

# 1 Food trade disruption after global catastrophes

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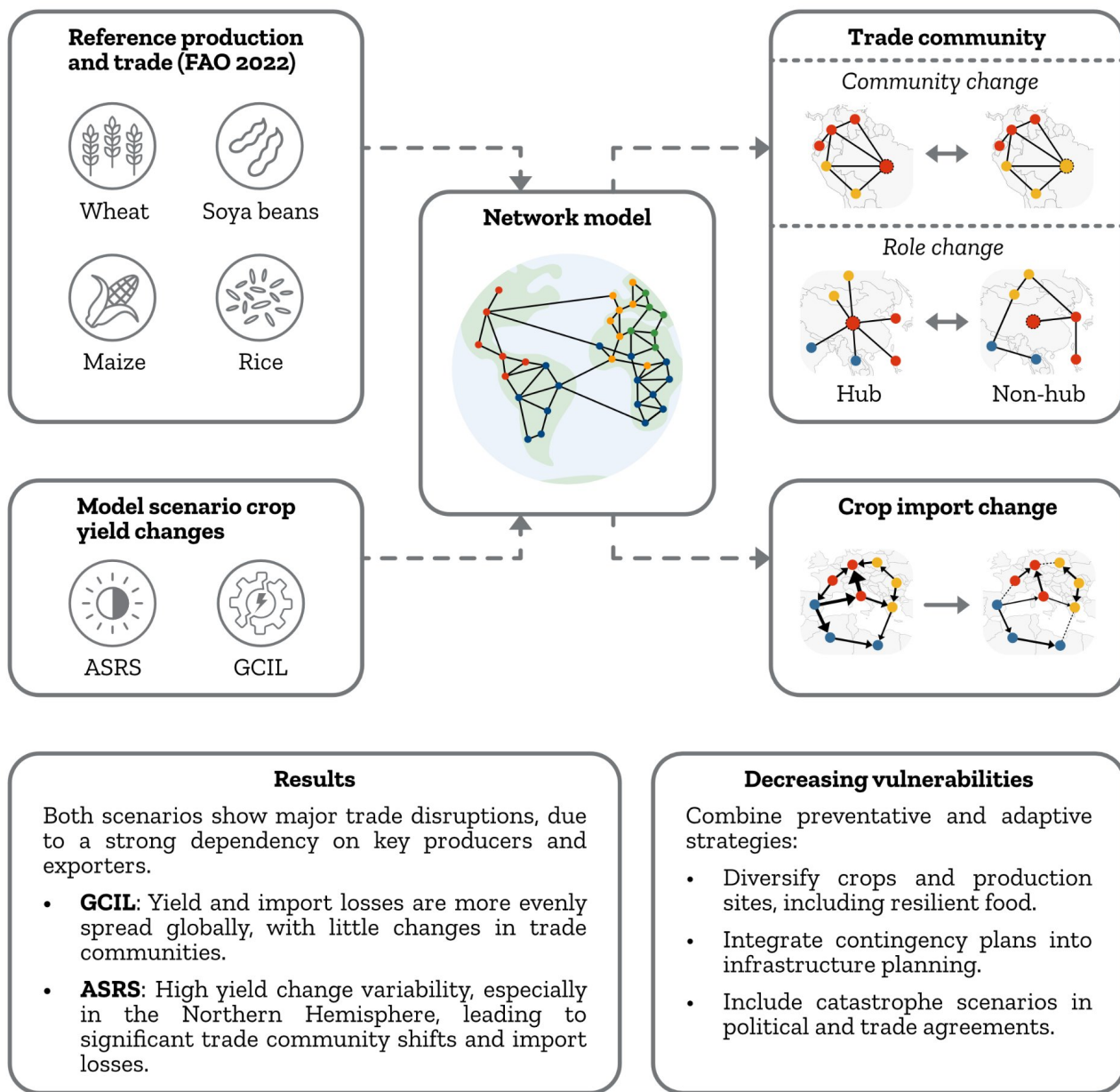
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16 **Abstract.** The global food trade system is resilient to minor disruptions but vulnerable to major ones. Major shocks can arise from  
17 global catastrophic risks, such as abrupt sunlight reduction scenarios (e.g., nuclear war) or global catastrophic infrastructure loss  
18 (e.g., due to severe geomagnetic storms or a global pandemic). We use a network model to examine how these two scenarios could  
19 impact global food trade, focusing on wheat, maize, soybeans, and rice, accounting for about 60% of global calorie intake. Our  
20 findings indicate that an abrupt sunlight reduction scenario, with soot emissions equivalent to a major nuclear war between India  
21 and Pakistan (37 Tg), could severely disrupt trade, causing most countries to lose the vast majority of their food imports (50-  
22 100 % decrease), primarily due to the main exporting countries being heavily affected. Global catastrophic infrastructure loss of  
23 the same magnitude as the abrupt sunlight reduction has a more homogeneous distribution of yield declines, resulting in most  
24 countries losing up to half of their food imports (25-50 % decrease). Thus, our analysis shows that both scenarios could significantly  
25 impact the food trade. However, the abrupt sunlight reduction scenario is likely more disruptive than global catastrophic  
26 infrastructure loss regarding the effects of yield reductions on food trade. This study underscores the vulnerabilities of the global  
27 food trade network to catastrophic risks and the need for enhanced preparedness.

28



## 32 1 Introduction

33 Humanity receives much of its food via the global trade network (D’Odorico et al., 2014; Janssens et al., 2020). However, with  
34 such interconnectedness comes the potential for large-scale systemic risk (Bernard de Raymond et al., 2021), where local failures  
35 can have cascading effects throughout the broader system. A significant component of the system’s vulnerability is its lack of  
36 diversity on all levels, ranging from seed varieties to the number of companies trading food and few but dominant exporters (Clapp,  
37 2023; Hamilton et al., 2020; Nyström et al., 2019). Global trade has been described as "robust, yet fragile," capable of weathering  
38 more minor shocks but increasingly vulnerable to major ones (Foti et al., 2013; Ma et al., 2023; Wang et al., 2023). Such major  
39 shocks could come in the form of “tipping points”, and involve cascading interactions with other processes such as conflict and  
40 migration in a globally interconnected world (Centeno et al., 2023; Spaiser et al., 2023). In this context, the World Economic  
41 Forum's Global Risk Report 2023 highlights food supply crises as one of the most severe risks in the coming years and decades  
42 (World Economic Forum, 2023).

43  
44 A key vulnerability in the food trade network lies in the potential disruption of the biggest food exporters (Clapp, 2023; Puma et  
45 al., 2015), and this vulnerability appears to be increasing over time (Ji et al., 2024; Ma et al., 2023). Currently, only five countries  
46 (China, United States, India, Russia and Brazil) are responsible for producing the majority of wheat, maize, rice and soya beans  
47 (Caparas et al., 2021), and these producers are especially vulnerable to disruptions of agricultural inputs (Ahvo et al., 2023). A  
48 stop of trade by, e.g., the United States could trigger cascading failures (Goldin and Vogel, 2010; Helbing, 2013; Ma et al., 2023),  
49 plausibly endangering the entire system. One possible reason for large yield shocks is synchronised multiple breadbasket failure,  
50 which means the simultaneous collapse of multiple major agricultural regions (Anderson et al., 2023; Gaupp et al., 2020;  
51 Kornhuber et al., 2023). Beyond this, there are various global catastrophic risk (GCR) scenarios which could involve large-scale  
52 food system disruption.

53  
54 GCR has been defined as the risk of “serious damage to human well-being on a global scale” (Bostrom and Cirkovic, 2008), and  
55 could occur due to a wide range of possible hazards. Here, we consider two specific scenarios particularly relevant to the food  
56 system. The first is global catastrophic infrastructure loss (GCIL), which could be triggered by High Altitude Electromagnetic  
57 Pulses (HEMPs) (Cooper and Sovacool, 2011; Wilson, 2008), geomagnetic storms (Baum, 2023; Cliver et al., 2022; Isobe et al.,  
58 2022), globally coordinated cyber attacks (Ogie, 2017), and extreme pandemics causing people to be unable or unwilling to work  
59 in critical industries (Denkenberger et al., 2021). These events, disrupting the electrical grid on a global scale and thus the  
60 production of inputs for the food system, like fertilisers, pesticides or fuel, could lead to a substantial reduction in global food  
61 yields (Moersdorf et al., 2024) and would thus further influence food trade.

62  
63 The second is that of abrupt sunlight reduction scenarios (ASRSs), which could result from nuclear war (Coupe et al., 2019; Toon  
64 et al., 2008), asteroid/comet/meteor (bolide) impacts (Chapman and Morrison, 1994; Tabor et al., 2020), or large volcanic eruptions  
65 (Rampino, 2002; Rougier et al., 2018). Such events could inject aerosol particles into the upper atmosphere, causing a significant  
66 drop in temperature and disrupting global agriculture (Coupe et al., 2019; White, 2013). A recent analysis of Xia et al. (2022)  
67 suggests that a nuclear war between Russia and the United States could lead to global yield reductions of up to 90% in the worst  
68 year following the war. Even a smaller nuclear war could disrupt global trade due to a massive spike in food prices (Hochman et  
69 al., 2022).

70  
71 The likelihood of large yield shocks may be substantial. For example, Rivington et al. (2015) estimate an 80% likelihood of a 10%  
72 or greater global yield shock due to multiple breadbasket failure within this century. This probability combined with the probability  
73 of the abovementioned catastrophes, based on current estimates and preparations, moves to over 90% for this century at least one

74 of them happening (Barrett et al., 2013; Denkenberger et al., 2021, 2022), with the majority of the probability mass coming from  
75 multiple breadbasket failures. While these numbers are highly uncertain, they highlight that there is the need to understand better  
76 what might happen if yield shocks on such a scale occur.

77  
78 While the impacts of climate change and extreme events on trade have been studied more in recent years (Hedlund et al., 2022;  
79 Thang, 2024), only limited research has been conducted regarding the effects of GCIL and ASRS on food production and trade.  
80 The research that does exist assumes that trade will continue as it is now or cease completely (Hochman et al., 2022; Rivers et al.,  
81 2024a; Xia et al., 2022). These simplifications reduce the enormous complexity of how our food system might react to global  
82 catastrophic risks. While some preliminary economic research on smaller nuclear conflicts has been conducted (Hochman et al.,  
83 2022), economic models struggle in modelling extreme shocks, such as those associated with ASRSs or global catastrophic  
84 infrastructure loss, as they do not account for the direct destruction, sudden and big changes, as well as loss of life and other effects  
85 of global catastrophes (Arnscheidt et al., 2024).

86  
87 For an initial assessment of how global trade might evolve after such global catastrophes, we study the shifts of trade communities  
88 and trade flows caused by GCIL and ASRS in a global food trade network model (Hedlund et al., 2022). In this context, trade  
89 communities refer to groups of countries that trade extensively with one another. Understanding them and their changes allows a  
90 more targeted assessment of the disruptions caused by changes in yield. The model is intentionally simple, focusing on the direct  
91 effects of yield changes on trade without considering second-order economic aspects. Our initial analysis can serve as a foundation  
92 for future, more detailed economic assessments, while the model itself offers policymakers and scientists a practical tool to analyse  
93 the direct effects of food production shocks on global trade. Such assessments are important because they advance our  
94 understanding of how global catastrophes impact food trade, revealing the different implications of various shocks to the system.  
95 By modelling these shocks under different scenarios, we can better understand and predict changes in the global food trade system  
96 after major disruptions.

## 97 **2 Methods**

### 98 **2.1 Model setup**

99 The model we used was introduced by Hedlund et al., (2022); for the present analysis, we have re-implemented it in Python (Jehn  
100 and Gajewski, 2024) (<https://github.com/allfed/pytradeshifts>). The global trade network is described as a weighted directed graph  
101 with the countries as nodes and trade volumes between two countries as the weight of the edges connecting the nodes. Compared  
102 to the original model, we have added the option to remove countries from the analysis to simulate an overall inability to take part  
103 in trade (e.g. due to destruction after a nuclear war). Other additional functionality is described in the Supplement (Section 1).

104  
105 To detect the communities in the trade network, we used the Louvain algorithm (Blondel et al., 2008), as implemented in NetworkX  
106 (Hagberg et al., 2008). It assigns every country a trade community, i.e., a group of other countries with which said country has the  
107 closest trade ties. As the Louvain algorithm is not deterministic, our model can be provided with a random seed parameter to ensure  
108 the reproducibility of the results.

109  
110 In the model, we accounted for re-exports to represent point-of-origin-to-point-of-destination trade movements, meaning that the  
111 resulting data only contain the direct trade between countries without intermediaries (more information about this in supplement  
112 section 2.2 and Hedlund et al. (2022)).

## 113 2.2 Production and trade data

114 The Food and Agriculture Organization of the United Nations (FAO) supplies annual data on crop production and bilateral trade  
115 for agricultural commodities. Our study utilised the most recent data available (2022), adjusting for re-exports and relies on crop  
116 production and trade matrix information in tonnes.

117 While research suggests a notable 'stickiness' in the trading system (Reis et al., 2020) and that countries tend to remain in the same  
118 trade communities for long periods (Ma et al., 2023), there can still be considerable changes over time, especially after major  
119 disrupting events like COVID-19 (Clapp and Moseley, 2020) or the Russian invasion of Ukraine (Jagtap et al., 2022; Zhang et al.,  
120 2024). We, therefore, used the most recent data (2022) to most accurately represent the current global food trade network. Our  
121 analysis focuses on wheat, rice, soya beans and maize. We used primary commodity data for wheat, maize and soya beans, and for  
122 rice, given that paddy rice is predominantly traded in processed forms, we used the milled equivalent in the FAO data. We focus  
123 on those crops because they are the most important staple crops, accounting for roughly two-thirds of calories and proteins  
124 consumed globally (D'Odorico et al., 2014).

125 We excluded bilateral trade flows falling below the 75th percentile in trade volume to concentrate on the main trade movements,  
126 following Hedlund et al. (2022). This maintained the majority of countries in the network.

