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SHORT COMMUNICATION

Supply chain disruptions would increase agricultural greenhouse gas emissions

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Abstract
We investigate the impacts of a global crisis to trade systems such as the Russia-Ukraine war on agricultural emissions, using two emissions accounting approaches: (1) the production-based approach, which only accounts for domestic emissions, and (2) the trade-adjustment approach, which considers imports and exports when calculating emissions. We find that global emissions can substantially increase in the crisis scenario. The relative degree of change, however, varies between the two approaches. At the country level, the largest increases are found in several import-dependent countries. Reasons are likely two-fold: (1) high dependence of certain countries on food imports from Russia and Ukraine, and (2) higher emission intensities (i.e., amount of emissions per unit of product) of imported food items relative to emission intensities in Russia and Ukraine. Very few countries show lower emissions in the crisis scenario. Our results thus highlight the urgent need for countries to lower domestic agricultural emission intensities to avoid negative repercussions on their domestic emissions while increasing agricultural production. Concurrently, our findings underscore the benefits of an emissions accounting process that considers trade flows. By reforming food systems and adopting a trade-adjustment approach in emissions accounting, food systems can contribute towards effective climate mitigation as well as become more resilient to global shocks.

Keywords Trade · emissions accounting · food systems · agriculture · global shocks

Introduction

The devastating impacts of climate change across the world, from the floods in Pakistan to the droughts across East Africa, are a stark reminder of the urgent need for the global community to address the climate crisis. One area where climate action needs to be prioritised is the food system. Emissions from the food system contribute 21–37% of global anthropogenic greenhouse gas (GHG) emissions, or 10.8–19.1 $GtCO_2e$/yr, during 2007–2016 (Rosenzweig et al. 2020). Moreover, food production emission intensities vary strongly between countries. Since a large share of the world's food is internationally traded, global as well as national GHG emissions are highly susceptible to trade patterns. For example, almost a third of the world's wheat was traded in 2020 (FAO 2023).

Supply chain disruptions due to climate extremes and armed conflicts could severely change existing trade patterns. For example, the Russia-Ukraine war, which began in February 2022, has led to major disruptions in agricultural trade and compromised food security (Mottaleb et al. 2022). Both Russia and Ukraine are critical global agricultural exporters, most notably of grains and oilseed crops.

In light of recent food supply disruptions with Russia and Ukraine largely dropping out as agricultural and food traders, we aim to assess how a global shock can affect agricultural emissions. Global shocks can have indirect consequences to food-related emissions, through its impacts on the

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prices of agricultural input and food. For example, higher input costs could reduce agricultural land use intensification and drive up agricultural land expansion and carbon stock losses (Alexander et al. 2023).

Specifically, we explore the impacts by using and comparing two emissions accounting approaches: (1) the production-based emissions (PBE) approach, and (2) the trade-adjusted emissions (TAE) approach. The PBE approach is the conventional approach towards emissions accounting based on the Intergovernmental Panel on Climate Change (IPCC) frameworks, which only account for emissions produced within a country's borders. The TAE approach, proposed by Foong et al. (2022), adjusts domestic emissions with trade flows (i.e., imports and exports) and thus considers consumption as driver of emissions. Since the Russia-Ukraine war is ongoing and real trade data is not yet available, we investigate the impacts by applying a simulation approach. Based on data from the Food and Agriculture Organization Statistical Database (FAOSTAT), we readjust trade flows to and from Russia and Ukraine, and compare the new emissions under the two budgeting approaches with a 'business-as-usual' situation. For estimating TAE, we apply the approach described in Foong et al. (2022). The objectives of this exemplary simulation study are threefold: (1) understanding the effects of disruptions in agricultural and food supply chains on global GHG emissions, (2) understanding the respective implications on the two alternative national emissions accounting approaches, and (3) deriving recommendations on how countries can reduce their exposure to risks for their national emissions budgets due to supply chain disruptions.

Materials and methods

We use data on agricultural production, trade and emissions for 2015-2017 available from FAOSTAT. We calculate PBEs and TAEs for the average year 2016 for both a 'business-as-usual' scenario and a 'crisis' scenario. We then compare the results of both approaches between the two scenarios. TAEs are calculated as shown in Equation (1):

$$TAE = PBE + Import\ emissions - Export\ emissions \quad (1)$$

Data processing and calculations are made using the same approach as in Foong et al. (2022).

