Journal Pre-proof

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PII: S0928-7655(19)30174-5

DOI: https://doi.org/10.1016/j.reseneeco.2019.101144

Reference: RESEN 101144

To appear in: *Resource and Energy Economics*

Received Date: 22 May 2019

Revised Date: 28 October 2019

Accepted Date: 4 December 2019

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Highlights

- We simulate implemented China–US trade friction and its different long-term trends.
- Trade barriers harm the economies of both but non-participants benefit indirectly.
- Trade barriers reduce global carbon and most participants' environmental emissions.
- Changes in trade patterns go against clean development in less-developed regions.
- Emission reductions from trade friction can't avoid catastrophic climate change.

Abstract

The anti-globalisation movement could simultaneously affect the worldwide distribution pattern of the economy and environmental emissions. However, most existing studies have focused on economic impacts, and relevant research on environmental effects are contextualised by trade liberalisation. Using a global computable general equilibrium model and taking the recent anti-trade policies of the Trump administration as an example, this study investigates the possible socio-economic and environmental effects of trade friction. Specifically, this study explores how the implemented six rounds of China–US trade friction and its different long-term development trends affects regional economic output, GHG emissions and air pollutants. Results show that trade barriers harm both countries' economies and such losses have a certain permanence, while non-participants can benefit indirectly. However, trade friction can reduce participants' emissions, change global GHG emission distribution patterns, and decrease the emission intensity of global carbon dioxide and some pollutants. However, the change in trade patterns is not conducive to clean energy development in the less-developed regions, including the Middle East, Africa, and Latin America, and emission reductions from trade friction are insufficient to avoid catastrophic climate change.

JEL codes: F18, F47, F62, F64, Q52, Q56, Q43

Keywords: Trade barrier; Tariff increase; Greenhouse gases; Pollutant emissions; Climate change

1. Introduction

The global trading system has enhanced the living standards of billions of people in many countries by developing a production system based on global value chains (Lawrence, 2018). With global trade, comparative advantages could fully play out, and consumers were rewarded with a high diversity of choices (Arkolakis et al., 2018). However, trade has become a significant source of discontent, especially in old industrial regions that become marginalised (Stiglitz, 2016), and is fuelling global environmental destruction(Rees, 2006). Under open and free world economic development patterns today, every country subject with certain economic strength will constantly struggle for its interests in international trade, which will inevitably bring trade friction. Moreover, trade friction among countries and regions are becoming increasingly fierce due to unbalanced economic development and inconsistent priority appeal from trade, such as previous trade friction between the US and Japan, the US and Canada, the US and Europe and so on. Given the crucial role of international trade in the development of nations, it is valuable and interesting to examine the possible worldwide effects of trade friction from a policy perspective.

Currently, the trade-friction literature has mostly analysed social and economic effects, such as trade flow, welfare, monetary loss, and economic loss (Lawrence, 2018; Li et al., 2018; Liu, 2018). This study, instead, will focus on environmental effects. Importing and exporting commodities also means emissions transfer among countries (Jiborn et al., 2018; Peters and Hertwich, 2008). These trade-embodied environmental emissions not only contribute a considerable share of global emissions (Liu and Wang, 2017; Sato, 2014), but also significantly affect the regional distribution of emissions:

empirical findings reveal that the environmentally unequal exchange remains significant even if domestic pollution intensity decreases (Duan and Jiang, 2017). Trade policies have also been influencing the quality of environment in various aspects. Most directly, trade policies can change commodities' comparative advantages, production costs and export costs, and international income transfers (Ocampo and Taylor, 1998; Palley, 2016). This will further affect macroeconomic conditions through the changes in terms of trade and endogenous entries and exits in many industries due to the general equilibrium adjustment of the input-output linkages (Caliendo and Parro, 2014; Melo, 1988). All of these will change producers' investment and production decisions, and consumers' purchase decisions, which would influence further resource allocation and environmental emissions (Huang and C. Labys, 2002; Morrison, 2017). In view of the obvious emissions embodied in trade and the intricate impact of trade policies on environmental quality, observers see a potential trade-off between gains from trade and environment. That is, the basic objective of trade policy is to liberalize international trade and attain the benefits of comparative advantage. However, trade-induced specialization will not only increase local pollution emissions in exporting countries, but also increase global GHG emissions if production occurs more in countries employing more carbon-intensive technologies (Frankel, 2009).

There is a whole genre of literature analysing the relationship between trade and the environment since Grossman and Krueger (1991) first explored the Environmental Kuznets Curve (EKC) and analysed the environmental effects of trade liberalisation. They considered that a reduction in trade barriers would generally affect the environment by expanding the scale of economic activity, by altering the composition of economic activity, and by facilitating change in techniques of production. The literature on trade and the environment has since grown substantially and expanded broadly. However, most of studies tend to analyse the environmental effects of tariffs reduction or trade liberalization, and there is still no consensus about the effects of trade on environment both theoretically and empirically. On the one hand, trade openness allows resources allocation efficiently, increases the access to clean technologies, and thus has a positive impact on environment (Aklin, 2016; Nemati et al., 2019). On the other hand, imbalanced trade patterns possibly induce overuse of scarce resources, and pollution increases because the negative externalities of production are not internalized; even if clean technologies gain a foothold, scale effects overcompensate and increase emission levels. With regard to empirical analyses, the findings are also inconclusive. Some researchers find trade openness reduces emissions and improves environmental quality (Antweiler et al., 2001; Frankel and Rose, 2005; Liddle, 2001). In contrast, some studies find that trade agreements reduce environmental quality (Bajona and Kelly, 2012; Kukla-Gryz, 2009; Yu et al., 2010). Even other studies find uncertain evidence on the relationship between free trade and environmental quality depends on different lengths of time period (Ahmed et al., 2015), types of environmental emissions (Stern, 2007), types of targeted countries (Baek et al., 2009; Dinda and Coondoo, 2006), etc. Thus, the inconsistent conclusions on trade openness could not provide counterevidence for those of trade frictions. The environmental issues related to trade barriers or frictions are so far rarely studied. Shapiro (2019) compared the effects of import tariffs and non-tariff barriers on upstream and downstream industries' CO_2 emissions, and suggested similar degree of trade policies to downstream (and clean) and upstream (and dirty) goods would help to decrease CO_2 emissions. Some studies found that trade penalties or sanctions constitute an economic instrument to influence trade partners to support a robust international climate agreement and reduce their emissions (Jakob et al., 2014; Lessmann et al., 2009; Nordhaus, 2015), but most of them are based on an indirect punishment. It is hence highly relevant to strengthen research in this aspect by directly exploring the environmental and climate effects of the opposite situation—tariff increase.

This analysis considers recent China–US trade friction as an example. Over the last three decades, China–US economic relations have expanded substantially; in particular, their bilateral trade has grown much faster since China's accession to the World Trade Organization (WTO). Their mutual total merchandise trade rose from \$27 billion in 1991 to \$656 billion in 2017, and the US import and export partner share for China has also risen to 21.9% and 8.4% respectively (Fig. 1). China is now the US's second-largest merchandise trading partner, the third largest export market and the largest source of imports (UNSD, 2017). However, the trade relationship between China and the US is uneasy and politically sensitive, and trade conflicts have always existed. On the one hand, based on its long period of slow GDP growth, weak employment growth, and sharp net loss of manufacturing employment, the US administration bemoans China's persistent surplus against the US (as Fig.1), China's failure to implement its WTO commitments and China's unreasonable acquisition of US technology (Kawasaki, 2018). On the other hand, China has criticised US restrictions on high-tech export products, their unfair treatment of China's market economy status, and unreasonable trade sanctions against China (USTR, 2018). The trade disputes have intensified after

Donald Trump took office; he claims that the US has been taken advantage of by its trade partners who run trade surpluses against it (Harper, 2018). The US has conducted the '301 investigation' into China since 2017 and introduced additional tariffs on many products imported from China, which were countered by tariffs on US exported goods by the Chinese government. Consequently, this action actively instigated trade friction starting in March 2018 (USTR, 2018). So far the trade friction has gone through six main rounds between both countries (details below).

Given that the US is the largest economy, and China's economic scale and international trade have been growing at a substantial rate, both countries' roles are significant globally, and the bilateral relations between the two will be a crucial determinant of the world's direction in the new century (Eaton et al., 2016). Accordingly, the trade friction between China and the US is likely to impact the world significantly. Here, we address this critical topic and explore how trade barriers shape environmental effects and climate change on the two countries and the world.