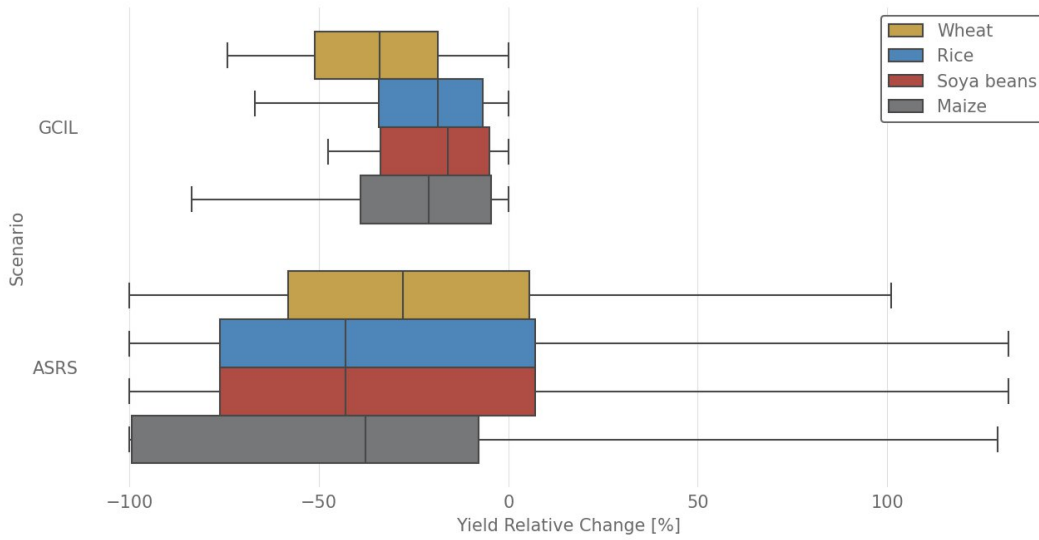
## 127 2.3 The impact of global catastrophic risk scenarios on yields

128 We focus on two main GCR scenarios: GCIL and ASRS (see introduction). We obtained yield losses for GCIL scenarios from  
129 Moersdorf et al. (2024). Moersdorf et. al (2024) assumed that if a GCIL happens, this will result in a global stop in the production  
130 of agricultural inputs like fuel, pesticides and fertilisers. Based on this they split their simulations into two phases. Phase 1 is the  
131 first year after GCIL with some stocks for fuel, pesticides and fertilisers remaining, while phase 2 simulates all following years,  
132 where all stocks are depleted. For our analysis, we used the phase 2 data to focus on the lowest yields. Since it is only available on  
133 a global (with a 5 arcmin resolution) and continental scale, we averaged the yield losses from global data for all points in each  
134 country. The resulting mean values of yield reduction differ slightly from the ones stated in Moersdorf et al. (2024) because 1)  
135 Moersdorf et al., assigned weights by pre-catastrophe productivity, while we did not apply any weights to ensure comparability  
136 with the nuclear war climate data and 2) we aggregate on country level first instead of taking a global average. The scenario by  
137 Moersdorf et al. likely would have wide ranging consequences for society beyond yield impacts, as it assumes a disruption of the  
138 industrial base. These further disruptions are not modelled here.

139  
140 For ASRSs we used the country-level nuclear war crop modelling data from Xia et al., (2022). We used nuclear war as a proxy for  
141 all ASRSs because nuclear war has the best climate model data available (Coupe et al., 2019), and the global impact on climate is  
142 possibly similar across different ASRS scenarios with similar magnitude. We used data for the third year after the nuclear war, as  
143 this represents the year with the lowest yields. To make the scenario more comparable with the GCIL scenario, we used the 37  
144 teragram (Tg) scenario from Xia et al. (2022) as the main comparison. This is meant to simulate a nuclear war between India and  
145 Pakistan with 250 nuclear weapons of 100 kt explosive yield each. In this scenario, some of the smaller and hotter countries  
146 experience increases in yield due to a better climate, and the climate model used with a horizontal resolution of 2 degrees cannot  
147 resolve such small countries correctly. Thus, we limit this effect to a maximum value compared to current yields to avoid  
148 unrealistically high values (Wheat: 100 %, Rice: 132 %, Soya Beans: 79 %, Maize: 129 %). Since more accurate crop growing  
149 models are not available for nuclear war, we determine this upper limit as the  $Q3+1.5(Q3-Q1)$ , where Q1 and Q3 are the 1st and  
150 3rd quartile respectively, of the data presented in Xia et al. (2022) (Tukey, 1977). Xia et al. (2022) did only model spring wheat.  
151 We are assuming here that spring wheat can be used as a proxy for wheat in general.

152

153 The ASRS with 37 Tg soot emissions has a median wheat yield decline similar to GCIL (Figure 1). Soya beans, maize and rice  
 154 have more dissimilar ranges (Figure 1). This makes wheat the most comparable crop across the two scenarios, while also being the  
 155 most traded and, therefore, our main focus; however, we also discuss the other crops and provide the figures for them in the  
 156 supplement.



157 **Figure 1: Relative yield change (%) in all affected countries (combined) for both the global catastrophic infrastructure loss (GCIL) and**  
 158 **the abrupt sunlight reduction scenario (ASRS), by crop (colour). The values for GCIL yield changes are taken from Moersdorf et al.**  
 159 **(2024), and those for ASRS yield changes from Xia et al. (2022) (see Section 2.3 for details). The boxplot displays data distribution using**  
 160 **five key summary points: the minimum, first quartile, median, third quartile, and maximum. The box spans from the first to the third**  
 161 **quartile, with a line at the median. Whiskers extend to the smallest and largest values within 1.5 times the interquartile range from the**  
 162 **quartiles. Outliers are circles beyond the whiskers. This is the same for all boxplots shown in this article.**  
 163

## 164 2.4 Trade communities before and after global catastrophes

165 The model allows a qualitative analysis of the changes by comparing the trade communities before and after the catastrophic event.  
 166 To allow for a more quantitative comparison as well, we used a variety of measures (described below and in supplement section  
 167 1 and 2) for changes in trade communities alongside the overall complexity and robustness of the resulting trade networks.

### 168 2.4.1 Change

#### 169 Jaccard distance

170 To assess how much the trade communities of all countries have changed before and after global catastrophes we used the Jaccard  
 171 distance. This measure allows us to compare how similar/different two trade communities are. It finds the percentage of common  
 172 countries between trade communities divided by the total number of elements between them. The Jaccard *similarity* (also called  
 173 Jaccard index) is typically defined as the size of the intersection of two sets divided by the size of the union of these sets, and has  
 174 a range from zero to one (Jaccard, 1901). The Jaccard distance ( $d_J$ ) is one minus the Jaccard similarity. Therefore, for any given  
 175 country, we can look at the set of countries that are in the same community before and after the catastrophe and compute the Jaccard  
 176 distance (dissimilarity score) for these sets.

177  
 178 Let  $A$  denote the set of community members of some country before a catastrophe and  $A'$  the set of community members of the  
 179 same country after the catastrophe. We can then define the Jaccard distance  $d_J$  as:

$$180 \quad 181 \quad d_J(A, A') = 1 - \frac{A \cap A'}{A \cup A'}, \quad (1)$$

182

183 In the context of this study, the Jaccard distance indicates how similar two trade communities are. A value of zero indicates that  
184 the trade community did not change, while a value of one indicates that the trade community has changed completely. The  
185 assumption here is that a larger change is bad, as countries build their infrastructure to accommodate their current trading partners  
186 and cannot be easily changed without preparation (Jagtap et al., 2022).

187

### 188 **Within-community degree and participant coefficient**

189 The functional cartography approach (Guimerà and Nunes Amaral, 2005) assumes that nodes within a network serve specific roles  
190 based on their connections within and across communities. A node's role is determined using two indices: one measuring its  
191 connectivity within its community ( $z$ ) and another assessing how its links are distributed among different communities ( $P$ ). The  
192 first index (the  $z$ -score) is defined as

$$193 \quad z_i = \frac{K_i - \overline{K}_{s_i}}{\delta_{K_{s_i}}}, \quad (2)$$

194 where  $K_i$  is the number of links of country  $i$  within its trade community  $s_i$ ,  $\overline{K}_{s_i}$  is the average number of links across all countries  
195 in  $s_i$ , and  $\delta_{K_{s_i}}$  is the standard deviation of the number of links  $s_i$ . The trade communities are delineated with the Louvain algorithm  
196 (see section 2.1) The second index (the participation coefficient) is defined as

$$197 \quad P_i = 1 - \sum_{s=1}^N \left( \frac{K_{is}}{k_i} \right)^2, \quad (3)$$

198

199 where  $K_{is}$  is the number of links of node  $i$  to nodes in community  $s$ ,  $k_i$  is the total number of links of node  $i$ , and  $N$  is the number of  
200 communities.

201 These indices define a parameter space where different regions correspond to specific roles based on threshold values. Guimerà  
202 and Nunes Amaral identified seven node roles:

- 203 1. **Hubs** (if  $z \geq 2.5$ ) and **non-hubs** (if  $z < 2.5$ ).
- 204 2. **Non-hubs** are further classified based on the  $P$ -dimension:
  - 205 ○ **Ultra-peripheral** (all or almost all links within their own community,  $P \leq 0.05$ ),
  - 206 ○ **Peripheral** (most links within their own community,  $0.05 < P \leq 0.62$ ),
  - 207 ○ **Connectors** (many links across different communities,  $0.62 < P \leq 0.80$ ),
  - 208 ○ **Kinless** (evenly distributed links across all trade communities,  $P > 0.80$ ).
- 209 3. **Hubs** are categorised as:
  - 210 ○ **Provincial hubs** (vast majority of links within their own community,  $P \leq 0.30$ ),
  - 211 ○ **Connector hubs** (many links to most other communities,  $0.30 < P \leq 0.75$ ),
  - 212 ○ **Kinless hubs** (evenly distributed links across all communities,  $P > 0.75$ ).

213 These roles represent different types of traders within the network, with provincial hubs being crucial for community cohesion,  
214 kinless hubs for global network cohesion, and connector hubs playing important roles in both aspects (see Figure 4).

## 215 **2.4.2 Centrality**

216 Centrality is a measure of the importance of a node in the whole network. This metric allows us to identify the main importers and  
217 exporters of food in our trade network. Here, we consider weighted degree centrality, which is calculated by dividing the sum of  
218 all incoming/outgoing edge weights (the amount of food traded) for a given node by the sum of all incoming/outgoing edge weights  
219 in the entire graph.

## 220 **3 Results**

### 221 **3.1 Changes in wheat trade**

#### 222 **3.1.1 Shifts in trade communities**

223 According to our modelling, the wheat trading communities (based on the Louvain algorithm, section 2.1) would evolve differently  
224 during GCIL and ASRS. This can be seen in the distribution of the trade communities globally (Figure 2), but especially in the  
225 amount of change that countries could undergo in their trade communities (Figure 3).

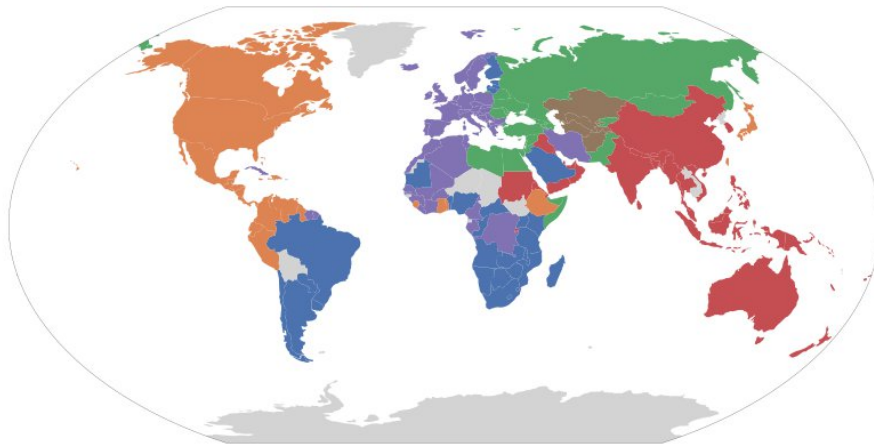
226 Under GCIL, most trade communities could remain relatively unchanged from the present configuration. Only a handful of  
227 countries, such as the United Kingdom, Ireland, Iran, Senegal, and the Democratic Republic of Congo, may experience a complete  
228 reconfiguration of their trade partnerships compared to the current state.

229 In contrast, the changes might be far more substantial in ASRSs. Nearly half of all countries could experience a shift in their trading  
230 partners, with eleven countries undergoing a complete or near-complete overhaul of their trade connections. Some countries  
231 affected are consistent with the GCIL scenario, like Iran and the Democratic Republic of Congo, while others, such as Japan or  
232 Finland, could be part of the transformed trade landscape.

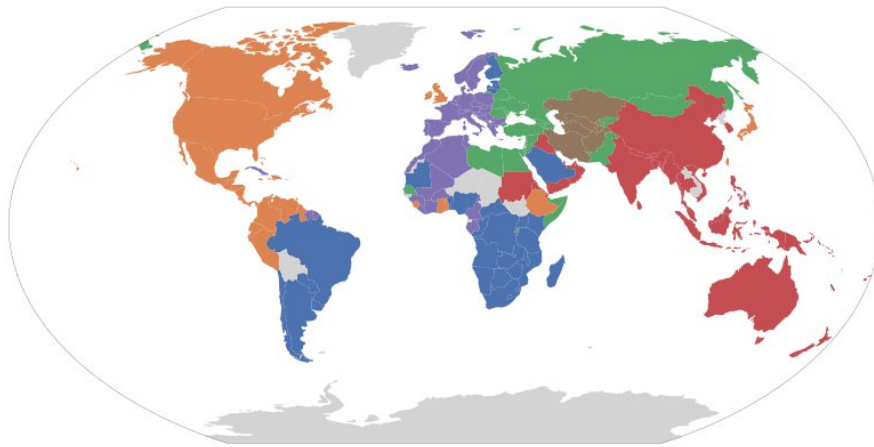
233 The global distribution of trading communities (Figure 2) reveals that this significant shift is primarily due to the expansion of the  
234 trading community containing Russia. Today, this community comprises mainly Russia, Eastern Europe, and a portion of North  
235 Africa. In the ASRS, however, it extends across all of Europe, most of North Africa, as well as parts of South and West Africa.



