We would like to thank the reviewers and the editor for their helpful and constructive comments on the manuscript “Food trade disruption after global catastrophes ”.

We found all of the feedback to be useful in improving and sharpening the research. We have now updated the manuscript to address the comments. We believe it has been significantly strengthened and is now suitable for publication. Below we have listed the reviewer and editor comments in black, along with our responses in light green. Text that has been added to the manuscript is in *italics and darker green*.

Reviewer #1 (Nick Wilson)

This study appears to be a very valuable addition to the literature. The topic is particularly important as the risk of nuclear war may be increasing with ongoing deterioration in international relations between nuclear weapon states. Also recent evidence suggests that events such as major solar storms might be more likely than previous thought [1]. The methods of this study seem appropriate and the results make good sense.

We thank the reviewer for their very positive assessment of our paper.

Some specific issues the authors could consider:

1. In the Introduction – references such as (Barrett et al., 2013) are perhaps somewhat outdated. Consider including findings from a recent major forecasting exercise: [2].

Changed as proposed.

2. The modelling is done on spring wheat which is reasonable as it is more common globally than winter wheat. But a limitation that could be noted is that in ASRS conditions many producer countries could switch to winter wheat which would be more resistant to adverse ASRS impacts (such as cooler temperatures and frosts). It is also usually more productive than spring wheat, eg, for 2023 USDA data: Average winter wheat yields were around 50-55 bushels/acre, compared to spring wheat’s 40-45 bushels/acre.

Added the following to the study limitations to address this:

The modeling of Xia et al. (2022), which we use to calculate yield reductions during a nuclear war, assumes the usage of spring wheat. However, during an ASRS, wheat producers could switch to winter wheat, which is more resistant to cooler temperatures and frost and generally has slightly higher yields than spring wheat. Therefore, the wheat yields in this study are potentially underestimated.

3. For a while I was wondering why in the ASRS scenario India and Pakistan still appeared to be involved in the food trade system (given the ASRS scenario involved them in a nuclear war). Then I saw the subsequent results where the modelling removed them. So perhaps explain earlier

in the text that the initial results did not include direct nuclear war-related impacts on the nuclear waring nations.

Added the following to section 3.1.1 to clarify this:

For this part of the analysis, we assume that all countries still participate in trade, even if they were involved in a nuclear exchange in the ASRS scenario. We separately look at the impacts of a complete removal of countries from the trade network in section 3.3.1.

4. The Discussion could consider stating that building country-level food system resiliency and reducing food trade dependence could be partly achieved by greater adoption of plant-based diets and with consumption of locally-produced fruits/vegetables/legumes (rather than imported grains). This is partly because much of the traded grain imported into some countries (especially soya beans, maize) is currently inefficiently used for animal feed (ie, inefficient from the perspective of food energy supplied to humans per energy inputs).

We agree that this could improve resilience under some circumstances, but also want to highlight that this could reduce the overall amount of food produced globally and thus the slack in the system in case of ASRS or GCIL. To address both of these points, we added the following to section 4.1:

Shifting dietary patterns could also help decrease vulnerability to trade disruptions. A move toward plant-based diets with more locally-produced fruits, vegetables, and legumes could reduce dependence on international grain trade, as much of the currently traded grain (especially soya beans and maize) is used for animal feed rather than direct human consumption. This conversion of grain to animal products is inefficient from an energy perspective. However, this strategy presents a trade-off: while reducing animal feed imports would decrease trade dependencies, it might also reduce the system's overall flexibility. Current livestock systems, despite their inefficiencies, create a buffer by maintaining large stores of grain that could be redirected to human consumption during crises. Additionally, ruminants can digest cellulose that humans cannot, potentially providing an additional food source during catastrophes. Therefore, while dietary shifts toward plant-based foods could improve local food security under normal conditions, maintaining some animal agriculture may provide valuable system redundancy for extreme scenarios. The optimal balance likely varies by region based on local agricultural conditions and trade relationships.

