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Beggar thy neighbor? On the competitiveness and welfare impacts of the EU's proposed carbon border adjustment mechanism

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ABSTRACT

Curbing climate change is gaining increasing consensus globally. While many countries seek to set carbon prices, significant price dispersion and policy stringency continue to raise concerns about competitiveness. To address this issue, the EU has proposed a carbon border adjustment mechanism (CBAM), which aims to level the playing field by levying a carbon price on EU imports. In this paper, we estimate the competitiveness and welfare impacts of the EU CBAM, based on a refined multi-regional IO approach. We quantify changes in the value of exports to the EU market upon CBAM implementation for both EU members and non-EU economies. It is found that the EU CBAM will lead to a redistribution of competitiveness among countries and regions. Specifically, it is estimated that EU output would increase by 0.38 per cent while output in rest of the world decreases by 0.1 per cent in the short run, when CBAM is set at \$US100/tCO_2e. The burden is unevenly distributed among regions, with China, Russia and India bearing the most. Moreover, a deeper sub-national-level analysis on China shows that, given its pervasive domestic production network, income losses in landlocked provinces exceed their export losses, contrasting with the pattern for trade-exposed provinces.

1. Introduction

Curbing climate change is gaining increasing consensus globally. In 2020, more than 60 central governments announced "net zero" carbon emissions commitments by either 2050 or 2060. Nevertheless, many countries still lack details on how they will eliminate their emissions and current progress varies from country to country. Sixty-four carbon pricing initiatives had been implemented or were scheduled for implementation globally, as of 2020. In 2019, the carbon prices ranged from less than \$US1/tCO_2e to a maximum of \$US127/tCO_2e (Ramstein et al., 2019). The significant price dispersion reveals the bleak outlook for a uniform global climate policy. Therefore, it is foreseeable that national climate policies that differ in stringency will keep raising concerns about competitiveness and carbon leakage, while the latter refers to the situation where carbon emissions are partly shifted to countries with less-stringent environment polices.

To tackle climate change, in September 2020, the European Commission proposed its 2030 Climate Target Plan. Specifically, its target is to reduce the EU's 2030 greenhouse gas emissions to be at least 55 per cent of the 1990 level and to prepare the EU for its "net zero" commitment by 2050 (European Commission, 2020). The new plan will put upward pressure on the carbon price in the EU, which is estimated to stabilize between 32 and 44 euros per tonne by 2030, measured in 2015 prices (Abnett, 2020). To counteract carbon leakage and the potential loss in competitiveness and to incentivize other countries to participate in combating climate change, the European Commission suggested the EU carbon border adjustment mechanism (i.e., CBAM), which will levy carbon tariff on imports. On July 14, 2021, the European Commission issued a formal proposal for a CBAM that will be officially implemented in 2023.

In theory, a CBAM is regarded as being effective in reducing carbon leakage and the negative impact on competitiveness induced by unilateral climate policies. However, this approach remains controversial in reality, especially as the latest studies find little evidence for carbon leakage caused by unilateral national environmental regulations (Franzen and Mader, 2018; Naegele and Zaklan, 2019).

Logically, by putting an additional price on products crossing borders, domestic products gain competitiveness at the cost of foreign products. As a result, the demand for domestic output is likely to grow, while the demand for imports could fall. Suppose such competitiveness impacts turn out to be substantial, where the CBAM may shift the burden of climate policy from developed regions (i.e., the EU) to trading

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partners, particularly developing regions. Such an outcome would violate the United Nations Framework Convention on Climate Change's (UNFCCC) principle of Common but Differentiated Responsibilities (CBDR). Developing countries pursuing export-led growth are likely to make such complaints as their production technology is usually carbon-intensive and trade exposure is relatively high. If perceived as protectionist, the mechanism could meet heavy political resistance, spark trade conflicts and undermine global cooperation on climate action. Therefore, quantifying the competitiveness impacts of the EU CBAM under different policy designs is central to facilitating discussions among academia and policymakers.

The use of a CBAM to counteract the potential negative impacts of unilateral climate policy has triggered long-lasting interests in academia and politics. The literature on CBAM can be roughly divided into two broad categories, namely, i) those discuss alternative designs of CBAM (see, e.g., Balistreri et al., 2019; Kortum and Weisbach, 2017; Trachtman, 2017; Ladly, 2012; Monjon and Quirion, 2010; among others), and ii) those investigate the economic efficiency. The economic efficiency of CBAM can be further split-up into direct and indirect effects. The direct effects are caused by relative prices changes induced by CBAM, which is the focus of this study; whereas indirect effect refers to when CBAM is announced as a threat, which changes behavior.[1]

Most relevant to the present study are those quantifying the direct impacts of the CBAM, specifically the EU CBAM. Using systematic review method, we conducted a comprehensive review of previous research that simulate the economic effects of CBAM. Vast majority of the *ex-ante* empirical studies concluded that CBAM to be effective, mitigating leakages and maintaining competitiveness. Clearly, the CBAM's impact, quantitatively and/or qualitatively is both related to policy design and structural characteristics of the economic units involved. In particular, trade exposure, composition of embodied emissions, trade (Armington) elasticities are among the major attributes determining the empirical impacts of CBAM on an economy (see e.g., Böhringer et al., 2015; Monjon and Quirion, 2011). Theoretically, altering these parameters could render CBAM ineffective or even make it counterproductive in extreme cases. As far as the majority of empirical studies on CBAM, especially on EU CBAM is concerned (see e.g., Antimiani et al., 2016; Foure et al., 2016, Schinko et al., 2014, Burniaux et al. 2013),[2] overwhelmingly report that the adoption of CBAM could mitigate leakage and maintain competitiveness to certain extent.

Regarding the methodology, it is found that the commonly employed approaches in the empirical literature are computable general equilibrium (CGE) models (41 out of 56 studies), followed by input-output (IO) models employed in 8 studies. Branger and Quirion (2014) reviews this issue that are CGE-based between 2004 and 2012 utilizing a meta-analysis. They conclude that a CBAM would reduce carbon leakages caused by unilateral climate policies, ranging from 5 to 25 per cent (a mean of 14 per cent) to 5 to 15 per cent (a mean of 6 per cent). According to our extended review, the majority of recent studies using CGE models from 2013 through 2020 largely confirm their conclusion (see e.g., Böhringer et al., 2021; Böhringer et al., 2017; Antimiani et al., 2016; Fouré et al., 2016; Mattoo et al., 2013; among others).

Studies opting for IO models, although belong to quantitative analysis, focus on computing embodied carbon content in trade, which serves the basis for CBAM duties, or the price changes caused by CBAM, leaving aside the impacts on demand and/or welfare (see, e.g., Zhang et al., 2017; Lopez et al., 2015; Zhou et al., 2012; Atkinson, 2011). IO framework has the advantage that it provides a transparent and straightforward way for estimating embodied carbon content, which is often also applied in CGE-based studies. However, in conventional IO analysis, final demand is assumed to be exogenous. Demand and welfare impacts are often missing in IO-based studies. Ward et al. (2019) provides an innovative and intuitive way to extend the IO framework so as to incorporate demand simulation. They could therefore use a multi-regional IO model to simulate the short-term impacts of a global uniform carbon tax on international trade flows. Compared with CGE models, their approach has two complementary features: first, it can simulate the initial impacts for high resolution country-industry details. Secondly, it allows to capture the short-term effects and the adaptation processes between equilibriums. As such, the IO approach provides complementary information to the CGE-based literature (Ward et al., 2019, p. 3).

We opt for their approach to study the short-term effects of the CBAM. As stated above, CGE-based studies dominate the empirical literature on CBAM; therefore, stimulating short-term effects with IO approach provides valuable complement to this body of knowledge. Besides, IO approach has two additional merits: firstly, it is relatively intuitive and transparent, contrasting with CGE models with a large number of parameter estimates and alternative functional forms (Costinot and Rodríguez-Clare, 2014). Second, multi-national IO tables are publicly available, ensuring the transparency and reproducibility. The WIOD database, which is used in this study, has facilitated large literature of accounting carbon embodied in trade (see, e.g., Chen et al., 2019; Moran and Wood, 2014; Boitier et al., 2012).

In this study, we simulate the EU CBAM with alternative policy designs and present its short-term impacts on trade at the country-sector level. Specifically, we consider how different carbon price levels, arrangements like exemptions and reductions for countries with domestic carbon pricing systems can affect trade among EU and non-EU economies. Furthermore, we extend the model to simulate sub-national economic implications of the EU CBAM, to investigate to what extent the national policy might have different effects on sub-national regions due to regional heterogeneity. Our study touches on this important yet underrepresent perspective using China as an example. We choose China for two reasons. Firstly, being a top emitter in the world and EU's largest trading partner, China will be a major stakeholder for the EU CBAM. Secondly, China is geographically vast with large discrepancies in regional economic development. Whether the EU CBAM tends to increase its regional disparities, triggers serious concerns for Chinese government besides the aggregate impacts. Finally, we extend the model to capture some mid- or long-term impacts of the CBAM. Specifically, we take into consideration that CBAM price would pass-through to EU's production costs and further to other country.

In sum, we contribute to literature on CBAM in four ways. Firstly, our study with IO approach not only increases diversification of methodology in the topical debates, but also complements the CBAM impact analysis from a short-term perspective, which is underrepresented in previous empirical literature dominated by CGE-based studies. Secondly, we expand the IO-based literature of CBAM to also simulate demand reactions. Our approach opens new possibilities for the adoption of IO framework in this burgeoning area. Thirdly, we extended and refined the model of Ward et al. (2019), which likely improved the simulation accuracy and capability of this analytical framework. Armed with the refinements, we are able to conduct a sub-national level impact analysis, an important yet underexplored aspect. Last but not least, we follow closely EU's statement on the CBAM policy, use latest EU ETS carbon prices and its projections to calculate CBAM duties, also

[1] For instance, non-climate coalition countries decide to join the climate protection coalition due to fear of upcoming CBAM duties (see Böhringer et al., 2016).