For the crisis scenario, we make the following changes to the approach used by Foong et al. (2022):

- **Emission intensities**: We recalculate regional and global emission intensities for all food groups, in light of our exclusion of agricultural production from Russia and Ukraine. Emission intensities are the total amount of greenhouse gas emissions generated within the farm gate that is associated with the production of one unit of commodity (FAO 2019a). Specifically, we exclude the agricultural emissions of Russia and Ukraine when calculating the emission intensities for each food group.
- **Trade flows with Russia**: We set all agricultural and food trade flows from and to Russia to zero. The assumption is that all other countries have imposed trade bans and economic sanctions on Russia, although we acknowledge that this is not the case for all countries. For example, the current set of economic and trade sanctions have mostly been imposed by the United States, the European Union and several other high-income countries (Ruta 2022). However, we consider the assumption because the war is still ongoing, and its severity remains uncertain.
- **Trade flows with Ukraine**: We set all trade flows from Ukraine to zero. The assumption is that the war has disrupted the country's infrastructure for agricultural production, transport and trade, thus impeding trade outflows from the country (UNCTAD 2022). While Russia and Ukraine have signed agreements to resume exports of grains and fertilisers since the outbreak of the war (Hayatsever and Nichols 2023), we maintain the assumption as the war and its trade implications remain uncertain.
- **Agricultural production replacements**: With no imports from Russia and Ukraine, all other countries would need to replace Russian and Ukrainian imports with domestic production or trade from other food-producing countries. We therefore replace Russian and Ukrainian imports with exports previously headed to Russia. For the remainder of the replacements, we replace imports with domestic production if a country is an agricultural producer of that food item. If a country is not a producer of a food item, we replace Russian and Ukrainian imports with imports from the country's region. In other words, we assume that a non-producer country imports from another country within the same region.

One key assumption of our simulation is that we exclude any behavioural change among other food-exporting countries due to both the war and any effects caused by associated food price changes. We argue that behavioural and price changes are secondary effects of the war and depend on the specific shock considered. As our study's primary aim is to investigate the war's first-level effect, i.e., on trade-adjusted emissions, we argue that the secondary effects would not affect our study's general findings.

Results

Using both the PBE and TAE approaches, we find that global emissions are substantially higher under the crisis scenario than the business-as-usual scenario. The higher emissions under the crisis scenario are because of the switch to domestic production for certain countries with more emission-intensive production systems.

Moreover, we find that the relative increase in global emissions in the crisis scenario is especially higher under the PBE approach than the TAE approach. In PBE terms, the increase is 1.5%, or 74.4 $MtCO_2e$. In TAE terms, the increase is 1.3%, or 63.6 $MtCO_2e$. Theoretically, at the global level, both the PBE and TAE approaches should have the same values. The differences can be explained by inconsistencies in export-import figures in the FAOSTAT trade datasets. The inconsistencies can arise, for example, when partner countries record a commodity under different names, or if reporting countries record a different place of origin or destination for a commodity, leading to partner country mismatches (FAO 2019b).

Several countries that are major importing partners with Russia and Ukraine have some of the largest increases in PBE and TAE in the crisis scenario (Fig 1). It is especially the case for several countries in the Middle East and North Africa (MENA), a region where high import dependence has been associated with domestic food insecurity and political instability (Mbow et al. 2019). For example, Egypt, Libya and Saudi Arabia have a 12.9%, 25.7% and 26% increase in PBEs, respectively (equivalent to 3.44 $MtCO_2e$, 0.64 $MtCO_2e$ and 1.43 $MtCO_2e$). In terms of TAE, the increases are 4.6%, 9.8% and 4.5%, respectively (equivalent to 1.95 $MtCO_2e$, 0.4 $MtCO_2e$ and 0.94 $MtCO_2e$). Possible reasons are two-fold. First, all three countries highly depend on Russian and Ukrainian cereal imports. According to FAOSTAT trade figures, 13.8%, 27.8% and 12.4% of their cereal supply in 2016 were derived from both countries. Second, these countries have emission intensities for cereals that are approximately three times higher than in Russia and Ukraine.

Besides the MENA region, other importing regions also exhibit large increases in emissions. Notable cases include Georgia and Norway, where the percentage increases in PBEs under the crisis scenario are 25.3% and 17%, respectively (equivalent to 0.54 $MtCO_2e$ and 0.82 $MtCO_2e$). In terms of TAE, the increases are 17.8% and 13%, respectively (equivalent to 0.43 $MtCO_2e$ and 7.8 $MtCO_2e$). The reasons are likely also two-fold. Both countries are major importers of Russian and Ukrainian oilseed crops such as rapeseed and sunflower. At the same time, their emission intensities for the food group 'others' (of which these products fall under) range between 2 to 20 times higher than in Russia and Ukraine.