Based on this background, this study will investigate China–US trade friction, and numerically explore and simulate environmental and economic effects of trade barriers by using a global computable general equilibrium (CGE) model. We first investigated the four tariff rounds instigated by the Trump administration and ex-post assessed the corresponding socio-economic and environmental effects. Then we explored four scenarios on the future developments of China–US trade friction. The China–US negotiations are fraught with high uncertainty, for example, there were signs of a truce at the end of last year while today the US has raised tariffs on part of products again. However, whatever the outcome of the recent China–US negotiations, setting and analysing different future development scenarios is necessary. A discussion of different scenarios helps to answer the following questions: if China–US trade friction stops soon, compared with continuing, escalating or full-scale barriers scenarios, how many economic and welfare losses will have been avoided? If the negotiation fails (China–US trade friction continues, or upgrades, or even escalates to world-wide barriers), compared with a stop situation, how much extra economic and welfare costs will be incurred? In terms of environmental effects: How do the already-happened trade sanctions impact global and regional GHG emissions and other pollutants? How will environmental emissions be affected in the long-term following the possible different development trends of friction? To what extent do the trade barriers affect global climate change in the future?

2. Methodology

2.1 C^3IAM/GEEPA model

One of the most popular approaches for evaluating the possible consequences of trade friction is the CGE model (Guo et al., 2018). CGE models stem from the Walras (1969) general equilibrium theory. The core principle is that the economic agents optimise their behaviour under given resource and technology constraints under signalling from market prices; households maximise their utility subject to their budget constraints, and firms maximise their profits subject to their production technology and resource constraints. Markets equilibrate demand and supply by adjusting prices. CGE models are good at describing the interactions among different agents in macroeconomic systems using a set of simultaneous equations and are suitable for assessing the direct and indirect impacts of a given policy (Liang et al., 2016); thus, they are widely used in various policy analyses, such as economic integration, global warming problems and tax reform. A CGE approach is therefore suitable for this study. Moreover, given that China and the US are large economies, their trade policy will produce repercussions to other countries, and a CGE model can capture these linkages and effects through price mechanisms (Hosoe et al., 2010).

This study simulates different tariff policies using the Global Energy and Environmental Policy Analysis Model of China's Climate Change Integrated Assessment Model (C^3IAM/GEEPA) we developed (Wei et al., 2018). GEEPA is a multi-regional recursive dynamic CGE model which can calculate likely outcomes of tariff policy ex-ante via mathematical simulation at the global level. It is composed of five basic modules: production, income, expenditure, investment, and foreign trade module. For detailed assumptions for each sub-module, please refer to Wei et al. (2018) (The elasticities of production and trade are shown in Supplementary material 1). As a model focusing on energy and environmental analysis, GEEPA covers multiple environmental emissions, based on their importance for climate change and data availability, including both GHG emissions and traditional air pollutant emissions. The GHGs included in the model are: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O); the traditional air pollutants considered are carbon monoxide (CO), sulphur dioxide (SO_2), nitrous oxides (NOx), ammonia (NH_3), black carbon (BC), organic carbon (OC) and non-methane volatile organic compounds

(NMVOCs). To focus on trade friction agencies and their primary trade partner, countries in this study are re-aggregated to form eight regions based on the original GEEPA model, including USA, China, Japan, EU (European Union), ROA (Rest of Asia), MAF (Middle East and Africa), LAM (Latin America), and ROW (Rest of the World) (see Supplementary material 2 for details). Additionally, commodities are aggregated to 48 major sectors, reflecting the structure of China–US trade relevant products with detailed manufacturing and agriculture classification especially. Generally speaking, the import tariffs imposed by the US on China mainly aim at the manufacturing industry, especially the products in the 'made in China 2025' strategic plan, while the import tariffs imposed by China on the US are distributed in the agriculture, automobile, chemical and other industries. A detailed sector description is given in Supplementary material 3.

2.2 Data sources, Pre-processing and Parameter Calibration

This study used the Global Trade Analysis Project (GTAP) Database version 9 with the latest reference year 2011 (Aguiar et al., 2016) for calibrating the Social Accounting Matrix (SAM), which is the core database of a CGE model.

The base year GHGs and air pollutants are drawn from the database of Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) (GAINS, 2011). The energy-related emission and non-energy-related emission can be differentiated through activity types within a sector for every discharge in the GAINS model. Thus, a sector's emission factor can be determined by total energy-related emissions divided by corresponding energy consumption or total non-energy-related emissions divided by corresponding gross output.

Additional tariff rates for Chinese and American products and corresponding product lists are collected from the Ministry of Finance of the People's Republic of China (MFPRC, 2018) and the Office of the United States Trade Representative (USTR, 2018), which provide each round of trade tariff increases with thousands of commodities. To match the sector and its containing products for modelling, we recalculate each sector's real tariff increase rate according to each detail product's trade value between China and the US, which are collected in WITS (2017) (see Supplementary material 4 for details).

3. Simulation and Results

3.1 Scenarios

We developed a baseline and multiple policy scenarios for the two parts of our analysis (ex-post scenario analysis in 2019 and ex-ante scenario analysis for the period after 2019 to 2100) (see Table 1). The baseline scenario was generated following the SSP2 narrative-a *Middle of the Road* pathway (see Supplementary material 5 for specific baseline scenario parameters, including GDP, population and various environmental discharges). In this scenario, the world follows a path in which social, economic and technological trends do not shift markedly from historical patterns, with some progress towards achieving development goals, reductions in resource and energy intensity at historical rates, and slowly decreasing fossil fuel dependency (O'Neill et al., 2017). Besides, the energy development is calibrated following the trends projected by EIA (U.S. Energy Information Administration), and the environmental emissions development is calibrated based on the trends in CMIP6 (the Climate Modelling Intercomparison Project 6) emissions(Gidden et al., 2019). By adopting such a pathway, we assumed the world is developing as an extension of historical experience or in their usual ways except in import tariffs because of trade friction.

Trade friction between China and the US have been escalating, and there have been six complete rounds of confrontation since March 2018 (see Supplementary material 6 for a detailed timeline and corresponding trade policy). Accordingly, our policy scenarios include two broad categories: first, beginning with the six stages of escalating trade friction between China and the US, we simulate these six corresponding policies in the model and conduct the status assessment after every round shock in 2018 and in 2019[1]; second, considering the long-term possible development and resulting influence, we establish another four policy scenarios to simulate the climate change and environmental effects when the trade friction experiences different trend or direction. Based on these results, the resulting environmental and economic impacts will be discussed.

3.2 An ex-post impact assessment of China–US trade friction

This section investigates how the implemented trade measures will affect different regions' economy and environmental emissions. Overall, the effects are increasing in most indicators with trade friction escalating following these six stages.

[1] Based on known tariff increase for different detailed trade products, here we figured out real tariff increase for the 48 sectors in our model according to the corresponding share of trade value from WITS, 2017. World Integrated Trade Solution. https://wits.worldbank.org/about_wits.html.

Through these six rounds of shocks, we observe the following changes in the global trade pattern, socio-economy and environmental emissions (without considering the impact of other policy shocks in the same period):

3.2.1 Changes in China–US trade

In general, the US's trade deficit with China has decreased by 44.4%. As shown in Fig.2, with the US imposing tariffs on China, its total imports from China decreased at the rate of nearly 44.60%, and most products' imports from China showed a significant decline. Roil, coal and ferrous metals particularly dropped more than 75%. Meanwhile, the US's exports to China also declined sharply because of China's retaliation tariffs, with a decline rate of nearly 47.49%. Exports of vegetables and fruits, coal and meat products all fell by more than 80%. Even so, the trade friction caused the US to import less from China than it exported, and eventually the trade deficit with China has fallen significantly.

Besides, trade friction between China and the US have also increased their trade communication with other regions (Fig.2). The US's both exports to and imports from all of other regions have raised. In detail, the US's imports increased by 10.40% from Japan, 8.58% from the European Union (EU), 12.79% from the rest of Asia (ROA), 4.65% from the Middle Eastern and African countries (MAF), 4.72% from Latin America (LAM), and 5.89% from the rest of the world (ROW), respectively. In addition, the US's total exports also increased by 0.93% (MAF) – 2.42% (LAM)。Similarly, China exports more products to other six regions, including Japan (7.5%), EU (8.3%), ROA (7.0%), MAF (7.8%), LAM (8.6%) and ROW (8.3%). However, the imports from other regions have been still decreased except that China's imports from Latin America (LAM) increased by 1.4%. Specifically, with the exception of some agricultural products (wheat, cereals, oilseeds, plant fibers, other crops), meat products, vegetable oils, beverage tobacco products and paper products, China's imports from other regions decreased for all other products. That is because, less products with a larger proportion of imports in total domestic consumption, mainly including oilseeds products (61.69%), crops (62.12%), crude oil (56.36%) and natural gas (90.44%), while most of the rest of the products are mainly dependent on domestic production. Thus, in the light of China's list of US tariffs, when China imposed import tariffs on the US, China increased its imports of agricultural products from other regions, while imports of most other products declined, as a result of falling aggregate consumer demand for related products and consumers switching to domestic products.