[2] In a few cases, e.g. Böhringer et al. (2015) finds that the implementation of CBAM in Switzerland leads to lower domestic emissions-intensive and trade-exposed (EITE) production in Switzerland due to its high proportion of embodied emissions in domestic production and high share of domestic production for exports. Also, Monjon & Quirion (2011) finds that not all EITE sectors benefits with respect to production when CBAM is implemented in the EU, where the EU cement sector's production would reduce instead.

considering exemptions and reductions.[3]

The remainder of this paper is organized as follows. Section 2 describes the empirical framework and data used to simulate the competitiveness effects of the EU CBAM. Section 3 designs four alternative scenarios, and section 4 presents and discusses the results. Finally, section 5 provides conclusions and policy implications.

2. Data and model

2.1. Data

We use four main datasets, namely the international Supply Use Tables (SUTs) from the World Input-Output Database (WIOD); Chinese Multi-Regional Input-Output (CMRIO) tables, China's customs data; and parameters from the GTAP database. We will describe each of them in order.

To construct the product-by-product CMRIO-WIOT, we use the 2012 international SUTs provided by the WIOD (Timmer et al., 2016) and the product-by-product CMRIO compiled by Mi et al. (2018). The advantages of using product-by-product tables are as follows: First, the CBAM price is levied on products, therefore, product-by-product IO tables provide natural carbon content accounting; second, the CMRIO table for 2012 is constructed as a product-by-product table; therefore, embedding it into the product-by-product WIOT avoids the issue of inconsistent data types (Chen et al., 2019). For the model construction, we use a set of international SUTs to construct a product-by-product WIOT, following the procedure documented in Chen et al. (2019). In the balancing procedure, we apply the standard RAS method to balance the blocks with the non-negative entries. For the blocks with negative values—for example, the columns that show inventory changes—we apply the cross-entropy (CE) matrix balancing method constructed in Lemelin (2009) instead of the Generalized RAS (GRAS) algorithm, which Chen et al. (2019) applied. While the GRAS and CE methods produce identical results when all entries are positive, the CE method performs better when zero and negative entries exist as it adheres to the minimum information loss principle (Lemelin, 2009). The derived product-by-product WIOT contains 43 countries and a block for the rest of the world, each of which has 56 product sectors.

Next, we embed the product-by-product CMRIO into the above-generated WIOT. The CMRIO contains 30 provinces (excluding Tibet due to lack of data) of Mainland China and 30 product sectors. Notably, the exclusion of Tibet is not likely to affect our results as the region only accounts for about 0.122 per cent of mainland China's GDP and less than 0.01 per cent of its trade volume for 2012. We map the 56 WIOT sectors and 30 CMRIO sectors into 23 product sectors, using N-to-1 matching (see the concordance between the original sector classification to the new ones given in Appendix 1). To incorporate the CMRIO into the WIOT, we adopt the method developed in Meng et al. (2013). To produce the initial values for the trade blocks between the Chinese regions and other countries, we use Chinese regional trade data for 2012 obtained from the General Administration of Customs of China. The final balancing strategy is the same as described above. The newly constructed CMRIO-WIOT contains 43 countries (the rest of the world is treated as one region) and 30 Chinese provinces. Each country/province has 23 product sectors.

We use the World Input-Output Database Environmental Accounts in Corsatea et al. (2019) for the carbon emissions data. The emissions data is consistent with the industry-by-industry WIOT; we convert it to match the product-by-product WIOT, using the same procedure as in Chen et al. (2019) when calculating the product-by-product value-added coefficient matrix.

Finally, we borrow the commodity-level substitution elasticities between domestic and imported commodities and among imports from different sources from the GTAP Database (Aguiar et al., 2019). The GTAP provides substitution elasticities for 59 GTAP commodities, which we aggregate to obtain elasticities for the 23 sectors consistent with the sector classification in the CMRIO-WIOT. The aggregation follows Horridge (2018), which is argued to produce a smaller aggregation bias than the prevailing treatment of the weighted average of the substitution elasticities.

2.2. Accounting for carbon content

Without loss of generality, we assume that the CBAM uses actual emissions data to determine the country-sector-specific benchmarks for non-EU products. Specifically, we calculate the emissions intensity for each commodity sector of each country. Alternatively, one may opt for a domestic (EU) benchmark, such as the EU average emissions intensity or best-available technology. Setting a uniform domestic benchmark could be more convenient in terms of data collection and it could avoid criticisms of discrimination, but it would disincentive foreign producers from reducing their emissions. With recent developments in accounting for the global carbon footprint, we believe the EU or other governments that are planning to implement a CBAM will have increasingly plausible grounds to use country-, sector- and even firm-specific emissions benchmarks and that this would provide better incentives.

To comply with WTO rules, the EU CBAM must not charge imports more than the domestic carbon price. Given that the EU's ETS covers only direct (Scope 1) emissions and indirect primary (Scope 2) emissions, as will be explained later, the EU CBAM should not cover more. Therefore, we assume throughout this paper that the EU CBAM covers Scope 1 and 2 emissions only.

Sectoral direct emissions account for emissions from sources that are owned or controlled by the reporting sector. So, the sectoral direct emissions coefficient associated with one unit of total output can be calculated as $f_i^{s,D} = F_i^s / X_i^s$, where $s \in S$ is the country index, $i \in N$ is the industry index and D stands for direct emissions. F_i^s and X_i^s are the total direct emissions and the total output of sector i in country s. Next, Scope 2 emissions account for emissions embedded in the amount of electricity, steam, and heating/cooling consumed for production. We calculate this as the direct emissions that are associated with the amounts of electricity, gas, steam, air conditioning supply, and water collection, treatment and supply consumed (Sector D35_E36). Therefore, the indirect Scope 2 emissions of one unit of the final output for sector i in country s are $f_i^{s,I} = f_{D35\_E36}^{s,D} \times \sum_r a_{i,D35\_E36}^{s,r}$, where $f_{D35\_E36}^{s,d}$ represents the direct emissions from one unit of total output of the energy sector in the exporting country, $a_{i,D35\_E36}^{s,r}$ is the direct consumption coefficient of sector i in country s for energy products from country r and I stands for indirect emissions. We obtain $a_{i,D35\_E36}^{s,r}$ from the WIOT. Here, we assume, for convenience, that the CBAM also covers the emissions embedded in energy imports and that their carbon content is calculated using the domestic benchmark $f_{D35\_E36}^{s,D}$. Finally, the carbon content of one unit of the sectoral output to be taxed by the CBAM is as follows:

$$f_i^s = f_i^{s,D} + f_i^{s,I} \tag{1}$$

2.3. Impacts on competitiveness

To start, we assume that the price changes associated with the EU CBAM are fully passed-through to EU consumers (see also Ward et al., 2019). Then, we could calculate the initial price changes EU consumers face and then simulate the EU's demand-side reaction within each economic sector. To better estimate the sectoral demand substitution among countries and to capture the sector heterogeneity, we propose a two-stage Armington structure on the demand side with sectoral heterogeneous substitution elasticities, contrasting with the global market assumption in Ward et al. (2019). The main difference between the two structures is that

[3] The up-to-date policy settings makes our simulation results even more policy relevant; also, to the best of our knowledge, the study is among the first to examine short-term impacts of EU CBAM and provide impact analysis with a wide range of country-sector details.

the global market assumption allows us to use uniform substitution elasticities across sectors and sources. However, substitution elasticities between the domestic supply and the country's imports are smaller than (usually half of) the elasticities among the imports that originate from different foreign sources (Jomini et al., 2008; Liu et al., 1998).

Therefore, using uniform elasticity is likely to underestimate the substitution effects among foreign supplies and to overestimate the substitution effects between domestic supply and imports (see the sensitivity analysis for the two elasticity assumptions in Appendix 3). Also, a nested demand structure prevails in the CGE literature, making it possible for us to borrow sector-level elasticities from this line of studies. Specifically, we employ for each product sector two different elasticities: i.e., σ_i^D for the substitution between domestic supply and imported products and σ_i^M for the substitution among imports from foreign sources. Table 1 demonstrates these elasticities.

Based on the unit carbon content derived in previous section, we can calculate the unit (import) price changes facing the EU market as $\Delta PM_i^s = \tau^s f_i^s$. τ^s is the carbon price levied on country s's exports to the EU. In the case of a flat CBAM price, τ^s is the same for every (non-EU) country. For EU countries, τ^s and therefore ΔP_i^s are zeros. Then, given an EU country r, its new expenditures on the domestic supply of i can be calculated in Eq. (2).

$$VD_i^{*r} = VD_i^r\left(1 + \Delta P_i^r - \Delta\overline{P}_i^r\right)^{\delta_i^D} \tag{2}$$

where VD_i^r and VD_i^{*r} are the actual and simulated expenditures of country r on i's domestic supply for both final and intermediate use; ΔP_i^r is the price change of i's domestic supply, which equals zero; $\delta_i^D = 1 - \sigma_i^D$. $\Delta\overline{P}_i^r$ is the average price change of product i in country r, a weighted average of the price changes of domestic supply (ΔP_i^r) and imports ($\Delta\overline{PM}_i^r$).

Next, country r's expenditures on i's imports are calculated in Eq. (3).

$$VM_i^{*r} = VM_i^r\left(1 + \Delta\overline{PM}_i^r - \Delta\overline{P}_i^r\right)^{\delta_i^D} \tag{3}$$

where VM_i^r and VM_i^{*r} are the actual and simulated expenditures of country r on i's imports, and $\Delta\overline{PM}_i^r$ is the import price change country r faces for import i, or a weighted average of i's price changes from all foreign sources (ΔPM_i^s, *where* $s \neq r$). Finally, country r's expenditures to import i from s are calculated in Eq. (4):

$$VM_i^{*rs} = VM_i^{rs}\left(1 + \Delta PM_i^s - \Delta\overline{PM}_i^r\right)^{\delta_i^M} \frac{VM_i^{*r}}{VM_i^r} \tag{4}$$

Table 1
Aggregated demand substitution elasticities.

