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Examining industrial air pollution embodied in trade: implications of a hypothetical China-UK FTA

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Abstract

Very few developed economies have a full free trade agreement (FTA) with China. This study employs one GTAP model and builds an extended environmental multi-region input–output model to investigate a hypothetical China-UK FTA, concerning embodied industrial emissions of SO_2, $PM_{2.5}$, NO_X, and NH_3. The economic sectors are also classified based on their embodied pollution intensity and trade advantage index under various FTA scenarios. Results show that the UK's GDP and welfare and China's welfare will increase, along with changes in their trade structures. Overall, this FTA brings about larger net impacts on embodied emissions of SO_2 than on $PM_{2.5}$, NO_X and NH_3, and both countries are net importers of the latter three pollutants. Key sectors such as non-metallic mineral products, chemical products, and agriculture are inclined to become less competitive and less polluting under the FTA. The inclusion of agri-food sectors exhibits slight counteracting effects in general. The findings are of policy importance as they provide insights into how best to target key sectors, seeking a balance between trade development and environmental protection.

List of symbols

FTA	Free trade agreement
GTAP	Global Trade Analysis Project
SO_2	Sulfur dioxide
$PM_{2.5}$	Fine particulate matter
NO_X	Nitrogen oxides
NH_3	Ammonia
GDP	Gross domestic product

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UK   United Kingdom
CPTPP   Comprehensive and Progressive Agreement for Trans-Pacific Partnership
EU   European Union
GHG   Greenhouse gas
SO_X Sulfur oxides
MRIO   Multi-regional input–output
US   United States
BRICS   Brazil, Russia, India, China, and South Africa
G20   Group of Twenty
SDG   Sustainable Development Goal
ARDL   Autoregressive-distributed lag
WTO   World Trade Organization
NMVOC   Non-methane volatile organic compound
RCEP   Regional Comprehensive Economic Partnership
GVC   Global value chain
CGE   Computable general equilibrium
GAMS   General Algebraic Modeling System
I–O   Input–output
NRCA   Normalized revealed comparative advantage

1 Introduction

Very few developed economies have a full free trade agreement (FTA) with China. The exceptional ones, such as Australia and Switzerland, usually focus on specific products such as minerals and specialist machinery, which make such a deal attractive to China. As the multilateral trade negotiations and more broadly the conventional globalization are increasingly pressed by protectionism (Fajgelbaum et al., 2019), among other factors, there is a growing interest in proposing and ratifying regional or bilateral trade agreements (Armand de Mestral, 2020; Tian et al., 2022). For example, both the United Kingdom (UK) and China have expressed serious interest in joining CPTPP[1] in early 2021 (Xinhua News, 2021; Zhong, 2021).

Trade volume between the UK and China has experienced a ten-fold increase from £6.1 billion in 1999 to a record high of £67.3 billion in 2018, with the UK having a trade deficit with China of -£22.1 billion (Ward, 2019b). The opportunity afforded by Brexit may further stimulate trade growth between China and the UK through the ratification of a bilateral FTA. However, this prospect may lead to serious environmental implications. A recent study illustrates that approximately half of the UK's true carbon footprint is made up of imports to the UK during 1990–2016 (WWF-UK, 2020). While the UK imported £357 billion worth of goods and services from the European Union (EU) in 2018, this accounted for 9.9% of the overall imported carbon footprint (Ward, 2019a; WWF-UK, 2020). This figure dwarfs the value of Chinese imports at £44.7 billion in 2018; however the imported carbon footprint of these goods and services stood at a not inconsequential level of 7.3%

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[1] CPTPP stands for the Comprehensive and Progressive Agreement for Trans-Pacific Partnership. For more details: https://www.mfat.govt.nz/en/trade/free-trade-agreements/free-trade-agreements-in-force/cptpp/

of the total (Ward, 2019b; WWF-UK, 2020). Consequently, the compositions of such trade and its associated environmental impacts should be further investigated.

The existing trade flows between the UK and China show that travel, vehicles and manufactured products are the key items of the current total and will likely be further strengthened with an FTA (Ward, 2019b). Furthermore, in light of the EU's long running failure to agree an FTA with China, the existence of an FTA between China and the UK following Brexit involving vehicles will open up the prospect of the UK becoming Europe's automotive export base for the China market, which again may have widespread environmental implications through increased trading volume between China and the UK.

In the arena of trade and environment, there exist widespread concerns over "unequal exchanges" of environmental burdens and resources between developed and developing countries (Dorninger et al., 2021). There are also studies underscoring the positive effects of trade on improving environment-related metrics (Xu et al., 2020). For China, trade-driven increases in domestic pollution are well recorded, involving not just greenhouse gases (GHGs) but also SO_X and NO_X (Liu et al., 2016b). Trade has also induced the emissions of a lesser-known pollutant, NH_3, and the NH_3 emissions can drive $PM_{2.5}$ pollution causing public health consequences (Ma et al., 2021). In addition, regarding trade and economy, note that the relationships between trade liberalization and economic growth are not necessarily positive, but could be ambiguous for China (Zheng & Walsh, 2019).

However still, not all trade expansion activities would add to environmental burdens. For example, the China-Australia FTA (Qi & Zhang, 2018) and the trilateral China-Japan-South Korea FTA (Cui et al., 2019b) are projected to produce counterintuitive outcomes, due to the mediation of trade-induced restructuring of sectors with disparity in pollution intensity. Moreover, the China-Japan-South Korea FTA with free agricultural trade may bring about further environmental benefits (Cui et al., 2019b). In fact, for countries heavily involved in agri-food trade, the agri-food sector is getting increasingly important for pursuing sustainable development in GHGs mitigation and land resources utilization (Zhao et al., 2021).

Based on the above, this study seeks to address the following questions that the existing literature yet to provide insights into: (1) If there were a China-UK FTA, how would such an FTA affect the economy and the environment in terms of embodied pollution, for both China and the UK, and the broader world? Herein the pollutants considered include $PM_{2.5}$, SO_2, NO_X, and NH_3. (2) Under such a bilateral FTA, what would be the key sectors contributing to China/UK's rise and fall in embodied pollution in trade, and how increasing trade liberalization would affect these sectors? (3) What environmental implications would a partial FTA with agricultural protection bring about?

This study makes contributions in the following aspects. First, it pays attention to a few major yet underrepresented air pollutants from an embodied perspective, rather than embodied CO_2 emissions as investigated in many other studies examining trade flows (Feng et al., 2013; Liu et al., 2016a; Tian et al., 2022) or economic structural changes (Ali et al., 2020). Second, compared with studies on multilateral trade agreements such as Tian et al. (2022), this study places greater emphasis on the additional impacts of a bilateral FTA on embodied pollution, offering multiple insights into these incremental changes. Third, the study derives the evolving paths of sectoral performance in comparative trade advantage and embodied pollution intensities, for China and the UK's industries under the influence of increasing trade liberalization. Such paths may help better inform decision-making, devising policies that seek for optimal levels of trade openness concerning environmental protection. Fourth, by examining multiple industrial air pollutants, this study will show that noteworthy disparities exist between different types of pollutants, especially

with regards to the effects of the FTA. Fifth, this study examines the bilateral FTA with and without agri-food exemptions, as the agri-food sector is increasingly important for sustainable trade, involving NH_3 emissions that have public health implications.

This study is among the first of its kind to explore how the outcome would be when China enters into a bilateral FTA with a conventional developed economy such as the UK. It helps uncover if the often-perceived patterns of developed vs. developing countries apply here. Such efforts can be also highly relevant for impact assessment when one country weighs an economic engagement with another country or entity.

The rest of this article is organized as follows: Sect. 2 provides literature review; Sect. 3 introduces the methods and data employed for this study; Sect. 4 presents the results and discussion; Sect. 5 concludes and derives policy implications.

2 Literature review

2.1 Embodied pollution in trade

Numerous studies were conducted to uncover the embodied pollution associated with international trade, especially for carbon emissions (Feng et al., 2013; Liu et al., 2016a). In most cases, the embodied perspective indicates a shift of emphasis to consumption-based measure of pollution, and the multi-regional input–output (MRIO) model is often applied for such analysis (Wiedmann et al., 2007). For example, in a classical MRIO study, trade activities were found to partially offset the domestic efforts of improving GHG efficiency in the United States (US), due to importing goods and services from GHG-intensive economies (Weber & Matthews, 2007). Meanwhile, resource flows embodied in international trade were frequently investigated. Lending support to the theory of "ecologically unequal exchange" (Dorninger et al., 2021), Tian et al. (2020) found that significantly higher amounts of resources are involved for each unit of economic gain in the BRICS (Brazil, Russia, India, China, and South Africa) than their high-income trading partners. Moreover, a recent study suggested that the consumption of the G20 countries in 2010 has driven $PM_{2.5}$ pollution with a global footprint of 1.98 + million pre-mature deaths (Nansai et al., 2021). Besides, for the lesser-known pollutant NH_3, there were studies showing that about 25% of the agricultural NH_3 emissions are trade-related, and cooperation between trading parties on structure adjustments and technology advancements would be key to mitigate the NH_3 emissions (Ma et al., 2021).