3.2.2 Changes in economic growth, employment and social welfare

With the increasing trade friction between China and the US, after six rounds of shocks, China suffered the most substantial economic loss (0.21%), and the US's GDP also decreased by 0.08%, as shown in Fig.3 (a). In terms of the composition of GDP, under the assumption of fixed government consumption, the change of GDP is mainly determined by changes in household consumption, investment and exports. As a result of the impact of import and export tariffs, China's and the US's total exports decreased significantly, with a proportion of 3.38% (USA) and 2.45% (China). At the same time, the tariff shock reduced household incomes in both countries by 0.01% (USA) and 0.55% (China), respectively, which led to declines of household consumption and investment, with US's household consumption and investment falling by 0.01% and 0.99%, respectively, and China's by 0.55% and 0.94%, respectively. At the same time, the reason that China's GDP loss is larger than the US is mainly a significant decline in household income. With the supply of labour and capital unchanged, the trade shock has reduced the demand for labour and capital. China's labour and capital demand has fallen even more because China's large exports of textiles, clothing and leather goods to the US are labour-intensive, while transportation equipment, machinery and other equipment manufacturing are capital-intensive, resulting in greater losses in China's GDP. Meanwhile, as the world's first and second largest economies, trade frictions between the US and China have caused significant obstacles to the development of global trade, and the negative impact of the China–US friction has spread to other world economies, such as Japan, which lost 0.01% of its GDP, EU (0.01%), MAF (0.02%), and ROW (0.01%). Finally, global GDP experienced a loss of 0.05%.

Trade friction has a high impact on the employment of relevant sectors in both countries, as shown in Fig.3(c). The US's employment declined in 34 of 48 sectors, mainly covering agricultural and agro-by-product processing industries. Industries with a larger decline in employment losses include the oilseeds sector (16.0%), plant-fibre sector (11.0%), wool cocoon's sector (10.4%), transport equipment manufacturing (3.4%) and non-ferrous metal manufacturing (3.0%). China also decreased in employment in 15 sectors, mostly in the manufacturing industries. Its larger job losses are mainly from the wool cocoon's sector (2.7%), electronic equipment manufacturing (3.6 %), wood products (2.0%) and leather products (1.6%). This is closely related to important trade products between China and the US. For example, in terms of exports of oilseeds products from the US, 66.84% of oilseeds products produced in the US are exported, while exports to China account for 65.74% of total exports, i.e. China is the largest purchase country of oilseeds products in the US. In the trade friction, China imposed tariffs of up to 35% on US's oilseeds products, while US's exports to China fell 49.18%. Although the US exported more products to the rest of the world, it was not enough to make up for the decline in exports to China, which eventually reduced until 17.54%. As a result, the decline in total demand for oilseeds in the US has significantly affected employment of this sector and even its downstream-sectors. On the contrary, China's job losses are mainly in the manufacturing sector, as China's main exports are concentrated in manufacturing and its exports to the US account for a larger proportion of total exports. For example, China's electronic equipment exports accounted for 40.66% of total production, while electronic equipment exported to the US accounted for 27.75% of total exports. As a result, the output of China's electronic equipment fell by 3.64%, resulting in job losses in the sector. In addition, since the backward correlation coefficient of manufacturing products is generally high (the backward correlation coefficient of China's electronic equipment manufacturing industry is 1.71), that is, the impact on other manufacturing industries is greater, further affecting employment in other manufacturing industries.

Trade friction leads to the deterioration of China's welfare, while the US's welfare slightly decreased (social welfare[2] is represented by Hicksian equivalent variation [EV]), as shown in Fig. 3(b). As seen from the figure, China's welfare lost about $27 billion after six rounds of friction, while that of the US decreased slightly ($1.4 billion). The reasons for the less welfare loss in the US than China are: on the one hand, the proportion of China's imports from the US in China's total imports are significantly less than that of US's imports from China in US's total imports (e.g., the two proportions are about 8% and one in five in the base period, respectively). Consequently, tariff shocks from both sides have increased much more US's tariff revenue (173%) than that of China (15.7%). Although the trade friction negatively impacts the production activities of the two countries, the households' income in the US only decreased by 0.01% because of the general government tax neutrality principle followed by this study, while China' households' income decreased by 0.55%, much bigger than the US. However,

[2] Note the welfare effects in this study, represented by Hicksian equivalent variation (EV), do not include the benefits of lower emissions. This is because our model has not yet been able to include damage functions, health effects, etc.

other six regions' social welfare increased by $2.8 billion (Japan), $10 billion (EU), $15.7 billion (ROA), $2.3 billion (MAF), $10.1 billion (LAM) and $5.2 billion (ROW), respectively. Finally, global welfare still increased about $18 billion. The rise in welfare in other countries around the world, with the exception of China and the US, is also due to the assumption that tax neutrality has led to higher incomes. Without the principle of tax neutrality, the impact on GDP in each region would be smaller, the employment impact of the various sectors would be similar, and the impact on welfare would be greater, even with the global welfare loss of more than $50 billion. (The relevant results are shown in Supplementary material 7).

3.2.2 Changes in regional GHG and air pollutant emissions

China–US trade friction has changed the distribution pattern of environmental emissions among countries around the world. In general, trade friction has had a significant impact on the emission reduction of GHGs and pollutants in China and the US, while most of the environmental emissions in other countries have increased.

In terms of GHGs, under six rounds of shocks, global CO_2 emissions decreased 0.16% compared with BAU. Total CO_2 emissions in China and the US decreased by 0.68% and 0.02% respectively. However, except for LAM, which produced 0.10% CO_2 emission reduction, the CO_2 emissions of the other regions showed an increasing trend with a change rate of 0.01% (ROW)-0.17% (ROA). Overall global CH_4 emissions decreased by 0.03%, mainly due to the decline of CH_4 emissions in the US (0.32%). However, for N_2O, global emissions increased by 0.03%, with the most significant increase in China's N_2O emissions by 0.70%. For pollutants, the China–US friction has reduced the emission of almost all air pollutants in the US, most notably NH_3 (1.76%), N_2O (1.23%), $PM_{2.5}$ (0.98%) and CO (0.60 %), and the emission reduction of SO_2, NOx, BC and OC has also exceeded 0.15%. In addition to the increase of NH_3 emission by 0.50%, the emissions of other pollutants in China also showed a significant decrease, with a rate of 0.44% ($PM_{2.5}$) –0.74% (NOx). In contrast, emissions from most other parts of the world increased. For example, the emission of various pollutants in LAM increased by 0.18% (BC), 0.19% (SO_2), 0.16% (NOx), 0.14% (CO), 0.10% (OC) and 0.03% ($PM_{2.5}$), respectively. Overall, after six shocks, global emissions of all pollutants decreased significantly, by 0.03% ($PM_{2.5}$) - 0.17% (BC).

To analyse the causes of changes in environmental emissions, this study decomposed regional changes in environmental emissions into scale effects (changes in output size), structural effects (changes in output share) and technical effects (changes in emission intensity) based on a modified version of the method proposed by Copeland and Taylor (2004), with results as shown in Table 2. (The derivation process is shown in Supplementary material 8). At the same time, it is analysed in the light of the proportion of sectoral emission changes in total emission changes in each region, changes in the output size in each sector, and changes in emissions per unit output in each sector (see Supplementary materials 9-12 for relevant sectoral results).

As can be seen from Table 2, for the US, the decrease in CO_2 emissions is mainly due to the combined effect of scale effect and technical effect, and the structural effect has a negative impact on CO_2 emission reduction. The declines in remaining gas emissions are mainly due to structural effects, and the technical effect gives a smaller contribution to the decline in other emissions. Under the impact of trade frictions, total output in 35 sectors in the US declined, and the size of total output across the country fell by 0.04%. Moreover, changes in the output structure of various sectors have also reduced emissions from most gases by 0.09% (SO_2) -1.72% (NH_3), but increased CO_2 emissions by 0.04% and NMVOCs emissions by 0.12%, which are also the main reasons for the increase in NMVOCs emissions nationwide. For China, scale, structure and technical factors have significantly contributed to one or more gases' emission change. Specifically, except for CH_4, N_2O and NH_3, which are mainly structurally active, and CO emissions, which are mainly based on scale and technical effects, the decline in the remaining gases' emissions is mainly due to three factors significantly. China's outputs in all 19 sectors have fallen in six rounds of trade friction, with total national output falling 0.22%. Structural effects increased emissions of CH_4 (0.34%), N_2O (0.94%) and NH_3 (0.72%), while reduced BC (0.07%), CO_2 (0.27%), NMVOCs (0.11%), NOx (0.12%), OC (0.22%), $PM_{2.5}$ (0.08%) and SO_2 (0.15%) emissions. The technical effect also significantly contributed the reduction of 8 gases, with a proportion of 0.41% (BC), 0.30% (CO), 0.19% (CO_2), NMVOCs (0.39%), NOx (0.40%), OC (0.20%), $PM_{2.5}$ (0.13%) and SO_2 (0.27%), respectively.