	Sector	σ_i^D	σ_i^M
A	Agriculture	1.72	3.44
B	Mining and quarrying	3.28	6.56
C10–C12	Food, beverages and tobacco	2.47	4.93
C13–C15	Textiles and apparels	3.42	6.84
C17–C18	Paper products, printing and recorded media;	2.95	5.90
C19	Coke and refined petroleum products	2.10	4.20
C20–C21	Chemicals and chemical products	3.15	6.29
C22–C23	Non-metallic mineral products	3.02	6.05
C24	Basic metals	3.24	6.48
C25	Fabricated metal products	3.75	7.50
C26	Electronics	4.40	8.80
C27	Electrical equipment	4.40	8.80
C28	Machinery	4.05	8.10
C29–C30	Transport equipment	3.16	6.32
C16_C31_C32	Wood and other manufacturing	3.65	7.30
D35_E36	Electricity, gas, steam and air conditioning supply	2.56	5.13
H49–H52	Transport and Warehousing	1.63	3.27
Others	All other service sectors	1.90	3.80

Source: Authors' own calculations. Note: Please refer to Appendix 1 for sector category. The data used for the calculations were taken from the GTAP database.

where VM_i^{rs} and VM_i^{*rs} are country r's actual and simulated expenditures on to import i from country s; where $\delta_i^M = 1 - \sigma_i^M$. Note that whenever s represents an EU country, ΔPM_i^{rs} equals zero. Inserting Eq. (3) into Eq. (4), we obtain Eq. (5):

$$VM_i^{*rs} = VM_i^{rs}\left(1 + \Delta PM_i^s - \Delta\overline{PM}_i^r\right)^{\delta_i^M}\left(1 + \Delta\overline{PM}_i^r - \Delta\overline{P}_i^r\right)^{\delta_i^D} \tag{5}$$

To analyze the CBAM's sub-national implications for China, we assume that the EU treats each province as a respective region, represented by s, and that the substitution elasticities of imports from different sources apply to imports among different Chinese provinces. Further, we assume that the CBAM taxes imports from all Chinese provinces according to the national sectoral emissions benchmark instead of the regional benchmark. Then, applying the standard IO technique to the CMRIO, we calculate the regional value added embedded in China's exports to the EU. By comparing the embedded value added in China's exports to the EU for the base year and the simulated scenarios, we derive the regional income losses induced by the EU CBAM.

So far, the basic empirical framework has been developed. Some caveats are in order, as also discussed in Ward et al. (2019). First, the IO framework implies that product homogeneity is assumed across different countries and can only provide country-sector-level results. Second, intermediate input and final demands are treated identically in terms of price elasticity, ignoring supply chain rigidities. Third, this framework is static in the sense that long-term uncertainties such as price changes of and substitution among primary factors, technological change, and substitution between different sectors are not considered. These assumptions, while plausible in short run, could be less so in the long term, therefore, the results presented here should be interpreted as short-run outcomes.

3. Scenarios

First, we consider that CBAM covers all emissions-intensive and trade-exposed (EITE) sectors in line with EU ETS coverage. Specifically, a total of nine sectors are covered in this paper, namely, *mining sector (B), paper and printing sector (C17–C18), coke and petroleum sector (C19), chemical sector (C20–C21), non-metallic mineral sector (C22–C23), basic metal sector (C24), fabricated metal sector (C25), energy sector (D35_E36),* and *transportation sector (H49–H52)*.

Four scenarios are developed. In Scenario 1, we consider a uniform CBAM carbon price of \$US50/tCO_2e levied on EU imports, which draws from the EU ETS average price for the second half of 2021. In Scenario 2, we consider a higher carbon price of \$US100/tCO_2e, which doubles the lower bound and per the latest projection for 2030 (see, e.g., Pietzcker et al., 2021; Euroactive, 2021). Next, to avoid the EU CBAM being regarded as protectionist and to increase its WTO compliance, an option is to allow tax exemptions and reductions for countries or sectors that have implemented comparable carbon prices. In Scenario 3, we add to Scenario 2 that the EU CBAM exempts countries with comparable carbon prices and allows reductions for imports that are already taxed for carbon nationally but considered not to a comparable level. We determine the compatibility of the national carbon system by comparing existing national carbon prices.[4] We use the nominal carbon prices on April 1, 2019 as a reference, and consider countries with a carbon price not lower than EU's then ETS price (\$US25/tCO_2e) to be exempted. Then, countries with positive carbon prices yet not considered as comparable will be charged with a CBAM price less their own national carbon prices. For instance, we use the projected carbon price that was officially operational on China's national carbon market in 2021, which

[4] It is noteworthy that a comprehensive comparability test should include criteria additional to carbon prices, as many countries also adopt non-market-based instruments, such as China and the US, which are not captured in prices. In this exercise, for the sake of brevity and transparency, we will stick to existing national carbon prices.

is CNY 49/tCO_2e (about $US7.6/$tCO_2$e) (Slater et al., 2020).

In the first three scenarios, we only consider the demand-side reactions to the import price changes induced by the EU CBAM. We interpret these as short-term impacts as production costs are assumed to be sticky and more-or-less constant. Over a longer timeframe, production costs, especially in the EU, might also increase as intermediate inputs become more expensive (given that some of the intermediate inputs are imported).

In Scenario 4, we relax previous assumption of price rigidity by allowing EU's production costs to change, namely pass-through the CBAM costs on imports. We assume for convenience a fully price pass-through, namely, EU's production costs increase by their CBAM costs. Then, this will lead to a rise in production costs of other countries that use EU-produced intermediate goods in turn. Such roundabout cost transmission can be obtained by using an IO price model, which calculates the final price effect as $\Delta\widetilde{\boldsymbol{p}} = (\boldsymbol{L})^{'}\Delta\boldsymbol{v}_c$ (Miller and Blair, 2009). Specifically, $\boldsymbol{L} = (\mathbf{I}-\mathbf{A})^{-1}$ is the Leontief inverse, $\mathbf{A}$ is the technical coefficients matrix and $\Delta\boldsymbol{v}_c$ is the vector for the value added cost changes.[5] Here, $\Delta\boldsymbol{v}_c$ represents the EU's production cost increases triggered by CBAM. This can be calculated straightforwardly using the technical coefficients matrix and the CBAM prices, namely $\Delta\boldsymbol{v}_c = \mathbf{A}\cdot\Delta\boldsymbol{PM}$.[6] $\Delta\boldsymbol{PM}$ is the vector with country-sector pair of CBAM costs facing EU.[7] The final result of the EU cost transmission can be calculated as:

$$\Delta\widetilde{\boldsymbol{p}} = (\boldsymbol{L})^{'}\mathbf{A}\cdot\Delta\boldsymbol{PM} \tag{6}$$

$\Delta\widetilde{\boldsymbol{p}}$ is a vector for production cost changes in all countries and sectors. In Scenario 4, we use the same policy setting as in Scenario 3, plus taking the production costs changes defined as in Eq. (6) into consideration. When calculating change in demand, non-EU countries face a change in purchase price (equal to the cost) of $\Delta\widetilde{\boldsymbol{p}}$, while EU countries not only pay the extra CBAM price $\Delta\boldsymbol{PM}$ when importing (i.e. the situation in Scenarios 1–3), but also pay for the cost transmitted $\Delta\widetilde{\boldsymbol{p}}$.[8] This exercise tentatively explores the long-term effects of CBAM. Noting that, here we consider only one mechanism of long-term impact, namely cost pass-through. Given that there are many uncertainties to be considered in the long run, scenario 4 needs to be interpreted with caution as a long-term simulation.

4. Results and discussion

This section presents four scenarios that demonstrate the competitiveness impacts of the EU CBAM. To provide a complete picture, we organize and analyze the results from four aspects. Section 4.1 starts with a general overview of the macro impact on EU and non-EU countries' trade and output, global carbon reduction and global welfare. Section 4.2 analyses the redistribution impacts at the sector level and identifies the relevant sectors. Section 4.3 shows the aggregated trade impacts at the country level. Section 4.4 focuses on China and demonstrates the impact of the EU CBAM on China's trade and income across its heterogeneous regions.

4.1. An overview

Previous studies usually find that the EU as a whole or EITE production would increase once the EU CBAM were implemented. For instance, EU's EITE production would incur less production loss in ETS Scenario from 1.89 per cent to 1.56 per cent if the CBAM is materialized (see Fouré et al., 2016). In similar vein, Böhringer et al. (2012) reported a larger competitive efficiency of CBAM, reducing the EITE output loss from 2.61 per cent to 0.45 per cent. Our simulation results are in line with these findings.

Table 2 shows the EU CBAM's coverage and overall impact of CBAM. In total, without exemption, EU CBAM will levy a price on about 1.64 per cent of global carbon emissions, which equals 13.95 per cent of the carbon content of EU's total absorption, which is defined as the total of intermediate and final demand. In Scenarios 3 and 4, in which three countries with comparable carbon prices are exempted, namely the United Kingdom, Switzerland, and Norway, the EU CBAM covers 1.50 per cent of the total global carbon emissions, accounting for 12.78 per cent of the carbon content of EU's absorption.