As concluded in a recent review, the consumption-based approach illuminated that without changes in consumer behaviors in importing countries and/or an improvement in resource and energy efficiency in exporting countries, the global environmental sustainability would not be attainable (Liu et al., 2017a).

2.2 Debate on the role of trade for environment

While international trade raises concerns on pollution transfer and ignites debates on responsibility allocation as reviewed above, Xu et al. (2020) found that international trade had positively influenced the world's progress towards achieving the environment-related Sustainable Development Goals (SDGs) in general, such as SDG 9.4 "promote clean and sustainable industrialization." For example, based on the SDG target scores derived by Xu et al. (2020), China's SDG performance increased markedly from 50.72 in 1995 to 68.99 in

2009 out of 100, while the UK's increased from 69.77 to 73.99 over the same period. It's worth noting that the UK scored much lower than other European countries such as Sweden, Finland, Austria, etc. Moreover, a comparison of adjacent and distant trade revealed that distant exchanges had been more beneficial for developed countries for approaching the SDG targets, whereas negative for developing countries (Xu et al., 2020). Despite the disparity, still international trade has the potential to support inclusive growth, benefitting poverty reduction, especially in developing countries (World Trade Organization, 2018).

Besides, note that resources depletion and associated environmental pollution is not just an issue for developing countries, but also for developed economies. A recent study on the UK showed that natural resources depletion had been a factor spurring CO_2 emissions over the period of 1970–2019, and that improving the industrial value-added could positively affect the environmental sustainability (Abbasi et al., 2021). For developing countries, the picture could be more nuanced. Using data on the period of 1990–2019 and employing the ARDL (Autoregressive-Distributed Lag) model, economic globalization was found to exhibit negative short-term impacts for Pakistan on both the consumption-based and the territory-based emissions, and it would be positive for the consumption-based emissions in the long run (Abbasi et al., 2022).

Recently, upon examining trade linkages, Yang et al. (2020) found that the Asia–Pacific region had been heavily engaged in the global virtual flows of resources, environmental emissions, and socioeconomic factors. Moreover, the region had seen decreasing intensities in resource and emissions embodied in final demand and trade, in which China had taken the lead in the transformation. Meanwhile, it's worth noting that in 2015 China had become a net importer of virtual water and employment, and a net exporter of embodied GHGs, energy, $PM_{2.5}$, and value-added within the Asia–Pacific region (Yang et al., 2020). A study examining energy flows embodied in trade during the period of 2001–2007 suggested that China had been a net exporter of energy (Cui et al., 2015). These results indicate that while progress has been made in bringing down the intensities of emissions and resources embodied in trade on an aggregated basis, certain countries such as China can still face increases in domestic environmental burdens.

2.3 Trade agreement and environment

Many studies investigated the effects of trade agreements, in various kinds, on participating countries' environmental aspects. For example, China has seen notable increases in domestic pollution since the WTO (World Trade Organization) accession in 2001 (Liu et al., 2016b). A more recent study found that the export demand induced a remarkable increase in domestic NMVOCs (non-methane volatile organic compounds) in China in 2013, the amount of which equated half of that in the EU (Ou et al., 2020). Also, there were estimates showing that the emissions of GHGs, SO_X, and NO_X embodied in exports account for about one third of China's respective totals during the 2000s, and these numbers are much larger than their corresponding totals of the UK (Liu et al., 2017b).

Most recently, Tian et al. (2022) explored the effects of the RCEP (the Regional Comprehensive Economic Partnership). They found that extra pressure would be brought about by the RCEP on global GHGs mitigation. Specifically, the trade-creating effects shall increase the annual world-level GHG emissions originated from fuel combustion by around 3.1%. While technological progress may ease the issue over the long run, coordinated efforts between countries would be required. Regarding China, the RCEP would increase its GHGs by 2.7% and 4.0% upon entering into force for 5 and 10 years, respectively;

meanwhile, China's deeper participation in global value chain (GVC) would ameliorate the emission intensity, by slightly 0–1.8% though (Tian et al., 2022).

Nonetheless, trade expansion does not always lead to more domestic pollution and resources use. For example, simulating the case of China-Australia FTA using one GTAP model, Qi and Zhang (2018) found that Australia shall scale up the land and resources intensive sectors, while China expands the capital-intensive sectors. The UK does not have such sectors that China can obtain benefits to its own interests (Barber, 2020). However, a partial and compromised FTA may still benefit both parties significantly (Qi & Zhang, 2018). A recent study on the trilateral China-Japan-South Korea FTA showed that, by implementing the tariffs exemption with agricultural protection, all the three parties would benefit from the arrangement socially, economically, and environmentally in terms of GHGs mitigation (Cui et al., 2019b). Moreover, the trilateral FTA would induce China to import more non-energy-intensive substitutes, partially replacing its own energy-intensive domestic products and leading to notable decreases in carbon emissions. Regulating the energy-intensive industries such as chemical products and iron and steel between the three countries was thus recommended (Cui et al., 2019b).

Based on the review above, this study will investigate the hypothetical China-UK FTA in aspects that could add value to the literature. Specifically, this study aims to uncover: (1) the economic and embodied air pollution impacts of the hypothetical FTA on China, the UK, and the world; (2) the hotspot sectors for China and the UK, if both economic gains and environment-friendly trade development are to be achieved; meanwhile, as the trade liberalization increases, how would the sectoral embodied pollution intensity and trade advantage evolve; and (3) whether the tariffs exemption with agricultural protection would make a difference. To explore these questions, the methods of general equilibrium analysis and input–output analysis used in the studies reviewed above, plus an index measuring trade competitiveness, will be integrated and used in this study.

3 Methods and data

3.1 Analytic framework

Figure 1 presents the overarching analytic framework of this study. The procedure is as follows: (1) specify exogenous shocks, namely, the changes in tariff rates herein; (2) feed the shocks into a computable general equilibrium (CGE) model, GTAP, for simulating economic equilibriums under different scenarios; (3) generate the multi-region input–output (MRIO) tables endogenously for the scenarios modeled; (4) build extended Environmental MRIO models; (5) calculate the scenario-specific embodied pollution and trade competitiveness by sector for the regions of interest.

3.1.1 Global Trade Analysis Project

The Global Trade Analysis Project (GTAP) model was employed to simulate the effects of the counterfactual China-UK FTA. The GTAP model is a CGE model developed by the Department of Agricultural Economics at Purdue University in the US. Covering multi-regions and multi-sectors, it is widely employed to assess the economic impacts of trade agreements or barriers including wars, energy policies, etc. (Britz & Hertel, 2011; Cui et al., 2019c; Qi & Zhang, 2018; Rutten et al., 2013; Wu et al., 2020; Xie et al., 2018). Applying the theory of Walrasian General
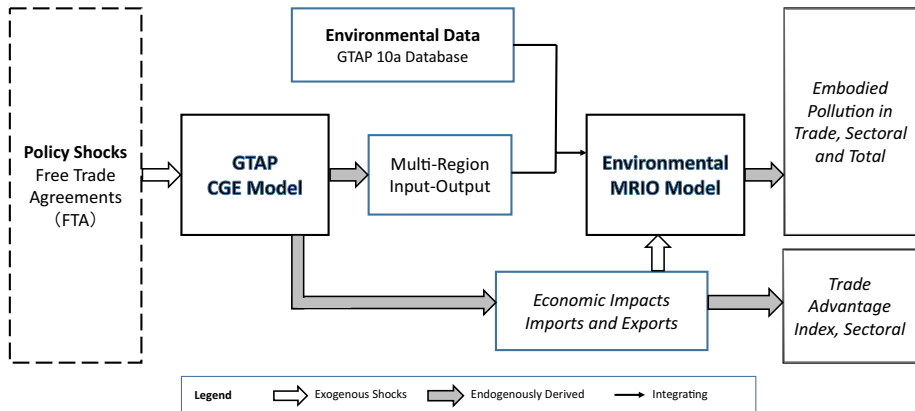
Fig. 1 Research framework for this study. *Notes*: They are provided in separate electronic files also

Equilibrium, the GTAP model programs the abstract economic theory into a computable and reasonably representative model simulating the real economy. Thereupon the GTAP model can project the shifts through adjusting prices and/or quantities of commodities and factors, which in turn shall result in new equilibriums sustained by the sectors modeled (Hertel, 2013).

In this study, one GTAP model written in GAMS (General Algebraic Modeling System) language, GTAP9inGAMS (Lanz & Rutherford, 2016), is employed and further modified for the simulation using the GTAP 10a Data Base (Aguiar et al., 2019). The baseline year set in 2014 is used.