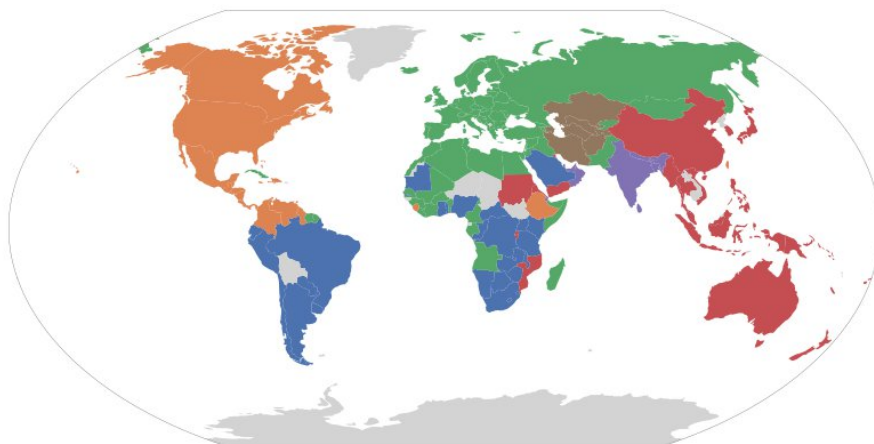
Trade communities for wheat with base year 2022



Trade communities for wheat with base year 2022  
in scenario: Global Catastrophic Infrastructure Loss



Trade communities for wheat with base year 2022  
in scenario: Abrupt Sunlight Reduction Scenario



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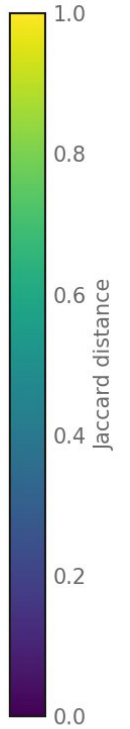
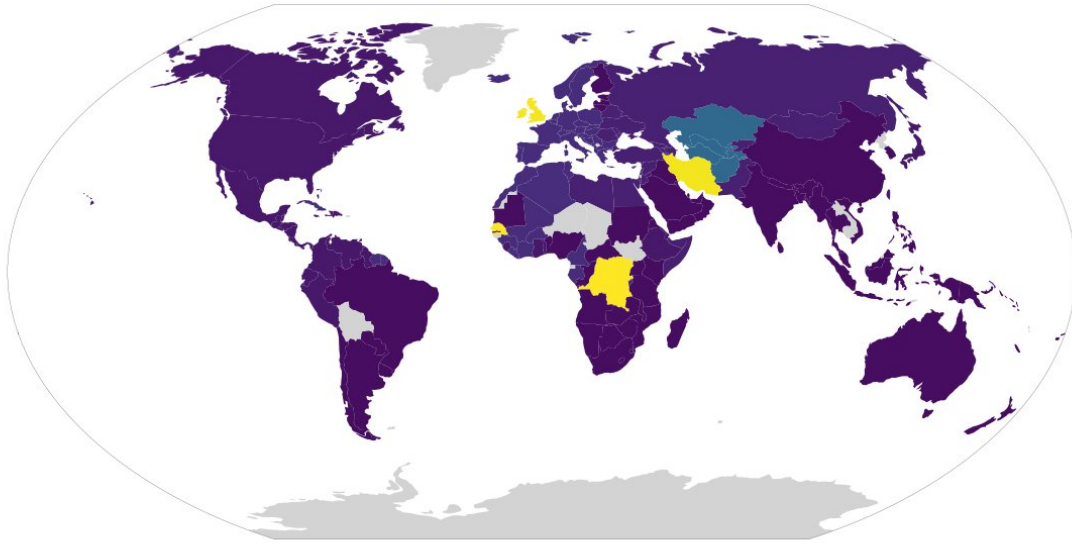
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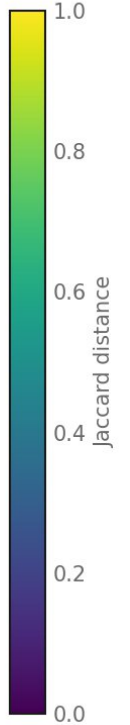
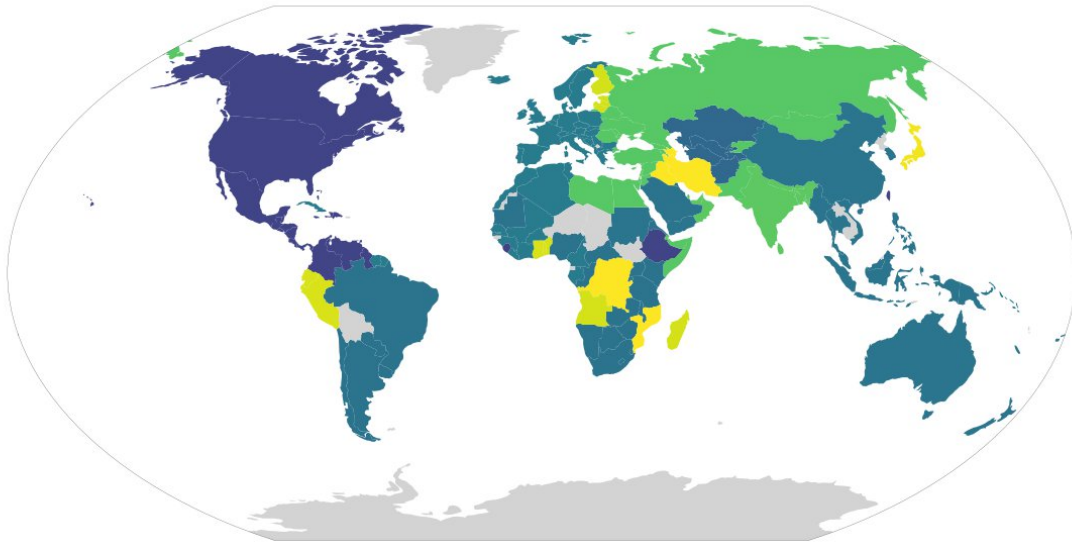
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**Figure 2: Trade communities for wheat in 2022 after yield reduction due to global catastrophic infrastructure loss as well as abrupt sunlight reduction. The colours indicate trade communities. In the GCIL scenario, despite large drops in yields, global trade communities remain relatively unchanged. However, in the ASRS, the changes are more substantial.**

Jaccard distance for wheat with base year 2022  
in scenario: Global Catastrophic Infrastructure Loss



Jaccard distance for wheat with base year 2022  
in scenario: Abrupt Sunlight Reduction Scenario



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241

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243

244

**Figure 3: Changes in wheat trade communities after yield reduction due to global catastrophic infrastructure loss as well as abrupt sunlight reduction, 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.**

### 245 3.1.2 Community roles of countries

246 Similar to the impact seen in trade communities, there are significant shifts in community roles under scenarios of abrupt sunlight  
247 reduction (Figure 4). When comparing the current situation to a GCIL scenario, there are only minor differences in country roles  
248 within the trade network and their communities.

249

250 In the ASRS, some countries transition from the role of non-hub connectors to peripheral non-hubs, and a few move into the  
251 provincial hub category. This indicates that the ASRS may lead to countries losing connections both within and outside their trade  
252 community, with a more pronounced impact on external connections. This means that the overall volume of imports decreases,  
253 but the imports that remain are mostly from within their trade community.

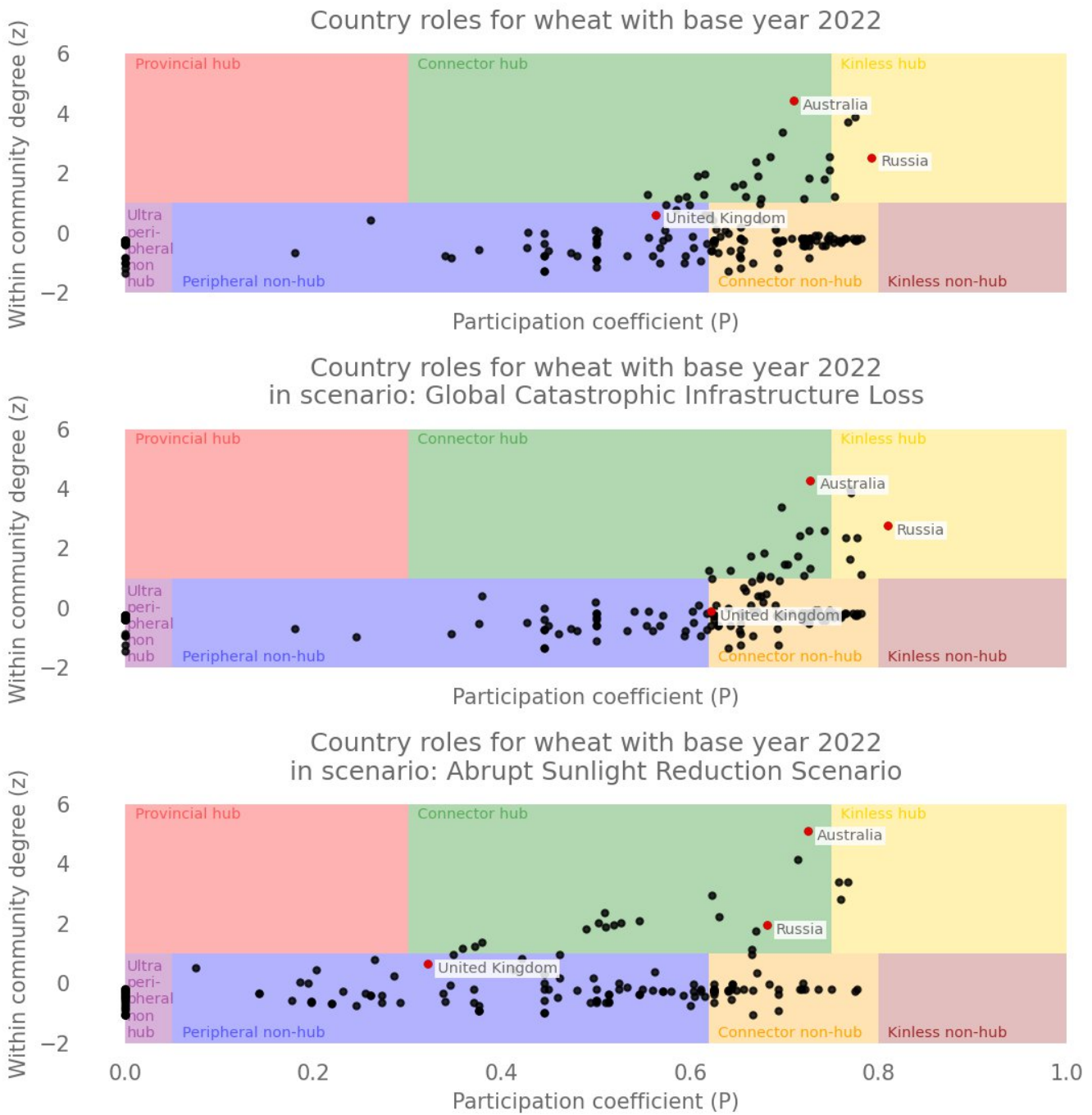
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255 Another way to assess country roles in the global trade network is through in- and out-degree centrality, which identifies key  
256 importing and exporting countries (Figure S1). In-centrality remains stable across all scenarios, reflecting the overall trade volume,  
257 although total imports decrease due to reduced yields. Out-centrality experiences more significant changes. Presently, Australia  
258 has the highest out-centrality, followed by the United States, France, Canada and Russia. This order remains largely unchanged  
259 after GCIL, though Russia's out-centrality slightly surpasses that of the United States and Canada. Likely because of its less  
260 intensive agricultural inputs in comparison with the other countries. The most substantial shifts occur in the ASRS, however, where  
261 Russia, Canada, and the United States experience considerable yield losses, resulting in significantly reduced out-centrality.  
262 Meanwhile, Australia maintains its top position, with France and Argentina rising to second and third place, respectively.

263

264 When we examine specific countries, we can see these changes clearly by scenario (Figure 4). Australia remains a central player  
265 in global wheat trade in both scenarios. It is less impacted by climatic changes in ASRS and uses fewer agricultural inputs, making  
266 it less affected by GCIL. Russia maintains its importance in GCIL but declines significantly in ASRS due to severe climatic  
267 impacts. The United Kingdom also remains stable in GCIL but loses most of its trade connections in ASRS. These examples show  
268 the disruptive nature of ASRS. In GCIL, most countries retain their positions in the trade network, experiencing similar yield  
269 losses. Conversely, in ASRS, many countries lose most of their connections, while a few remain largely unaffected, causing a  
270 major shift in the trade network.

271



272

273 **Figure 4: Country roles in the global wheat trade network in 2022 and after yield reduction due to global catastrophic infrastructure**  
 274 **loss, as well as, abrupt sunlight reduction; based on within community degree and participant coefficient (see Section 2.4.1).**

275

276 **3.1.3 Changes in trade flows**

277 When examining the decline in imports by country, we observe greater impacts under ASRSs compared to GCIL (Figure 5).  
 278 Ukraine and Argentina, which only export wheat, remain unaffected in both scenarios. Under GCIL, most countries see a 20-30%  
 279 reduction in imports, with some African and European nations experiencing up to a 40-60% decrease in imports.