5. The Discussion could consider stating that building country-level food system resiliency and reducing food trade dependence could also be improved by reducing wasteful use of agricultural land that occurs at present eg, growing crops for biofuel (where this is heavily subsidized and where adopting electric vehicles is far more efficient), and growing crops that are a hazard to health (eg, tobacco). The need to reduce the relatively high levels of food waste in many countries is also a potentially very cost-effective way to build food system resiliency.

As with the change to plant-based diets, a reduction in food waste and phasing out of biofuels could result in a mixed impact on resilience in the food system. To address this, we added the following to section 4.1:

Similarly, more strategic use of agricultural land could enhance resilience. Currently, significant agricultural capacity is devoted to non-food purposes – particularly biofuel production and crops like tobacco. While biofuel crops are often heavily subsidized, transitioning to electric vehicles would be more energy efficient and free up land for food production. The land used for tobacco cultivation could be repurposed for food crops, providing dual benefits of improved food security and public health. Additionally, reducing food waste, which accounts for approximately one-third of food production in many developed countries, represents a readily available opportunity to build resilience (Alexander et al., 2017). However, as with dietary shifts, these changes present trade-offs. Some biofuel infrastructure could potentially be repurposed to produce food during crises, similar to how breweries can be converted to produce sugar from cellulose (Throup et al., 2022). Moreover, maintaining diverse agricultural systems and processing capabilities, even for non-food crops, helps preserve farming knowledge and infrastructure that could be valuable during catastrophes. The key is finding a balance between efficient land use under normal conditions and maintaining adaptable agricultural systems that can respond to major disruptions.

6. The Discussion could note that although the Xia et al 2022 modelling was very sophisticated – it still had various limitations eg, it did not consider nuclear war impacts on: supply of irrigated water, surface ozone levels, on ultraviolet light damage to agriculture, and “the availability of pollinators, killing frost….”

We added this to our research gaps section, extending another comment around cascading and systemic risk:

There exists some research that acknowledges the potential cascading effects and systemic risk of an ASRS, like nuclear war, for instance, recent summaries by Green (2024) or Glomseth (2024), but for many of the events that could cause GCIL, we know only very little about the potential cascading effects. Beyond this, even sophisticated modeling efforts like Xia et al. (2022) have limitations - they did not account for several factors that could further impact agriculture after nuclear war, such as changes in irrigation water availability, increased surface ozone levels, ultraviolet light damage, effects on pollinators, and killing frost risk. For many of the events that could cause GCIL, we know even less about the potential cascading effects and systemic risks.

Trivial points

1. Add an open bracket “(” before: Bernard de Raymond et al., 2021)
2. Improve wording of the sentence: “Likely because of its less…”
3. Where “teragrams” is first used – could say this is “equivalent to megatonnes” as the latter is probably a bit more understandable to most readers.
4. Fix typo: “Southern Hemisphere.although”

All changed as proposed.

Reviewer #2 (Kilian Kuhla)

Summary

The authors compute adapted grain trade networks using national yield changes under two scenarios (nuclear fall and major infrastructure loss) and analyze these resulting static networks for wheat, rice, maize, and soybean. They put substantial effort into comparing these networks using a range of metrics.

General comment I thank the authors for their work in this important research field. While reading this comprehensive study, several points arose that, in my view, require further clarification or revision.

Main points

I. The central element driving the results is the network model introduced by Hedlund et al. (2022). However, the main text offers no insights into how or why trade connections shift, which hinders interpretation and undermines confidence in the findings. Even after consulting the supplement and the Hedlund et al. paper, it remains unclear how trade changes are modeled—it appears to rely on a gravity model of trade. The authors should explain the main methodology and the points below:

Have the authors verified that a gravity model can reproduce observed trade networks (e.g., from FAO data)?

How strongly do historical trade patterns influence the gravity-modeled network?