3.1.2 Environmental input–output model

Input–output (I–O) analysis is a quantitative approach widely used for investigating the inter-relationships between industries in terms of input and output flows within an economy (Leontief, 1974). The I–O analysis has been frequently carried out in the arena of environmental assessments (Leontief, 1970; Steenge, 1999; Weber & Matthews, 2007; Wiedmann et al., 2007). This study derives the MRIO tables, based on the GTAP model results under different scenarios. The formulas involving the MRIO tables are then used to calculate embodied pollution, consulting on studies such as Tian et al. (2020) and Weber and Matthews (2007).

Equations 1 and 2 illustrate the basics of an I–O model for region r.

$$X_r = A_r X_r + Y_r \qquad (1)$$

Herein X_r represents the vector of sectoral output levels for region r, A_r denotes the input–output matrix describing the intermediate consumption of outputs between the sectors, and Y_r indicates the vector of final demand, consisting of private, government, investment, and export demand.

The matrix of direct consumption of commodities includes two parts: one is for the domestic input technological coefficients A_r^d, while the other portion is for the import coefficients A_r^m.

$$A_r = A_r^d + A_r^m = \left[x_{r,ij}^d / x_{r,j} \right] + \left[\sum_{s \neq r} x_{sr,ij}^m / x_{r,j} \right] \qquad (2)$$

Herein $x^d_{r,ij}$ denotes the domestic input from the sector i for producing $x_{r,j}$, and $x^m_{sr,ij}$ denotes the input imported from region s by the sector i in producing $x_{r,j}$.

A simplified matrix notation form of MRIO is exhibited as below.

$$
\begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ \vdots \\ X_n \end{bmatrix} = \begin{bmatrix} A^d_1 & A^m_{21} & A^m_{31} & \cdots & A^m_{n1} \\ A^m_{12} & A^d_2 & A^m_{32} & \cdots & A^m_{n2} \\ A^m_{13} & A^m_{23} & A^d_3 & \cdots & A^m_{n3} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A^m_{1n} & A^m_{2n} & A^m_{3n} & \cdots & A^d_n \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ \vdots \\ X_n \end{bmatrix} + \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ \vdots \\ Y_n \end{bmatrix} \tag{3}
$$

where A^m_{sr} represents the matrix of imports of intermediate inputs from region s to region r.

By considering the international transport endogenously when deriving multi-regional I-O table (Peters et al., 2011), this study derives the scenario-specific MRIO from the GTAP model results. Note that our approach is different from the scenario-based projections of MRIO tables as in Beaufils and Wenz (2021), where the projections on trade and GDP plus base MRIO are used to build new MRIO tables. This study relies on GTAP model outcomes, where GDP, prices, exports, domestic and imported input coefficients, etc., are consistent with each another under the general equilibrium framework for each scenario. Further, by incorporating data on environmental pollution into the MRIO, this study builds the environmental MRIO that links the environmental and economic dimensions.

Specifically, direct pollution coefficients for sectors in region r are given by Eq. 4 as follows.

$$
DI^k_{r,i} = P^k_{r,i}/x_{r,i} \tag{4}
$$

where $DI^k_{r,i}$ represents the intensity of direct discharge of pollutant k by sector i, $P^k_{r,i}$ the direct discharge of pollutant k by sector i, and $x_{r,i}$ the total output of sector i.

The embodied intensity of domestic pollutant discharge is derived using Eq. 5.

$$
\begin{bmatrix} TI^k_1 \\ TI^k_2 \\ TI^k_3 \\ \vdots \\ TI^k_n \end{bmatrix} = \begin{bmatrix} \widehat{DI^k_1} & 0 & 0 & \cdots & 0 \\ 0 & \widehat{DI^k_2} & 0 & \cdots & 0 \\ 0 & 0 & \widehat{DI^k_3} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & \widehat{DI^k_n} \end{bmatrix} \left\{ \begin{vmatrix} I & 0 & 0 & \cdots & 0 \\ 0 & I & 0 & \cdots & 0 \\ 0 & 0 & I & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & I \end{vmatrix} \right.
$$
$$
\left. - \begin{bmatrix} A^d_1 & A^m_{21} & A^m_{31} & \cdots & A^m_{n1} \\ A^m_{12} & A^d_2 & A^m_{32} & \cdots & A^m_{n2} \\ A^m_{13} & A^m_{23} & A^d_3 & \cdots & A^m_{n3} \\ \vdots & \vdots & \vdots & & \ddots & \vdots \\ A^m_{1n} & A^m_{2n} & A^m_{3n} & \cdots & A^d_n \end{bmatrix} \right\}^{-1} \tag{5}
$$

where TI^k_r with $(r = 1, 2, \ldots, n)$ represents the vector of the intensity of embodied discharge of pollutant k by sector in region r, while DI^k_r indicates the corresponding diagonal matrix for the intensity of direct discharge by sector. Also, $(I - A)^{-1}$ (a simplified expression for the terms in curly braces) is the Leontief inverse.

Synthesizing the equations above, the pollution embodied in exports, imports, and the balance of trade can be calculated by using Eqs. 6–8 as follows.

$$\text{EEX}_r^k = \text{TI}_r^k * \text{EX}_r \tag{6}$$

$$\text{EEM}_r^k = \sum_{s \neq r} \text{TI}_s^k * \text{IM}_{sr} \tag{7}$$

$$\text{BEET}_r^k = \text{EEX}_r^k - \text{EEM}_r^k \tag{8}$$

where EEX_r^k represents the vector of the discharge of pollutant k embodied in exports by sector in region r, and EX_r the vector of the export values by sector in region r. EEM_r^k and IM_{sr} denote the case for imports, which involves aggregating over the source countries. BEET_r^k denotes the case for net balance for pollutant k in region r.

Compared with the approach that factors in exogenous changes in final demand, intermediate input structure, and stressor matrix (e.g., emissions per unit of sector output) as in Wiebe et al. (2018), this study mainly differentiates by not considering the changes in stressor matrix. Also note that Wiebe et al. (2018) focuses on "looking forward," emphasizing the dynamic changes, where this study simulates the static scenarios of a hypothetical China-UK FTA in varying degrees of liberalization.

3.1.3 Measure of trade competitiveness

Besides the environmental aspect, to aid identifying the hotspot sectors with economic interest, this study employs the normalized revealed comparative advantage (NRCA) index to measure the comparative advantage of China's sectors, by referring to Yu et al. (2009). The NRCA index measures the degree of deviation of one country's actual exports from the neutral point of its comparative advantage (Yu et al., 2009). The NRCA index is a useful tool for quantifying regional comparative advantage (Bojnec & Ferto, 2018; Fourie, 2011; Sarker & Ratnasena, 2014) and can be calculated by Eq. 9 as follows.

$$\text{NRCA}_j^i = E_j^i/E - E_j E^i/EE \tag{9}$$

where E represents the world's total export volume, E_j the world's total export volume of sector j, E^i the total export volume of country i, and E_j^i the total export volume of sector j in country i. If the value of NRCA index is: (1) greater than 0, then it means a competitive advantage; (2) equals to 0, then trade self-balancing; (3) less than 0, then a competitive disadvantage. The data required for calculation shall be derived from the GTAP model results.

3.2 Model coverage and data

For the model representation, the GTAP 10 Data Base (Aguiar et al., 2019) was used, covering 141 regions and 65 production sectors. This study further aggregates the regions into 28 new regions by referring primarily to Lanz and Rutherford (2016), and aggregates the production sectors into 30 economic sectors based on the industrial sectors reported in the *China Statistical Yearbook on Environment* (2015) (NBSC, 2015) and the sectors modeled in GTAP for this study (see Tabs s1 and s2 in Online Resource 1). The 28 aggregated regions mainly include G20 countries or regions, as well as China and the UK's major trading partners (see Tab s3 in Online Resource 1).

For environmental pollution, this study uses the air pollution data accompanying the GTAP 10a Data Base (Chepeliev, 2020), from which the atmospheric pollutants such as sulfur dioxide (SO_2), particulate matter ($PM_{2.5}$), nitrous oxides (NO_X), and ammonia (NH_3) were selected. The data on P_r^k (emissions of pollutant k by sector in region r) as shown in Eq. 1 were obtained from Chepeliev (2020).

3.3 Hypothetical China-UK FTA scenarios

The scenarios modeled in this study consist of two dimensions: (1) tariff rate reduction levels; (2) whether or not to include agri-food sectors under the FTA, as liberalization of agricultural trade can be a controversial issue (Cui et al., 2019b; Moon, 2011). For the 1st dimension, the levels range from r0 (keeping baseline) to r10 (zero-rate), with 10% as the arbitrary incremental step. Meanwhile, the export subsidies or taxes were kept unchanged if there are any. For the 2nd dimension, the agri-food sectors refer to the agricultural production (AGR), processing of agricultural products (AGP), and the food manufacturing (OFD) sectors. Thus, in total 21 scenarios are used (see Tab s6 in Online Resource 1). In addition, for simplicity of analysis, this study focuses on using the Cobb–Douglas function to describe the demand curves when applying the GTAP model written in GAMS (Lanz & Rutherford, 2016).