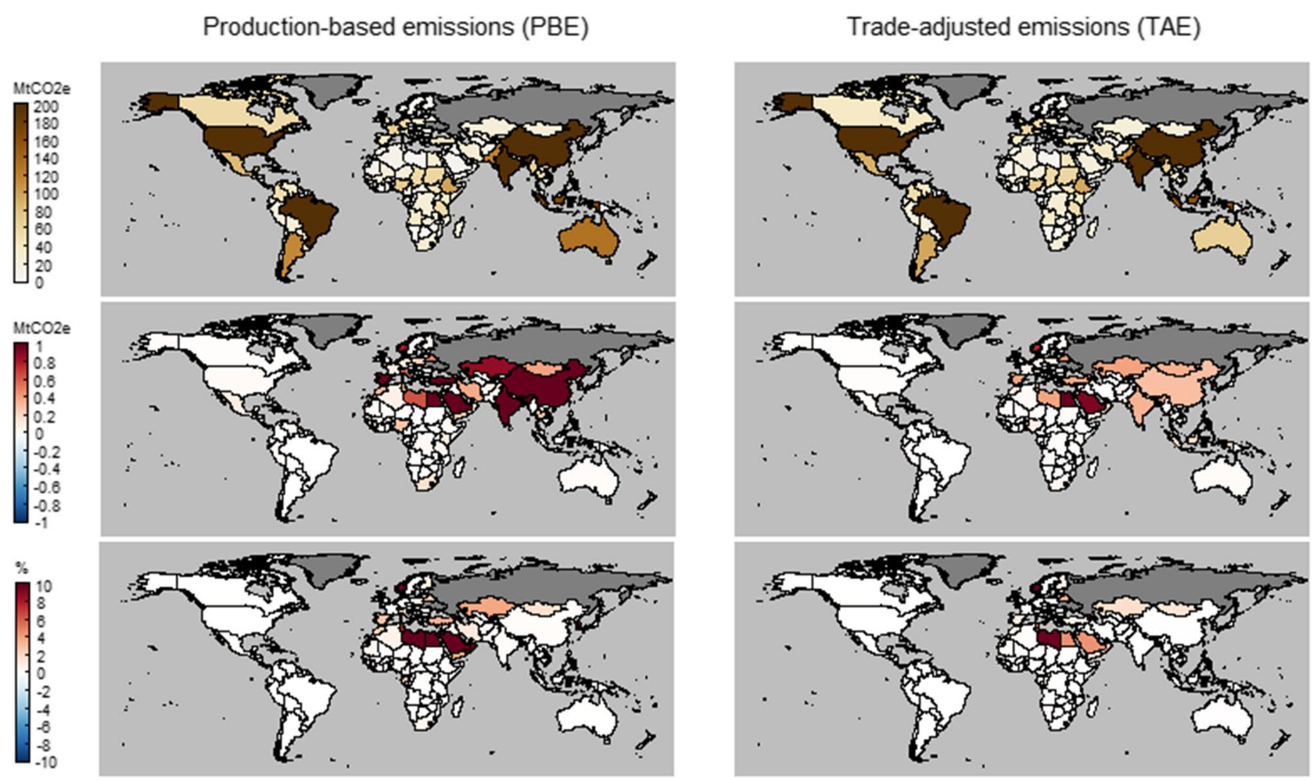

Fig. 1 Estimated production-based emissions (PBE) and trade-adjusted emissions (TAE) under the crisis scenario for the mean year 2016 (top row). Differences in PBEs and TAEs between the crisis scenario and business-as-usual scenario are shown in MtCO2e (middle row), and in percentage terms (bottom row). Red colours indicate larger PBEs and TAEs under the crisis scenario, while blue colours indicate lower PBEs and TAEs under the crisis scenario

Out of the 203 countries analysed in this study, only 16 countries show lower TAEs in the crisis scenario. Furthermore, the percentage changes are small. The largest decrease is in Syria, where the reduction in TAE is 0.2%, or 0.014 $MtCO_2e$. It is likely because of two reasons. Syria's emission intensities for cereals (0.12 $kgCO_2e/kg$) are lower than in Russia and Ukraine (>0.13 $kgCO_2e/kg$). Moreover, almost half of Syria's cereal imports are derived from both countries.