These limitations should be explicitly addressed in the discussion.

We appreciate this comment and use the opportunity to improve our model description in sections 2.1 and 2.3.

Importantly, we do not use a gravity model of trade in the paper. A gravity model is implemented in pytradeshifts, but was not used for our study here. We describe this in the supplement, so potentially interested researchers are aware of this capability of our model and can use it if they wish to do so. Our model instead is a graph/network. In this network, each country isa node and the trade (after removing the re-exports) is the weight of the connection between countries. This means that our analysis is a weighted network analysis, where we only change the weight of the inter-country-connections by the amount of yield reductions. No additional connections are introduced, and no connections are removed unless the yield reduction is 100%. This removes the link. Our community analysis compares which countries cluster together before and after the change of the weights. We have extended our explanations of how the model is constructed in sections 2.1 as follows:

The model we used was introduced by Hedlund et al., (2022); for the present analysis, we have re-implemented it in Python (Jehn and Gajewski, 2024) (https://github.com/allfed/pytradeshifts). The global trade network is described as a weighted directed graph with the countries as nodes and trade volumes between two countries as the weight of the edges connecting the nodes. In the model, we accounted for re-exports to represent point-of-origin-to-point-of-destination trade movements, meaning that the resulting data only contain the direct trade between countries without intermediaries (more information about this is in the Section 2.2 of the supplement and in Hedlund et al. (2022)). The model determines post-catastrophe trade by applying country-specific yield changes directly to export volumes. For example, if a country experiences a 30% yield reduction, all its exports decrease proportionally – by 30%. We do not introduce new connections, though trade connections can become 0 if the yield is reduced by 100%. Compared to the original model, we have added the option to remove countries from the analysis to simulate an overall inability to take part in trade (e.g. due to destruction after a nuclear war). Other additional functionality is described in the Supplement (Section 1).

II. Similarly, further detail on the Louvain algorithm is needed. Since this method underpins the community analysis that drives many key findings, a brief explanation would aid interpretation.

We have added an explanation of the algorithm to section 2.1:

The Louvain algorithm identifies communities by optimizing modularity, which measures the density of connections within communities versus connections between communities. The algorithm works iteratively:

1. *It assigns each country to its own community*
2. *For each country, it evaluates whether moving it to a neighbor's community would increase modularity*
3. *After all possible improvements, it aggregates each community into a single node*
4. *It repeats the process until modularity cannot be further improved*

This approach allows us to detect natural trading blocs based on connection patterns without imposing geographical constraints.

III. Focusing solely on yield changes (e. g., Fig. 1) to explain trade shifts overlooks the role of total (national) production. A 100% yield loss in a major producer has greater impact than in a minor one. Consider including crop production figures or a map showing regional yield or production changes (even in the supplement).

The impact of larger producers is already reflected in our analysis as follows: The trade communities are determined by how much of the absolute trade remains between countries after the relative yield changes have been applied. Similarly, the relative import reduction we show is also based on the absolute import numbers before and after applying the yield changes.

To further make the absolute remaining production clearer, we also added two additional figures to the supplement, which show the absolute wheat production in both scenarios and describe them in section 3.1.3:

The impact to the trade network is also visible when examining remaining wheat production (Figure S5, S6). The scenarios differ markedly. The GCIL scenario (Figure S5) preserves more wheat production, particularly in Russia, where farming depends less on fertilizer than in Central Europe or the US. However, in ASRS, Russian production drops severely as lower temperatures make wheat growing nearly impossible. Australia, a major wheat exporter, continues production but at reduced levels. India produces the most wheat in ASRS, but primarily grows it for domestic use and may not become a major exporter.