4 Results and discussion

4.1 Economic impacts

Figure 2a shows that the China-UK FTA brings about mixed effects on gross domestic product (GDP), with China's decreasing by about 0.05%, while the UK's increases by over 0.31%. These changes are primarily due to the expansion of China's imports of automobiles, the monetary value of which outnumbers that of the increasing exports of wearing apparels. Meanwhile, the countries in the EU and India see reductions at levels of around 0.02%, suggesting that the conventional trading partners of the UK would lose under the China-UK FTA. If the agri-food sectors are to be included under the FTA, the estimated losses in GDP would be enlarged for China. This may result from the increases in imports of agri-food products. Figure 2b shows that the China-UK FTA shall benefit both China and the UK, raising their welfare levels by over $3.0 billion (US$2014). Since China's GDP is projected to decrease under the FTA, this welfare increase implies that the FTA would primarily benefit consumers for China. On the other hand, the major EU and Asian economies may incur losses of about $0.1 billion. The US and the MIC countries would incur larger losses of about $0.3 billion. If including the agri-food sectors under FTAs, then both China and the UK's welfare will increase further, with the Republic of Ireland, Netherlands, France, and Japan experiencing notable losses.

The results imply that the bilateral strengthening of trade ties would primarily benefit the parties directly involved, with the consumer welfare enhanced and the production profits potentially enlarged. However, such welfare increases occur at the expense of welfare in the rest of world. Besides, notwithstanding prospective trade and economic growth through a China-UK FTA, the UK will likely prioritize post-Brexit trade deals with the EU, the US, and other Commonwealth nations such as India (Edgington, 2020). The results here show that the China-UK FTA shall induce decreases in GDP and welfare for these regions.
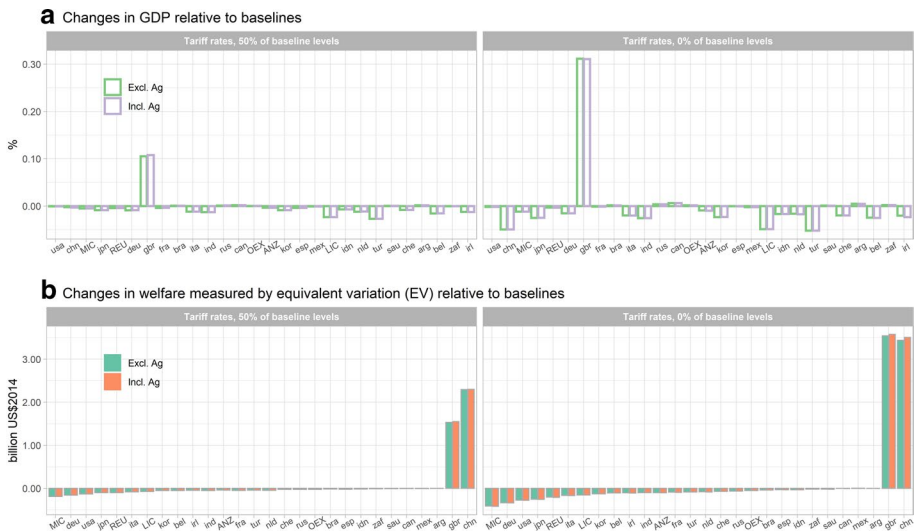
a Changes in GDP relative to baselines

b Changes in welfare measured by equivalent variation (EV) relative to baselines

Fig. 2 Changes in GDP (**a**) and welfare (**b**) by region under selected China-UK FTA scenarios with respect to baselines *Notes*: ANZ—Australia and New Zealand, REU—rest of Europe, OEX—other oil exporters, LIC/MIC—other low/middle-income countries. See Tab s4 in Online Resource 1 for more details. In panel **a**, from left to right, the regions are arranged in descending order of GDP ($2014), with the hollow bars indicating the percentage deviations of GDP with respect to baselines. In panel **b**, from left to right, the regions are ranked in ascending order of EV, with the solid bars indicating the changes in welfare with respect to baselines

4.2 Overview of embodied pollution

Table 1 presents the FTA-induced changes in pollutant discharges embodied in trade. Focusing on balance (net exports), the largest increases for China would occur for SO_2, by over $+34.0\%$ under the zero-rate FTAs. Much milder decreases are expected for NO_X. This implies that China would export more goods and services embodying SO_2 emissions, such as chemical products (chm). For the UK, the increases in embodied SO_2 emissions are also much more notable than other air pollutants.

A comparison between China and the UK shows that the UK experiences greater percentage changes in emissions embodied in trade than China, with SO_2 as an exception. Globally, the FTAs enlarge the magnitudes of exports and imports of embodied air pollutants. While on net, there would be decreases in the magnitudes of balance. Note that the baseline balance (net exports) levels for the world are negative, suggesting that the world is inclined to import goods and services that are more emission-intensive on an aggregated basis.

4.2.1 Decomposition of balance

A comparison of China and the UK (Fig. 3a) shows that except SO_2, in total China is a net importer of embodied $PM_{2.5}$, NO_X, and NH_3 emissions with markedly larger magnitudes. Agriculture (AGR) and non-ferrous metals (nfm) appear to be among the major net importing sectors for $PM_{2.5}$ and NO_X, whereas for NH_3, the sector of mining and washing of coal (coa) joins the agricultural sector as the main importers. Such sectoral pattern generally applies to the UK, except that the non-ferrous metals sector remains virtually neutral.

Table 1 Percentage changes in emissions embodied in trade under China-UK FTA Scenarios with respect to baseline levels

	Exports			Imports			Balance (Net Exports)		
	chn	gbr	wld	chn	gbr	wld	chn	gbr	wld
Tariff Rates, 50% of Baseline Levels, Excl. Ag									
NH_3	0.22%	0.55%	0.01%	0.06%	0.14%	0.01%	0.03%	0.12%	0.00%
NO_X	0.20%	0.29%	0.02%	0.09%	0.34%	0.02%	0.07%	0.34%	−0.01%
$PM_{2.5}$	0.23%	0.49%	0.03%	0.05%	0.32%	0.02%	−0.08%	0.30%	−0.03%
SO_2	0.20%	0.02%	0.04%	−0.09%	1.34%	0.03%	12.36%	1.51%	−0.04%
Tariff Rates, 50% of Baseline Levels, Incl. Ag									
NH_3	0.23%	0.73%	0.01%	0.05%	0.12%	0.01%	0.02%	0.08%	−0.01%
NO_X	0.21%	0.51%	0.02%	0.07%	0.25%	0.02%	0.04%	0.23%	−0.02%
$PM_{2.5}$	0.23%	0.62%	0.02%	0.03%	0.27%	0.02%	−0.12%	0.22%	−0.04%
SO_2	0.19%	0.05%	0.04%	−0.10%	1.30%	0.03%	12.41%	1.46%	−0.04%
Tariff Rates, 0% of Baseline Levels, Excl. Ag									
NH_3	0.57%	1.36%	0.02%	0.06%	0.37%	0.02%	−0.02%	0.32%	−0.02%
NO_X	0.54%	0.63%	0.05%	0.11%	0.91%	0.04%	0.04%	0.94%	−0.03%
$PM_{2.5}$	0.57%	1.18%	0.06%	0.01%	0.98%	0.04%	−0.42%	0.95%	−0.07%
SO_2	0.52%	−0.19%	0.10%	−0.30%	3.30%	0.09%	34.93%	3.75%	−0.03%
Tariff Rates, 0% of Baseline Levels, Incl. Ag									
NH_3	0.59%	1.76%	0.02%	0.04%	0.29%	0.02%	−0.04%	0.21%	−0.03%
NO_X	0.56%	1.13%	0.04%	0.08%	0.66%	0.03%	0.00%	0.62%	−0.07%
$PM_{2.5}$	0.58%	1.47%	0.05%	−0.01%	0.81%	0.04%	−0.47%	0.73%	−0.10%
SO_2	0.54%	−0.11%	0.10%	−0.31%	3.40%	0.09%	36.08%	3.84%	−0.04%

chn = China, gbr = UK, wld = World. The abbreviations "Excl. Ag" and "Incl. Ag" mean excluding and including the agri-food sectors under hypothetical China-UK FTA scenarios, respectively

Additionally, the sector manufacturing non-metallic mineral products (nmm) is a noteworthy net exporter of embodied $PM_{2.5}$ emissions for China.

For SO_2, the UK appears to be a net importer, with the majority share coming from the sector smelting and pressing non-ferrous metals (nfm). On the other hand, for China, the non-ferrous metals sector (nfm)'s net import of embodied SO_2 emissions is largely offset by the net export associated with chemical products (chm).