In general, this exercise confirms that the CBAM could help reduce global carbon emission, yet the impact is modest. The global carbon reduction rate in Scenario 1 with carbon price of $US50 is only 0.10 per cent. In scenarios 2 and 3, where the CBAM price doubles, the reduction rate is slightly higher, but still marginal with 1.51 per cent. The reasons for these reductions are twofold: First, the import price increases induced by the CBAM lower EU residents and firms' purchasing power, lead their consumption in real terms and thus cause the carbon content to fall. Second, the CBAM reduces carbon leakage by shifting purchasing from carbon-intensive regions back to the EU and regions with cleaner

Table 2
EU CBAM's aggregated emissions coverage and trade impacts.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	uniform CBAM price of $US50	uniform CBAM price of $US100	Scenario 2 plus exemptions and price reductions	Scenario 3 plus production cost adjustments
CBAM-covered carbon emissions as a % of global carbon emissions	1.64		1.50	
CBAM-covered emissions as a % of the total carbon content of EU's absorption	13.95		12.78	
EU's price index change in %	0.095	0.189	0.171	0.443
EU's real absorption change in %	−0.053	−0.041	−0.025	−0.307
EU output change in %	0.185	0.381	0.334	−0.180
non-EU output change in %	−0.053	−0.095	−0.081	−0.032
Global carbon reduction in %	0.104	0.153	0.151	0.221
Global output change in%	−0.010	−0.007	−0.004	−0.059

Source: Authors' own calculations. Note: value changes given above are in constant price of 2012.

[5] For the mathematical derivation of the model please refer to Miller and Blair (2009, pp. 41–53). It is worth mentioning that in the textbook example, the price change variable $\Delta\boldsymbol{v}_c$ refers specifically to changes in value added cost. In the input-output table, taxes are treated in the same way as both wages and capital prices – a part of value added. Therefore, here we treat the cost paid by EU firms for CBAM as a production tax. Then, we treat the CBAM as a cost increase of value added occurred to EU's producers in the model.

[6] The use of $\mathbf{A}$ implicitly assumes that no technology change occurs, an assumption may not hold in the long run. In this sense, it is important to point out that the results of scenario 4 depict one long-run mechanism, namely cost pass-through, leaving other channels unaffected.

[7] The element of this matrix are ΔPM_i^s, as calculated above. This price change is 0 for all EU and non-EU sectors not covered by CBAM.

[8] This cost adjustment is purely a price effect, with no technological change taking place. Because the size of the cost adjustment is calculated based on technical coefficients matrix $\boldsymbol{A}$, and $\boldsymbol{A}$ implicitly assumes that the (fixed-proportion) production technology remains unchanged. An increase in the input price causes a production cost increase in proportion to that input's share in production.

production technologies. In scenario 4, full cost pass-through pushes up prices and increases the reduction rate of CBAM to 0.22 per cent.

We find that the overall price index in the EU does not significantly change. If we only consider the import price changes, a CBAM price of $US100 will only increase the EU's aggregate price index by 0.19 per cent (Scenario 2). If it also allows production costs to adjust, the EU's aggregate price index will increase more, namely by 0.44 per cent (Scenario 4). The marginal aggregate price index changes are partly due to the dominant share of inter-regional trade within the EU. In 2012, of the sectors covered by the CBAM, only about one-fifth of the EU's total absorption came from non-EU countries. The large internal market size helps mitigate the import price shocks induced by the EU CBAM.

As mentioned above, the increased price level also leads to decreasing purchasing power and causes the EU's total real absorption to fall. Given a CBAM price of $US50 and $US100, the EU's absorption in real terms fall by 0.053 per cent and 0.041 per cent compared with 2012. In both scenarios, the impacts on the EU's total absorption are relatively small. However, if production costs in the EU increase and are passed-through to other countries, then this effect will be magnified. In scenario 4, the EU absorption decreases by 0.31 per cent.

Contrasting EU with non-EU countries makes the distributional effect of CBAM quite evident, namely shifting the environment burden from EU to non-EU countries. In Scenario 1 and 2, the EU's total output increases by 0.19 per cent and 0.38 per cent, whereas non-EU countries output falls by 0.05 percent and 0.1 percent, all compared with 2012. In Scenario 4, it can be found that in the long run, if cost pass-through materializes, it will reduce the distributional effects to certain extent. The export reduction in non-EU countries smoothens, and EU output rise due to higher costs is also reduced. Finally, allowing for exemptions and reductions in Scenario 3 mitigates the overall distributive effect between EU and non-EU regions, whereas countries that are not qualified for exemption or reduction would suffer more. Moreover, as shown later, output losses for non-EU countries are more heterogeneous.

In terms of global output, the impact of CBAM is trivial. In scenarios 1, 2 and 3, the reduction in global output affected by CBAM is less than 0.01 per cent. This effect amplifies to 0.06 percent when considering the global price increase due to CBAM. Clearly, the overall change is limited (see also Fouré et al., 2016, who reported 0.005 per cent added fall of global GDP in their simulation).[9]

4.2. Sectoral perspective

Concerning the sectors hit hard by CBAM, previous literature often finds that the EITE sectors, such as steel and iron, chemicals, non-metallic minerals sectors, are the most affected (see, e.g., Schinko et al., 2014; Böhringer et al., 2012; Kuik and Hofkes, 2010). Our results confirm these conclusions. We specifically look at the sectoral variances of the price and sales changes the CBAM induced in the EU market. These two variances are conducive to characterizing each sectors' sensitivity. The variance of the price changes on the X-axis demonstrates the disparity between sectoral emissions intensities; the variances in output changes on the Y-axis show the magnitude of the competitiveness redistribution among countries. We exemplify the results of Scenario 3 to display the sectoral sensitivity. The results are given in Fig. 1.

It is shown that the price changes induced by the CBAM differ across sectors. The sectors with relatively large variances in price changes include sector D35_E36 (*electricity, gas, steam, and air conditioning supply; water collection, treatment, and supply*), sector B (*mining and quarrying*), sectors C22–C23 (*non-metallic mineral products*), sector C24 (*basic metals*) and sector H49–H52 (*transport and warehousing*). Not surprisingly, these are emissions-intensive sectors in which production technologies significantly vary so that the CBAM causes significant price inequality between clean and dirty technologies.

Looking along the Y-axis, we also observe significant deviation of output changes across sectors. Generally, sectors with larger price variances also tend to have larger variances in their output changes. The reason is straightforward, recalling in the model that larger price changes lead to larger demand changes, *ceteris paribus*. As indicated in the figure, the CBAM triggers the most violent shifts in output in *non-metallic mineral* sector. Further, *chemicals* sector, *basic metal* sector and *mining* sector are also highly sensitive. Sectors with significant price changes but low trade exposure, such as the *energy/power* sector show moderate shifts in market share despite high price variance. In conclusion, we reaffirm that the most emissions-intensive trade-exposed sectors are also the most sensitive to CBAM.

Next, we focus on the four sectors to which the most significant competitiveness impacts occur. The results are given in Fig. 2.[10] Of the *non-metallic mineral* sector (C22–C23), China incurs an enormous export loss of $US5,255M to the EU, accounting 0.46 per cent of its total sectoral output in 2012. Other countries facing significant losses are Turkey, India, and Indonesia, with export losses of $US2,437M (6.30% of sectoral output, hereafter same as here), $US771M (0.72%), and $US402M (0.80%), respectively. In contrast, most EU countries are able to increase their sales within the EU market. For instance, Germany, Italy and France see their sectoral output increasing by $US4,679M, $US2,265M, and $US1,879M, respectively, accounting for 3.30, 2.54 and 2.68 per cent of respective 2012 output.

For *chemicals and chemical products* (C20–C21), the largest loss occurs to the rest of world—a proxy for other countries not included in the WIOT. Among individual countries, China suffers an enormous export loss valued at $US3,640M (0.26%). In addition, the *chemical* sectors in

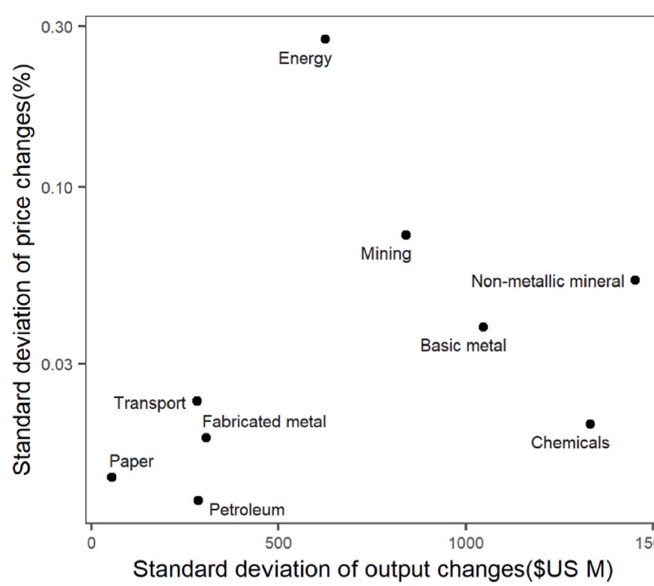

Fig. 1. Price change variances and output change variances by sector (Scenario 3).
Source: Authors' own calculations. Y-axis is transformed into log10 scale.

[9] Table 6 in their study reports that, global GDP would decrease by 0.443 per cent compared with the baseline scenario (without considering unilateral environmental policies) if EU adopts ETS. With the BCA implemented on top of the ETS (Scenario BCA), global GDP would decrease by 0.448 per cent relative to the baseline scenario. We take the differences in global GDP changes between these two scenarios as the impact of the BCA policy, i.e. 0.005 = 0.448–0.443.

[10] It is worth mentioning that for non-EU countries, their export losses are equal to output losses in Scenario 1–3 by construction. Hence, we may also use export loss in the text to emphasize that the loss in output change comes from export change. For the EU countries, their output change equals the change in their sales in the EU, while there is no change in other trade flows.