Further combined with the contribution of sectoral emission changes, it can be found that the changes in CO_2 emissions in the US come mainly from the emissions decline of two carbon-intensive sectors — the electricity sector and the chemical industry. The shock of trade friction resulted in a 0.52% reduction in the output size of the electricity sector (scale effect), while a decline in coal inputs reduced CO_2 emissions per unit in the electricity sector by 0.09% (technical effect). Finally, the electricity sector is reducing emissions 3.4 times that of the national total emission reduction. However, the increasing effect of the structure on CO_2 emissions is mainly due to the increase in the share of output (0.003%) and output size (0.11%) in the oil smelting and coking sector. And the CO_2 emission intensity in this sector is the highest, resulting in the absolute increase of CO_2 emissions is about 2.8 times the total CO_2 emission reduction. The decline in China's CO_2 emissions is mainly from the contributions of the electricity sector, the oil smelting and coking sector, and the non-metal mineral products industry. Specifically, after six rounds of trade friction, the output share of China's these three sectors decreased by 0.005%, 0.01% and 0.01% respectively (structural effect), while output size decreased by 0.52%, 0.49% and 0.68% respectively (scale effect). In addition, CO_2 emission intensity in the electricity sector and non-metal mineral products decreased by 0.38% and 0.12%, respectively (technical effect). Meanwhile, these three sectors are major contributors to the reduction of multiple pollutants (SO_2, NOx, $PM_{2.5}$, BC, OC and CO) in China.

Oilseeds farming contributed to the decline in US's multiple gases, accounting for BC (57.62%), CO (38.30%), N_2O (61.40%), NH_3 (36.94%), NOx (36.18%), OC (47.68%) and $PM_{2.5}$ (53.94%). China is the largest importer of oilseeds for the US, as stated in Section 3.2.1, in the six rounds of friction so far, China's import tariffs on US's oilseeds products have reduced US's exports to China by nearly 50% and total exports by nearly 20%. This has had a significant dampening effect on oilseeds production in the US. Specifically, the output of this sector in the US fell by 12.79%, which saw the largest decline among all sectors, and its share of industrial structure fell by 0.02% (3rd). Moreover, the sector's emission intensity is relatively high, ranking in the top 15 of all 48 sectors. As a result, the structural effect significantly reduced the emission of a variety of gases. In contrast, oilseeds cultivation is the main sector that causes a significant increase in China's N_2O and NH_3 emissions, and the corresponding increase proportion is 42.73% and 35.84%, respectively. From the perspective of trade shocks, more than half of China's oilseeds consumption comes from imports (for example, the total consumption of oilseeds products in China in 2019 is about \$120.6 billion, of which \$74.4 billion come from imports. Oilseeds products imported from the US account for nearly 40% of total imports. Thus, on the one hand, the import price of China's total oilseeds products increased by about 11% due to the increasing import tariffs, and residents switched to consumer domestic products, thus stimulating the rise in domestic output. On the other hand, the impact of Sino-US trade frictions caused the world price of oilseeds products in China to fall by 1.54%, thus the relative income of residents has increased, which further stimulating the production of domestic enterprises.

For CH_4, coal mining, and other livestock and poultry farming are two important sectors contributing to the reduction of CH_4 emissions in the US, while they are also the main sectors contributing significantly to the increase in CH_4 emissions in China, with the proportions of 18.62% and 27.56% (for the US), and 60.35% and 23.06% (China) respectively. The main reason for the significant change in CH_4 emissions in coal mining is that it has high emission intensity, and the small changes in the output share and the output size can result in big changes in the total CH_4 emissions. The other livestock and poultry farming's contribution to CH_4 emissions reduction can be attributed to the significant change in output size and output share. For example, according to the results of this study, the actual tariff rate imposed by China on US's other livestock and poultry to date is 34.4%, which results in a 67.10% reduction in China's imports from the US and a 6.44% increase in China's total import prices, and stimulates consumption of the corresponding domestic products (0.24%), hence the size of this sector has risen significantly.

For NMVOCs emissions, the significant increase in the US is mainly from the oil smelting and coking sector, which has increased NMVOCs emissions by about 13 times as much as the country. In contrast, the oil smelting and coking sector contributed 70.54% of China's emissions reduction. Refined oil is an important intermediate input product, Sino-US trade friction has led to a decline in the world price of refined oil, while most of the declining output is in the manufacturing sectors in China, where demand for refined oil products is high. That results in a decline in total domestic demand for refined oil products (0.74%), thus oil smelting and coking sector total output fell. However, a marked decline in US's imports of manufactured goods from China has stimulated demand for domestic refined oil production in the US, and output in the oil smelting and coking sectors has risen significantly (0.11%). The NMVOCs emission intensity in the oil smelting and coking sector is the largest in both China and the US, and small changes in the output share and the output size in this sector will significantly affect NMVOCs emissions across the country.

For the remaining six regions, almost all gases increased emissions, with the exception of CH_4, N_2O and NH_3, as shown in Table 2. The emissions increase in Japan and LAM is mainly due to the technical effects, the emissions (except $PM_{2.5}$) increase in MAF is mainly due to structural effects, the emissions increase in ROA and ROW is due to the combined effect of technology and scale, and the emissions increase in the EU is due to the combined effect of technology and structure. For CH_4, N_2O and NH_3 emissions in these six regions, the changes in emissions are mainly due to structural effects. According to the contribution of sectoral emission changes, for these six regions, the eight other gas emission increases, are mainly in the electricity sector, oil smelting and coking sectors, the chemical industry, non-metal mineral products, other manufacturing industries, construction and transportation services. In addition, the decline in CH_4 emissions is mainly due to a reduction of the output share in livestock and poultry farming and coal mining. The changes in N_2O and NH_3 emissions are mainly consistent with the change in the output share of various agricultural sectors, particularly in relation to the cultivation industry, and NH_3 emissions in particular to livestock and aquaculture.

3.3 An ex-ante impact prospect of China–US trade friction for the future

This section elaborates on the potential economic and environmental impacts of different future development trends of China–US trade friction and further evaluates long-term climate change.

3.3.1 Impacts on GDP and welfare

From the perspective of overall impact, if China and the US stop imposing tariffs after 2019 (scenario SE), the global economic loss will be significantly reduced, and the damage will only last until 2030. Otherwise, with the escalation of trade friction, the global economy and social welfare will be increasingly negatively affected (Fig. 4). In particular, when global trade barriers exist (scenario WF), global GDP will decline by 2.80% in 2050, and global welfare will decrease by more than \$140 billion in 2050.

From the perspective of each region, if the China–US trade friction stops after 2019, the simulation results show that the economic losses of China and the US will continue, while the overall GDP of most other regions and the world will generally turn to growth. However, the extent of profit and loss of each region is small, and there is a trend of a gradual recovery in the long run. However, if China–US trade friction continues (scenario CK) or escalates (scenario UA) after 2019, both countries' GDP and welfare will continue to deteriorate. For example, under scenario CK and UA, the GDP loss of the US in 2050 is 0.40% and 1.33% respectively, and the welfare loss is $74.4 billion and $31.3 billion respectively. Similarly, compared with BAU, China's GDP will be reduced by 0.26% and 0.71% respectively in 2050, and the residents' welfare will be reduced by $56.4 billion and $134.7 billion respectively. If trade friction was to spread globally (scenario WF), the economies of all regions would be severely affected, and social welfare would be damaged to varying degrees. The GDP loss of each region will be 0.63% (Japan) – 4.92% (MAF), and the welfare loss will be $24.2billion (Japan) – $335.4billion (MAF) in 2050, respectively.

Overall, the economic losses caused by trade friction on the conflicting parties have a certain permanence, while the non-participants can generally benefit indirectly. Moreover, the negative impact of trade friction on global society and economy cannot be ignored. However, the current cessation of China–US trade friction can avoid significantly greater global economic losses and ensure the well-being of residents.

3.3.2 Impacts on energy consumption

If China–US trade friction stops after 2019 (scenario SE), there will be no significant change in global and regional energy consumption (as Fig.5). Otherwise, global economic growth slows down due to China-US trade dispute, and the global total energy consumption will decline significantly, among which, the proportion of decline in 2050 is 0.08% (CK), 0.14% (UA) and 4.83% (WF), respectively. At a regional level, trade friction between China and the US have reduced energy consumption on both sides but increased it in most other regions. The reason is that, on the one hand, the energy industries of China and the US are directly affected by the imposition of tariffs, resulting in a decline in the exports to each other and thus a decline in energy output. On the other hand, the trade friction between China and the US has caused a decline in the outputs of most industrial sectors, especially energy-intensive industries, which has an indirect negative impact on energy demand. Meanwhile, China and the US will increase their energy demand to the rest of the world and exploit new energy supply markets, thus increasing energy consumption in most other regions. For example, when the China–US trade friction escalates (scenario UA), the total energy consumption in the US and China would decrease by 0.51% and 0.83% in 2050, while the total energy consumption in other regions would increase by 0.02% (Japan) – 0.32% (MAF). Global trade barriers (scenario WF) have significantly reduced total energy consumption in all regions except MAF and LAM which increased 1.51% and decreased slightly 0.10% of total energy consumption, respectively, with a reduction of ROW (4.17%)–Japan (10.20%) by 2050.