The above indicates that both China and the UK are inclined to rely on imported non-ferrous metals and coal resources. Meanwhile, on balance, China's sectors that manufacture chemical products and non-metallic mineral products are key exporting sectors of embodied SO_2 and $PM_{2.5}$ emissions, respectively.

Under the hypothetical bilateral FTA scenarios, China sees increases in net exports of embodied $PM_{2.5}$ emissions, with the non-metallic mineral products sector contributing substantially to the rise. On the other hand, the UK sees increases in net imports in total and of the non-metallic mineral products. Also notable is that China sees increases in net exports of embodied SO_2 too, with both the non-metallic mineral products and the chemical products sectors contributing virtually on par. The UK sees the opposite, with the total and the two sectors seeing increases in their net imports of embodied SO_2 emissions. These imply that the hypothetical bilateral FTA stimulates the trade flows of non-metallic mineral products and chemical products between China and the UK.
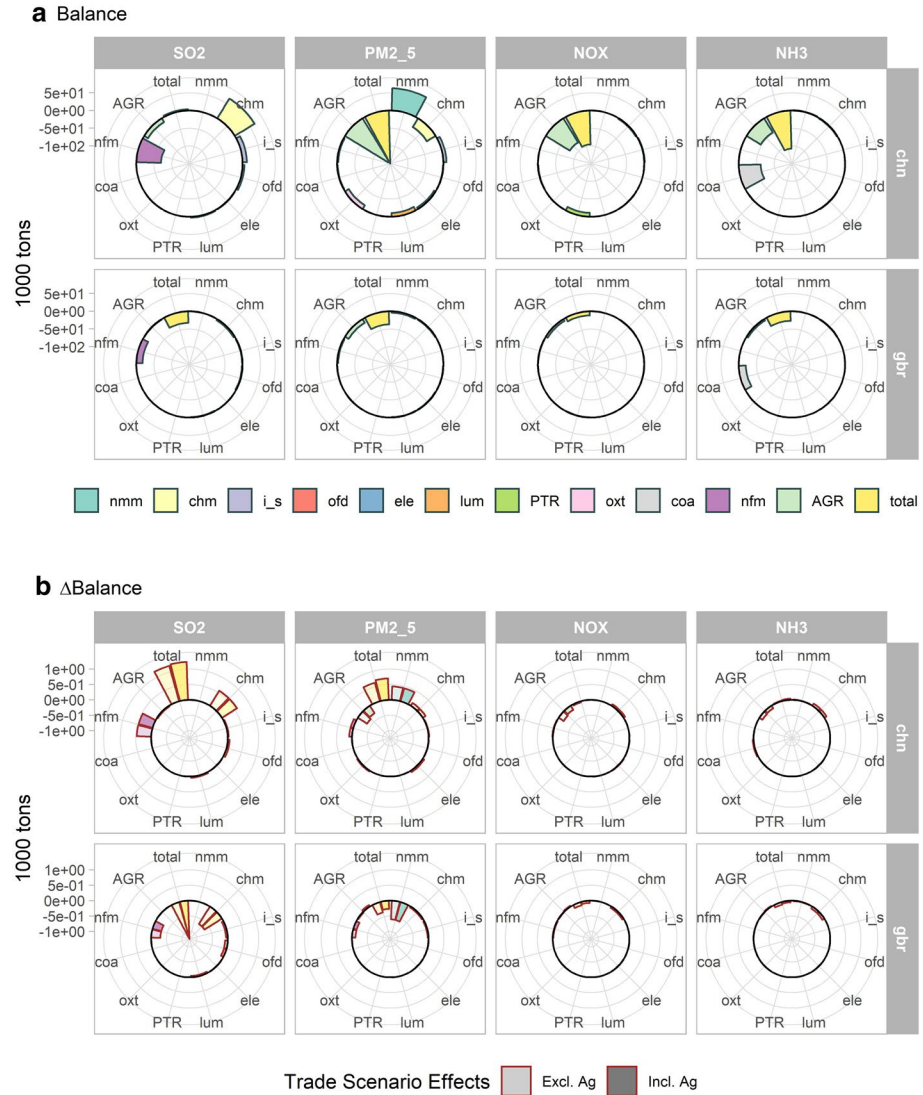
Fig. 3 Air pollution embodied in balance of trade (**a**) and the changes under China-UK FTA scenarios (**b**) by sector Notes: PM2_5=PM2.5, nmm=non-metallic mineral products, chm=chemical products, i_s=ferrous metals, ofd=food products (nec), ele=electronics, lum=wood products, PTR=oil and gas, oxt=minerals (nec), coa=coal, nfm=metals (nec), AGR=agriculture, total=all, where nec means "not elsewhere classified." See Tables s1 and s5 in Online Resource 1 for more details on sector definition and aggregation. Panel **a** shows the values for China (chn) and the UK (gbr) under Default, while panel **b** exhibits the changes with respect to baselines. To save space and for clarity, only the sectors with magnitudes (in balance) > 3% of the maximum sectoral magnitude (for both China and the UK) are presented here

Regarding the inclusion of agri-food sectors under the China-UK FTA, Fig. 3b shows that China sees marginally larger net exports of embodied PM$_{2.5}$ in total, due to smaller net imports of agriculturally related PM$_{2.5}$. On the other hand, the UK's agricultural sector

Fig. 4 Air pollution embodied in exports and imports (**a**) and the changes under China-UK FTA scenarios ▶ (**b**) by sector Notes: "free_nonag" indicates excluding agriculture (primary, processing, and foods) under China-UK FTA, while "free_trade" means including agri-food sectors under China-UK FTA. Panel **a** contrasts China (chn) and the UK's (gbr) embodied air pollution in exports and imports under Default, while panel **b** presents the associated changes relative to baselines, with a diverging color gradient being applied. For sector abbreviations, see Fig. 3 and Tabs s1 and s5 in Online Resource 1 for more information

(AGR) sees a marginal increase in net exports of $PM_{2.5}$, leading to a decrease in net imports of embodied $PM_{2.5}$ in total.

4.2.2 Decomposition of exports and imports

A detailed examination of exports and imports of embodied pollutant emissions helps reveal the changes underneath the balance.

Figure 4a demonstrates that unlike China, the UK's totals for balance are largely a reflection of the imports, with the non-ferrous metals and the agricultural products being the main sectors. On the other hand, more intense offsetting between exports and imports occurs for China, especially for the chemical products sector under all the four pollutants examined, and the non-metallic mineral products sector under $PM_{2.5}$.

With the presence of FTA, notable increases would be spotted for China's exports of embodied SO_2 emissions associated with the chemical products sector, and $PM_{2.5}$ from the non-metallic mineral products sector. Correspondingly, marked decreases would be spotted for the UK's imports.

For non-ferrous metals, China sees magnitude decreases in imports of embodied SO_2 emissions (baseline negative), whereas the UK exhibits the opposite. This indicates that the China-UK FTA may direct more of the world trade flows of non-ferrous metals toward the UK, meanwhile away from China. This may also correspond to that the UK would increase exports of automobiles (mvh) under the FTA. Additionally, the inclusion of agri-food sectors would slightly increase the net exports of embodied emissions in total for China, and decrease the amounts of net imports of embodied emissions for the UK.

### 4.3 Sectoral embodied pollution & trade competitiveness

Figure 5 classifies different sectors according to embodied emission intensity and trade competitiveness. From an integrated economic-environmental perspective, sectors falling in the fourth quadrant are the "ideal" ones (low–high), because they demonstrate comparative advantages in the global trade, as measured by the NRCA index, meanwhile generating less embodied pollutant discharge per unit of economic value. The second quadrant (high-low) however represents the opposite. Figure 6 presents the evolving paths of major sectors' two-dimensional measure as the tariff rate moves from full-rate (r0) to zero-rate (r10).