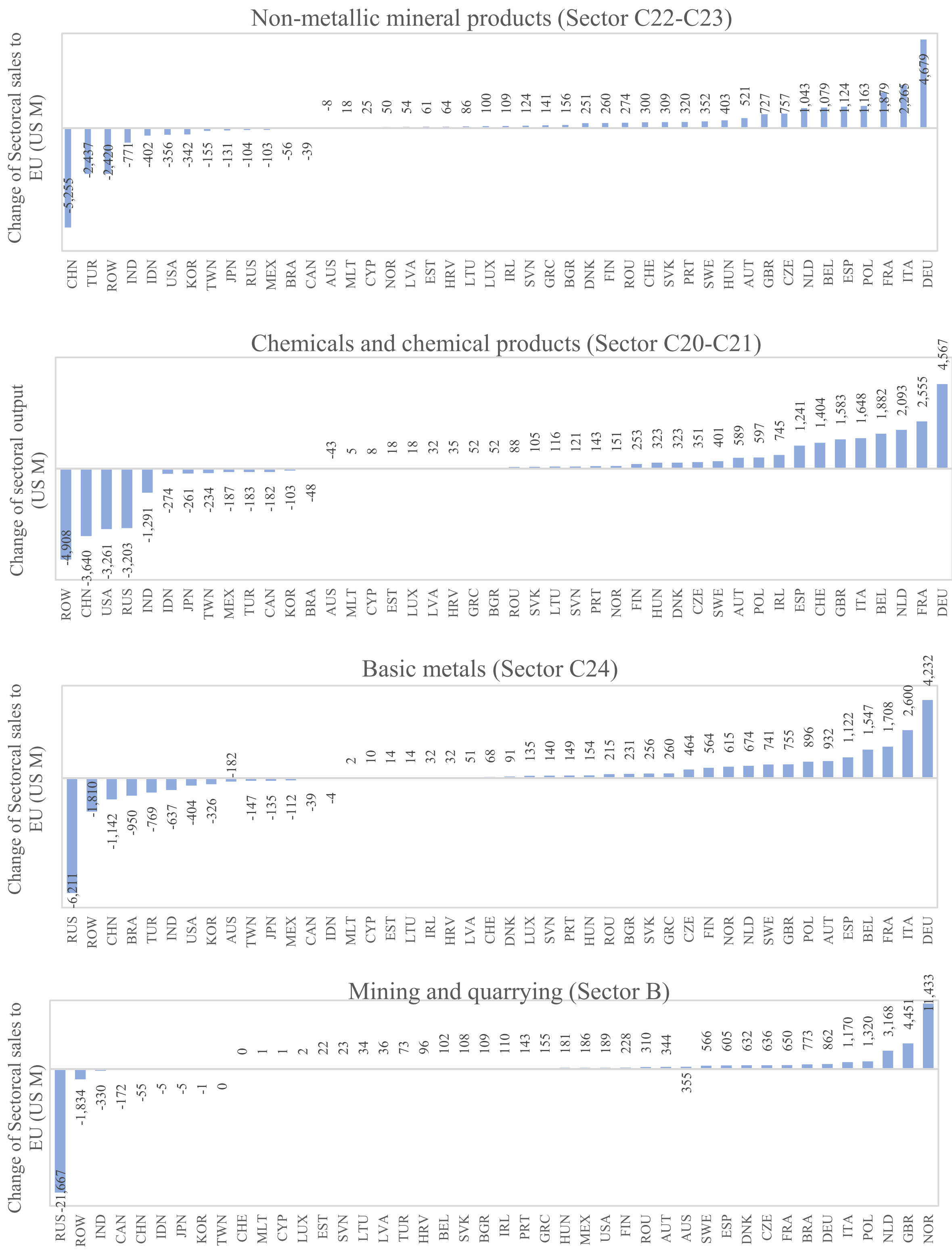

Fig. 2. Redistribution of competitiveness under EU CBAM in selected sectors (Scenario 3).
Source: Authors' own calculations.

the United States, Russia and India are also sensitive. Again, EU countries such as Germany, France and the Netherlands would expand their supply to the EU market.

For *basic metal* (C24) and *mining* sector (B), Russia, as the EU's largest resource and intermediate supplier, bears the brunt of the CBAM. Its export of these two sectors to EU fall by $US6,211M and $US2,1667M, respectively, accounting for 4.39 and 4.97 per cent of the sectoral output in 2012. Further, China and Brazil also see moderate declines in their basic metal export. In the EU, Germany, Italy and France can expect their supply for the EU market to increase significantly. For *mining and quarrying* sector, Norway, the UK and the Netherlands see increases of 8.25, 6.27 and 9.62 per cent of total sectoral output.

A closer look into industries, our simulation results generally suggest that EU CBAM would generate a greater impact on developing countries, such as China, India, Turkey, Russia, among others. This is comparable with the findings based on CGE models, yet our simulations extend country coverage and industry details.

4.3. Country-level impacts

This section focuses on changes in average prices and total sales revenues at the country level. In general, developing countries with dirtier production technologies and higher EU trade exposures suffer more from the EU CBAM; the higher the CBAM price, the larger the impact.

Fig. 3 demonstrates the impacts of our four scenarios in terms of the import price changes to non-EU products in the EU market. We find that the most significant price increases occur for Russia, India and the rest of the world, whereas developed countries, such as Switzerland, Japan, the United States, Korea, the UK and Norway, only see modest price increases.[11]

Logically, the doubling of the CBAM price also doubles the price changes from Scenario 1 to Scenario 2. In terms of Scenario 3, the countries that are allowed price reductions or exemptions experience lower price increases than do the countries in Scenario 2, whereas other countries remain unchanged. Finally, considering the production cost adjustments (Scenario 4) further pushes up prices, albeit marginally.

Fig. 4 and Fig. 5 show sectoral output changes of non-EU and EU countries in four scenarios. Overall, CBAM causes a significant distributional effect between EU and non-EU countries. The magnitude of this effect is proportional to the level of CBAM price. Implementing exemptions and reductions can reduce the burden on non-EU countries that already have a carbon price in the country, but countries that do not have carbon pricing in place may suffer greater loss. Meanwhile, countries that do not currently implement carbon pricing tend to be low-income and under-developed countries. Finally, in the long run, the distribution impact of CBAM weakens when taking into account EU production price adjustments which pass through to other countries.

In the case of a flat CBAM price of $US50 (Scenario 1), we find that an enormous loss occurs to Russia, who has a large share of emissions-intensive resources and raw material exports to the EU, making it highly elastic to the CBAM. Its export decreases by $US17,859M, accounting for 0.52 per cent of its total output in 2012. Given a higher CBAM price of $US100 (Scenario 2), Russia's export to the EU is reduced by $US32,577M (0.95% of total output, hereafter same as here). In Scenario 3, the impact on Russia is exacerbated by the presence of the exemption and reduction. Its output loss increases by 5.78 percentage points, relative to the loss in Scenario 2, since Russia would receive neither an exemption nor reduction materializes in Scenario 3. For Russia, the price changes remain the same as in Scenario 2, yet the exemptions and reductions in other countries drive down the average price relative to Scenario 2 and make Russia's products relatively more expensive. As a result, countries like Russia, which lacks national carbon pricing scheme, subject to greater distributional impact if the EU CBAM includes exemption and reduction. Finally, considering the costs transmission (Scenario 4), the EU's production cost increases mitigate Russia's export reduction.

The impact on China is quite substantial in absolute terms. In Scenarios 1 and 2, China's export to the EU drop by $US7,239M (0.03%) and $US12,621M (0.05%). Although China's export losses are relatively large in absolute terms, the relative losses, in terms of total output, are not big since China has a larger economy and more diversified economic structure, contrasting with Russia. Next, if exemptions and reductions are allowed (Scenario 3), China would be better off relative to Scenario 2. In fact, China started its cap-and-trade pilot schemes in seven cities in 2013 and officially started its national carbon market on January 1, 2021. Assuming the EU CBAM price for China is cut by Chinese carbon price of $US7.6 per tonne, in 2021, China's export losses decrease by 5.16 per cent in Scenario 3 compared with Scenario 2. Clearly, it is demonstrated that exemptions and price reductions that consider current carbon prices worsen the situations of countries without carbon prices. Likewise, in Scenario 4, CBAM's distribution impacts on China's output lessened.

Overall, the size of the simulation results in this paper (in terms of absolute changes in values) is larger than those reported in Fouré et al. (2016). For China, the absolute change in value of Chinese exports to the EU in our Scenario 1 is almost three times as large as those reported in comparable scenario (i.e., BCA Indirect emissions). On the one hand, this is partly due to the fact that our choice of CBAM covers more sectors, including both the mining and transport sectors; On the other hand, we speculate an overshooting effect plays a role, i.e. policy shocks in the short-run tend to be larger than in the long-run (a phenomenon usually debated concerning the volatility of exchange rates).[12] Only a few non-EU countries benefit from implementing the EU CBAM, namely Norway and Switzerland in all four scenarios, and the United Kingdom if exemptions are allowed (Scenarios 3 and 4). Due to the extremely low emissions intensity in Norway and Switzerland, only moderate price changes would occur to their products under a flat CBAM price. With their price changes remaining far below the average increase, the EU's demand for exports increases, promoting their output. In Scenario 3, these countries are exempted by CBAM, which further strengthens their competitive advantage. After considering cost pass-through in Scenario 4, price increases in these countries are also lower than that in other countries, and outputs thus tend to grow further.

Fig. 5 shows the change in output in the EU countries after the implementation of CBAM. In absolute terms, Germany sees the largest incremental output. In Scenario 1 and 2, Germany's output increase by $US10,527M (0.16%) and $US21,666M (0.33%). Italy's output rises by about $US5,526M (0.14%) and $US11,307M (0.28%). In Scenario 3 with exemptions and reductions, competition from exempted countries reduces benefits for EU countries. In the case of Germany, its output increase in Scenario 3 falls by 13.14 per cent compared with that in Scenario 2.

