at risk of neutralizing the effect of the carbon price, unless the recycled revenues are targeted toward the development of low-carbon alternatives.

Alternatively, the EU CCBAM revenue could be used to foster low-carbon development and to compensate for the damage caused by historical CO2 emissions. Recycling schemes based on historical climate damages (Fig. 4c, here based on an empirically derived estimate of the influence of anthropogenic climate forcing on historical economic output[20]), or on per-capita revenue (Fig. 4d) would strongly benefit countries in Africa, South-East Asia, and South America. In particular, a recycling scheme aligned with historical or expected climate damages could support the "loss and damages" climate fund agreed upon at the 27th United Nations Conferences of the Parties in 2022[21]. In conclusion, a recycling scheme targeted at helping low- and middle-income countries to adapt to a warmer climate and to develop low-carbon technologies could be a compensation for these countries and render them more likely to accept the implementation of an EU CCBAM. However, such a recycling scheme would not decrease the risk of retaliation from major EU trade partners such as the US, China, and fuel-exporting countries, as these would remain net losers in most settings assessed here. Designing an inclusive revenue recycling scheme for the EU CBAM will hence require balancing these conflicting interests.

Discussion

Our analysis is based on a throughflow-based accounting framework that evaluates the effects of a comprehensive EU CBAM in terms of upstream and downstream pressures, based on the CO_2 emissions that would be covered by the implementation of an EU CCBAM. Our approach does not depict possible dynamic adjustments in production, trade, and consumption patterns, such as a transition to low-carbon energy production by trade partners or a shift to importing goods with a lower carbon intensity in the EU[8]. Considering possibilities to respond to a carbon price by, for instance, applying more efficient production technologies or using low-carbon energy sources would lower the adjustment burden and reduce the EU CCBAM revenue and coverage estimated here. The extent to which countries can adjust depends inter alia on their export portfolio, their technological capabilities, and their potential to produce renewable energy[22].