The moving paths offer a glimpse of how the sectors would evolve as the tariff rates between China and the UK get increasingly reduced. Taking the balance of economic gains and protecting the environment into consideration, prudence may be particularly needed for policy-making concerning the "high-low" inclined sectors, such as many agricultural and energy industries.
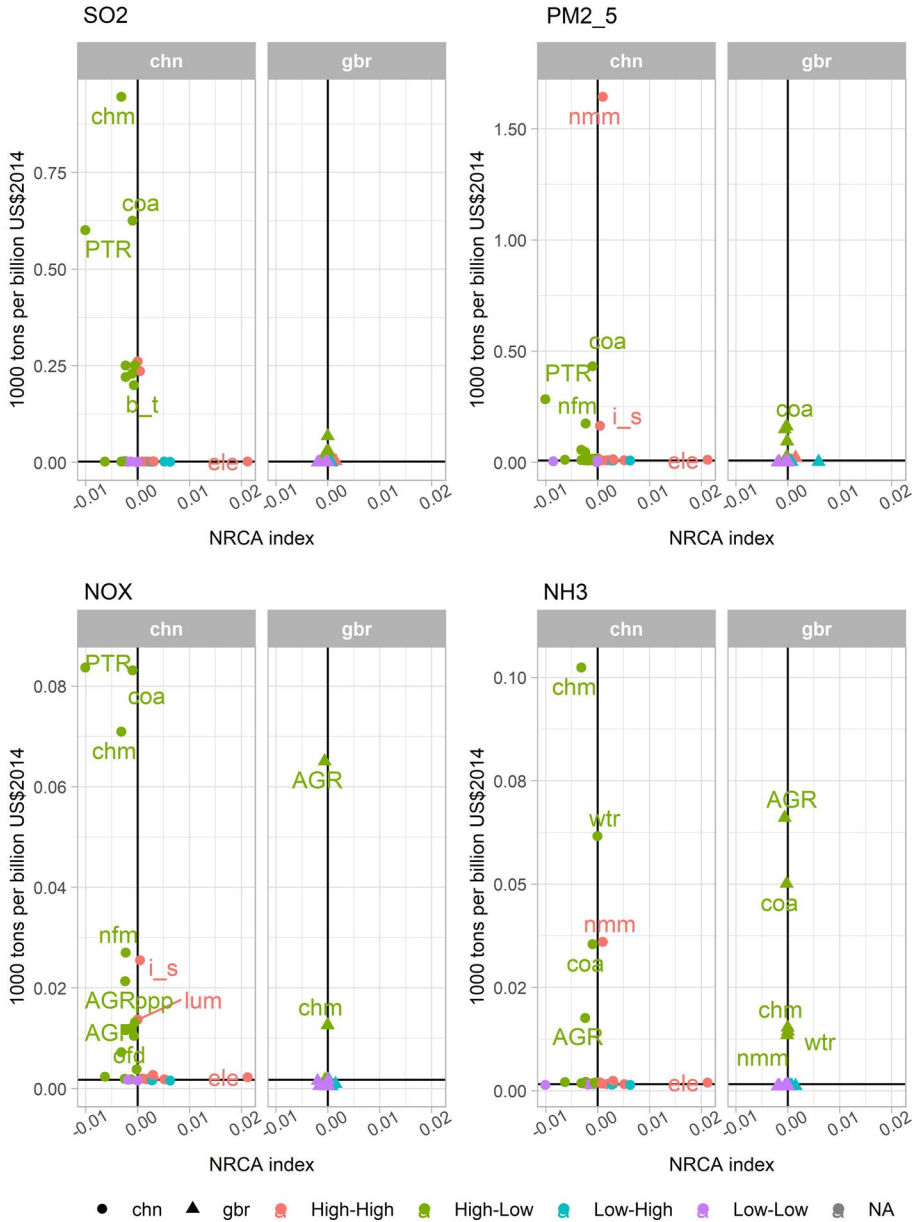
a Export & Import
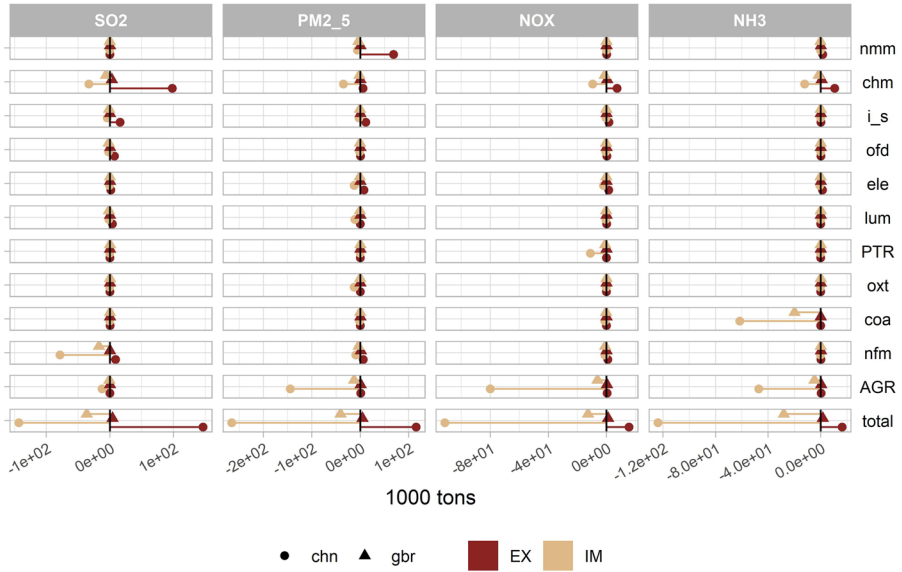
b ΔExport & ΔImport
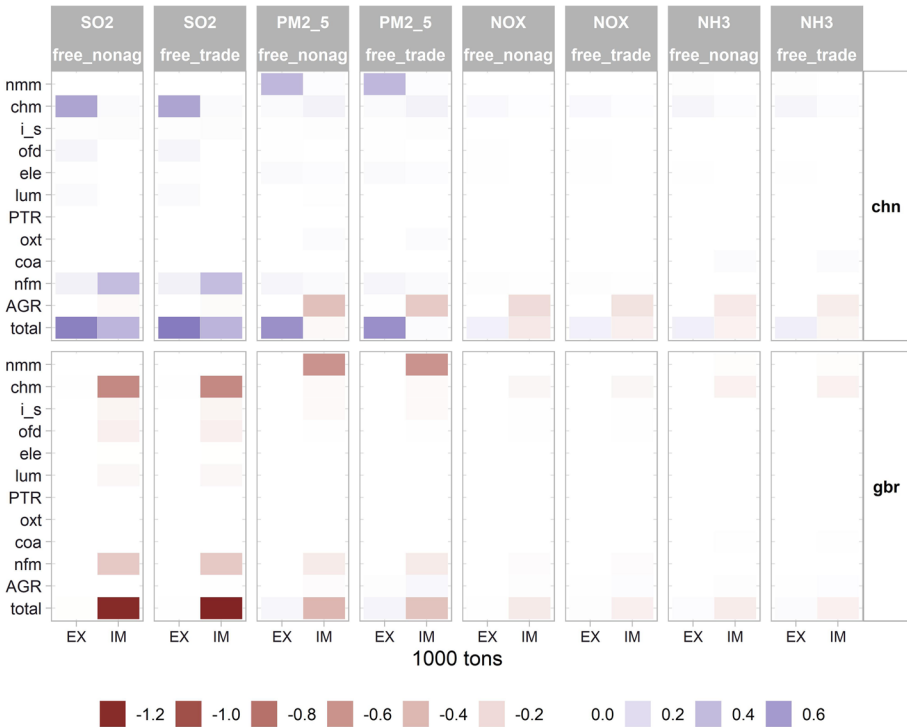
Fig. 5 Embodied air pollution intensity vs. NRCA index by sector for China and the UK under default
Notes: In SO₂, b_t = manufacture of wine, drinks, refined tea, and tobacco; in NOₓ, AGP = agricultural processed products, ppp = paper products and publishing; in NH₃, wtr = production and supply of water. See Fig. 3 and Tables s1 and s5 in Online Resource 1 for more details on sector definition and aggregation. The quadrants are defined as follows: for embodied air pollution intensity (1000 tons per billion US$2014), the median values are used as the separating planes; for NRCA index, the value of zero is used as the separating plane. In classification, "NA" occurs due to lack of pollution data for that particular sector

4.3.1 Embodied emission intensity versus NRCA index

Comparing China and the UK across the four air pollutants (Fig. 5) examined herein, it turns out that the magnitudes of the embodied emission intensity (in 1000 tons per billion US$2014) for NO_X and NH_3 are comparable, whereas marked disparities exist for SO_2 and $PM_{2.5}$. For example, the upper limit of the range for the Chinese sectors' embodied $PM_{2.5}$ intensity is 1.50+units, whereas for the UK it is around 0.25 units.

The sector-quadrant categorization for $PM_{2.5}$ shows that the sector of mining and washing of coal (coa) is high emitting and low competitive for both China and the UK. Other noteworthy second quadrant sectors for China include crude oil and gas (PTR) and non-ferrous metals (nfm). As for the first quadrant, non-metallic mineral products (nmm), ferrous metals (i_s), and electronics (ele) are categorized as high emitting and highly competitive sectors.

Regarding NO_X, in addition to coal, oil and gas, and non-ferrous metals, the sectors manufacturing chemical products (chm), agricultural processing (AGP) and primary products (AGR), food products (ofd), and paper products (ppp), are also the "non-ideal" high-low sectors for China. For the UK, it is the agricultural products (AGR) and the chemical products (chm) that stand out as the "non-ideal" sectors. As for the high-high category, in addition to the sectors smelting and pressing ferrous metals (i_s) and manufacturing computers, communications equipment, and other electronics (ele), the sector processing timber and manufacturing wood products (lum) is also classified as high emitting and highly competitive.