In general, the market share of non-fossil fuels in each region has no significant change, and the range of change in most regions is less than one percentage point (see Supplementary material 13 for changes in non-fossil energy share). If China and the US cancel the policy of imposing tariffs (scenario SE), the share of non-fossil fuels in each region is almost maintained at the base level. From the perspective of change direction, in the scenario of continuous (CK) or escalating (UA) China–US trade friction, the share of non-fossil fuels in the US shows a downward trend while China' share continues to growth. At the same time, the change of the share of non-fossil energy in the two countries is deteriorating over time, that is, the reducing proportion of non-fossil energy share in the US is gradually increasing and the rising proportion of China's corresponding share is decreasing. The corresponding share in most other regions will have opposite improving trend – generally decrease during 2020 – 2030 then increase after 2030. For example, under scenario UA, the share of non-fossil fuels will be reduced in the US by 0.01% in 2030 and 0.06% in 2050, increased in China by 0.06% in 2030 and 0.01% in 2050, while decreased by 0.02% in 2030 then increased by 0.02% in 2050 for EU respectively. This shows that in the short term, the trade friction between China and the US is conducive to China's non-fossil energy development, the US and most other regions are not conducive to. However, the energy impact of Sino-US trade friction is not conducive to both sides but beneficial to other regions in the medium to long term. In addition, the LAM region is an exception, its share of non-fossil energy will continue to grow. Due to the impact of Sino-US trade friction, the decline in electricity prices and economic growth will promote consumers' consumption of electricity. However, more than half of the sectors' exports and output will decline in LAM. For example, output in the oil smelting and coking sector will be reduced by 0.55% in 2020, resulting in a reduction in the demand and consumption of crude oil. Eventually, the share of non-fossil energy in LAM will gradually increase. When the global trading system is divided (WF), the share of non-fossil fuels in all regions, except MAF and LAM, is generally on the rise. The increasing proportion is 0.04% (ROW) – 1.63% (EU) in 2050. The results show, the increase in the global share of non-fossil energy is mainly due to the increase in the cost of fossil energy in most regions. Specifically, the regional distribution of production and consumption of fossil energy is quite different from that of non-fossil energy, with there being almost no trade transfer of non-fossil energy. Thus trade friction increases the consumption cost of fossil energy, leading to the substitution of non-fossil energy. Specifically, the high tariff on fossil energy promotes the improvement of the power generation structure in each region itself, which increases the consumption share of non-fossil energy. For example, under global trade barriers, by 2050, the share of non-fossil energy generation will rise by 0.41% (USA), 1.05% (China), 2.35% (Japan), 2.47% (EU), 0.55% (ROA) and 0.82% (ROW), respectively, and the share of non-fossil energy generation will rise by 0.83% globally. In terms of specific energy consumption types, nuclear energy consumption in Japan, ROA and EU and hydropower consumption in China will continue to grow over time, whilst the declining proportion of wind energy, solar energy and nuclear energy consumption in various regions is also significantly lower than that of fossil energy consumption.

To sum up, the continuous or upgraded tariffs between China and the US is conducive to reducing the total energy consumption of both sides, but is not helpful to the improvement of energy structure and the transformation development of clean energy. It is worth noting that, when global trade barriers occur, contrary to the situation of energy consumption in most regions, the total energy consumption of MAF will continue to rise. Although the total energy consumption of LAM has a slight decrease, the share of non-fossil fuels of MAF and LAM will continue to decline. The change of trade pattern goes against the clean energy development of MAF and LAM. This is because, as the main production regions of fossil energy, the production of fossil energy in MAF and LAM is higher than the consumption; thus, it is mostly used for export. The Middle East is particularly dependent on fossil energy due to its abundant oil resources, and clean energy accounts for a very low proportion in the energy consumption structure. Consequently, when trade barriers are introduced, energy exports decline, and crude oil prices in MAF and LAM fall significantly, more oil energy is sold domestically, increasing the total domestic energy consumption.

3.3.3 Impacts on environmental emissions

(1)Total GHG emissions

The impacts of Sino-US trade disputes on industry production and energy consumption are major sources of GHG emission changes. In general, trade friction will be conducive to long-term GHG emission reduction, and the more intense the friction, the greater the reduction. According to the equilibrium results under various policy scenarios, the impact of trade friction on the global emissions of major GHGs is shown in Fig. 6. Under the armistice scenario (SE), there is no significant change in global GHG emissions, and the escalation of trade friction will increase GHG emission reduction incrementally. For example, under scenario CK, UA and WF, global total GHG emissions will be reduced by 0.07%, 0.14% and 4.23% respectively in 2050. Moreover, all GHG emissions under global trade barriers (scenario WF) will be significantly reduced, and the change proportion is 4.95% (CO_2), 0.86% (CH_4) and 2.07% (N_2O) in 2050, respectively.

At the regional level, trade disputes between China and the US can reduce both sides' total GHG emissions, but emissions would increase elsewhere. For example, in scenario UA, GHG emissions in the US will be reduced by 0.54% in 2050, including 0.32% CO_2 emission reduction, 1.38% CH_4 emission reduction and 4.29% N_2O emission reduction. Although China's N_2O emissions increased by 1.03%, GHG emissions will still decrease by 0.68%, mainly due to the reduction of CO_2 emissions (0.81%) and CH_4 emissions (0.34%). However, CO_2, CH_4 and N_2O and total GHG emissions are on the rise in most other regions. When the global trading system collapsed (WF), GHG emissions would fall significantly in most regions except MAF. For example, compared to the baseline level, global GHG emissions were reduced by 4.23% in 2050, with emission reductions by regions such as the US (7.14%), China (5.34%), Japan (10.46%), the EU (9.20%), ROA (3.12%), LAM (1.41%), and ROW (5.35%).

(2)Total air pollutant emissions

Trade friction helps reduce air pollutants and improves environmental quality. Fig.6 also shows the changes in global air pollutant emissions under various scenarios. When the China–US trade tariff is restored to the previous level (scenario SE), there will be no significant change in global air pollutant emissions in the medium run. However, if China–US trade friction continues or escalates (CK and UA scenarios), global emissions will all have a relatively significant reduction. For example, under the scenario of CK and UA, the global emission reduction in 2050 is 0.01% (NH_3) – 0.09(CO), and 0.01% (NH_3) - and 0.15% (CO), respectively. When global trade is differentiated (scenario WF), the emission reduction of pollutants is the most significant, compared with BAU, the reductions of various pollutants are between 0.41% (NH_3)–5.10% (SO_2) in 2050.

On a regional scale, when trade friction only occurs between China and the US (scenarios SE, CK and UA), the emissions of most pollutants in the US and China are gradually reduced, whereas, the emissions of almost all pollutants in most other regions are higher than in the BAU scenario. For example, if the China–US trade conflict escalates (UA), the US and China would reduce SO_2 emissions by 0.37% and 0.67% accumulatively by the end of the century, respectively, while most other regions would increase SO_2 emissions, including Japan (0.05%), the EU (0.18%), ROA (0.21%), MAF (0.08%), LAM (0.24%), and ROW (0.22%). If trade friction spreads across the world (scenario WF), emissions would fall sharply almost everywhere.

3.3.4 Impact of climate change

If trade friction was to spread across the world (WF scenario), climate change indicators would improve slightly, with a positive impact on mitigation. The above changes in environmental emissions drive the changes in atmospheric GHG concentration, radiation forcing, and temperature rise under the four policy scenarios, as shown in Fig. 7. As tariff shocks spread across the globe, climate indicators will be more significantly affected. From Fig. 7, by the end of the century, WF scenario increases by about 3.4 ℃ and fell by nearly 0.1 ℃ compared with the BAU. Meanwhile, by 2100, the corresponding GHG concentration will drop by 2.54%, and radiation forcing will be close to 6.4 W/m^2, down by 0.1 W/m^2. However, when trade friction only occurs between China and the US (SE, CK and UA), the relevant results are similar to those in the BAU scenario, which indicates that, although trade friction between China and the US is beneficial to the mitigation of climate change, their impacts are not significant.

4. Conclusion

This study adopted a global computable general equilibrium model—C^{3}IAM/GEEPA to simulate the four rounds of trade friction between China and the US and their different development trends in the future, and to analyse the economic, environmental and long-term climate impacts caused by different tariff barriers on the world and various regions. Major conclusions include the following:

Several rounds of trade friction between China and the US have significantly weakened bilateral trade, reduced the US's trade deficit with China to a certain extent, and strengthened the trade links between each of the two economies and other countries. Employment in the agricultural sector in the US and manufacturing industry in China has declined significantly. Trade friction also reduced the GDP of not only China and the US, but also the rest of the world in 2019. In the long term, economic losses caused by trade friction on the conflicting parties have a certain permanence, while the non-participants can benefit indirectly.