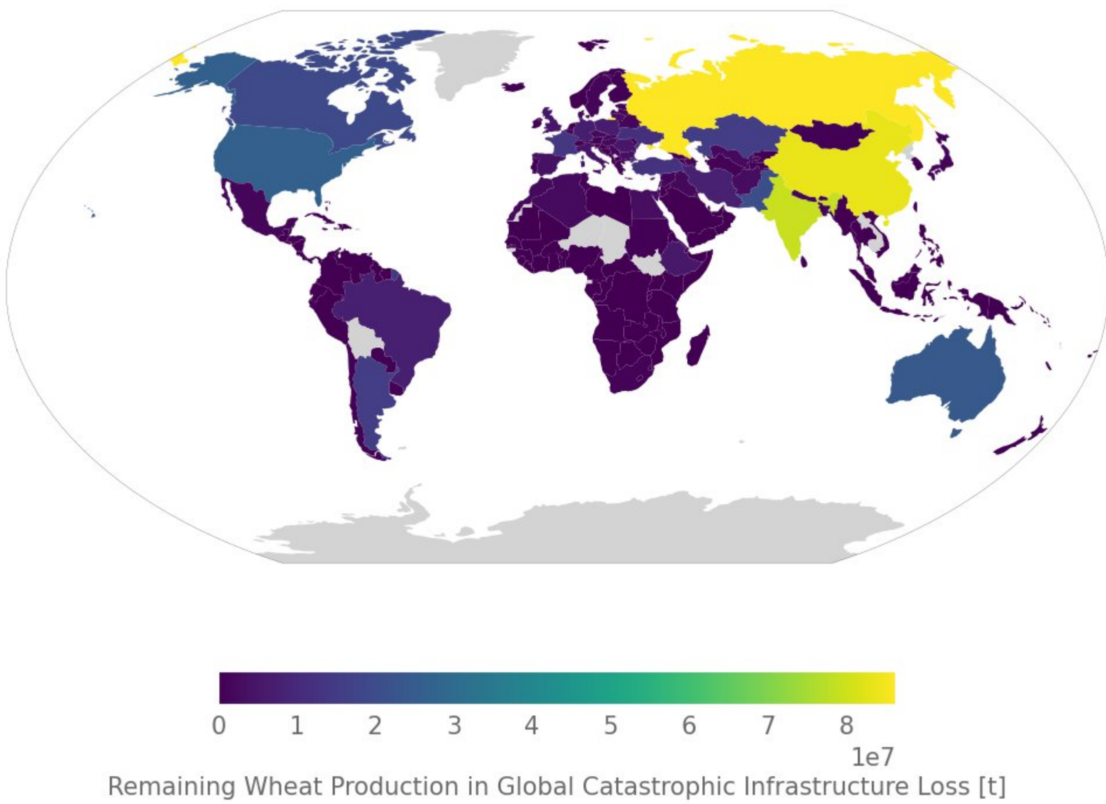

Figure S5: Remaining wheat production after global catastrophic infrastructure loss (in tonnes per year).