In scenario 4, we see that the competitive advantage of the EU is deteriorated when considering EU production price increases. The change in output even sees reversal in some countries. This is where, in the long run, the EU needs to be concerned about the potential costs of the CBAM imposed on EU imports alone. That is, from a supply-chain point of view, import prices driving up EU costs may eventually reduce if not alter the competitiveness of EU products in the world market. Fig. 6 shows the changes in production prices in the EU countries due to CBAM. The most remarkable production cost increases are in the Central and Eastern European countries, such as Lithuania, Bulgaria, Latvia, Slovakia and Estonia.

By and large, this concern could be addressed by introducing a full CBAM, i.e. adjusting both exports and imports (for instance, via rebating exports). While for non-EU economies, if the EU does not rebate exports, the competitiveness effect due to the CBAM in the short run may weaken on its own in the long run, due to the presence of cost adjustment mechanisms.

4.4. Provincial perspective (China)

Overall, China accounts for 18.61 per cent of the total output loss in non-EU countries (Scenario 3). In this section, we discuss how this loss is

[11] We consider a situation with no exemptions and reductions for the United States. Although President Joe Biden has recently reinstated the US in the Paris Climate Agreement, we are interested in quantifying potential costs for the United States for being absent from global climate cooperation. We find that the CBAM only leads to a moderate fall in US output, even though the US is the EU's major trading partner.

[12] Indeed, CGE models often allow for substitution among production factors to various extent, which tends to smoothing the shock. Yet, this mechanism plays a minor role in short term and is therefore not observable in our model.

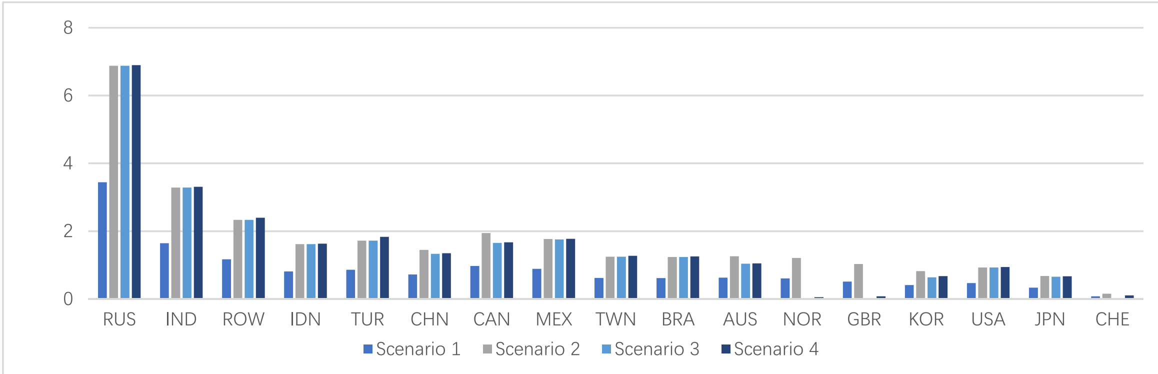

Fig. 3. Import price changes for EU by source country (%).
Source: Authors' own calculations. The price changes here refer specifically to the weighted average of the price changes for each country's exports to Europe.

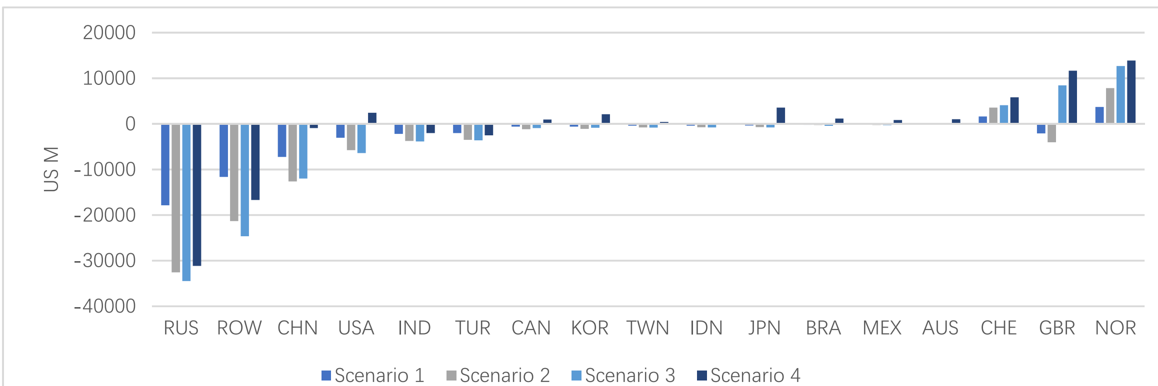

Fig. 4. Changes in total output by (non-EU) countries.
Source: Authors' own calculations.

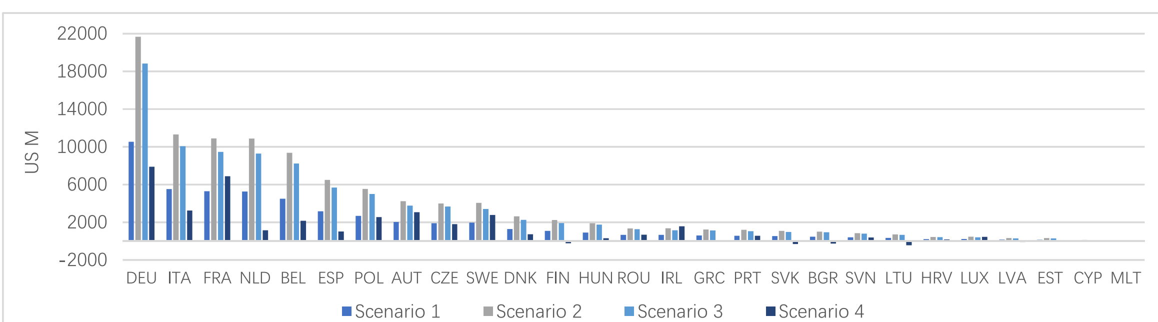

Fig. 5. Changes in total output by (EU) countries.
Source: Authors' own calculations.

distributed among the Chinese provinces. We first show the impacts of the EU CBAM on China's provincial exports to the EU. Table 3 screens out a few of the most-affected sectors and shows the corresponding changes in output as well as total output by Chinese province. The results indicate that the EU CBAM tends to have more direct impacts on coastal regions than on landlocked ones, due to the former's higher trade exposure.

Next, we focus on how the EU CBAM's welfare impact is distributed across Chinese regions, given provincial differences in trade openness and position on domestic production chains. Intuitively, regions with higher openness in China should be more sensitive to the CBAM than less-open regions. However, as regions serve different roles along the supply chain, it is likely that landlocked regions, although not directly engaged in exporting, may indirectly suffer income losses as a negative demand shock can propagate through inter-regional industrial linkages.

The phenomenon where a negative demand shock in an exporting region drives down output in another region is called a demand spillover (Bems et al., 2010; Pei et al., 2018). As coastal regions are usually more engaged in international trade, in China's particular case, we expect their direct export losses to be larger than those of landlocked regions. However, given that landlocked regions usually serve as upstream suppliers to coastal regions, they should be more indirectly affected than their direct exposure would imply.

Fig. 7 shows provincial losses in terms of value added and exports under the EU CBAM in Scenario 3. Coastal and export-exposed provinces such as Guangdong, Zhejiang, Jiangsu, Shandong, Fujian, and Shanghai have lower value-added losses compared to their export losses. In contrast, landlocked and less developed regions are mainly located in the bottom left corner of the plot and lie above the reference line ($x = y$).

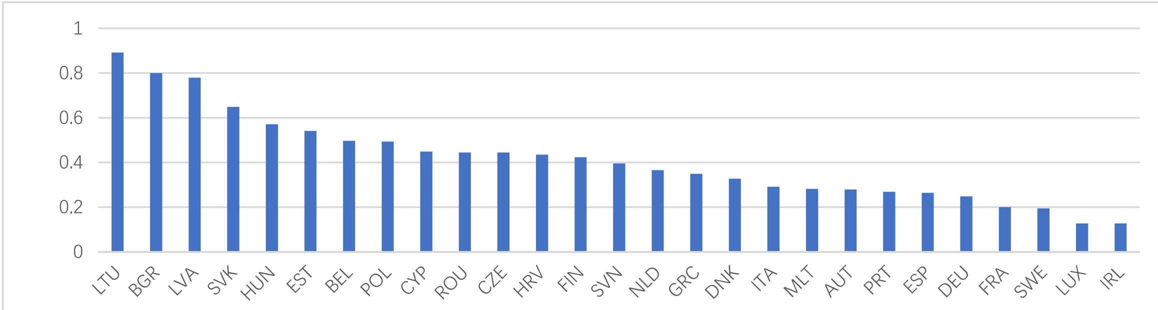

Fig. 6. EU's production cost changes by country (%, Scenario 4).
Source: Authors' own calculation.

Table 3
Changes in Chinese exports to the EU by province (selected sectors, Scenario 3).