The implemented China–US trade friction reduced environmental emissions of both sides but increased environmental emissions in other countries, have overall reduced global CO_2 emissions and some pollutant emissions. In the long run, if China–US trade friction stops after 2019, global and regional energy consumption and environmental emissions will not change significantly. However, continued or increased trade friction will significantly reduce participants' and the world's overall energy consumption, contributing to long-term reductions in GHGs and air pollutants.

Particularly, concerning global trade barriers, total global energy consumption and most of the regional environment emissions will fall significantly, and global trade barriers could increase the share of non-fossil fuels in most regions except for the Middle East and Africa and Latin America. However, the modest environmental improvement is far not enough to achieve a significant response to climate change, thus an independent mitigation policy is necessary. Moreover, it is challenging to consider both economic benefits and environmental benefits simultaneously, and such a distorting trade policy would be at the cost of substantial economic and welfare losses. Specific effects could be of dramatic consequences. For example, in the case of effects on international soybean markets, the trade war could mean disaster for deforestation in the Amazon, as China is increasingly sourcing soy from Brazil instead of the US (Fuchs et al., 2019). More importantly, the emission reductions induced by trade barriers would not avoid catastrophic climate change and would disable the international cooperation needed to fight climate change. In conclusion, free trade, with preference on carbon-free goods, and a simultaneously implemented environmental policy (e.g. carbon tax) could be better policy options for keeping residents' welfare whilst improving environment.

Declarations of interest

None.

Funding sources

This work was supported by the National Key Research and Development Program of China [grant numbers 2016YFA0602600]; and the National Natural Science Foundation of China [grant number 71422011, 71461137006, and 71521002].

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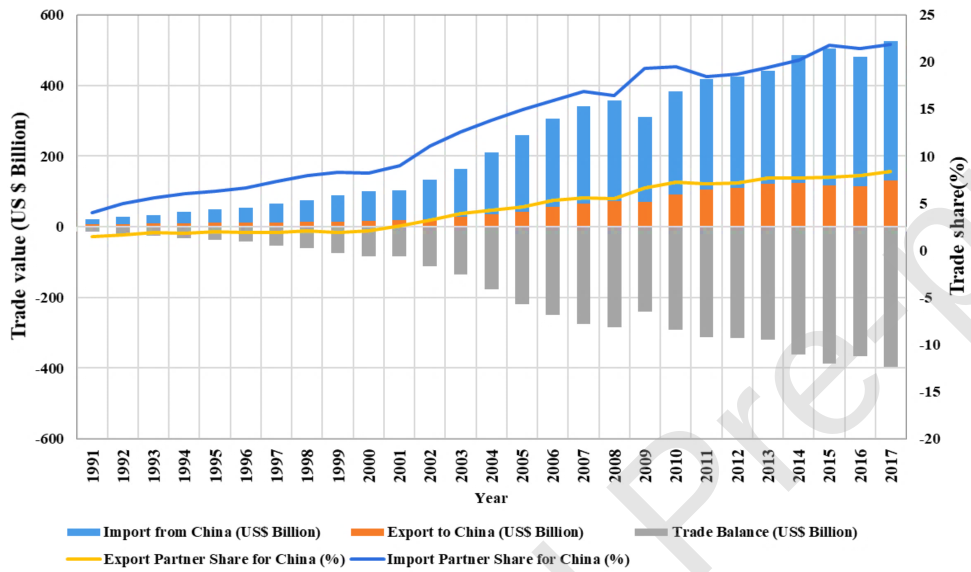

Fig. 1. China–US bilateral trade. Data source: WITS - UNSD Comtrade (UNSD, 2017).

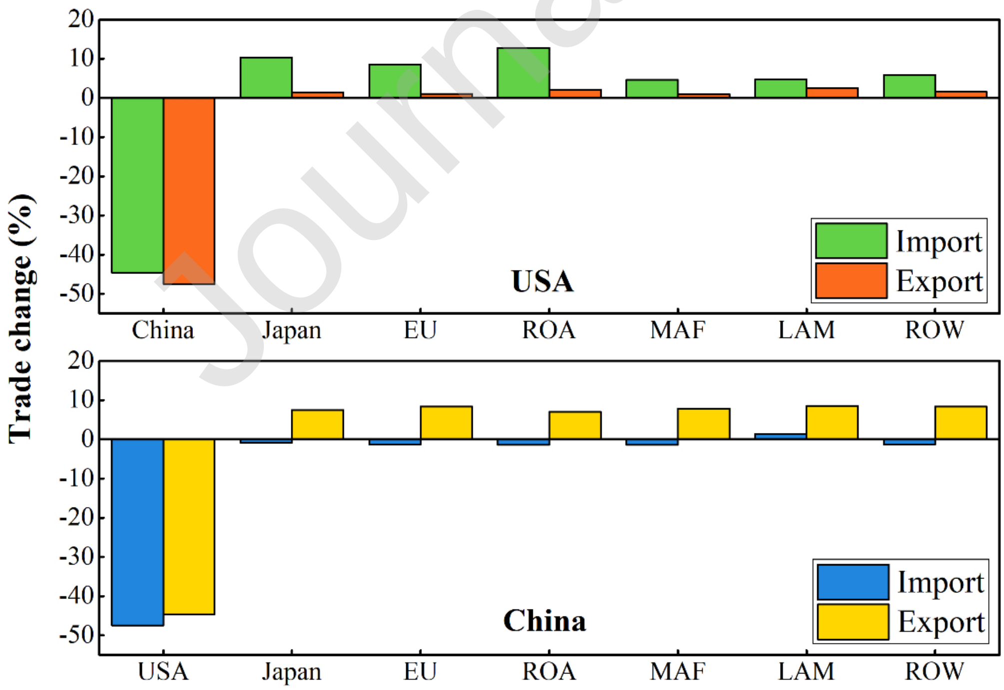

Fig. 2. The impacts of trade friction on imports and exports of the two countries.

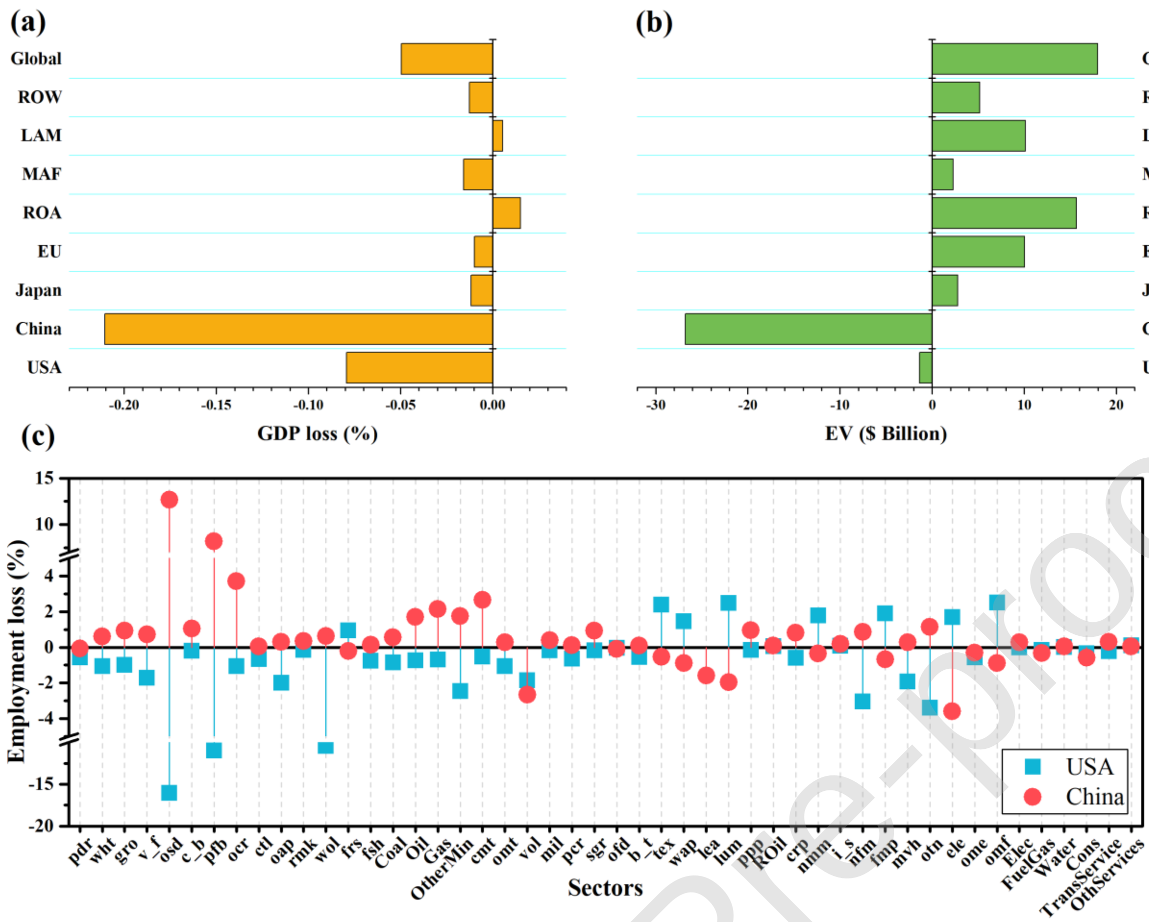

Fig. 3. The impacts of trade friction on regional GDP and social welfare, and on China's and US's employment.