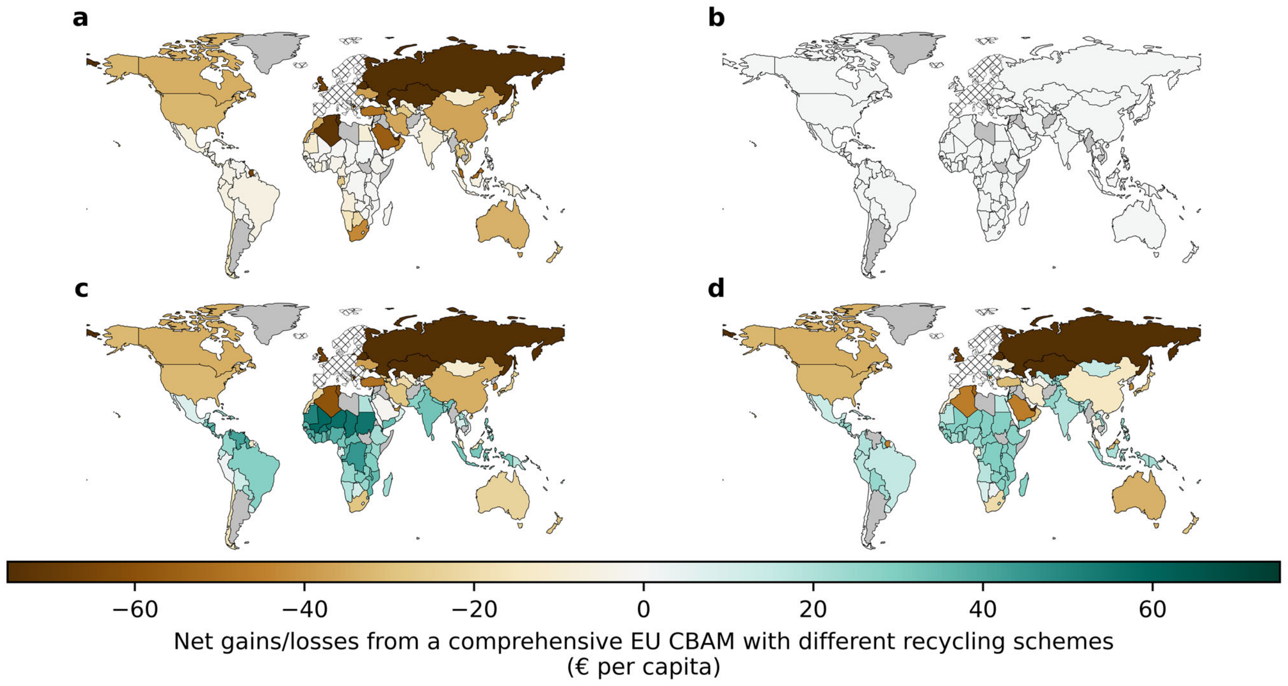

Fig. 4 Inclusiveness of a comprehensive EU CBAM without export rebates if the revenue is fully recycled towards non-EU countries based on different indicators. The proportion of the revenue each country receives is estimated based on the following indicators (see Materials and Data for details): **a** No recycling; **b** Emissions covered by the comprehensive EU CBAM; **c** Historical impacts of anthropogenic warming on economic output[20]; **d** Difference in per capita Gross Domestic Product to the EU average. Losses are assumed to correspond to the upstream pressure, measured as the value of CO_2 emissions caused in a country to supply the final demand in the EU multiplied by a carbon price of 100€ per tCO_2. Grey indicates lack of data, hatchings indicate member countries of the EU ETS. Supplementary Fig. 2 shows the revenue recycled to each individual country on a per capita basis.

For instance, whereas producers of energy-intensive products can draw on a range of available mitigation options, exporters of fossil fuels will face larger challenges to reduce the emission intensity of their exports. Hence, the former will find it easier to adjust to an EU CCBAM than the latter. The implications of these adjustments cannot be addressed by our method: quantifying such effects requires making a range of assumptions on parameters for which a strong empirical basis is largely missing. This would add substantial uncertainty to the analysis and make the interpretation of the results of our analysis challenging. Instead, a static approach similar to ours is frequently employed in analyses of the distributional effects of climate policy for the sake of tractability[23]. Reconciling our framework with dynamic models allowing some level of adjustment while conserving a high enough regional resolution is a promising avenue for future research.

Our methods and data entail several sources of uncertainties that may affect our numerical results. First, economic network and emission data from middle- and low-income countries may be of limited quality and have a limited sectoral resolution[10,11]. Second, our assessment of the CO_2 emissions caused by EU imports uses process-based emission data, while the EU CBAM is applied at the product level. Since few studies have focus on the impact of a CBAM on low- and middle-income countries, further research using alternative data sources and methods is required to validate our findings. Another source of uncertainty is the temporal dimension: our analysis uses data from 2016, while the EU CBAM will become operational in the forthcoming years. Technological change such as the implementation of low-carbon processes and energy sources should arguably reduce the volume of emissions covered by the EU CBAM. As high-income countries are globally setting more ambitious abatement targets than middle- and low-income countries, it is likely that the wealthiest trade partners of the EU will decarbonize their economies faster than low- and middle-income countries. Our finding that the latter are more strongly exposed to the EU CBAM hence seems robust to this aspect. Hydrogen production is also not included in our model as it was marginal in 2016, even though it may become a larger source of emissions in the future as the trade of hydrogen is set to increase in the next decades[24]. Using prospective models and data might provide guidance on the future distributional effects of the EU CBAM but would also imply major uncertainties regarding technological change and economic development scenarios.

As shown in Fig. 1, the comprehensive EU CCBAM that we analyze is more ambitious than the EU CBAM currently envisioned: based on our analysis, an EU CCBAM would cover between 3 and 20 times more emissions than the current policy proposal and fully level the playing field between the EU producers and their international competitors with regard to carbon pricing. However, the implementation of such a CCBAM faces challenges that we cannot address here. For instance, the proper channeling of the EU carbon price would require an accurate, regularly updated, and transparent estimation of the CO_2 emissions caused for the production of each individual product imported to the EU, which goes beyond the capability of current evaluation techniques[25]. Even if such product-level assessment was available, the administrative costs of monitoring such an EU CCBAM and the induced trade frictions could exceed the financial benefits of extending the EU CBAM to a comprehensive product and scopes coverage[5]. While an EU CCBAM is largely hypothetical, it remains theoretically attractive as it provides a simple benchmark to compare possible implementations to. At the same time, it allows avoiding assumptions on the exact design of the EU CBAM, which is still under debate, thus making our analysis more transparent. Still, we acknowledge that both the