Turning to NH_3, besides coal, agricultural, and chemical products, the production and supply of water (wtr) is classified as high emitting and low competitive for China. The UK exhibits almost the same, with the non-metallic mineral products (nmm) sector being classified as an "non-ideal" sector as well. On the other hand, the non-metallic mineral products sector is high-high for China.

As for SO_2, as mentioned above, a noteworthy magnitude disparity exists for the embodied emission intensity for China and the UK. It is not surprising to find that the sectors of chemical products, coal, and crude oil and gas are among the "non-ideal" high-low sectors for China. Meanwhile, the sector manufacturing wine, drinks, refined tea, and tobacco (b_t) belongs to the second quadrant too.

Overall speaking, the embodied SO_2 intensities for China's sectors are much higher than those in the UK. Similar applies to $PM_{2.5}$, especially that the sector of non-metallic mineral products involves an intensity 6+times higher than the largest sectoral intensity (coa) for the UK. Regarding NO_X, the primary high emitting sectors for the UK are agriculture and chemical products, while for China, many other industries ranging from agricultural processing to crude oil and gas are also categorized as high-low sectors. As for NH_3, China and the UK share quite a few high-low sectors in common, including chemical products, agricultural products, water services, and coal. The difference is that the non-metallic mineral products sector (nmm) is high-high among the Chinese sectors, but high-low within the UK context. This also corresponds to that the FTA induces China to see greater magnitudes of exports of embodied $PM_{2.5}$ emissions, while the UK expects larger embodied imports of $PM_{2.5}$.

4.3.2 Moving directions

With the FTA, the majority of the high-emitting sectors see decreases in trade competitiveness, for both China and the UK. For SO_2, the exception is that the lumber sector (lum) processing timber and manufacturing wood products would be inclined to see an increase in trade advantage for China, and a reduction in embodied emission intensity for the UK.

What's more notable is that the embodied SO_2 intensity of chemical products (chm) trends downward for China.

Turning to $PM_{2.5}$, the Chinese sectors of non-metallic mineral products (nmm) and lumber (lum) are seeing increases in trade competitiveness, whereas the corresponding the UK sectors experience the opposite. Both China's and the UK's non-metallic mineral products sectors see decreases in embodied emission intensity though.

For NO_X, again, the exception is that the lumber sector in China sees an increase in relative trade competitiveness. Also, the inclusion of agri-food sectors induces a less steep downward slope for the embodied emission intensity for the agricultural sector in the UK. Regarding NH_3, the most notable is that the non-metallic mineral products sector in China exhibits a moving direction of increasing trade competitiveness, whereas the UK's displays a decreasing intensity of embodied emission. Also, the inclusion of agri-food under FTA results in a more drastic moving direction toward a lower embodied emission intensity for the agricultural sector (AGR) in the UK. In general, the hypothetical FTA's incorporating the agri-food sectors has notable effects on UK's agricultural sector.

4.4 Comparison with other studies

This study shows that when China enters a trade deal with a major developed economy such as the UK, China's GDP does not necessarily increase, and China may not benefit from the trade deal from an environmental perspective either. This is counterintuitive, as various recent studies imply that China's increasing trade with other countries could help preserve domestic natural resources (Dorninger et al., 2021) and reduce environmental footprints for certain industries (Tian et al., 2017b). Our study however shows that this is not always the case, and the underlying reason may lie in whether it is the resource- or pollution-intensive sectors that are most effected by the FTA. Regarding the GDP decrease, Zheng and Walsh (2019)'s explanations can help here: on one hand, trade may induce specialization resulting from comparative advantage; on the other hand, trade may help bring in advanced technologies and management know-how. The net effects in terms of economic growth depend mainly on how these two forces interact (Zheng & Walsh, 2019).

Regarding embodied pollution, our results show that from a global trade perspective, China is a net importer of embodied air pollution except for SO_2, while for the UK, it is a net importer for all the major air pollutants examined here in this study. Note that in Yang et al. (2020), China is a net exporter of $PM_{2.5}$ and GHGs within the Asia–Pacific region.

The results in this study also echo or contrast with the environmental findings in other studies. For example, the unabated emission factor is the primary contributor to SO_2 emissions for the non-ferrous metals sector in China (Qian et al., 2021). Herein, this study suggests that SO_2 is more of a concern for China than for the UK, and efforts are needed to reduce SO_2 emissions along the industrial chains involving chemical products and non-ferrous metals.

For NO_X and $PM_{2.5}$, energy intensity improvement is identified as the main driver for China's emission reductions in non-energy sectors during the first half of the 2010s (Qian
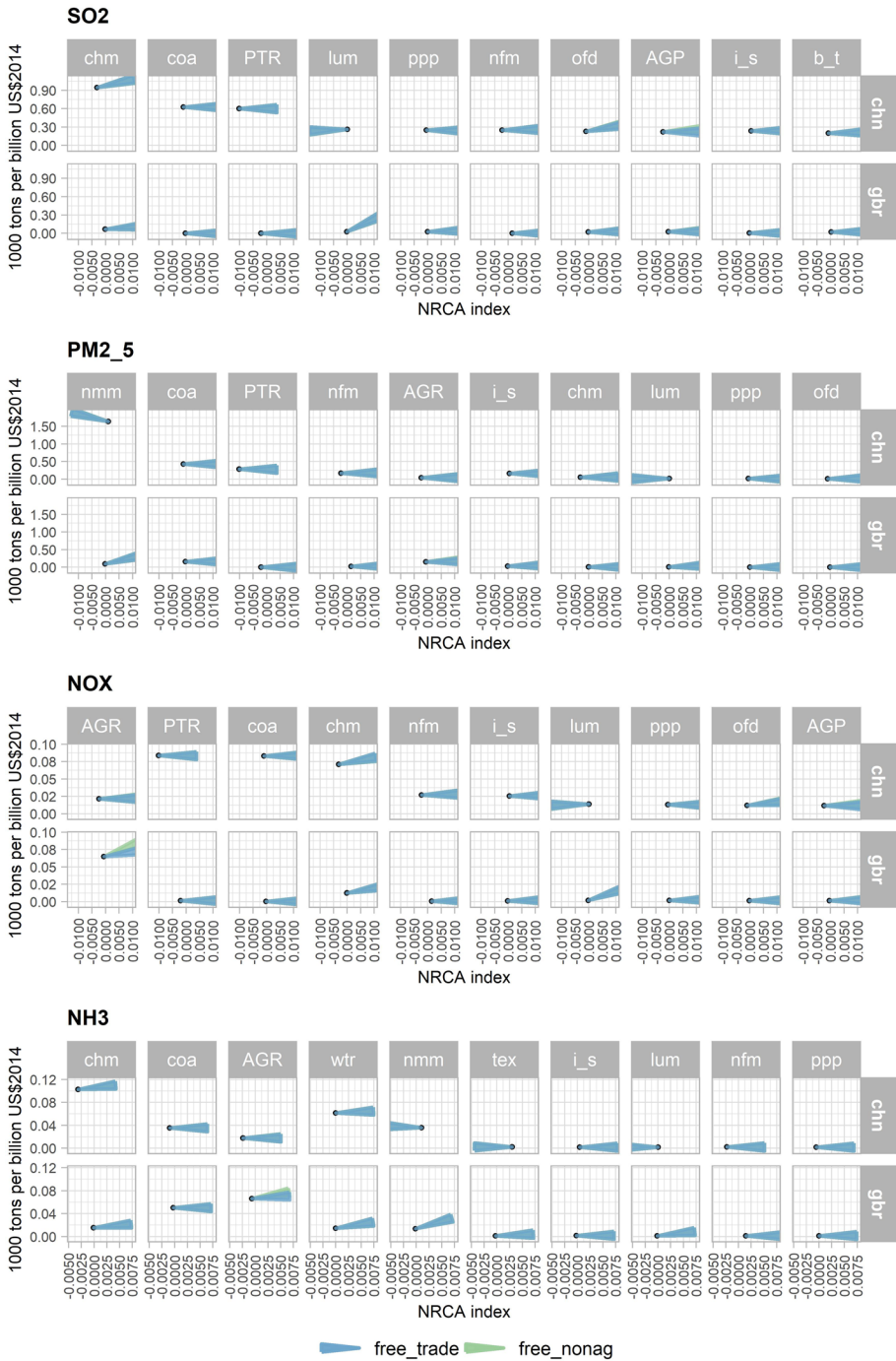
et al., 2021). This study shows that despite the achievement in reductions, China's non-metallic mineral products sector deserves particular attention as its embodied $PM_{2.5}$ emission intensity is considerably high and this sector is trade competitive, which may lead to further expansion of the sector and more $PM_{2.5}$ emissions. While for NO_X, the chemical products sector and the energy sector (oil and gas) would need attention for achieving further improvement in emission reduction. Besides, both China and the UK may need to scrutinize the agricultural sector for better tracking and managing NO_X emissions embodied.