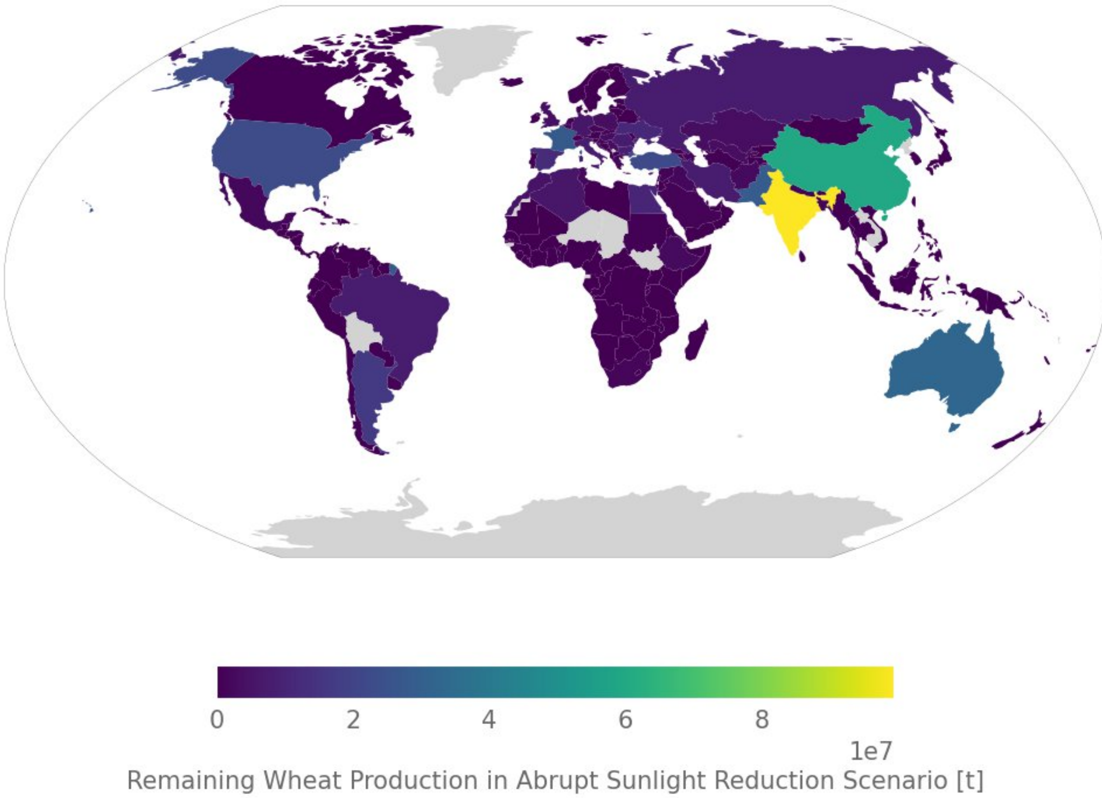

Figure S6: Remaining wheat production in an abrupt sunlight reduction scenario (in tonnes per year).

IV. Yield reductions under GCIL: It is unclear why the authors did not use productivity-weighted yield changes, as in Moersdorf et al. They say yield changes from GCIL should be comparable those from ASRS, but the scenarios are not directly comparable due to the much wider yield change range under ASRS—this should be clarified.

There are differences between the two scenarios, but we wanted to make sure that they are as comparable as possible. Therefore, we decided not to apply a productivity weighting to the GCIL data, as the ASRS data is also not productivity weighted. Also, as the weights between countries in our model are based on the actual amount traded (corrected for re-exports), using yield changes which had been previously weighted by productivity would skew the results in unexpected ways. To explain this better, we rephrased the second half of the first paragraph in section 2.3:

The resulting mean values of yield reduction differ slightly from the ones stated in Moersdorf et al. (2024) because: 1) Moersdorf et al., assigned weights using pre-catastrophe productivity, but as the nuclear war data is not productivity weighted, we used Moersdorf et al's unweighted data to ensure comparability between the two scenarios. The wider yield change distribution under ASRS compared to GCIL thus reflects genuine scenario differences rather than methodological artifacts. 2) In our model, the connections between countries are based on the actual amount traded (corrected for re-exports). Weighting the yield changes by their productivity would thus skew the results.

Comments on figures

a) Figures 5 and 7: “Import relative difference” vs. “Imports relative difference” should be consistent.

Changed as proposed.

b) Figure 5: Since positive changes also occur (see Fig. 7), the color scale should reflect values above 0%.

Changed as proposed.

c) Figure 6 appears to be missing.

Figure 6 is not missing, but all figures following Figure 5 had been mislabeled in their count. This is fixed now.

Minor points

Graphical abstract: Avoid non-standard abbreviations (ASRS, GCIL).

Changed as proposed.

Line 125: “We excluded bilateral trade flows falling below the 75th percentile in trade volume to concentrate on the main trade movements”—how sensitive are results to this threshold?