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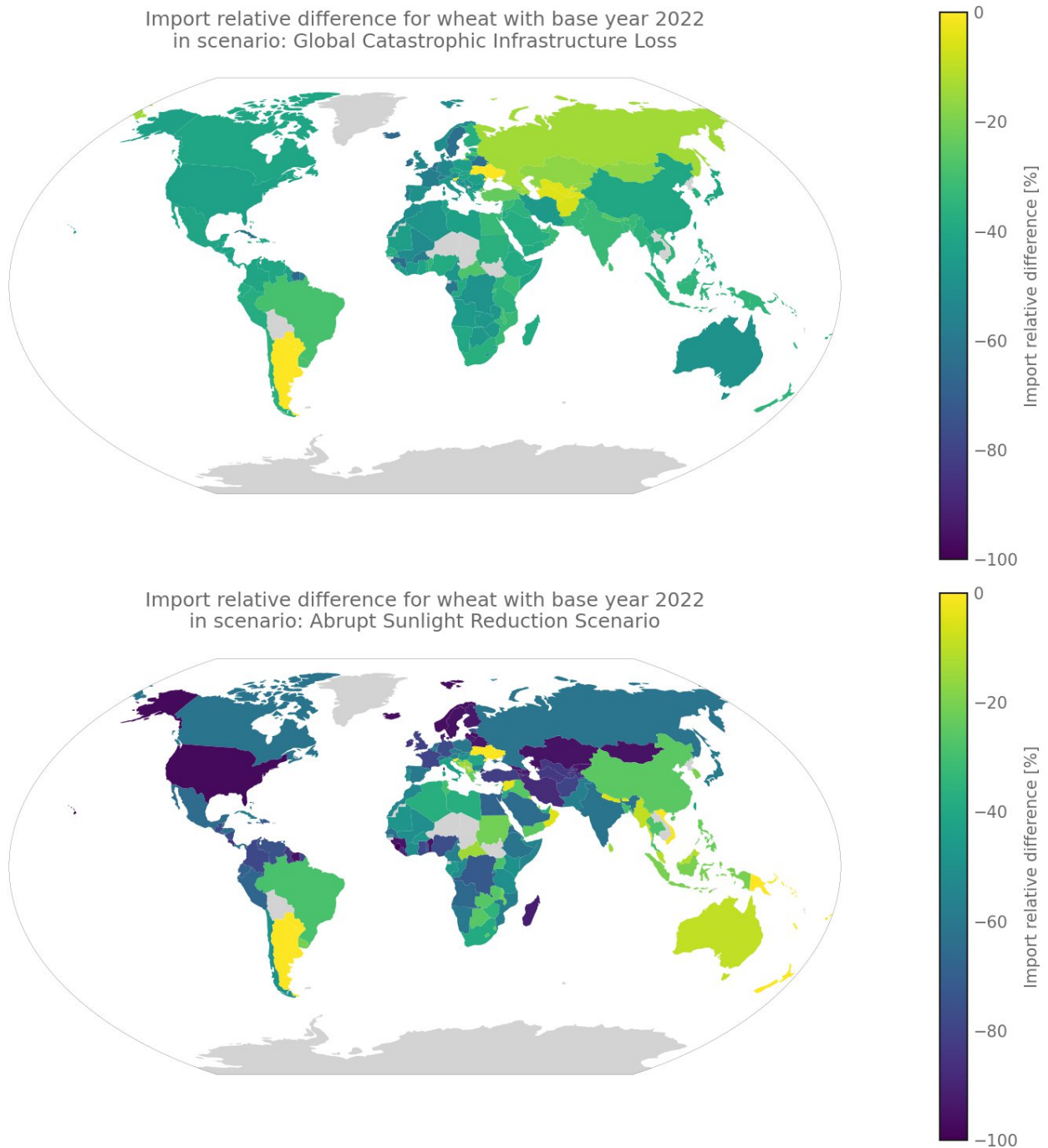
281 In contrast to GCIL, ASRSs result in a broader range of import changes. Nations such as the United States, Norway, and Mongolia  
 282 lose up to 100% of their wheat imports, primarily due to reduced yields in major wheat-exporting countries like Canada, the United  
 283 States, Russia, and Ukraine. These changes are mirrored in both degree-centrality measures, indicating a significant loss of

284 centrality for these previously major exporting countries (Figure S1). This leaves Australia as the only remaining major exporter  
285 of wheat.

286

287 Additionally, we performed robustness checks of our results with different metrics. The shifts in trade patterns and the heightened  
288 impact of ASRSs are also evident in other metrics, like community satisfaction and node stability. Community satisfaction gauges  
289 the proportion of a country's trade within its trade community, while node stability indicates a country's ability to replace lost trade  
290 partners. Both metrics highlight the challenges faced by nations reliant on Russia and the United States. More information on those  
291 measures is provided in the supplement (section 3.2).

292



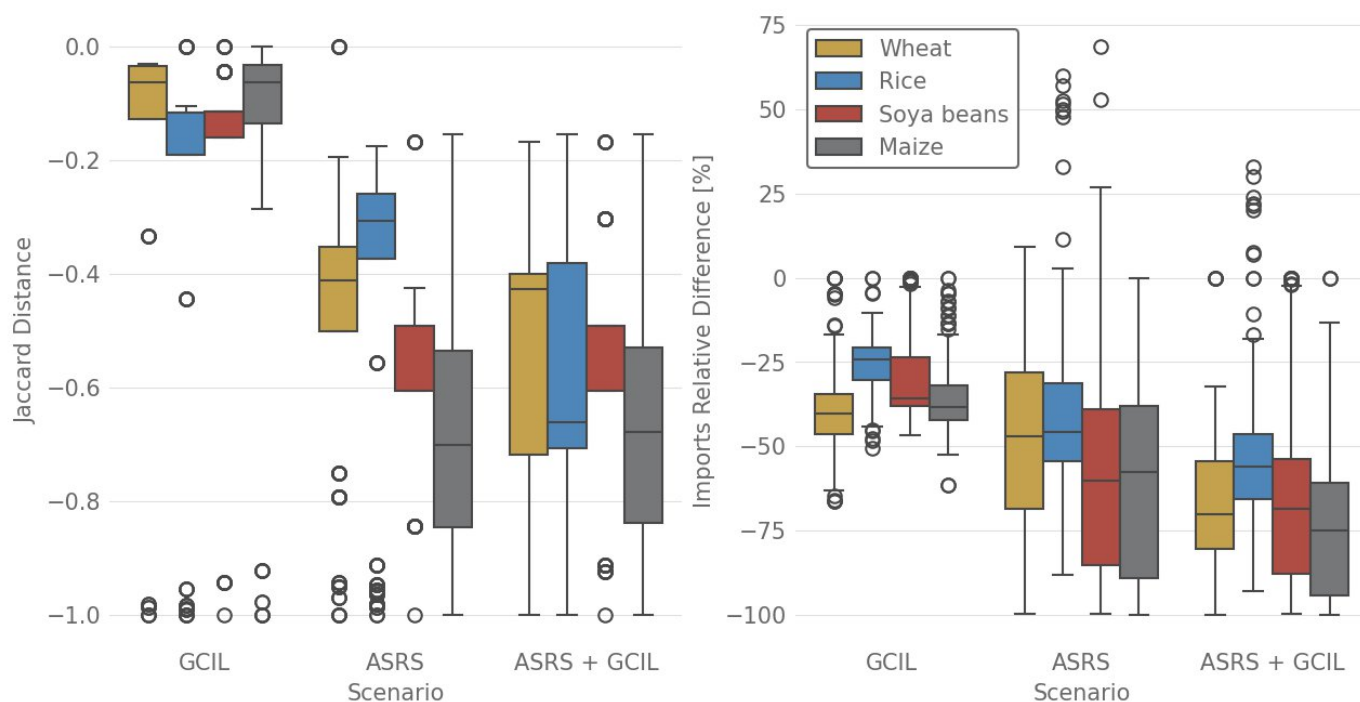
293

294 **Figure 5: Relative changes in wheat imports after global catastrophic infrastructure loss and abrupt sunlight reduction scenarios in**  
295 **comparison to today.**

## 297 3.2.1 Overall pattern and comparison across scenarios

298 The patterns observed in the wheat data are also evident in rice, maize, and soya beans (Figure 7). Across all crops, the impact of  
 299 ASRSs is larger than GCIL. This is especially true for the outliers in the distribution. In the case of wheat, for instance, while the  
 300 median remains similar across scenarios, certain countries experience a complete loss of imports under abrupt sunlight reduction,  
 301 which does not happen in GCIL. Considering the variations in yield reduction (Figure 1), it becomes clear that at 37 Tg of soot  
 302 emissions, the effects are generally comparable for both scenarios when it comes to yield reductions. However, the range of impacts  
 303 and change in trade communities would be much more extensive in ASRSs. Additionally, the most affected countries vary between  
 304 crops due to differing trade volumes across world regions.

305 Combining the effects of ASRS and GCIL, which could occur during a nuclear war that influences climate and disables industry  
 306 due to direct destruction and HEMP, has a very severe impact on food trade. However, the overall impact is less than the sum of  
 307 their individual effects. Many countries severely affected by ASRS have already experienced significant yield losses and the  
 308 additional disruption due to GCIL has thus little effect. Nonetheless, this combined catastrophe would severely impact yields and  
 309 food trade.



310  
 311 **Figure 7: Jaccard Distance and reduction in imports, for each country and crop, for Global Catastrophic Infrastructure Loss (GCIL),**  
 312 **and the Abrupt Sunlight Reduction Scenario (ASRS).**

313  
 314 **3.2.2 Rice**

315 For rice, the import reduction and trade community disruptions are similar between abrupt sunlight reduction and GCIL, differing  
 316 mainly in magnitude. Under GCIL, most countries typically lose around 20-30% of their rice imports, whereas it ranges from 30-  
 317 50% under ASRSs. Most countries also maintain much of their pre-catastrophe trading community, with exceptions including  
 318 Russia, Ukraine, Norway, the UK, Spain, and around half of the African countries. However, a majority of the countries experience  
 319 at least some shift. This more limited degree of change in comparison to wheat is also evident in community roles, which remain  
 320 largely consistent across all scenarios. This stability can be attributed to India's prominent role as the leading rice exporter, its

321 relatively low reliance on agricultural inputs compared to other countries, and it is still relatively high temperatures during ASRSs,  
 322 thereby stabilising the rice trade network even during catastrophes. See supplement section 4.1 for the figures showing the trends  
 323 described here.

### 324 3.2.3 Maize

325 In GCIL, the impact on maize is evenly spread worldwide. However, under ASRSs, there's a stark contrast between the Northern  
 326 and Southern Hemispheres. Nearly all Northern Hemisphere countries lose most or all of their maize imports, while in the Southern  
 327 Hemisphere, South America, much of Africa, and Southeast Asia maintain some imports, mainly from less affected regions like  
 328 South America. Country roles are similarly affected as in wheat, but many countries switch to the connector non-hub role, likely  
 329 as most countries experience low trade volumes overall. The maize trade network in ASRSs exhibits low stability and is heavily  
 330 affected by the removal of the other major exporters, after the United States' decline in importance due to yield reductions. See  
 331 supplement section 4.2 for the figures showing the trends.

### 332 3.2.4 Soya beans

333 Regarding soya beans, there is a shift in the distribution of affected countries compared to wheat. Many African countries remain  
 334 relatively unaffected, primarily due to their low trade volumes. Under GCIL, most countries face a similar reduction, roughly 20-  
 335 40%, in imports. In ASRSs, the patterns resemble those of wheat, except for South-East Asia, Oceania, and Argentina. These  
 336 regions still receive wheat imports from Australia and each other, but their soya bean imports mainly come from the United States,  
 337 resulting in a decline. This trend is reflected in trade communities, which remain mostly stable for GCIL but converge into two  
 338 primary and one minor communities for ASRSs. Soya bean export is heavily concentrated in the United States, so a sharp yield  
 339 decline there disrupts trade communities significantly. Only countries importing soya beans from Brazil maintain higher import  
 340 levels, and the trade community with Brazil stays very stable. Similarly to wheat, the role of countries in their communities shifts,  
 341 with most staying the same for GCIL but losing much connectivity in ASRSs. Another notable deviation from wheat patterns lies  
 342 in network vulnerability to node removal. With only two major exporters, the United States and Brazil, if the United States is  
 343 already affected by yield reduction, the network becomes less stable, experiencing another shock when Brazil is removed. See  
 344 supplement section 4.3 for the figures showing these trends.

## 345 3.3 Comparison of nuclear war scenarios

### 346 3.3.1 Impact of removing countries

347 The ASRS data is based on nuclear war simulations. To explore these further, we simulated the removal of Russia/United States  
 348 and Pakistan/India from the 37 Tg scenario (Figure 8). We compared these scenarios with the ASRS that includes all countries and  
 349 the wheat trade of today. The findings reveal that while removing these countries affects both trade communities and overall  
 350 imports (Figure 8), the effect of the yield reduction due to abrupt sunlight reduction is already so big that the removal of those  
 351 countries is negligible. Thus, if countries involved in a nuclear conflict were to cease as trading partners due to the destruction of  
 352 their territories, it would cause additional disruptions to the global trade network beyond those due to the yield reductions, but only  
 353 marginally and for a subset of countries.



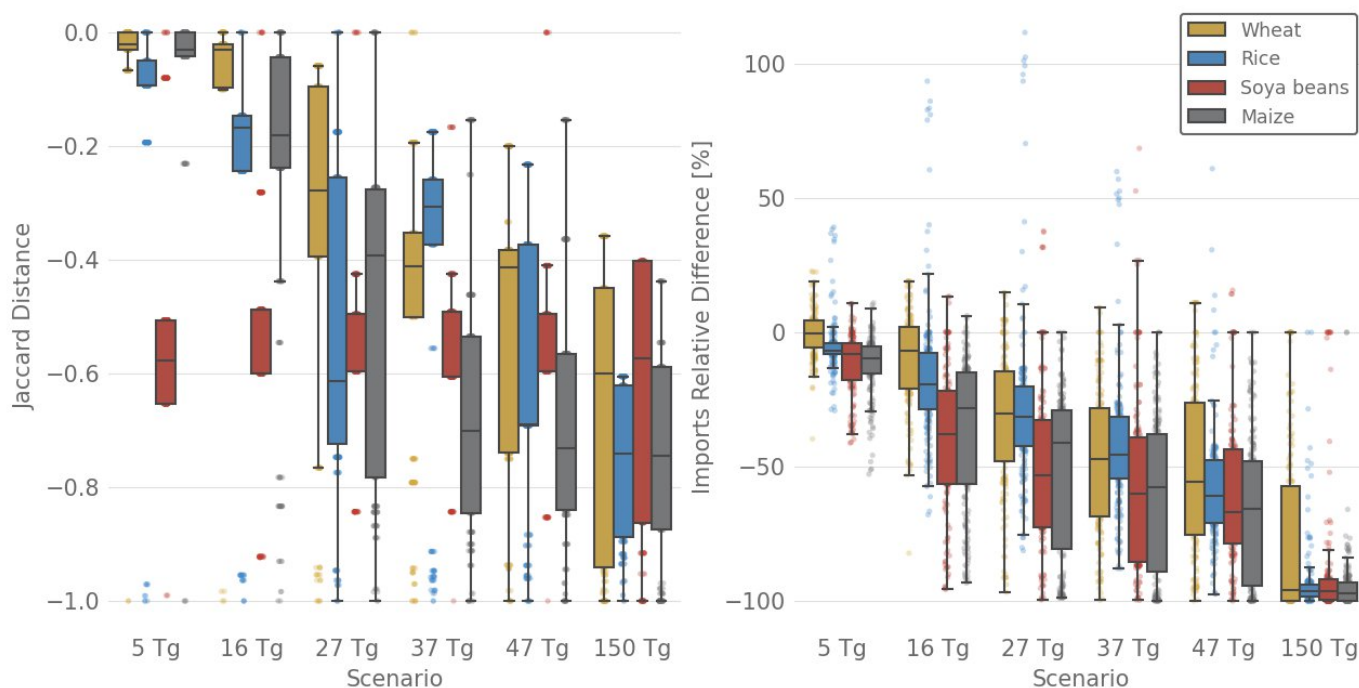
354 **Figure 8: Country removal impact on wheat imports in nuclear war scenarios.**  
 355

356 When simulating the gradual removal of nodes, the results indicate that removing random nodes causes a slow but steady decline  
357 in network stability. In contrast, specifically targeting the most active exporting nodes results in a rapid decline in stability,  
358 leading to network collapse after removing 10-20% of these crucial nodes. Further details can be found in Supplement Section  
359 3.3.