	Mining		Chemicals		Non-metallic mineral		Basic metal		Total
	Export loss ($US M)	In total export (%)	Export loss	In total export	Export loss	In total export	Export loss	In total export	In total export (%)
Coastal regions									
Zhejiang	−0.04	−0.26	−1258.83	−5.69	−231.57	−8.49	−133.23	−3.29	−0.86
Jiangsu	−0.12	−1.24	−1175.62	−4.46	−355.91	−6.59	−256.64	−2.22	−0.58
Shandong	−6.36	−3.49	−1025.92	−4.13	−193.04	−6.90	−14.51	−2.05	−0.69
Guangdong	−2.12	−0.45	−668.11	−3.83	−725.79	−5.02	−72.56	−1.34	−0.40
Fujian	−2.84	−0.49	−455.25	−5.19	−700.08	−7.74	−116.46	−3.20	−1.41
Shanghai	0.00	−0.50	−306.05	−3.13	−63.90	−6.06	−83.39	−1.90	−0.36
Hebei	−1.83	−0.64	−137.87	−3.90	−147.74	−6.05	−120.86	−1.54	−1.33
Tianjin	−2.59	−0.39	−120.84	−4.12	−9.82	−4.22	−44.77	−0.89	−0.46
Liaoning	−15.67	−2.48	−106.85	−3.33	−269.08	−6.31	−216.07	−2.69	−1.15
Hainan	−0.03	−0.34	−5.50	−4.95	−5.64	−9.26	−0.07	−2.52	−0.58
Landlocked regions									
Hubei	−14.25	−2.34	−444.98	−5.40	−9.74	−8.14	−56.25	−3.44	−1.51
Henan	−0.86	−4.14	−99.64	−5.68	−110.88	−6.04	−32.86	−3.31	−0.90
Sichuan	−0.49	−2.63	−94.52	−3.60	−183.68	−7.17	−42.59	−1.50	−0.91
Anhui	−0.35	−5.22	−81.21	−4.43	−210.07	−9.20	−13.04	−1.91	−1.33
Shaanxi	−11.23	−10.68	−57.97	−2.35	−165.40	−7.43	−71.27	−2.19	−1.15
Inner Mongolia	−0.37	−4.93	−57.69	−6.41	−31.21	−7.32	−15.58	−0.87	−0.72
Jiangxi	−0.03	−2.75	−41.88	−3.80	−367.19	−7.37	−55.60	−3.72	−2.37
Beijing	−2.90	−0.35	−37.86	−3.49	−27.86	−4.86	−2.99	−1.65	−0.22
Heilongjiang	−0.07	−1.45	−36.10	−3.49	−28.28	−5.37	−6.35	−2.54	−0.72
Guizhou	−6.74	−6.38	−35.89	−2.02	−40.74	−6.37	−4.14	−2.68	−2.46
Guangxi	−1.76	−0.68	−33.54	−3.03	−11.55	−2.11	−45.47	−4.33	−0.67
Hunan	−1.00	−5.51	−21.05	−3.58	−59.64	−9.06	−11.10	−0.78	−0.99
Yunnan	0.00	−5.49	−19.99	−4.37	−4.85	−5.98	−3.84	−1.40	−1.45
Jilin	−0.40	−4.20	−18.08	−3.54	−21.52	−5.91	−4.26	−5.63	−0.78
Ningxia	0.00	−15.63	−16.60	−5.59	−8.16	−12.52	−4.65	−1.29	−2.05
Xinjiang	−0.28	−7.57	−12.19	−1.32	−31.70	−3.04	−14.43	−1.12	−0.78
Shanxi	−29.23	−1.02	−6.36	−1.70	−22.93	−7.49	−101.07	−4.77	−2.27
Gansu	−0.05	−12.47	−6.17	−3.22	−44.81	−7.58	−9.95	−4.47	−2.55
Chongqing	−0.01	−3.70	−4.32	−5.55	−4.33	−7.48	−0.70	−5.22	−0.56
Qinghai	0.00	−11.07	−3.38	−8.20	−102.47	−12.49	−0.52	−0.52	−8.15

Source: Authors' own calculations.

This indicates that landlocked regions have greater losses in the overall value added of their industrial production than in the value of their exports. In short, their overall economic sensitivity is higher than their direct exposure to the EU CBAM. Therefore, whether from the perspective of the EU or the Chinese government, when formulating subsidies or investment policies, landlocked regions should not be ignored, even though at the first glance they appear to be less directly affected by the EU's carbon policy.

Finally, as shown in Zhou et al. (2020), China's national carbon intensity is more determined by its developed provinces and there are significant heterogeneity in carbon intensity across regions. Therefore, the use of a national benchmark to tax the exports of different regions would disincentivize firms to reduce emission. This concern may be mitigated by using a regional industry-level benchmark if the data are available.

5. Conclusion and policy implications

This paper examined and quantified the impacts of the EU CBAM on competitiveness and welfare on EU and its trading partners. Building on Ward et al. (2019), we refined the demand structure of their model and adopted sector heterogeneous substitution elasticities, and extend the model to estimate sub-national impacts. These extension and refinements improve the capability and accuracy of this IO framework on trade impact analysis of the CBAM.

Our simulation results are in line with theoretical expectations and previous studies that CBAM would introduce a notable redistribution impact among signatories and their counterparts. In our context, EU's demand for its own supply increases while that for non-EU products decrease. This means that CBAM can preserve the competitiveness of the EU and reduce the carbon leakage caused by the EU ETS. However, the impact on global carbon

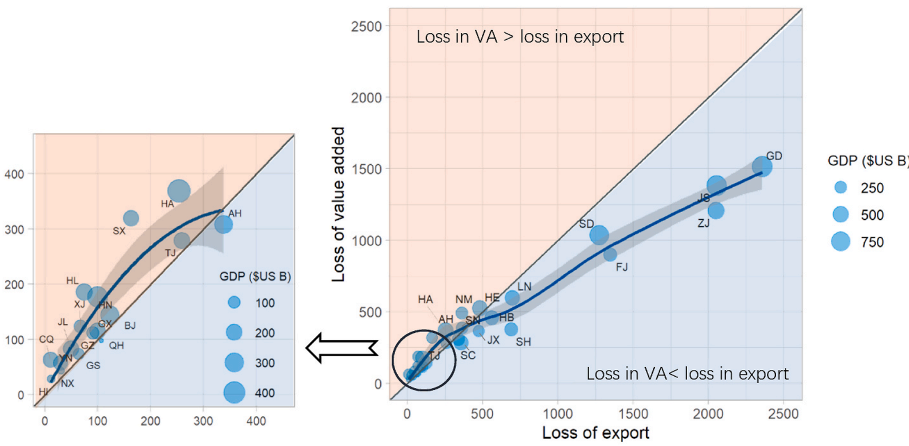

Fig. 7. China's regional losses in value added and exports (Scenario 3).
Source: Authors' own calculations. Definitions for the abbreviations of the Chinese provinces are provided in Appendix 2. The smoothing curve is obtained using a statistical technique called the LOESS curve. The 95% confidence interval is displayed around the smoothing. The size of the point represents the regional GDP.

reduction is at best limited. Therefore, in terms of direct effect alone, CBAM cannot be considered as an effective measure to reduce global carbon leakage. In addition, CBAM may also serve as an indirect effect of threat. Although this paper does not directly address this issue, we show that the negative effects of CBAM on countries that have not adopted carbon pricing bear an opportunity cost of inaction, building CBAM's strategic value.

Specifically, we quantified the competitiveness impacts on countries and sectors. At the sector level, the CBAM leads to the most significant redistribution of market shares in emissions-intensive and trade-intensive sectors. At the country level, countries that are most significantly affected by the CBAM are those with a large share of exports from emissions- and trade-intensive sectors and high export exposure to the EU. Within our sample, Russia, China, India, and Turkey are among the countries that are relatively sensitive to the CBAM and are therefore the most likely to initiate counter measures to this policy. Besides, the arrangement of exemptions and reductions determined by current national carbon prices tend to exacerbate the burden in less developed regions. In practice, therefore, we recommend a more comprehensive comparability standard to avoid disproportionate shift of the costs of climate action to developing countries.

Moreover, we show how alternative policy designs translate to different trade effects. Firstly, a higher CBAM price level leads to larger redistribution impact. Second, recognizing trading partners' existing climate efforts by allowing exemptions and reductions would in principle increase "fairness". Yet it may also increase the burden of low-income countries, generating unintended "unfairness". Therefore, it is suggested that the EU could also consider increasing the acceptance and equity of CBAM by helping low-income countries to establish carbon pricing systems, and/or by investing CBAM revenues to green technology in low-income countries.

In fact, our simulation results are in line with previous studies on the effects of CBAM. Interestingly, we have reached similar results using different dataset and methodology (recalling the widely-used CGE model based on GTAP in previous literature). Furthermore, we extend this impact analysis to sub-national level with a tractable framework, which is under-explored in the CGE literature on CBAM. Our simulation shows that demand spillover effects exist at the sub-national level, where the income loss in landlocked provinces exceeds their export loss, while the pattern for the trade-exposed provinces is the opposite. In this regard, it is necessary to consider the demand spillover effects at the sub-national level when using regional policy to counteract the welfare loss induced by the CBAM.

A final word about the EU CBAM. In an era of global production chains, the effectiveness of policies needs to be carefully evaluated. By design, the CBAM aims to level the playing field for EU products and imports in the EU market; while it does not change the competitiveness in the global market. Moreover, if EU producers cannot absorb the increase in production costs caused by CBAM in the long run (through whatever means, say advancements in production processes and technologies), CBAM may also reduce the competitiveness of EU products in the world market. This is exactly the situation in Scenario 4. Even worse, such development trajectory does not contribute to global welfare or emissions reduction targets. In this sense, CBAM is best seen as a temporary and transitional policy or a threat to promote the participation of non-climate coalition countries in global climate cooperation. In the long run, the development of green technologies is the key to solve competitiveness and climate problems, and the EU could take a lead to synthesis the efforts worldwide.