The results change very little when different percentiles are used. Testing at the 50th or 90th percentiles yielded similar outcomes to those in the manuscript. We chose this specific percentile to match Hedlund et al. (2022), making direct comparisons easier. Since a small number of large trading connections dominate trade flows, the percentile choice has minimal impact on the overall results. To emphasize this, we added a sentence at the end of section 2.2:

However, the results are robust across a wide range of percentile cut-offs, as trade is dominated by a small number of large exchanges (Figure S1).

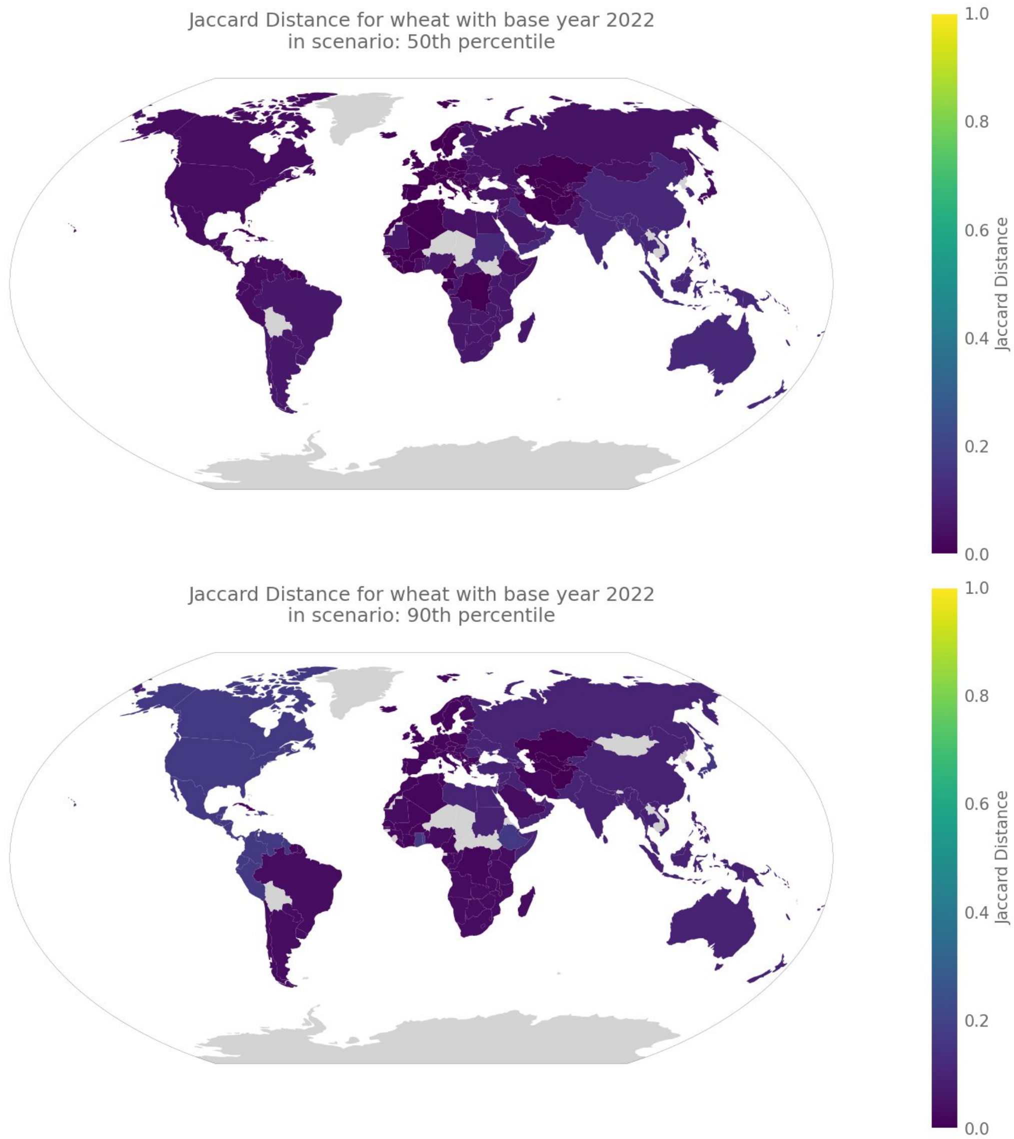

Figure S1: Changes in wheat trade communities after excluding the 50th percentile or 90th percentiles of trade flows, in comparison to the communities in 2022. Colours indicate the magnitude of change as the Jaccard distance. Yellow means the trade community of a country has changed completely, and dark blue that the country remains in the same trade community. Again, we see that changes in trade communities are much more pronounced in the ASRS.

Figure 5 and Figure 7: Also consider showing absolute import calorie losses per capita or total supply losses to see how severe the (imported and domestic) crop losses are.

We have added a figure with absolute changes to the supplement and reference it in section 3.1.3:

We can also study the absolute changes in wheat imports (Figure S4). This highlights similar patterns across both GCIL and ASRS, albeit still with a higher impact in the ASRS. The strongest effects in both scenarios can be seen in China, Turkey, Indonesia and Egypt. All these countries import large amounts of wheat from Russia and Central Asian countries like Kazakhstan, which experience major yield losses in both scenarios. In particular, Turkey would experience a massive loss of wheat imports in absolute terms in an ASRS, with around 8 million tonnes of wheat imports lost.