### 360 3.3.2 Impact of emission magnitude

361 Assessments of the impacts for nuclear war scenarios of different magnitudes (Figure 9) show a consistent pattern across all crops  
362 analysed. While the most significant impacts can be seen in the worst nuclear war with 150 Tg of soot emitted (nuclear winter),  
363 the effects would already be quite severe at 37 Tg (nuclear fall). The 37 Tg scenario engenders a substantial of about 60 % import  
364 loss, suggesting that trade would be massively impacted in the 37 Tg case. However, for most countries, food imports would have  
365 ceased almost entirely in a 150 Tg scenario. In addition, even at merely 5 Tg, some countries could experience a 50 % loss of maize,  
366 and at 16 Tg, a considerable number of countries have import reductions from 40 % to almost 100 % across all crops.

367 While trends remain comparable across all crops, including major import changes, wheat seems to be the least affected. Soya beans  
368 experience a stark shift in trade communities at as low a magnitude as 5 Tg. However, the change then stays relatively constant for  
369 all other magnitudes.



370  
371 **Figure 9: Relative change in imports and Jaccard distance for the four primary crops and nuclear war climate changes resulting from**  
372 **the emission of 5, 16, 27, 37, 47, and 150 teragrams (Tg) of soot across all countries. Coloured points represent individual countries.**

## 373 4 Discussion

374 Overall, the main finding of this study is that the two food-system relevant GCR scenarios we have considered may affect  
375 agriculture quite differently in both the magnitude of their effects as well as the spatial distribution, suggesting that they will need  
376 different mitigation strategies to increase societal resilience against them. ASRS will be challenging as it will hit a fraction of  
377 countries very hard, while leaving others mostly unaffected. GCIL on the other hand would affect all countries, but on a similar  
378 magnitude.



379

380 Our results show clear differences between the effects of ASRSs and GCIL on food trade. The scenarios have different effects on  
381 how much trade communities are disrupted, the decrease in overall imports, and the roles of countries within their trade  
382 communities. Across all these measures, ASRSs lead to much larger disruption than GCIL, even for a similar net global yield loss.  
383 This is due to the way these global catastrophes play out and the spatial distribution of their effects.

384

385 When both scenarios are combined to simulate the co-occurrence of both kinds of catastrophes, the impacts increase and result in  
386 food import losses in the range of 70-100 % for many countries. The impact on yields (Figure 1) and trade (Figure 7) change for  
387 both catastrophes in a similar way. We can see that the median losses are similar for both trade and production. However, while  
388 there are still countries that will likely see little impact on their food production by direct effects of the catastrophes, almost all  
389 countries experience a major loss in their food imports. This is due to the countries that are least affected are usually not major  
390 exporters. For GCIL the least affected countries are those that have very low input agriculture, which is usually also not very  
391 productive, while for ASRS the positive effects are mostly in countries which are too warm now for most agriculture.

392

393 As Moersdorf et al. (2024) have shown, in a GCIL scenario, the countries hit the hardest are those doing the most intense agriculture  
394 when it comes to industrial input like fertilisers. This is also in line with other research studying the impact of losing these inputs  
395 (Ahvo et al., 2023). These highly productive countries are also typically the countries that export the most food. Also, the effects  
396 are felt in all countries globally with no exceptions, as industrial inputs are in use worldwide. This results in a very homogenous  
397 impact on food trade, where most countries experience a relatively similar level of trade disruption.

398

399 On the other hand, for ASRSs, we see a much larger split between which countries are more or less affected. Generally, the higher  
400 the country's latitude, the more it is affected (Coupe et al., 2019). In addition, countries in the Northern Hemisphere are affected  
401 more overall. This is partly because nuclear war would most likely occur in the Northern Hemisphere (Coupe et al., 2019), resulting  
402 in somewhat lower soot concentrations in the Southern Hemisphere. In addition, the Southern Hemisphere has more land closer to  
403 the equator and more ocean (which acts as a temperature buffer), suggesting that the Northern Hemisphere may still be more  
404 affected even for ASRSs that do not involve nuclear war. These factors may lead to an especially large yield decline in the United  
405 States, Canada, Central and Northern Europe and Russia. These are all major food exporters, particularly for wheat or, in the case  
406 of the United States, for all major crops. This loss of exports from the major exporting countries cascades across the whole system.  
407 For all crops we can see significant changes in trade communities and large declines in the amount of imported food. This is  
408 especially true for maize, as maize is not very cold tolerant and, therefore, especially vulnerable to drops in temperature.

409

410 Focusing more specifically on the nuclear war scenario, we can see that the main effects of these disruptions are due to the yield  
411 decline. The complete removal of the countries involved in a war only introduces little additional shifts in the overall imports.  
412 However, removing Russia and the United States brings additional disruptions to the trade communities, as both countries are the  
413 anchors in their respective trade communities. We can also observe that the effects of the nuclear war increase considerably with  
414 rising amounts of soot ejected into the atmosphere. While a 5 Tg emission has relatively minor effects, except in soya bean trade  
415 communities, the effects quickly grow with higher soot emissions.. This emphasises that even if nuclear weapons were used, it is  
416 extremely important to limit further escalation in order to prevent additional disruption to the global food system.

#### 417 **4.1 Implications for the food system**

418 Clapp (2023) identifies three primary vulnerabilities in the food system: 1) dependence on a limited number of staple crops, 2)  
419 domination by a small group of major exporters, and 3) concentration of food trade among a few companies. While we did not

420 explore the role of companies, the issues of reliance on a few staple crops and dominance by major exporters are also evident here.  
421 The main vulnerability is the extremely central role of the United States in the food trade network. Every scenario resulting in yield  
422 reduction in the United States or even its complete removal from the system will result in massive cascading disruptions, both in  
423 the overall communities and the amount of food traded. The vulnerability would decrease considerably if the food system were  
424 less concentrated in the United States. Other studies of the current trade network show a high dependency on other major exporters,  
425 such as Brazil and Russia (Ji et al., 2024). Our results also indicate that a disturbance of these nodes is very significant. For instance,  
426 Australia would be the last remaining major exporter of wheat during an ASRS (Figure S1). Therefore, if this country were to stop  
427 exporting, the wheat trade would effectively end globally.

428  
429 We know that complex networks become more susceptible to perturbations as they get more centralised (Wiliński et al., 2013),  
430 and the food system is getting increasingly centralised and concentrated (Clapp, 2023). This means that if we do not alter our  
431 approaches to food trading, we will get more and more vulnerable to major shocks and the kinds of scenarios we have described.  
432 There are some indications that this global concentration of trade might be beginning to change (Kang et al., 2024; Mamonova et  
433 al., 2023), as more countries rethink how they handle food and trade more generally. Whether these trends continue depends on  
434 how the geopolitical situation develops in the coming years and decades.

435  
436 Our research also shows that the ASRS has a much wider range of effects. Some countries could even increase imports, as their  
437 neighbouring countries profit from the changed climate (e.g. more precipitation and cooler temperatures in some semi-arid  
438 regions), while others could lose all of their incoming food products. This means that recommendations to tackle these scenarios  
439 have to be tailored to specific countries, as there can be no approach that applies to all countries. For GCIL, more general  
440 recommendations might be possible, as all countries are affected similarly.

441  
442 Recent studies have compiled lists of countries that have experienced substantial food import shocks in the past (Zhang et al.,  
443 2023b). While there is some overlap between these countries and the ones affected the most here, it also becomes clear that  
444 especially the Central European countries, as well as the major exporting countries, have not experienced large food import shocks  
445 on that scale in modern history. This indicates that these countries have no experience with import shocks and are possibly less  
446 prepared to handle the scenarios described in this study.

#### 447 **4.2 Study Limitations**

448 The research presented is, to our knowledge, the first to take a more nuanced look into what might happen to the food trade system  
449 after global catastrophe, meaning that there is much room for improvement in future work. We consider the main limitations of  
450 our study to be:

- 451 - We only looked at the direct effects of yield reduction on trade flows and did not consider any additional adaptations. For  
452 example, it seems likely that many countries would introduce export bans if their own yields dropped significantly,  
453 worsening the overall situation. This means that our study can be seen as the minimal amount of change that one can  
454 expect to happen after global catastrophes by the yield changes alone, barring the introduction of resilient food adaptations  
455 to counter the loss of yields (Pham et al., 2022). Further research is needed to understand how societies might react to the  
456 effects explained here.
- 457 - GCIL also includes the assumption that we lose the majority of our mechanisation and transportation. This is not modelled  
458 in this study, but plausibly could have major implications beyond the impact on yields and make it more catastrophic than  
459 ASRSs. A GCIL would disrupt fossil fuel production, hampering international trade. However, possible interventions

460 include retrofitting ships to be wind powered (Abdelkhalik et al., 2016) or wood gasification to replace fossil fuels (Nelson  
461 et al., 2024).

- 462 - We studied the four major food crops in isolation to understand what effects might play out on that level. However, the  
463 food system also consists of other parts like fisheries or livestock. While those are also predicted to decline after a global  
464 catastrophe (Scherrer et al., 2020; Xia et al., 2022), it remains unclear how the totality of all food trade might be affected  
465 by global catastrophes. Livestock would be more strongly affected than major crops because it mostly depends on them;  
466 whereas fisheries, while less affected than crops, make up a small percentage of global caloric requirements (<2%).
- 467 - Additional layers of interaction from non-food products through social dynamics to economic policies could be considered  
468 in a multi-layer network model, which has been shown to be impactful and effective in other scientific disciplines (De  
469 Domenico, 2023; Kivelä et al., 2014; Paluch et al., 2021).
- 470 - We treated nuclear war simulations as a proxy for large size impact over the land and super volcanic eruptions. While this  
471 is a reasonable assumption, the results might end up very different, especially if the impact/eruption happens in the  
472 Southern Hemisphere, as nuclear war scenarios usually only involve the Northern Hemisphere, as there are no nuclear  
473 weapon states in the Southern Hemisphere. although these extreme events all produce large amounts of aerosols in upper  
474 atmosphere, which block sunlight and cause significant cooling, the compositions of the aerosols differ. This results in  
475 variations in the duration of the cooling and some climate impacts. Recent research indicates that a simulated volcanic  
476 winter shows similar trends (Enger et al., 2024) to previous studies on nuclear winter (Coupe et al., 2019), although  
477 volcanic winters are likely to be shorter in duration. Additionally, there is a possibility that multiple mid-sized volcanic  
478 eruptions could occur simultaneously, releasing enough sulphate aerosol to cool the Earth significantly.
- 479 - Even for such a relatively well-studied global catastrophe as nuclear winter, there is still much we do not understand. For  
480 example, the work of Coupe et al., (2023) suggests that nuclear winter can paradoxically lead to a decrease in Antarctic  
481 sea ice despite global cooling. As our understanding of global catastrophic risks increases, we may see shifts in our  
482 expected effects on the food system.
- 483 - Trade is only a part of the global value chain, and if we look at the whole value chain, we can expect many more  
484 disruptions (Ibrahim et al., 2021).
- 485 - We only consider the global aspects of the catastrophes. However, there are a variety of plausible scenarios where regional  
486 effects could have global repercussions. For example, the food system has several so-called choke points (Bailey and  
487 Wellesley, 2017; Key et al., 2024; Wellesley et al., 2017), where much food trade is funnelled through a small geographic  
488 area. Some of these choke points are near volcanoes and could be severely affected by eruptions (Mani et al., 2021).  
489 Should these choke points close in the aftermath of a global catastrophe, the disruption of the food system would further  
490 increase.

### 491 **4.3 Comparison to climate change**

492 The model employed in this study was originally developed to study the effects of climate change on food trade (Hedlund et al.,  
493 2022). We can see that the impact of a rather severe climate change scenario based on RCP 8.5 has considerably lower effects than  
494 the catastrophes explored here and even results in an increase in imports for almost all countries (Figure S20). For all crops the  
495 trade communities stay mostly the same, while they would be much more disrupted in our scenarios. A similar pattern holds up for  
496 all crops considered. These differences are likely due to the different magnitudes of the catastrophes considered. For RCP 8.5, a  
497 land surface air mean temperature increase of around 5°C is expected by 2100 (Zhang et al., 2023a), while for a 37 Tg nuclear fall  
498 scenario, a land surface air mean temperature drop of up to 8 °C is predicted in the 3rd and 4th year after the nuclear war. (Xia et  
499 al., 2022). Therefore, the ASRS considered here not only has the larger temperature change, but also in a much shorter time period.  
500 Also, in the case of climate change, the countries that will be more affected are those closer to the equator (Frame et al., 2017).

501 Since the main exporting countries are mostly at higher latitudes, they will be less affected by climate change, contributing to a  
502 more stable food trade in comparison to the scenarios we explored.