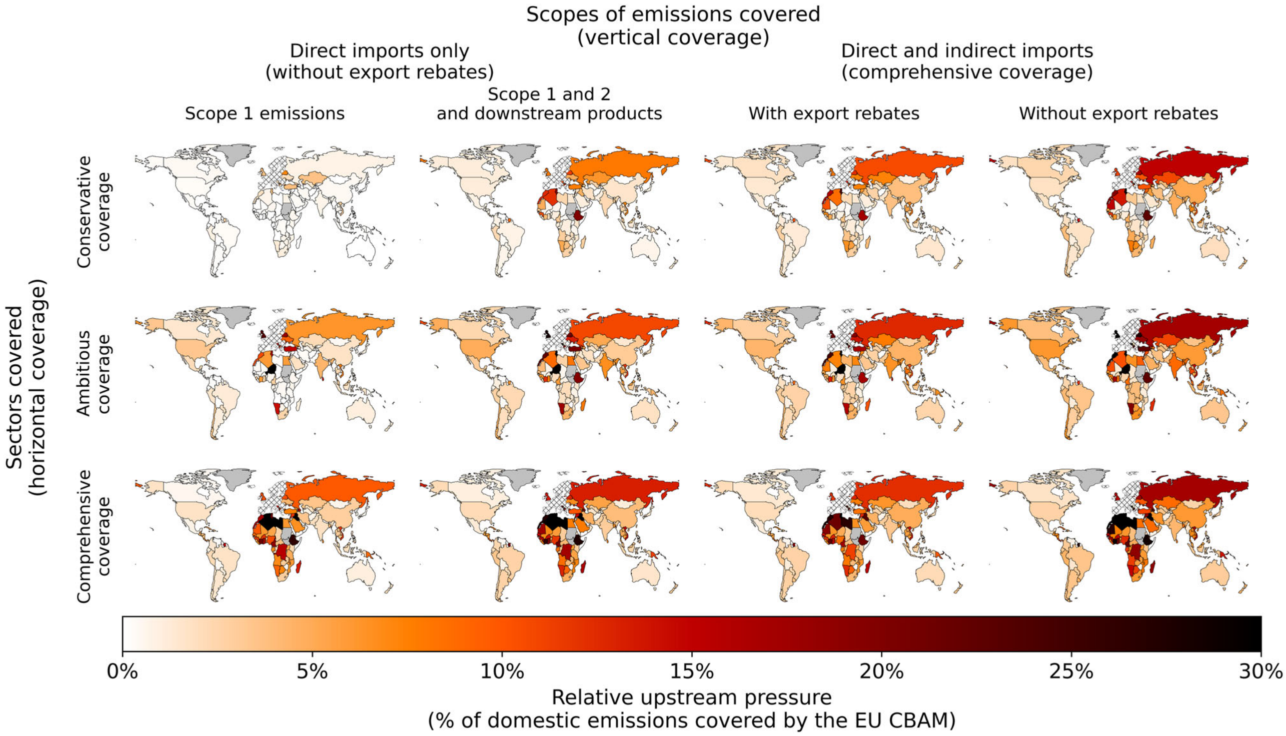

Fig. 5 Distribution of the relative upstream pressure under different EU CBAM implementations. Coloring shows the share of domestic emissions of each country covered by the EU CBAM implemented. Rows indicate the types of emissions covered by the EU CBAM (see Fig. 1). Columns correspond to the scope of emissions being covered by the EU CBAM (see Fig. 1). The numerator of the relative upstream pressure corresponds to the volume of emissions caused in the corresponding country and priced by the EU CBAM (absolute upstream pressure). The denominator is the domestic volume of emissions in the sectors covered by the EU CBAM. The upper-left panel corresponds to the most conservative estimation of the coverage of the EU CBAM (only direct emissions from a few sectors). The bottom-right panel corresponds to a comprehensive EU CBAM without export rebates, as shown in Fig. 2.

volume of CO_2 emissions covered by a realistic EU CBAM and the subsequent fiscal revenue raised would be lower than estimated here. With regard to the robustness of our findings, Fig. 5 shows the relative upstream pressure caused by the different EU CBAM implementations analyzed in Fig. 1. We find that, even with more conservative EU CBAM implementations, low- and middle-income countries dependent on the EU for their exports would still be disproportionally exposed to the relative upstream pressure caused by the EU CBAM, even though with a lower intensity. Our qualitative results thus remain largely valid for implementation options in line with the current policy proposal.