Interestingly, when comparing the differences between the two emissions accounting approaches (i.e., between PBE and TAE), there is a reverse in the sign of the differences for some countries when looking at the crisis scenario. It is particularly the case for Kazakhstan, Spain and Türkiye. Under the business-as-usual scenario, TAEs are higher than PBEs for the three countries. However, under the crisis scenario, PBEs become higher than TAEs. Again, the reasons are likely due to the relatively higher emission intensities of certain food items in the three countries compared to those in Russia and Ukraine. For example, more than a quarter of Türkiye's imported cereals are derived from Russia. At the same time, Türkiye's emission intensity of cereals (0.26 $kgCO_2e/kg$) is larger than in Russia (0.13 $kgCO_2e/kg$). As Türkiye has to increase domestic cereal production with the cessation of Russian imports, Türkiye's PBE exceeds that of its TAE under the crisis scenario.

Discussion

Our study shows that disruptions in agricultural and food supply chains such as the Russia-Ukraine war would lead to a substantial increase in global agricultural emissions. To avoid such undesired side effects of regional conflicts on domestic and global emissions, our study's findings thus highlight the need for countries to keep their domestic agricultural emission intensities low. We have seen, for example, how having higher emission intensities for heavily traded agricultural products (e.g., grains and oilseeds) compared to the emission intensities of the exporting partner countries (in this case, Russia and Ukraine) can increase a country's trade-adjusted agricultural emissions by more than 25% in the event of a global shock.

Conversely, for countries with lower emission intensities than in the crisis countries, we observe that their overall trade-adjusted agricultural emissions are lower under the crisis scenario. In other words, countries with low emission intensities can avoid increasing their domestic agricultural emissions in a global shock. However, as we have seen in our analysis, such cases are few given the specific food groups considered. Therefore, food systems need to be readjusted to more sustainable and resilient structures worldwide.

In light of our findings, what actions can countries take to avert a global food system emission spike when a global shock strikes? An obvious first step would be to lower domestic agricultural emissions, for example, by adopting agricultural technologies that reduce emissions and improve soil carbon storage (Northrup et al. 2021). Technological changes could include, for example, improvements in agricultural yields to reduce the need for cropland expansion, and changes in irrigation, cropping, and fertilisation methods as well as in manure management (Springmann et al. 2018; Billen et al. 2021). Additionally, there is scope for countries to lower emissions in other parts of the food supply chain, such as transport and food loss and waste (Porter et al. 2016; Pradhan et al. 2020). At the broader level, efforts should also seek to transform food systems towards a more needs-based system, combined with more equitable income distribution and carbon pricing strategies to make food systems carbon neutral (Bodirsky et al. 2022).

Countries should also consider substituting domestic food consumption with other similar food types with lower emission intensities. Substitutions in food consumption could include, for example, replacing high red meat intake with less emission-intensive meats and more plant-based food items. In the context of the Russia-Ukraine war, dietary changes can also help strengthen the resilience of food supply systems from global shocks by, for instance, reducing the demand for grains needed for animal feed (Sun et al. 2022). In addition, dietary changes from highly emission-intensive food items could offer a number of health benefits (Tukker et al. 2011; Bodirsky et al. 2019).

To keep track on changes in domestic emissions, trading partners should also adopt a trade-adjustment approach. The approach presents a number of benefits. First, a trade-adjustment approach takes into consideration both trade flows and relative emission intensities, which enables countries to more accurately track changes in emissions embodied in the food trade (Foong et al. 2022). As we have seen in the examples of Kazakhstan, Spain and Türkiye, the trade-adjustment approach produces noticeably different patterns of calculated emissions relative to the production-based approach, when estimating the effects of trade disruptions.

Second, the trade-adjustment approach follows the bilateral trade input-output (BTIO) method, which is suited for analysing bilateral political agreements and trade and climate policies. By following the BTIO method, the trade-adjustment approach is therefore helpful in informing climate and trade policymaking (Peters 2008).

By showing how domestic agricultural emissions can increase with trade disruptions, our study highlights the urgent need for countries to implement sustainable food system reforms to reduce domestic emissions. To calculate emissions, countries need to incorporate trade flows into their respective emissions accounting processes. Trade considerations are particularly important as trade is, and is likely to remain, an important means for many countries to access food and essential nutrients. By transforming food systems and ensuring that emissions embodied in trade are adequately considered, food systems can become not only an important driving force towards effective climate mitigation, but also a sector that is resilient to major global changes.

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