#### 503 **4.4 Gaining a deeper understanding of how global catastrophes impact the food system.**

##### 504 **4.4.1 Research gaps**

505 The research presented here is a first step in understanding what might happen to food trade after global catastrophes. However,  
506 there are still a wide range of factors we do not understand. With the introduction of terms like multiple-breadbasket failures, food  
507 system research has increased in scope (Clapp, 2023; Jahn, 2021; Nyström et al., 2019; Savary et al., 2020). Still, this kind of  
508 research does not consider events where all countries are affected simultaneously and on a scale not seen in modern history, leaving  
509 the effects of global catastrophic risks unexplored. This means that global food system research should also include global  
510 catastrophic risk in order to have all angles covered. Due to this general lack of focus on global catastrophes, we outline specific  
511 topics that warrant further attention:

- 512 - Understanding how global catastrophic risk might affect different parts of the global population by socio-demographic  
513 metrics. We know that climate impacts are felt differently depending on how rich the country is (Levermann et al., 2024)  
514 and also increase wealth inequality (Méjean et al., 2024). Therefore, it is likely that these differences also exist as a  
515 consequence of global catastrophes.
- 516 - While there is little research on the effects of the dependency on very few food trading companies (Clapp, 2023), there is  
517 none when it comes to the question of how this might affect the outcomes of global catastrophic risk scenarios.
- 518 - There exists some research that acknowledges the potential cascading effects of ASRSs like nuclear war, for instance,  
519 recent summaries by Green (2024) or Glomseth (2024), but for many of the events that could cause GCIL, we know only  
520 very little of the potential cascading effects.
- 521 - We need more understanding of the effects of catastrophes like geomagnetic storms and how the loss of industrial inputs  
522 might affect agriculture. There is some global research on the direct effects (Cliver et al., 2022; Isobe et al., 2022; Rivers  
523 et al., 2024b) but less on the indirect effects, especially on agriculture (Moersdorf et al., 2024). There are some recent  
524 research studies which explore similar effects yet do not frame it in regards to global catastrophic risk but instead as a  
525 general disruption in the trade of industrial inputs for agriculture (Ahvo et al., 2023; Sandström et al., 2024).
- 526 - There is a good chance that catastrophes will not happen in isolation but interact with each other and existing  
527 vulnerabilities. An example is the possible interaction between nuclear winter and planetary boundaries (Jehn, 2023) or  
528 termination shock caused by civilization collapse (Baum et al., 2013). These are only two of the possible interactions, and  
529 many others are entirely unexplored (for example, having a major geomagnetic storm during a pandemic).
- 530 - Our food system is not reliant on the food trade network alone but on a highly complex supply chain with many interacting  
531 goods and services (Ibrahim et al., 2021), also consisting of many non-food items. It would be valuable to understand  
532 how these might react to the scenarios described in this manuscript. There has been some work to study this for current  
533 conditions (Deteix et al., 2024), but not with a focus on global catastrophes.
- 534 - We do not know what might happen after the initial effects play out, as this paper only describes the minimal amount of  
535 change that is expected to happen due to the yield changes alone. However, if we look into history, we can see that such  
536 disruptions of trade networks can have massive consequences. If they unravel the whole network, countries lose access  
537 to many goods they need, leading to internal problems and possibly collapse, as happened in the Late Bronze Age (Linkov  
538 et al., 2024). Important insights could be gained here by applying insights from quantitative history to the last 100 years,  
539 as proposed by Hoyer et al. (2024). This could be built upon by using historical worst cases and using them as downward  
540 counterfactuals to create more realistic and comprehensive scenarios (Woo, 2019).

541

542 Furthermore, all those research topics that need further exploration and studies like ours should be regularly re-assessed. As the  
543 Russian invasion of Ukraine has shown, major disruptions in the food network can and are likely to happen again (Miller et al.,  
544 2024). They reshuffle existing trade connections, making research like this less accurate as time passes.

#### 545 **4.4.2 Decreasing vulnerability to global hazards**

546 Since the global food system is vulnerable to major disruptions, it is of high priority to decrease these vulnerabilities. Myers et al.  
547 (2022) suggest a list of interventions that could decrease the vulnerability of agriculture to climate change. Some of these  
548 suggestions would also help here, like having more diverse crops to ensure flexibility with respect to climate conditions or  
549 strengthening international trade agreements to ensure that the flow of food is stable. This also ties in with the criticism of  
550 concentration in the food system by Clapp (2023). These concentrations on all levels of the food system increase the risks of  
551 collapse and need to be decreased, especially for the safety of people in net food importing countries (Yıldırım and Önen, 2024).

#### 552 **4.4.3 Increasing resilience after a global catastrophe**

553 It is not only important to decrease the risk of a hazard spiralling into a catastrophe, but also to prepare if it happens despite  
554 precautions (Cotton-Barratt et al., 2020). The complex events following the described catastrophes would constitute major crises,  
555 but historical evidence suggests societies can withstand such a polycrisis by building resilient infrastructure, maintaining the ability  
556 to respond effectively at scale, and having high social cohesion (Hoyer et al., 2023). We should increase the overall resilience of  
557 the food system and see the resilience of our food supply chains not as something that aims to bring back a system to the status  
558 before the catastrophe but as a system that is able to persist, adapt and transform even under intense pressure (Wieland and Durach,  
559 2021). This can be accomplished by a variety of strategies concerning infrastructure, politics and technology (Jagtap et al., 2024).  
560 One way is to incorporate contingency plans into our infrastructure. The Russian invasion of Ukraine has shown that it is very  
561 difficult to change your trading partners on short notice without a plan or infrastructure (Jagtap et al., 2022) in place. If plans are  
562 drawn up that highlight what is needed for different scenarios, this could be taken into account when new infrastructure is built.  
563 Also, our food system is very dependent on large amounts of industrial inputs like fertilisers or water use. This has been identified  
564 as one the main problems in agriculture right now (Foley et al., 2011). If we could reduce the need for inputs now, this would both  
565 increase sustainability, but also make it easier to cope after catastrophe when fewer inputs are available. Another important avenue  
566 is to ensure there is a variety of resilient foods that could be scaled up massively if other parts of the food system fail. Examples  
567 for ASRSs include seaweed (Jehn et al., 2024), protein from natural gas (García Martínez et al., 2022) hydrogen (García Martínez  
568 et al., 2021), sugar from fibre (Throup et al., 2022), and greenhouses (Alvarado et al., 2020). The crops we use are also adapted to  
569 current climate conditions and show very little diversity (Clapp, 2023). This low diversity in crops has recently also been  
570 highlighted as an inhibiting factor in maintaining crop production during ASRS (McLaughlin et al., 2024). Finally, establishing  
571 political agreements (for example trade agreements that also consider global catastrophes) before catastrophes could reduce the  
572 need to negotiate in the aftermath of a global catastrophe. For example, Wellesley et al. (2017) discuss this in the context of choke  
573 points that critical food corridors could be agreed upon in collaboration with the United Nations and the World Food Programme  
574 to offer alternative routes should the choke points become blocked.

## 575 **5 Conclusion**

576 Our research highlights the substantial impact of global catastrophic risks on the food system, both directly through yield reductions  
577 and indirectly via trade disruptions. Among the scenarios we studied, abrupt sunlight reduction scenarios disrupt trade communities  
578 more than global catastrophic infrastructure loss due to their uneven spatial distribution, particularly affecting higher-latitude  
579 countries that are key food exporters. Our analysis focuses solely on yield reduction effects and does not consider second-order  
580 economic effects and political events. Even so, the impacts are already substantial. If second-order effects would be taken into

581 account, it is plausible that GCIL could lead to a larger disruption, as it directly impacts the industrial base that is needed to cope  
582 with catastrophes.

583 The results show that in both kinds of scenarios, the food system would be massively disrupted, underscoring the urgent need for  
584 better preparation. The food system's reliance on a few major exporters, especially the United States, amplifies its vulnerability.  
585 This concentration means that any yield reduction or removal of these countries from the trade network results in major disruptions.  
586 We suggest diversifying crop production, securing trade agreements, and developing resilient food sources that can be rapidly  
587 scaled in crisis scenarios.

588 We need both preventive and adaptive strategies to safeguard the global food system. Future research should continue to explore  
589 these dynamics, incorporating broader aspects of the food supply chain and potential cascading effects. Such efforts are crucial,  
590 especially in light of recent global disruptions like COVID-19 and the Russian invasion of Ukraine, which have highlighted the  
591 food system's vulnerabilities. Successfully navigating global catastrophes requires understanding and preparation, necessitating  
592 both research efforts and policy interventions.

### 593 **Data and code availability**

594 The most recent data can be directly downloaded from the Food and Agriculture Organization:

- 595 1) Trade: <http://www.fao.org/faostat/en/#data/TM>
- 596 2) Production: <http://www.fao.org/faostat/en/#data/QC>

597 The model code (with additional documentation) can be found at: <https://github.com/allfed/pytradeshifts> (Jehn and Gajewski,  
598 2024).

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601

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603

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842

# Supplemental information for

## “Food trade disruption after global catastrophes”

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### 1 Additional features of the model

During development of the model additional features were implemented to study the changes of the trade communities in more detail. For the main text we used the most intuitive measures. However, the additional features can be used to explore the disruptions in more detail. Below, we provide an overview of select features we believe could aid other researchers using the model outlined in this study. For a comprehensive understanding of the model's capabilities, see the repository: <https://github.com/allfed/pytradeshifts> (Jehn and Gajewski, 2024).

#### 1.1 Measuring changes in the trade flows

##### 1.1.1 Frobenius measure

The Frobenius measure computes the distance between graphs G1 and G2 as the distance between their adjacency matrices:

$$r(G1, G2) = \sqrt{\sum_{ij} (a_{ij}^{G1} - a_{ij}^{G2})^2} \quad (1)$$

Where  $a_{ij}^G$  represents the element  $i,j$  of an adjacency matrix of a graph  $G$  (Shvydun, 2023). In the context of the food trade system the Frobenius measure represents how much the network has changed between the compared scenarios/graphs.

## 28 1.2 Measuring the status of the network before and after disturbance

### 29 1.2.1 Community satisfaction

30 The sum of imports to a country from within its community divided by the sum of all imports to said country. This allows us  
31 to identify how much of a country's food demand is met by their current trade community (Ji et al., 2014; Wang et al., 2023).

32

### 33 1.2.2 Node stability

34 Node stability is a measure of how easily each country can replace their import partners, based on their political stability, trade  
35 volume and geographical distance. For this index, we gather data from The World Bank's governance indicator and calculate  
36 the mean of all distinct indicator values. Given that the values typically fall within the range of [-2.5, 2.5], we standardise the  
37 data to ensure the outcome lies within the range [0, 1] (Ji et al., 2014; Wang et al., 2023). Node stability  $S$  of node  $j$  is given  
38 by:

$$39 \quad S(j) = \sum_i P_i d_i^{out} r_{ij}^{-1} \quad (2)$$

40 where the sum is over all other nodes (countries).  $P_i$  is the stability index of country  $i$ . The variable  $d_i^{out}$  denotes the normalised  
41 out-degree centrality, indicating the proportion of total exports attributed to country  $i$ . Additionally,  $r_{ij}$  signifies the distance  
42 between countries  $i$  and  $j$ . A larger value signifies a higher capacity to ensure consistent trade.

43

### 44 1.2.3 Network stability

45 Stemming from node stability it is:

$$46 \quad \sum_j d_j^{in} S(j) \quad (3)$$

47 Where  $S(j)$  is the stability of node  $j$ , and  $d_j^{in}$  is the (normalised) in-degree of node  $j$  representing the fraction of all imports that  
48 the country  $j$  is responsible for. This therefore represents the weighted stability of all nodes in the network and thus the overall  
49 stability of the network.

50

### 51 1.2.4 Betweenness

52 The betweenness centrality of a node is determined by adding up the proportion of all possible shortest paths that go through  
53 that particular node. When calculating the overall betweenness for the entire graph, it involves taking the average across all  
54 nodes. As a trade graph falls under the category of flow graphs, when calculating the shortest paths, we treat the edge weights  
55 as the inverses of trade volumes.

56

### 57 1.2.5 Clustering

58 The clustering coefficient of a node gauges the proximity of its neighbours to forming a clique, or complete graph. In the  
59 context of directed and weighted graphs, clustering is determined by the geometric average of the edge weights within the

60 (directed) subgraph (Fagiolo, 2007). To assess the overall graph clustering, we calculate the average clustering coefficient  
61 across all nodes.

### 62 **1.3 Simulating the more difficult trading conditions after catastrophe**

63 The model is now also capable of simulating the challenges of long distance trade after global catastrophes. To represent this  
64 we used a gravity based model of trade, which scales the exports downward with increasing distance. The gravity model of  
65 trade is an empirical model in economics, in which, similar to Newtonian gravity, trade between countries is attracted by their  
66 economic size (like mass) and hampered by distance (like dispersion of the field). In short, bigger economies trade more, and  
67 distance makes trade more expensive (Karpiarz et al., 2014). It relates trade volume,  $T_{ij}$ , between two countries,  $i$  and  $j$ , to the  
68 product of their GDP's, i.e.  $Q_i Q_j$ , and to the geographic distance (country centroid to country centroid in km),  $r_{ij}$ , between  
69 them. The simplest form of the gravity equation for the bilateral trade volume is (Karpiarz et al., 2014):

$$70 \quad T_{ij} = G \frac{Q_i Q_j}{r_{ij}^a} \quad (4)$$

71 Where  $a$  is the distance coefficient obtained from data and  $G$  is a constant scaling parameter. To simulate more/less difficult  
72 trading conditions we can modify the trade volumes by changing the coefficient  $a$  such that it is larger/smaller. Thus, in our  
73 model we multiply the trade matrix by  $r_{ij}^{-b}$ , changing (1) into

$$74 \quad T_{ij} = G \frac{Q_i Q_j}{r_{ij}^{a+b}} \quad (5)$$

75 Where  $b$  is our control parameter. When  $b > 0$  the trade volume is decreased with distance, when  $b=0$  nothing changes, and  $b$   
76  $< 0$  trading becomes easier. For both global catastrophic infrastructure loss and abrupt sunlight reduction scenarios we explored  
77 a variety of values for  $b$ , based on the historical range (see repository for calculation of past values).  
78

## 79 **2 Additional information for the methodology**

### 80 **2.1 Choice of community detection algorithm**

81 We acknowledge that the Louvain algorithm, being a modularity-based method, may not be the most accurate approach  
82 (Fortunato and Hric, 2016); however, due to its prevalence in previous studies and simplicity of operation, we find it to be the  
83 most adequate choice. This choice is further justified because we do not need to consider ourselves with the “ground truth”  
84 labelling of community memberships since we are interested in changes in the community structure. That said, the model  
85 implementation allows the use of more advanced approaches like the Leiden algorithm (Traag et al., 2019) or Infomap  
86 algorithm (Rosvall et al., 2009).

### 87 **2.2 Explanation of re-export algorithm**

88 Should we use the trading data directly for inferring the trade network structure, in some instances, the calculated domestic  
89 supply of domestically produced goods would turn out negative which is, of course, erroneous (Croft et al., 2018). This error  
90 happens because the trade data do not differentiate if something was genuinely produced in a country or just passed through it  
91 (re-exported). The re-export algorithm aims to work around this by estimating the actual trade amounts. Therefore, yield  
92 reductions due to the scenarios can be directly applied to the trade flows in the model. For example, if the yield of the United  
93 States drops by 30 %, all outgoing trade flows from the US would reduce by 30 % as well. In global catastrophes, states would  
94 likely decrease their exports further to protect their own population. However, this model tries to estimate the changes implied  
95 by the yield reduction alone to isolate this effect and does not consider additional policies that might change exports.

### 96 **2.3 Network resilience**

97 After a global catastrophe, it seems likely that further instability will follow. This could result in the complete removal of  
98 countries from the network (e.g. by destruction through war or import/export restrictions and bans). To simulate such events,  
99 we assessed how resilient the network is against random and structured removal of nodes by using the methodology from  
100 Restrepo et al. (2008).