We here suggest the inclusion of an international revenue recycling scheme to the EU CBAM, to enhance the international acceptability of this policy and to foster global climate cooperation. Our analysis highlights which general principles could be used to design such inclusive policies, thereby abstracting from practicability concerns. First, our recycling indicators are based on several plausible normative perspectives on who should be entitled to receive this revenue. Our analysis hence provides a preliminary assessment of the dimensions along which an inclusive use of revenues could be designed and highlights potential trade-offs between these illustrative recycling options. For the design of an actual recycling scheme, these indicators should be carefully balanced and negotiated in order to build large enough international support to avoid major trade retaliation. Such indicators should be transparently evaluated and use up-to-date and robust data. The use of region-specific damage estimates as done here could provide a guidance in that direction, even though these estimates are subject to large uncertainties[26].

Second, building a truly inclusive recycling scheme raises governance issues, both within the EU and at the global level. At the EU level, consumers would bear most of the cost of the EU CCBAM as consumption prices would increase because of the extension of carbon pricing. Fostering the acceptability of the EU CBAM internally arguably requires some internal revenue recycling mechanism as well, as already planned in the current EU CBAM[1]. Balancing such internal redistribution mechanism with an international recycling scheme requires further work and collective deliberation. The use of dynamic approaches that account for both production and consumption elasticities could likely provide guidance in that direction[7,27]. At the international level, an inclusive recycling scheme would also require some level of shared governance between the EU and its trade partners, particularly if this recycling is targeted toward adaptation and mitigation projects. Global discussion forums such as the Conferences of the Parties may in principle support these multilateral negotiations, but the unanimity principle involved there is likely not compatible with the ambition of the EU CBAM. Smaller forums such as the G7, the G20, or the OECD could also host such discussions, but would exclude low- and middle-income countries. Alternatively, the EU could involve third countries into the governance of the recycling of the EU CBAM revenue based on the voluntarily adhesion to an international Green New Deal, providing the adoption of minimal climate targets, for instance[28]. At the cost of an increase of financial support toward low- and middle-income countries, the EU could then use a CBAM to reconcile the protection of its local industry against carbon leakage with a global reinforcement of climate mitigation policies. However, this solution will require overcoming the conflicting interests of its trade partners.

Methods

Data. Our model is based on the EORA 26 Multi-Regional Input Output Table (MRIOT) for 2016, which describes trade flows at the industry level between

26 sectors and 189 regions worldwide[10,11]. EORA is the dataset with the most detailed spatial coverage available at the time of the study. Data on CO_2 emissions stem from the Primap-hist[29] and Primap-crf[30] datasets. Primap-hist contains emission data for all countries signatory of the United Nations Framework Convention on Climate Change (UNFCCC)[17], but with limited details on the emitting sectors. Primap-crf provides a detailed disaggregation of CO2 emission by process level following the Intergovernmental Panel on Climate Change (IPCC) classification, but is limited to Annex I countries of the UNFCCC. We use a tailored procedure to combine these two datasets and to map the resulting emission data to the EORA trade data[9]: First, detailed data from Primap-crf are extrapolated to all UNFCCC countries using aggregated data from Primap-hist and production data from EORA. Second, resulting emission estimates are allocated to EORA sectors. Note that PRIMAP emission data do not include emissions from international transportation nor from Land-Use, Land-Use Change, and Forestry (LULUCF). We also exclude direct emissions from final users from our analysis, as these would not be covered by a CBAM.

Modelling of the different CBAM implementation options. The different horizontal coverages (number of products covered by the CBAM) correspond to different grouping of process-based emission data based on their IPCC emission category (see Supplementary Table 2). The vertical coverages (scope of emissions accounted) are estimated using the MRIOT. Let imp^{ic} denote the value of imports of products from sector i in country c to the EU in basic prices and q_k^{ic} the volume of CO_2 emissions per unit of output in sector i in country c for IPCC category k. "Scope 1 emissions" from category k from country c, $E^{k,c}_{\mathrm{scope1}}$ are estimated by multiplying the import array by the corresponding intensity emission array:

$$E^{k,c}_{\mathrm{scope\,1}} = \sum_i q_k^{ic} \times \mathrm{imp}^{ic}. \quad (1)$$

"Scope 2 and downstream emissions" are estimated by computing the emissions caused by the direct inputs required to produce imports to the EU. Let a_{ic}^{js} denote the technical coefficient, quantifying the value of input from sector i in country c required to produce one unit of output in sector j in country s, extracted from the MRIOT[31]. The emissions caused by inputs to EU imports for IPCC emissions category k ($E^{k,c}_{\mathrm{scope2}}$) in country c are then:

$$E^{k,c}_{\mathrm{scope\,2\,and\,downstream}} = \sum_i \sum_{j,s \notin \mathrm{EU}} q_k^{ic} \times a_{ic}^{js} \times \mathrm{imp}^{js}. \quad (2)$$

"Scope 1 and 2 and downstream emissions" values are then obtained by summing "Scope 1 emissions" and "Scope 2 and downstream emissions".