Disclosure statement for the paper

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CRediT authorship contribution statement

Jiarui Zhong: prepared the data, tables and figures, conducted the analysis and wrote the paper. **Jiansuo Pei:** conducted the analysis and wrote the paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix 1a. Sector classification

ISIC rev4	WIOT 56 Sectors	CMRIO-WIOT 23 Sectors																						
		A	B	C10–C12	C13–C15	C17–C18	C19	C20–C21	C22–C23	C24	C25	C26	C27	C28	C29–C30	C16_C31_C32	D35_E36	F	C33_G45-G47	H49–H52	I	M69_M70_M73_N	M72_M74_M75	Other services
A01	Crop and animal production, hunting and related service activities	1																						
A02	Forestry and logging	1																						
A03	Fishing and aquaculture	1																						
B	Mining and quarrying		1																					
C10–C12	Manufacture of food products, beverages and tobacco products			1																				
C13–C15	Manufacture of textiles, wearing apparel and leather products				1																			
C16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials															1								
C17	Manufacture of paper and paper products					1																		
C18	Printing and reproduction of recorded media;					1																		
C19	Manufacture of coke and refined petroleum products						1																	
C20	Manufacture of chemicals and chemical products							1																
C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations							1																
C22	Manufacture of rubber and plastic products								1															
C23	Manufacture of other non-metallic mineral products								1															
C24	Manufacture of basic metals									1														
C25	Manufacture of fabricated metal products, except machinery and equipment										1													
C26	Manufacture of computer, electronic and optical products											1												
C27	Manufacture of electrical equipment												1											
C28	Manufacture of machinery and equipment n.e.c.													1										
C29	Manufacture of motor vehicles, trailers and semi-trailers														1									
C30	Manufacture of other transport equipment														1									
C31_C32	Manufacture of furniture; other manufacturing															1								
C33	Repair and installation of machinery and equipment																		1					
D35	Electricity, gas, steam and air conditioning supply																1							
E36	Water collection, treatment and supply																1							
E37-E39	Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services																							1
F	Construction																	1						
G45	Wholesale and retail trade and repair of motor vehicles and motorcycles																		1					

(*continued on next page*)

(*continued*)

ISIC rev4	WIOT 56 Sectors	CMRIO-WIOT 23 Sectors																						
		A	B	C10–C12	C13–C15	C17–C18	C19	C20–C21	C22–C23	C24	C25	C26	C27	C28	C29–C30	C16_C31_C32	D35_E36	F	C33_G45-G47	H49–H52	I	M69_M70_M73_N	M72_M74_M75	Other services
G46	Wholesale trade, except of motor vehicles and motorcycles																		1					
G47	Retail trade, except of motor vehicles and motorcycles																		1					
H49	Land transport and transport via pipelines																			1				
H50	Water transport																			1				
H51	Air transport																			1				
H52	Warehousing and support activities for transportation																			1				
H53	Postal and courier activities																							1
I	Accommodation and food service activities																				1			
J58	Publishing activities																							1
J59_J60	Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities																							1
J61	Telecommunications																							1
J62_J63	Computer programming, consultancy and related activities; information service activities																							1
K64	Financial service activities, except insurance and pension funding																							1
K65	Insurance, reinsurance and pension funding, except compulsory social security																							1
K66	Activities auxiliary to financial services and insurance activities																							1
L68	Real estate activities																							1
M69_M70	Legal and accounting activities; activities of head offices; management consultancy activities																					1		
M71	Architectural and engineering activities; technical testing and analysis																							1
M72	Scientific research and development																						1	
M73	Advertising and market research																					1		
M74_M75	Other professional, scientific and technical activities; veterinary activities																						1	
N	Administrative and support service activities																					1		
O84	Public administration and defence; compulsory social security																							1
P85	Education																							1
Q	Human health and social work activities																							1
R_S	Other service activities																							1
T	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use																							1
U	Activities of extraterritorial organizations and bodies																							1

Appendix 1b. Sector classification

ISIC rev4	WIOT 56 Sectors	CMRIO-WIOT 23 Sectors									
		A	B	C10–C12	C13–C15	C17–C18	C19	C20–C21	C22–C23	C24	C25
1	Agriculture	1									
2	Coal mining		1								
3	Petroleum and gas		1								
4	Metal mining		1								
5	Nonmetal mining		1								
6	Food processing and tobaccos			1							
7	Textile				1						
8	Clothing				1						
9	Wood processing and furnishing										
10	Paper making				1						
11	Petroleum refining						1				
12	Chemical industry							1			
13	Nonmetal products								1		
14	Metallurgy									1	
15	Metal products										1
16	General and specialist machinery										
17	Transport equipment										
18	Electrical equipment										
19	Electronic equipment										
20	Instrument and meter										
21	Other manufacturing										
22	Electricity and hot water production and supply										
23	Gas and water production and supply										
24	Construction										
25	Transport and storage										
26	Wholesale and retailing										
27	Hotel and restaurant										
28	Leasing and commercial services										
29	Scientific research										
30	Other services										

CMRIO-WIOT 23 Sectors												
C26	C27	C28	C29–C30	C16_C31_C32	D35_E36	F	C33_G45-G47	H49–H52	I	M69_M70_M73_N	M72_M74_M75	Other services
				1								
		1										
			1									
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1												
1												
				1								
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						1						
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							1					
									1			
										1		
											1	
												1

Appendix 1c. Sector classification

A	Agriculture
B	Mining and quarrying
C10–C12	Manufacture of food products, beverages and tobacco products
C13–C15	Manufacture of textiles, wearing apparel and leather products
C17–C18	Manufacture of paper and paper products; Printing and reproduction of recorded media;
C19	Manufacture of coke and refined petroleum products
C20–C21	Manufacture of chemicals and chemical products
C22–C23	Manufacture of non-metallic mineral products
C24	Manufacture of basic metals
C25	Manufacture of fabricated metal products, except machinery and equipment
C26	Manufacture of computer, electronic and optical products
C27	Manufacture of electrical equipment
C28	Manufacture of machinery and equipment n.e.c.
C29–C30	Manufacture of Transport equipment
C16_C31_C32	Manufacture of wood and of products of wood and cork; manufacture of articles of straw and plaiting materials; other manufacturing
D35_E36	Electricity, gas, steam and air conditioning supply; Water collection, treatment and supply
F	Construction
C33_G45-G47	Wholesale and retail trade; repair of motor vehicles and motorcycles
H49–H52	Transport and Warehousing
I	Accommodation and food service activities
M69_M70_M73_N	Leasing and commercial services
M72_M74_M75	Scientific research and development
Other services	Other services

Appendix 2. Abbreviations for Chinese Provinces

Full name	Code	Full name	Code	Full name	Code
Anhui Province	AH	Hainan Province	HI	Shandong Province	SD
Beijing Municipality	BJ	Heilongjiang Province	HL	Shanghai Municipality	SH
Chongqing Municipality	CQ	Hunan Province	HN	Shaanxi Province	SN
Fujian Province	FJ	Jilin Province	JL	Shanxi Province	SX
Guangdong Province	GD	Jiangsu Province	JS	Tianjin Municipality	TJ
Gansu Province	GS	Jiangxi Province	JX	Xinjiang Uyghur Autonomous Region	XJ
Guangxi Zhuang Autonomous Region	GX	Liaoning Province	LN	Yunnan Province	YN
Guizhou Province	GZ	Inner Mongolia Autonomous Region	NM	Zhejiang Province	ZJ
Henan Province	HA	Ningxia Hui Autonomous Region	NX		
Hubei Province	HB	Qinghai Province	QH		
Hebei Province	HE	Sichuan Province	SC		

Appendix 3. Sensitivity test

As mentioned above, theoretically, heterogeneous sectoral demand substitution elasticities are preferred over uniform elasticities as they are likely to produce more realistic estimates. To test the sensitivity of sectoral estimates against alternative assumptions on elasticities, we perform the simulation of Scenario 3 again, but with a uniform sectoral elasticity, and compare the results with the earlier outcome. Explicitly, we set δ^D and δ^M to -2.84, as in Ward et al. (2019), implying a uniform elasticity of substitution value of 3.84. In Fig. 8, we plot the simulated demand changes in the earlier Scenario 3 on the Y-Axis and those in the new Scenario 3 with a uniform elasticity on the X-axis. As Fig. 8 indicates, adopting a uniform elasticity of 3.84 does not overturn the earlier conclusions yet tends to produce smaller estimates of sales changes in terms of absolute value, both on the sectoral and national level. Therefore, we see that both trendlines (the dotted lines in Fig. 8) have a slope lower than 1 (the reference line y = x, indicating identical simulation outcomes). One reason for this observation is straightforward: the applied uniform elasticity of 3.84 is lower than most of the σ_i^M and about half of the σ_i^D adopted in our earlier simulation. Recalling the model, it can be seen that lower elasticities tend to produce more moderate changes. Therefore, adopting the uniform elasticity of 3.84 tends to underestimate the redistribution of competitiveness among imports from foreign sources while it underestimates that between domestic supply and imports for sectors with a higher σ_i^D and overstate that for sectors with a lower σ_i^D.

(a) EU's demand changes by country ($US M) (b) EU's demand changes by country-sector pair ($US

M)

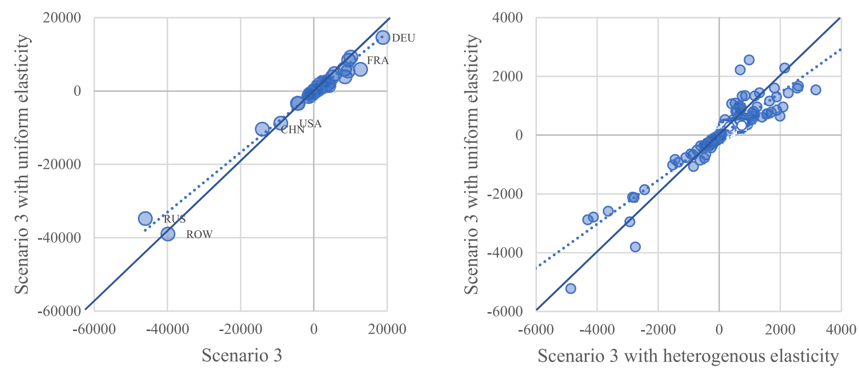

Fig. 8. Simulation with sector heterogeneity and uniform demand elasticities (a) EU's demand changes by country ($US M) (b) EU's demand changes by country-sector pair ($US M) Source: Authors' own calculations.

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