101 The objective is to anticipate when the network crosses the percolation threshold, which means the point where it loses the  
102 majority of its connectedness. Our approach involves constructing an attack vector  $W$ , where  $W_i = 1$  signifies the removal of  
103 node  $i$ , and 0 denotes its retention. Subsequently, we compute a matrix,  $F = R(1-W)$ , where  $R$  represents the adjacency matrix  
104 of the graph. The indicator for network percolation is the largest eigenvalue of matrix  $F$ . If it surpasses 1, the network  
105 percolates; if it falls below 1, the network collapses, leading to the disappearance of the giant connected component (Newman,  
106 2018).

107 We consider two attack strategies:

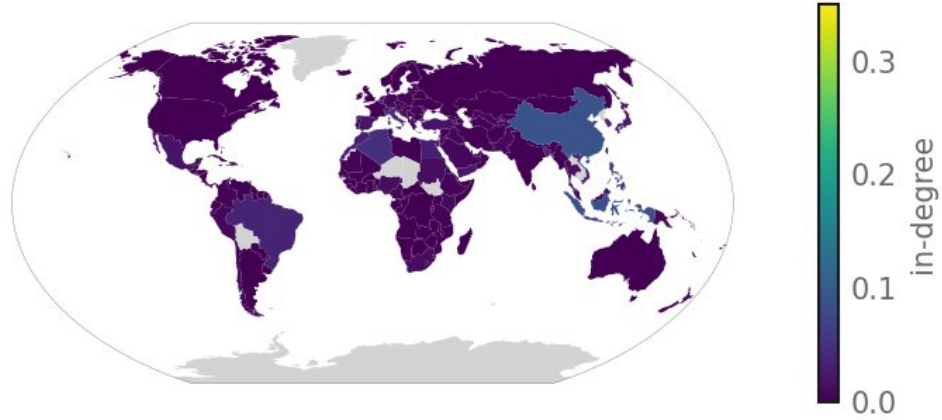
- 108 - Export-Weighted: We remove nodes in order highest to lowest by their out-degree (fraction of total export)
- 109 - Random: We remove nodes at random and average the results over several realisations.

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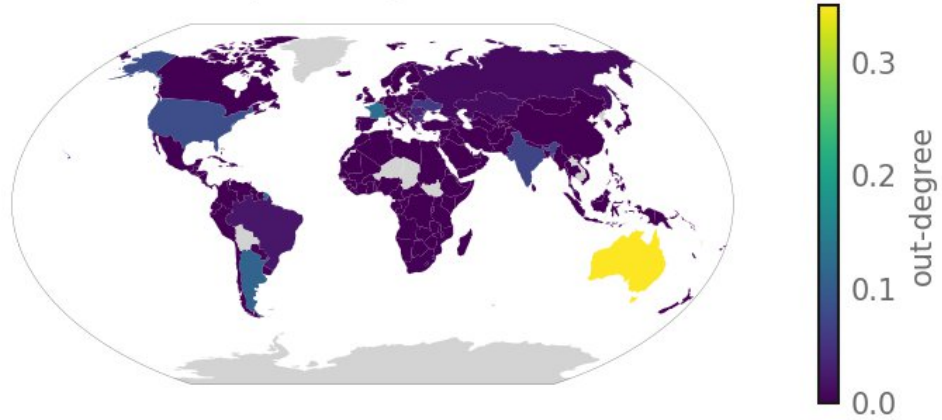
111 Initially, we also considered more advanced attack strategies, such as entropic degree used in power transmission grid  
112 vulnerability assessments (Bompard et al., 2009), but preliminary results showed them to not be much more effective than the  
113 simple “highest export first” approach. We thus opted not to include them here, for the sake of methodological simplicity  
114 without losing generality of our results.

115

in-degree for wheat with base year 2022  
in scenario: Abrupt Sunlight Reduction Scenario



out-degree for wheat with base year 2022  
in scenario: Abrupt Sunlight Reduction Scenario



118  
119  
120 **Figure S1: In and out centrality for the abrupt sunlight reduction scenario.**  
121



122 **3.2 Node stability and community satisfaction for wheat**

123 **3.2.1 Changes in community satisfaction**

124 Community satisfaction indicates a country's ability to meet its import demands from within its trade network. During global  
125 catastrophic infrastructure loss, overall satisfaction remains relatively stable across countries due to similar global yield  
126 reductions (Figure S2). Consequently, nations cannot increasingly depend on external trade partners, as these partners also  
127 experience reduced export capacity.

128

129 During abrupt sunlight reduction scenarios, the impact is more pronounced (Figure S2). The United States and Somalia are  
130 severely affected. The United States, a major food exporter, typically sources wheat from Canada. However, Canada's export  
131 capability is significantly hindered in these scenarios, leaving the U.S. reliant on non-community imports. Similarly, Somalia,  
132 which imports most of its wheat from Ukraine, faces challenges as Ukraine's exports decline sharply. This trend is observed  
133 to a lesser degree in other regions like North America and Central Asia as well.

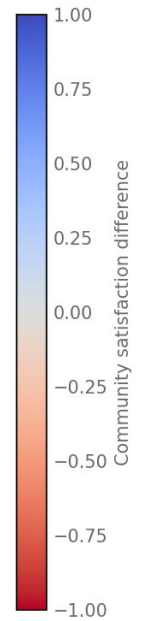
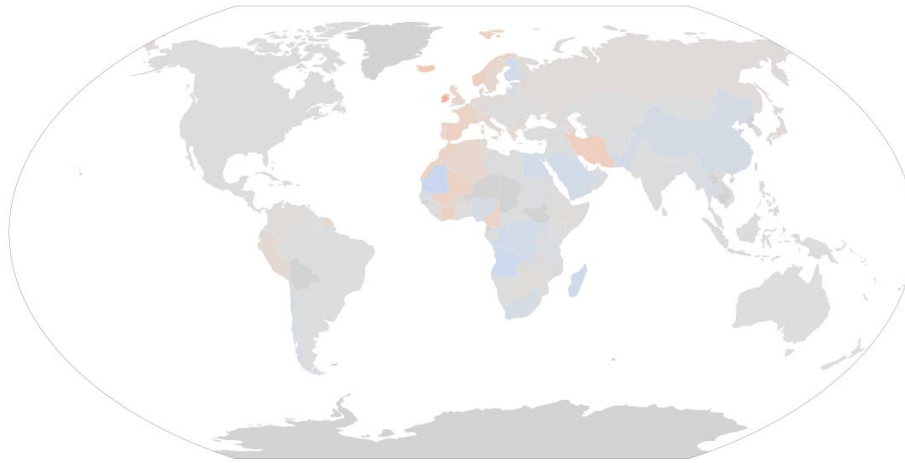
134

135 Surprisingly, we also have some countries which have an improved community satisfaction after abrupt sunlight reduction  
136 scenarios (e.g. Belarus). This is caused by the large extension of the trade community with Russia as its centre. This results in  
137 many countries having the majority of their trade partners suddenly in their trade community, which increases the satisfaction.

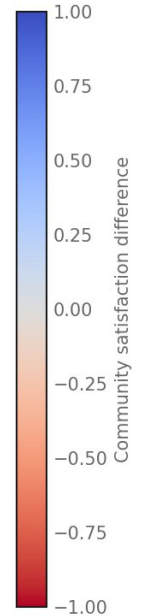
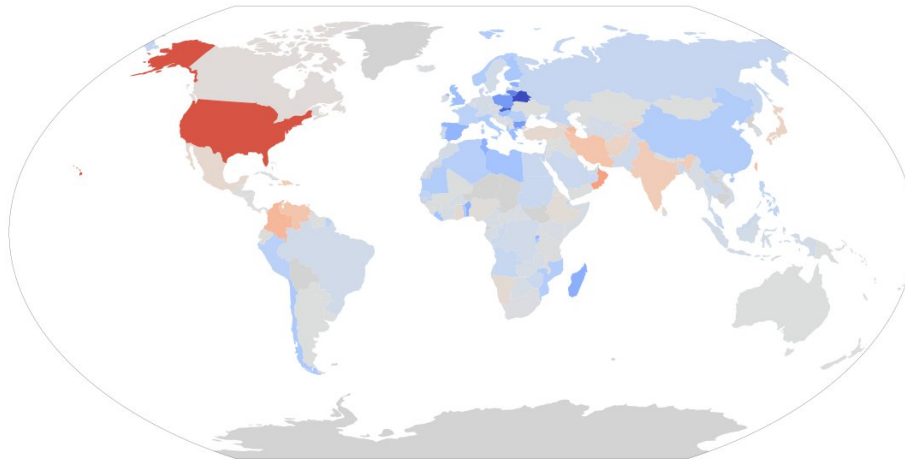
138

139 Notes that these numbers are scaled by the overall imports and not the actual amount of food that a country needs. If this was  
140 the measure, the values would also be worse for global catastrophic infrastructure loss, but likely still very uniformly worse  
141 globally. There also would not be any positive changes in abrupt sunlight reduction scenarios.

Community satisfaction difference for wheat with base year 2022  
in scenario: Global Catastrophic Infrastructure Loss



Community satisfaction difference for wheat with base year 2022  
in scenario: Abrupt Sunlight Reduction Scenario



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**Figure S2: Differences (alternative scenario minus base scenario) in community satisfaction in comparison to the 2022 wheat trade network for global catastrophic infrastructure loss and abrupt sunlight reduction scenarios. Community satisfaction has a range of 1 (all needs satisfied from within the community) to 0 (no needs satisfied from within the community). Therefore, a value of 1 for the relative change would be a country whose needs were not satisfied from their community before, but all needs are satisfied in the alternative scenario. Grey indicates no change in community satisfaction, blue increased community satisfaction and red decreased community satisfaction.**

### 150 **3.2.2 Changes in node stability**

151 Node stability is a measure of how easily a country can replace its trade partners, based on proximity, trade volume and political  
152 stability. The values show that for global catastrophic infrastructure loss the node stability is relatively stable in comparison  
153 to the situation in 2022 (Figure 5). Only Central Europe and North Africa have clearly negative values, meaning that those  
154 countries will have more difficulties replacing their trade partners. The most severely affected countries are Belgium, the  
155 Netherlands and Austria. A few countries also have slightly positive values. These are mostly concentrated in South-East Asia  
156 and the neighbouring countries of Argentina (Chile, Paraguay and Uruguay). These positive values are shaped by the proximity  
157 to Australia and Argentina, both major wheat exporters, which also do not use as much inputs like European countries and are  
158 therefore less affected by global catastrophic infrastructure loss.

159

160 We can see considerably larger changes of the node stability for abrupt sunlight reduction scenarios, but the overall trend is  
161 similar (Figure 5). Central European countries have difficulties replacing their trade partners, as all countries around them  
162 have considerably lower yields as well. In this scenario the same is true for the United States, which does not have any close  
163 countries which could replace the loss of imports from Canada. In addition, Australia has a much decreased node stability  
164 here, as it has no countries it could replace its import losses with. However, the countries close to Australia can replace their  
165 import losses from elsewhere by importing from Australia. To a lesser extent this is also true for Argentina and its neighbouring  
166 countries.

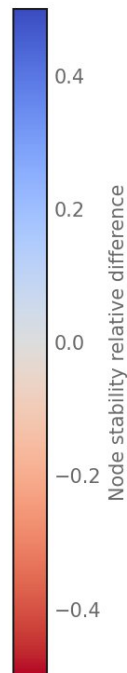
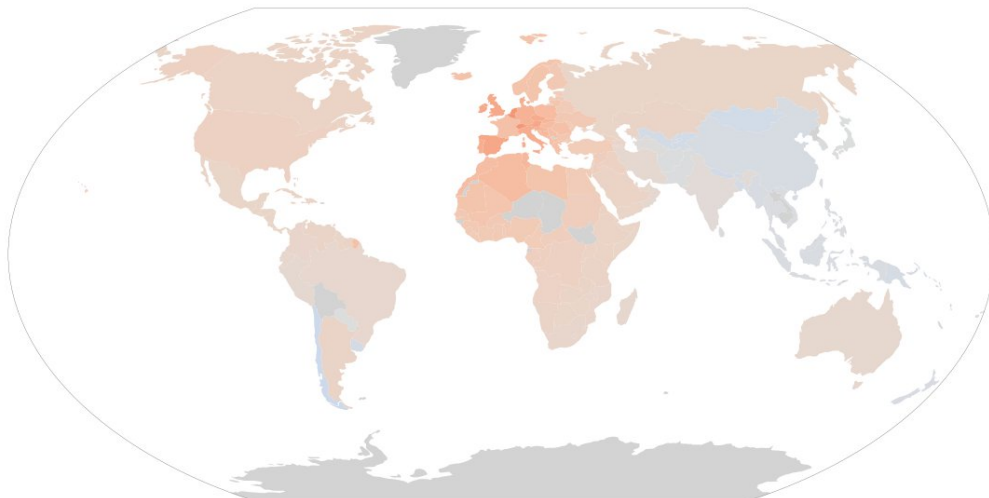
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168 The results show that most countries globally will have difficulties in finding new trading partners, with the exception of the  
169 countries who are close to Australia and Argentina, as those countries are less affected by global catastrophes due to their  
170 lower use of inputs like fertilisers and their more stable climate.