Finally, the comprehensive coverages (i.e., "Direct and indirect imports") are estimated using the Throughflow Based Accounting (TBA) method[9]. The TBA is an Input-Output Analysis technique to quantify the volume of upstream CO_2 emissions caused by supply chains starting from, going through, or ending in the EU. The core idea is to artificially exclude the EU from the global economy and to compare the actual world CO_2 emissions to the emissions in the hypothetical scenario where all supply chains involving EU countries are extracted. This difference is further decomposed into four elementary flows (intra-EU, imports, exports, and traversing) depending on where emissions occur physically and on where final users are located (see Fig. 2a). Emissions caused by traversing flows are excluded from the computation when exploring an EU CCBAM with export rebates, as these emissions are caused outside of the EU for making products ultimately exported from the EU. In absence of export rebates, both imported and traversing emissions are counted. A detailed description of the TBA method can be found in Beaufils et al.[9].

Analysis of different revenue recycling schemes. Our recycling estimates (Fig. 3, Supplementary Fig. 2) use population and Gross Domestic Product (GDP) data from the World Bank for 2016[13,32]. Historical costs of climate change at the country-level are here approximated by the impact of anthropogenic warming on annual economic growth as empirically estimated for the period 1991–2010[20]. The estimates for the EU CCBAM-induced losses correspond to the value of CO_2 emissions caused in a country to supply the final demand in the EU (upstream pressure), assuming a carbon price of 100€ per tCO_2. The revenue estimates under the different recycling schemes are detailed below.

In panel a, no recycling is applied and the losses simply correspond to the volume of CO_2 emissions covered by an EU CCBAM without export rebates, assuming an illustrative carbon price of 100€ per tCO_2.

In panel b, the revenue is recycled proportionally to the emissions covered by the CBAM. We note p^c the population of country c, E^c the volume of emissions from country c covered by the EU CBAM. With τ the carbon price, the per capita fiscal revenue of country c in recycling scenario b, (r_b^c) is computed as:

$$r_b^c = \frac{1}{p^c} \times E^c \times \tau. \quad (3)$$

Panel c assumes no revenue for the countries which benefited from climate change (i.e., with negative historical damages[20]). Climate damage estimates[20] are expressed as relative GDP losses (i.e., percent of GDP lost due to climate change), noted l^c. We weight these climate damages by a country's population (p^c) to account for the number of people exposed. Revenue r_c^c is then allocated proportionally to the share of each country in the global damages:

$$r_c^c = \frac{\max(0, l^c)}{\sum_{s \notin \mathrm{EU}} \max(0, l^s) \times p^s} \times \left(\sum_{s \notin \mathrm{EU}} \tau \times E^s \right). \quad (4)$$

Finally, revenue recycling in panel d accounts for the income per capita of a country c, noted w^c. Countries that have larger GDP per capita than the EU average receive no revenue in this scheme. Again, revenue differences are weighted by population. Per capita revenue recycled to country c in panel d, r_d^c, is finally computed as:

$$r_d^c = \frac{\left[1 - \min\left(\frac{w^c}{w^{\mathrm{EU}}}, 1\right)\right]}{\sum_{s \notin \mathrm{EU}} \left[1 - \min\left(\frac{w^s}{w^{\mathrm{EU}}}, 1\right)\right] \times p^s} \times \left(\sum_{s \notin \mathrm{EU}} \tau \times E^s \right). \quad (5)$$

Data availability

All data used and generated for this study are available on Zenodo[33] (https://zenodo.org/record/7741702), at the exceptions of proprietary MRIO data[10,11], accessible under academic license at https://worldmrio.com/eora26/.

Code availability

Python and iPython scripts used for processing data and generating the figures of this study are available in the Zenodo repository[33], with detailed instructions on how to replicate the results and figures (https://zenodo.org/record/7741702).

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T.B., M.J., H.W., and L.W. designed the study, interpreted the results, and revised the paper. T.B. collected and processed data, prepared figures, and wrote the manuscript with contributions from M.J., H.W., and L.W.

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