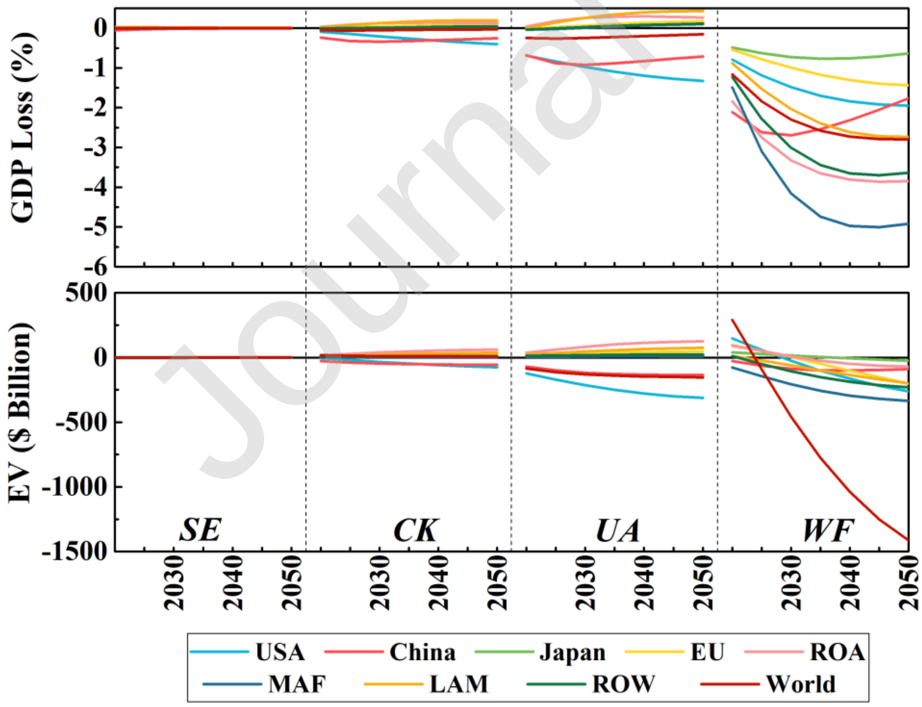

Fig. 4. The impacts of trade friction on economic growth, welfare under different post-2019 scenarios in the long-run.

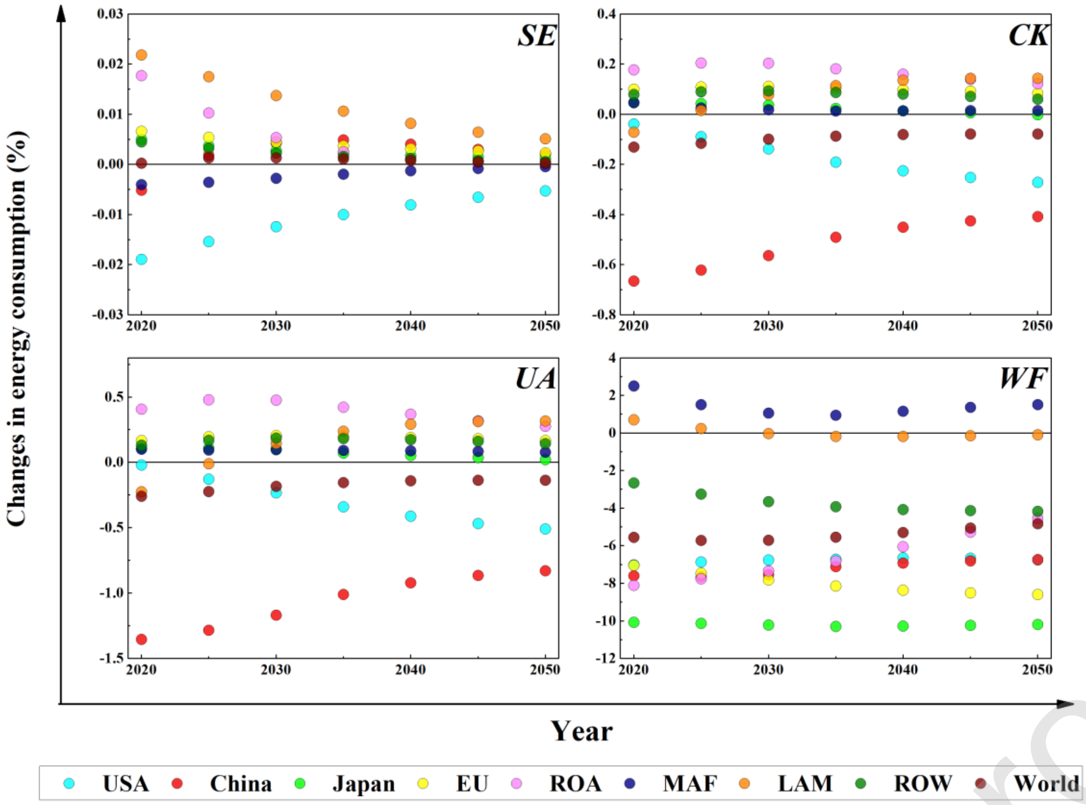

Fig. 5. The impacts of trade friction on energy consumption under different post-2019 scenarios in the long-run.

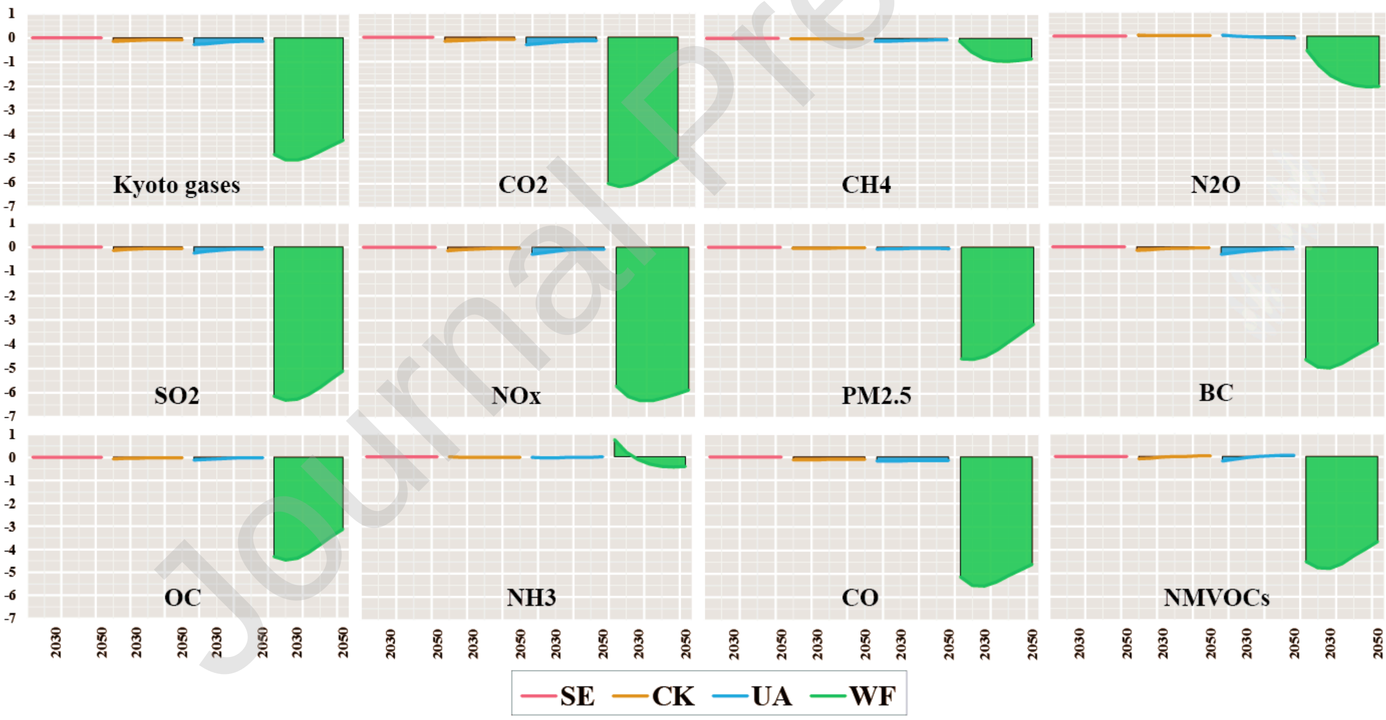

Fig. 6. The impacts of trade friction on greenhouse gas and air pollutant emissions at the global level under different post-2019 scenarios in the long-run. The regional results of environmental emissions are shown in Supplementary material 14.