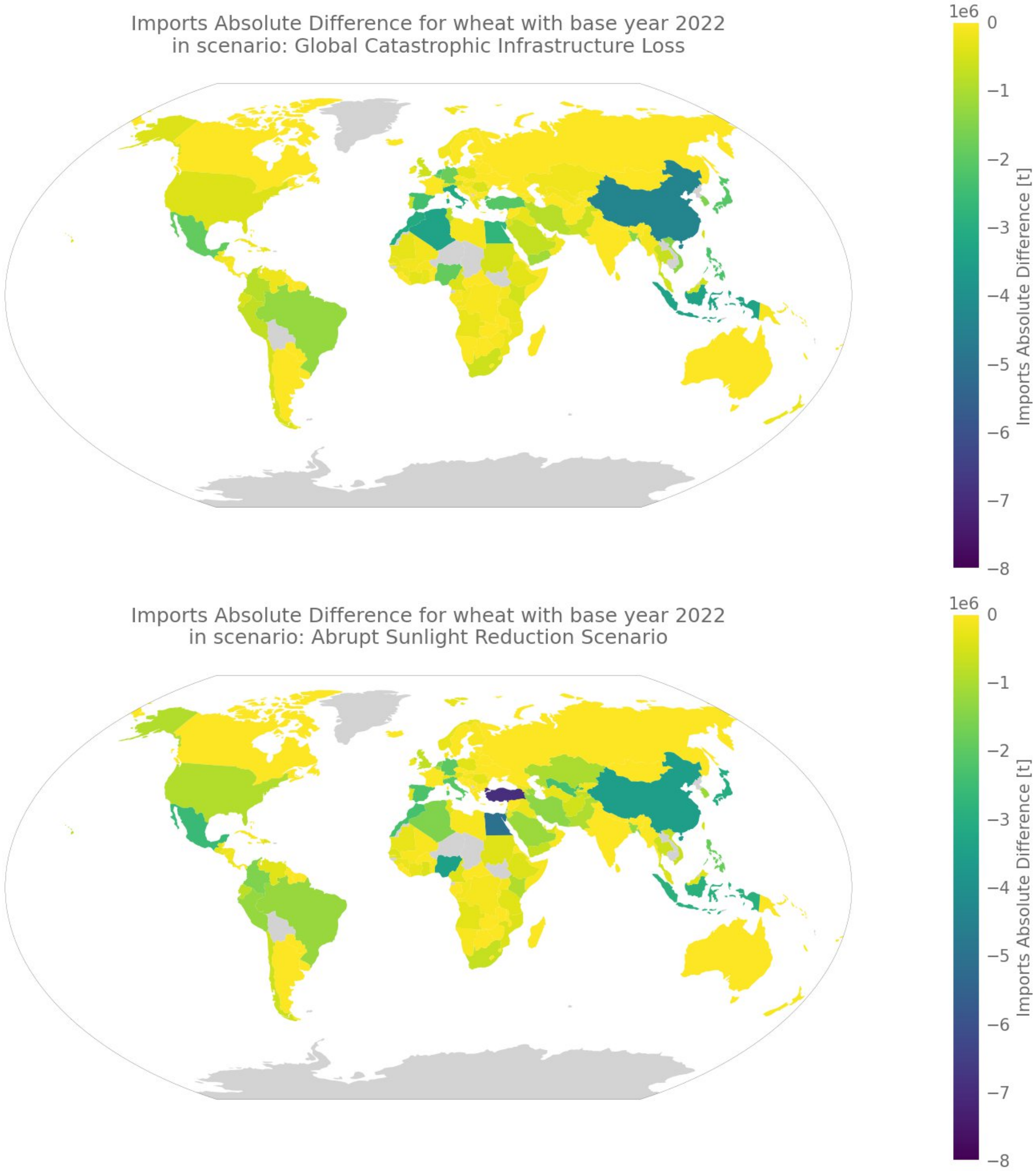

Figure S3: Absolute changes in wheat imports for ASRS and GCIL (in tonnes per year).

Update Levermann et al. (2024) from preprint to published version: https://doi.org/10.1038/s41893-024-01430-7

Changed as proposed.

Consider restructuring the Discussion. Section 4.3 may fit better under Results; Sections 4.4.2 and 4.4.3 could be streamlined or moved, depending on their relevance.

While 4.3 contains some minor results, it is mostly a discussion. Therefore, we would prefer to keep it in that section. Splitting into two separate paragraphs, one in the results and one in the discussion, would not work well for reading, because they would both be short and relate to one another, but would be far away from each other in the manuscript.

We think 4.4.2 and 4.4.3 are relevant discussions to have, as one of the motivations of research like this is to increase resilience to global catastrophes. It is, therefore, unclear to us how exactly the reviewer would like us to streamline these sections.

Line 150: Please confirm whether the reference to Tukey (1977) is appropriate here.

This reference was meant to give readers a source for the quartile calculations and is thus intentional. We moved it directly to the mention of the quartiles to emphasize this.

Other changes

While addressing the reviewer comments, we noticed some discrepancies in our analysis, which we corrected for the updated version of the manuscript. The specific problems were:

1) For some of the analysis, we accidentally used the 47 Tg nuclear war scenario instead of the intended 37 Tg scenario.
2) For figures 6, 7 and 8, the Jaccard distance was incorrectly calculated as [Jaccard similarity - 1] instead of [1 - Jaccard similarity].

Problem 1) did result in some minor changes in some figures, but the overall picture remains the same, and the conclusion is not changed. The main difference which resulted from this correction is that in Figure 4, we cannot see a clear difference between ASRS and GCIL anymore when it comes to country roles in the trade network. To emphasize this shift in behaviour, we added a paragraph to section 3.1.2:

However, we note that in larger ASRSs, country roles within trade networks do shift significantly. The 47 Tg scenario (Figure S2) reveals distinct transitions: some countries shift from non-hub connectors to peripheral non-hubs, while others become provincial hubs. This suggests countries lose connections both *within and beyond their trade communities, with external connections most affected. Countries maintain fewer imports overall, but those remaining imports come primarily from within their trade community. These patterns indicate a potential tipping point between 37 Tg and 47 Tg, where the system shifts from minimal change to substantial reorganization*

Problem 2) did not result in any changes in the results, as the overall differences between the scenarios remain the same.