Regarding NH_3, a study focusing on North China Plain finds that NH_3 may be a more effective lever than NO_X for controlling $PM_{2.5}$ nitrate, as it speeds up deposition of total inorganic nitrate (Zhai et al., 2021). For the UK, farm use of fertilizers and manure from livestock production are listed as the main sources of ammonia NH_3 emissions (Warren, 2018). This study shows that the presence of FTA would deepen UK's imports of embodied NH_3 emissions, with the agri-food FTA ameliorating the net imports. Thus, it may be worthwhile to devise policies supporting the reduction in NH_3 emissions, not just within the agricultural sectors, but also the sectors mining and washing coal resources (coa), performing water services (wtr), producing non-metallic mineral products (nmm), and chemical products (chm).

Besides, an MRIO-based examination of China-EU trade flows shows that China's electrical equipment and textile industries, had been among the main providers of environmental and resource footprints for selected EU countries (Tian et al., 2017b). Also, based on an investigation of how to optimize export structure with both economy and CO_2 emissions reduction considered, Wu et al. (2019) suggests that the effective measures for China mainly include increasing the export of services and transport equipment, especially electrical vehicles (EVs), and reducing the export of textiles (Wu et al., 2019). This research however suggests that the chemical products (chm) is the key sector, and it would experience enlarged flows of embodied industrial emissions (SO_2), with China sees increases in exports and the UK sees increases in imports. As for $PM_{2.5}$, non-metallic mineral products (nmm) would be the key sector. Sector-wise, for non-ferrous metals (nfm), the UK sees proportionally larger net imports of embodied SO_2 emissions, whereas China experiences reductions. Regarding the agricultural sector (AGR), the UK sees ameliorated net imports of embodied $PM_{2.5}$ emissions, while China sees further increases in net imports. Overall speaking, the China-UK FTA would induce more of the embodied air pollutant flows to occur via intermediate inputs such as non-ferrous metals, non-metallic mineral products, etc., instead of final consumer products such automobiles and wearing apparels.

5 Conclusions and policy implications

The results show that the China-UK FTA has the potential to increase the UK's GDP, and raise the welfare for both the UK and China. Environmentally, this FTA delivers greater increasing impacts on net exports or imports of embodied SO_2 emissions than $PM_{2.5}$, NO_X, and NH_3, for both China and the UK. The tariffs exemption with agricultural protection exhibits slight counteracting effects in general. Also, half FTA (r5)'s effects appeared disproportionally smaller than full FTA's effects, especially for the UK and the world, suggesting that tariff rates exhibit nonlinear and heterogeneity effects.

Globally, the hypothetical China-UK FTA may not facilitate inclusive growth, and the world-level effects are minimal in magnitude. Economically, low-income countries would

see notable decreases in GDP, and middle-income countries would incur losses in welfare. Environmentally, emissions embodied in both exports and imports at the world-level are projected to increase. On aggregate, the world-level net imports would see reductions in magnitude with the presence of China-UK FTA, which suggests an ameliorated imbalance between exports and imports of embodied emissions. In general, such a bilateral FTA does not benefit the world in principle.

A detailed examination suggests that the FTA may induce notable alterations in both China and the UK's trade structure, as indicated by the sectoral decompositions of embodied air pollutant emissions. Specifically, the FTA may induce greater flows of embodied SO_2 emissions between China and the UK via mainly the chemical products sector, with the UK being the receiver and China as the emitter. Also, the non-metallic mineral products sector shall be responsible for the enhanced flows of embodied $PM_{2.5}$ emissions. As a net importing sector of embodied SO_2 for both China and the UK, non-ferrous metals may see world-level embodied SO_2 flows being diverted away from China and moving towards the UK under the FTA.

To better understand economic and environmental implications, this study classifies the sectors based on intensity of embodied pollution and NRCA index for each sector-pollutant pair. This study also derives the evolving paths in two-dimensional measure for each sector-pollutant pair, as the tariff rates under the China-UK FTAs move from full rate to zero. In general: (1) the "high-emitting and high-competitive" non-metallic mineral products sector (nmm) is inclined to become more competitive and less polluting in terms of embodied pollution intensity, for $PM_{2.5}$ in China; (2) the non-ideal "high-emitting and low-competitive" agricultural (AGR) sector, would move towards "low-emission and lower-competitiveness," for NO_X and NH_3 in the UK, with the inclusion of agri-food sectors slowing down the tendency toward "low-emission"; (3) chemical products' "high-emission and low-competitiveness" may shift toward "milder-emission and lower-competitiveness" in China as the bilateral tariff rates get reduced. These incremental results may be of use for policy-making because they reveal in detail how nuanced the issue can be when manufacturing countries such as China seek to find a balance between trade development and environmental protection.

5.1 Policy implications

5.1.1 Continue making the efforts on air pollution control

The gaps between China and the UK's embodied emission intensities across various air pollutants (except NH_3) suggest that China's industries still need to continue making efforts in environmental protection, not just for the lower reaches of the value chains, but also for better sourcing of intermediate inputs that contribute to pollution. This resonates particularly with the conventional pollutants that may receive greater public attention, such as SO_2, $PM_{2.5}$, and NO_X.

5.1.2 Utilize the co-effects of carbon trading mechanism

A bright news is that studies show that across China's provinces or municipalities that run pilot carbon emission trading schemes, industrial structural upgrading occurred mainly as a result of technological innovation's mediating effects (Wang et al., 2021). Besides, firms' conducting carbon abatement activities also helped reducing carbon emissions

and generating co-benefits such as reducing $PM_{2.5}$ (Liu et al., 2021). As China initiates a national-level carbon market in 2021, more in-depth industrial structure upgrading and wider adoption of abatement technologies may happen accordingly.

5.1.3 Craft policies that improve the technology for key sectors

While this study shows that the FTA would induce expansion of exports and imports that bear even more embodied emission flows, one should caution that, if technology innovation steps in, the picture of the embodied pollution may get ameliorated, or even reserved. Besides, trade can help facilitate transfer of technologies between different countries, and thus may help on reducing emissions. Given that China is the powerhouse of manufacturing, to reduce embodied pollution, policies encouraging technology transfer and management know-how communications could be developed. In particular, the sectors of non-metallic mineral products and chemical products need to see technology advancements.

5.1.4 Pay more attention to NH3 emissions

Serious attention may be needed for controlling NH_3 emissions, and this is an area where the disparity between developed and developing countries remains limited. While the UK is taking the lead in regulating ammonia emissions, other countries with significant ammonia emissions such as China and the US have not followed so far, due to inventory building and data uncertainty issues (Plautz, 2018). Currently, the UK is among the few countries that started to pay serious attention to NH_3 pollution. This study shows that for both China and the UK, water supply, coal mining, chemical products, and agriculture are the main sectors embodying NH_3 emissions. This may also help other countries to set priority when identifying key NH_3 emitting sectors.

5.2 Limitations and future research

This study is certainly subject to at least a few limitations. First, the environmental measures in this study are linked to the economic outputs. Future studies may incorporate material flow analysis for better accuracy on environmental outcomes. Although this study attempted to use the most disaggregated scheme that harmonizes the sectoral data from GTAP 10 and the *China Statistical Yearbook on Environment*, the sectoral aggregation may have still masked underlying changes that can lead to notable deviations from real values (Zhang et al., 2019). Furthermore, regional disparities should be considered by policy makers due to imbalanced economic development and different resource endowments (Tian et al., 2017a). Future research may link regional and global MRIO datasets (Su et al., 2021) to tackle the issue of potentially masked disparities that bear significant local implications. In addition, most recent significant trade agreements such as RCEP (Tian et al., 2022) and disruptions such as COVID-19 that potentially bring about substantial changes to the world trade (Guan et al., 2020) need to be taken into account as well. Policy-wise, more research would be needed for investigating the effects of coordinating reduction plans (Cui et al., 2019a) and sector-specific trade policies (Cui et al., 2015).

The findings of this study may be of help for global mitigation efforts combating environmental pollution. First, this study suggests that, in addition to controlling CO_2 emissions, research on an integrated plan that considers multiple types of pollutants may be desirable for future endeavors. The China-UK FTA is projected to have noteworthy

inducing effects on embodied SO_2 emissions. This would call for devising policies coordinating the mitigation of CO_2 emissions that have global implications, and the reduction in pollutant discharges that present more regional and perhaps acute challenges. Second, the pollutant-varying quadrant categorization of the sectors offers a glimpse into how sectors vary in performance of trade advantage and embodied pollution intensity. More research on such aspects can provide insights for formulating targeted sectoral environmental policies in trade agreements. Moreover, deriving the evolving paths of sectoral embodied pollution-trade advantage measures may help inform policies for sectors that demonstrate dedicated trade and environmental influence.

Declarations

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