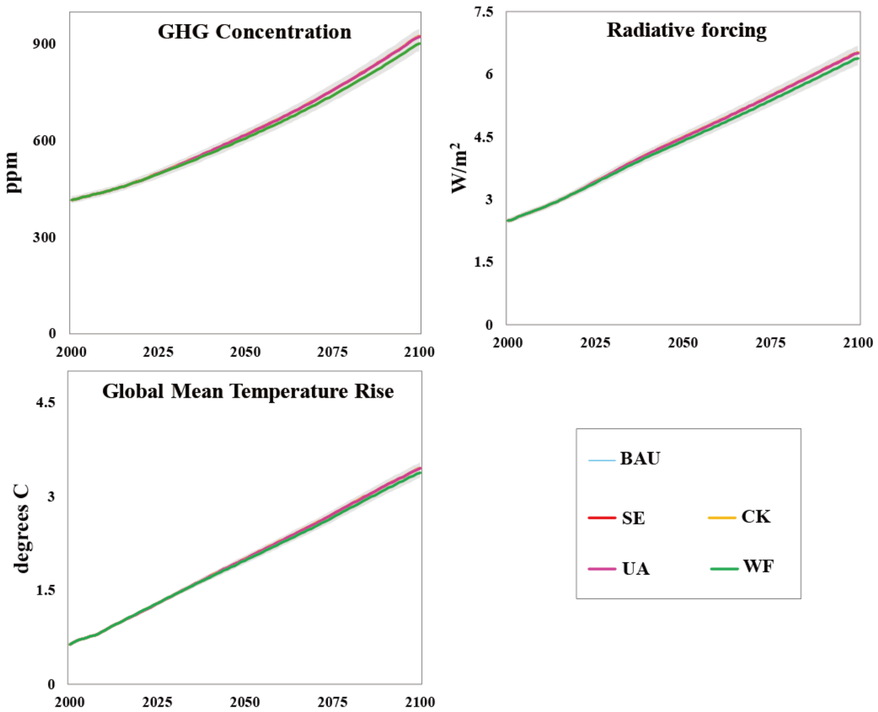

Fig. 7. The impacts of trade friction on climate change under different post-2019 scenarios in the long-run.

Table 1. Reference and policy scenarios

Scenarios		**Description**
Baseline	***BAU*** (Reference scenario)	Following the middle development path in SSP2, and no further trade policy constraints are imposed.
Ex-post assessment	***R1*** (Round 1)	The US imposed an import tariff of 25% on Chinese steel products and 10% on aluminium products; China imposed tariffs of 15% on 120 items such as fruits and their products from the US and 25% on eight items such as pork and its products from the US.
	R2 (Round 2)	Based on R1, the US imposed an import tariff of 25% on 818 products worth $34 billion to China; China imposed tariffs of 25% on 545 US agricultural products, automobiles and aquatic products worth $34 billion.
	R3 (Round 3)	Based on R2, the US imposed 25% import duties on 279 products worth $16 billion to China; China has imposed tariffs of 25% on 114 US products worth $16 billion, including chemicals, medical equipment and energy products.
	R4 (Round 4)	Based on R3, the US imposed an import tariff of 10% on 5,745 products with a value of about $200 billion on China; China imposed tariffs of 10% or 5% on 5,207 items worth $60 billion to the US.
	R5 (Round 5)	The US increased the import tariffs from 10% to 25% for above products worth $200 billion, and impose tariffs of 10% on additional products worth $300 billion on China; China increased tariffs on above $60 billion to 25%, 20%, 10% or 5%.
	R6 (Round 6)	The US increased the import tariffs from 25% to 30% for above products worth $200 billion, and from 10% to 15% for above products worth $300 billion; China imposed tariffs of 10% or 5% on 4341 items.
Ex-ante simulation	***SE*** (Stop and Ease)	China and the US stop and ease current trade disputes and restore original import tariffs in BAU.
	CK (Continue and Keep)	China and the US continue to a keep current import tariffs after six rounds imposition.

UA (Upgrade and Aggravate)	The trade conflict will escalate and aggravate. According to Trump's prior claim, the US will impose 100% import tariff on all products to China.
WF (World Fragment)	The world will fragment with stronger trade conflict. That is, based on UA, China and the US impose 100% import tariffs on each other; simultaneously, the other regions impose 30% import tariffs on all products to other regions.

Table 2. Emission change and its sources in terms of scale, composition and technique effects.

	USA				**China**				**Japan**				**EU**			
	EC	SE	CE	TE	EC	SE	CE	TE	EC	SE	CE	TE	EC	SE	CE	TE
CO_2	-0.02	-0.04	0.04	-0.02	-0.68	-0.22	-0.27	-0.19	0.06	0.01	0.01	0.04	0.12	0.01	0.07	0.04
CH_4	-0.32	-0.04	-0.27	-0.02	0.09	-0.22	0.34	-0.03	-0.05	0.01	-0.07	0.01	0.03	0.01	0.02	0.00
N_2O	-1.23	-0.04	-1.19	0.00	0.70	-0.22	0.94	-0.02	-0.21	0.01	-0.24	0.02	-0.07	0.01	-0.08	0.00
SO_2	-0.16	-0.04	-0.09	-0.04	-0.64	-0.22	-0.15	-0.27	0.10	0.01	-0.01	0.10	0.15	0.01	0.05	0.09
NOx	-0.23	-0.04	-0.13	-0.07	-0.74	-0.22	-0.12	-0.40	0.06	0.01	-0.01	0.06	0.10	0.01	0.03	0.06
$PM_{2.5}$	-0.98	-0.04	-0.90	-0.04	-0.44	-0.22	-0.08	-0.13	-0.01	0.01	-0.05	0.03	0.04	0.01	0.01	0.03
BC	-0.45	-0.04	-0.42	0.00	-0.71	-0.22	-0.07	-0.41	0.02	0.01	-0.01	0.03	0.08	0.01	0.04	0.03
OC	-0.36	-0.04	-0.26	-0.07	-0.65	-0.22	-0.22	-0.20	0.00	0.01	-0.03	0.03	0.11	0.01	0.03	0.07
CO	-0.60	-0.04	-0.56	-0.01	-0.49	-0.22	0.04	-0.30	0.05	0.01	0.00	0.04	0.05	0.01	0.02	0.03
NMVOCs	0.08	-0.04	0.12	0.00	-0.73	-0.22	-0.11	-0.39	0.05	0.01	0.03	0.00	0.12	0.01	0.11	0.00
NH_3	-1.76	-0.04	-1.72	0.00	0.50	-0.22	0.72	0.00	-0.19	0.01	-0.20	0.00	0.01	0.01	0.00	0.00
	ROA				**MAF**				**LAM**				**ROW**			
	EC	SE	CE	TE	EC	SE	CE	TE	EC	SE	CE	TE	EC	SE	CE	TE
CO_2	0.17	0.09	-0.01	0.10	0.05	0.00	0.05	0.00	-0.10	0.04	-0.21	0.07	0.01	0.02	-0.02	0.01
CH_4	-0.09	0.09	-0.19	0.00	0.05	0.00	0.06	0.00	-0.04	0.04	-0.08	0.01	-0.02	0.02	-0.05	0.00
N_2O	-0.16	0.09	-0.26	0.00	0.00	0.00	0.00	0.00	0.40	0.04	0.36	0.00	-0.10	0.02	-0.13	0.00
SO_2	0.22	0.09	-0.02	0.15	0.02	0.00	0.02	0.01	0.19	0.04	-0.11	0.26	0.13	0.02	0.05	0.06
NOx	0.09	0.09	-0.09	0.08	0.02	0.00	0.02	0.00	0.16	0.04	-0.11	0.23	0.10	0.02	0.04	0.04
$PM_{2.5}$	0.20	0.09	-0.03	0.14	0.00	0.00	-0.01	0.01	0.03	0.04	-0.10	0.10	0.05	0.02	-0.02	0.05
BC	0.07	0.09	-0.08	0.07	0.04	0.00	0.04	0.00	0.18	0.04	-0.08	0.22	0.08	0.02	0.04	0.03
OC	0.18	0.09	-0.04	0.14	0.00	0.00	0.00	0.01	0.10	0.04	-0.12	0.18	0.10	0.02	0.02	0.05
CO	0.11	0.09	-0.10	0.12	0.03	0.00	0.03	0.00	0.14	0.04	-0.14	0.23	0.11	0.02	0.05	0.04
NMVOCs	0.07	0.09	-0.06	0.04	0.06	0.00	0.07	0.00	-0.16	0.04	-0.22	0.03	0.07	0.02	0.04	0.01
NH_3	-0.09	0.09	-0.18	0.00	0.05	0.00	0.05	0.00	-0.01	0.04	-0.04	0.00	0.01	0.02	-0.01	0.00

Note: "EC" indicates Emission Change (%); "SE" indicates Scale Effects (%); "CE" indicates Composition Effects (%); TE indicates Technique Effects (%)