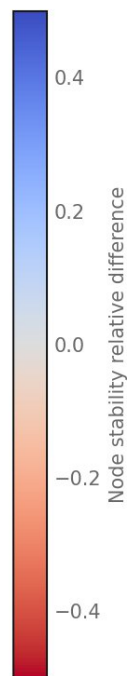
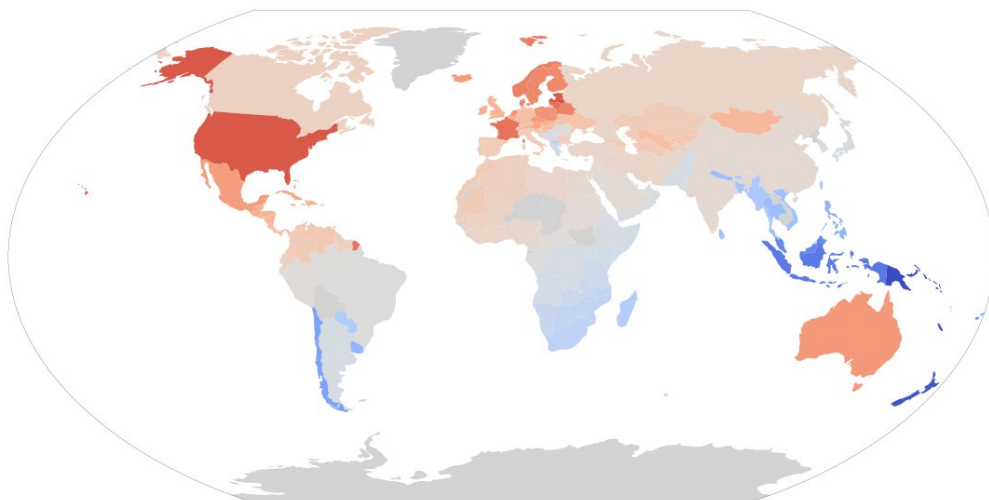
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Node stability relative difference for wheat with base year 2022  
in scenario: Global Catastrophic Infrastructure Loss



Node stability relative difference for wheat with base year 2022  
in scenario: Abrupt Sunlight Reduction Scenario

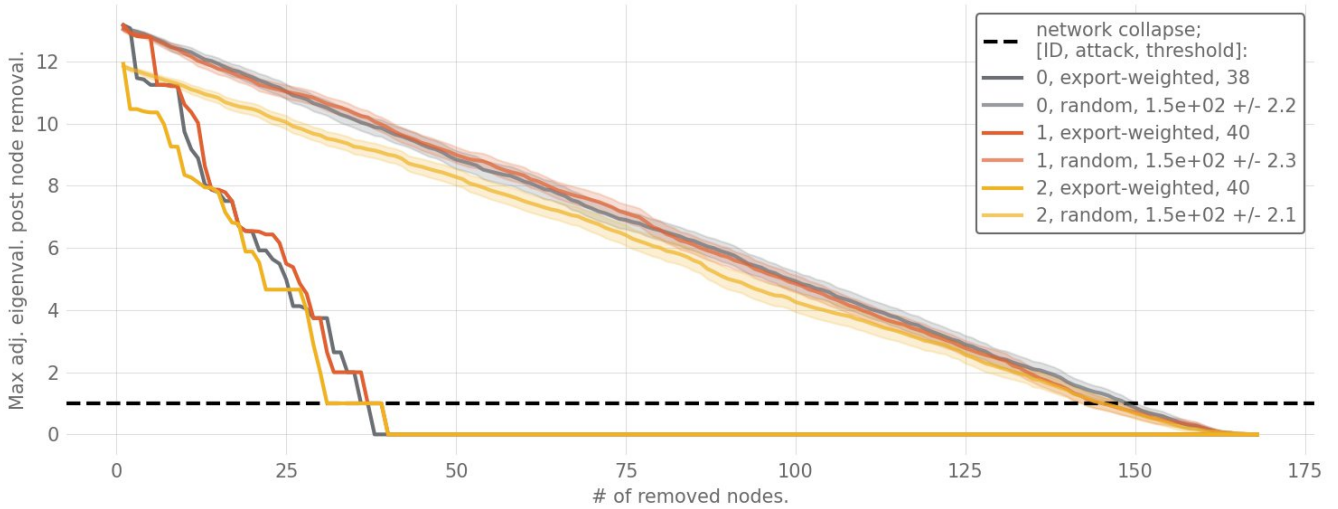


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174 **Figure S3: Relative changes in node stability in comparison to the 2022 wheat trade network for global catastrophic infrastructure**  
175 **loss and abrupt sunlight reduction scenarios. Relative change was used to make the values more easily comparable between**  
176 **scenarios. A value > 0 here means that the stability has increased (blue), while a value < 0 means that the stability has decreased**  
177 **(red). Grey indicates no change.**

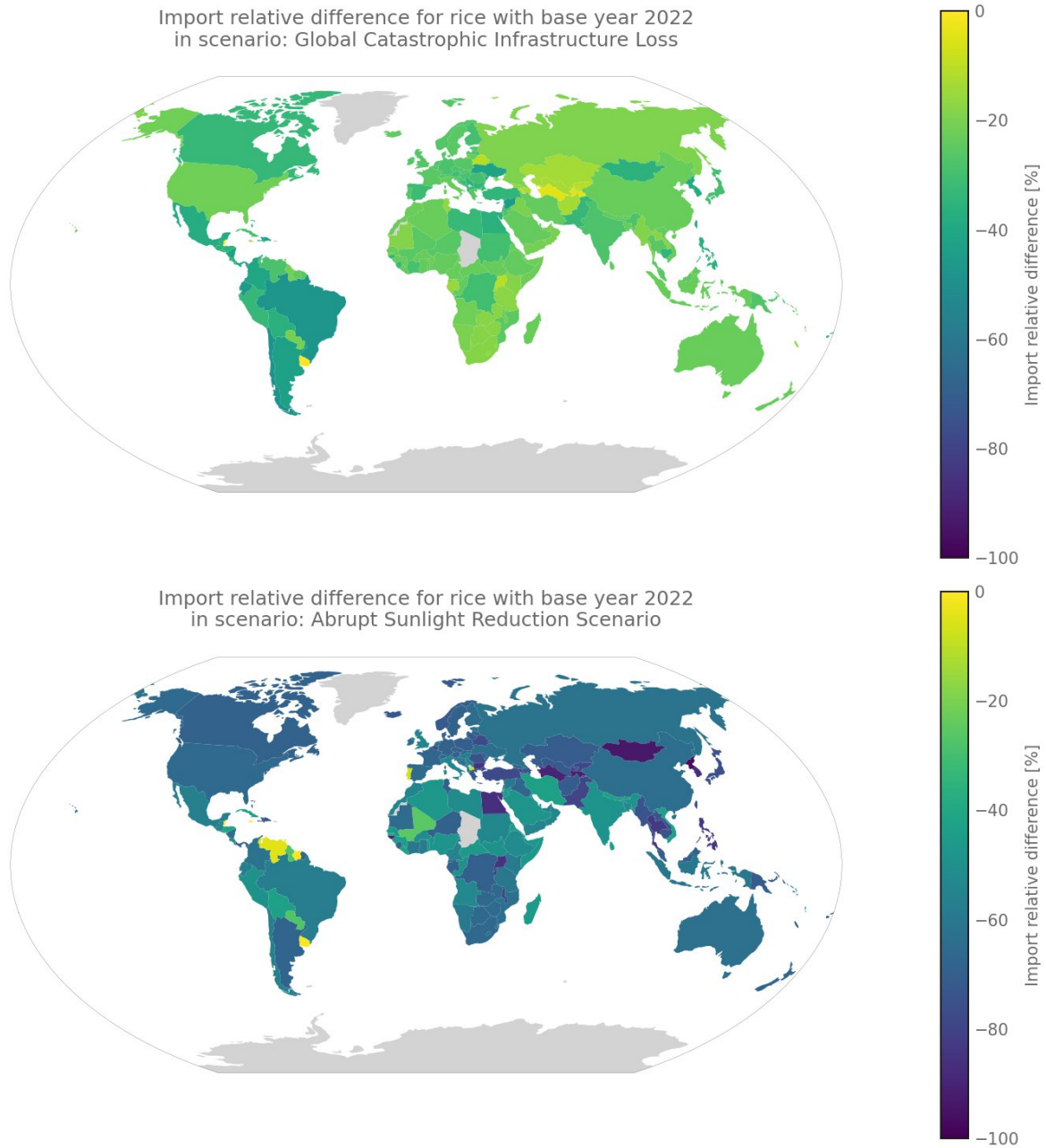
178 **3.3 Vulnerability against loss of nodes**

179 The scenarios vary in how vulnerable the network is to node removal, but the distinctions are minor (Figure S4). The GCIL  
180 network (shown in orange lines) behaves similarly to the current network (grey lines). In the ASRS (yellow lines), initial  
181 stability is lower compared to the others and reaches the collapse threshold slightly sooner, although not by much, implying  
182 that the yield reduction changes the trade communities, but the underlying structure of the network stays very similar. All three  
183 networks collapse much faster when the most exporting nations are removed first.



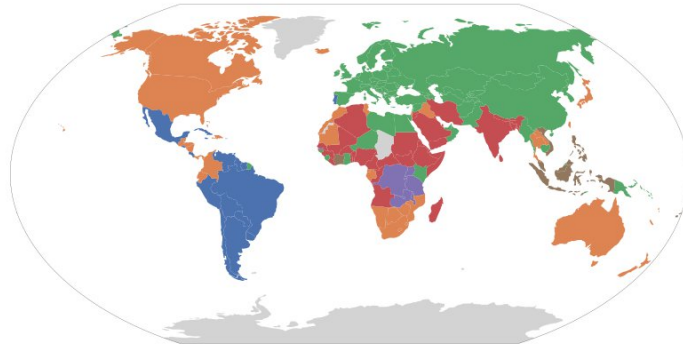
184

185 **Figure S4: Vulnerability of the different scenarios for wheat to the removal of nodes. ID 0 = wheat trade today, ID 1 = global**  
186 **catastrophic infrastructure loss, ID 2 = abrupt sunlight reduction scenario. Dotted line marks the collapse threshold of the network.**

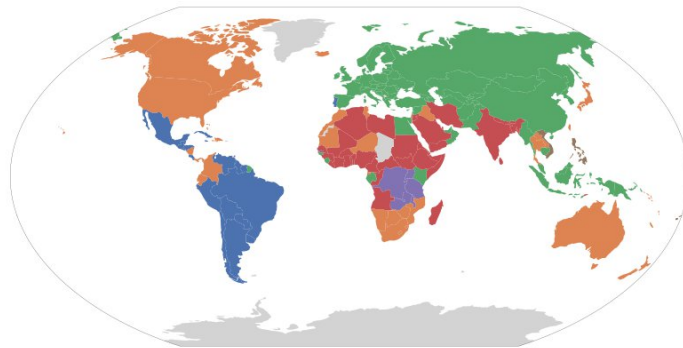


189 **Figure S5: Relative changes in rice imports after global catastrophic infrastructure loss and abrupt sunlight reduction scenarios in**  
190 **comparison to today.**  
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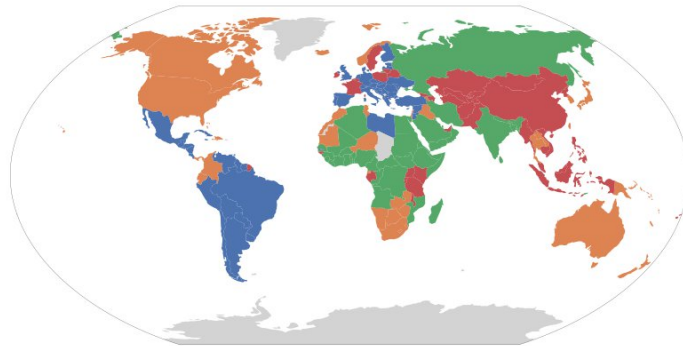
Trade communities for rice with base year 2022



Trade communities for rice with base year 2022  
in scenario: Global Catastrophic Infrastructure Loss



Trade communities for rice with base year 2022  
in scenario: Abrupt Sunlight Reduction Scenario



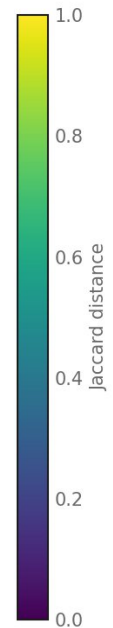
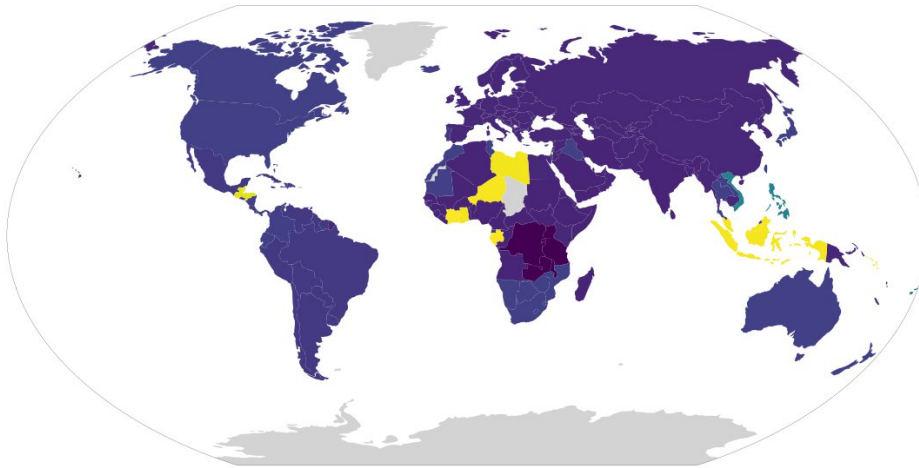
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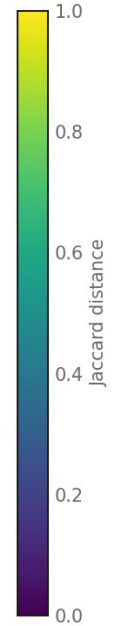
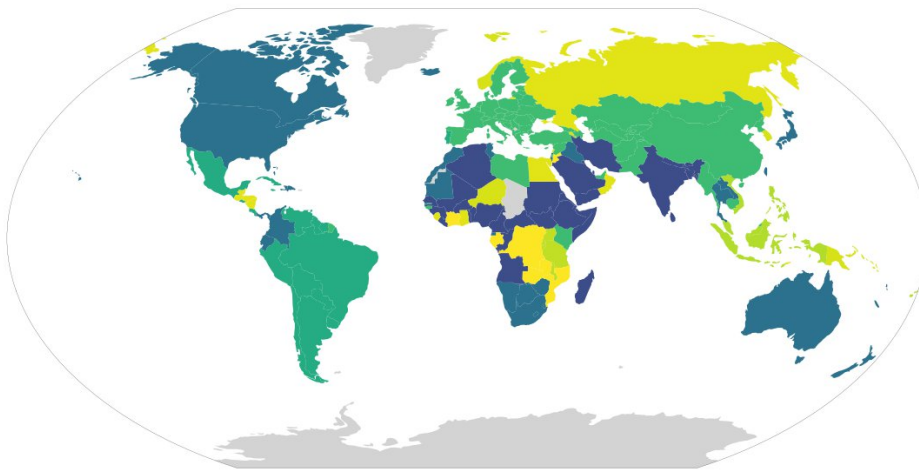
196 **Figure S6: Trade communities for rice in 2022 and after yield reduction due to global catastrophic infrastructure loss as well as**  
197 **abrupt sunlight reduction. The colours show which countries belong in which trade communities.**

198

Jaccard distance for rice with base year 2022  
in scenario: Global Catastrophic Infrastructure Loss



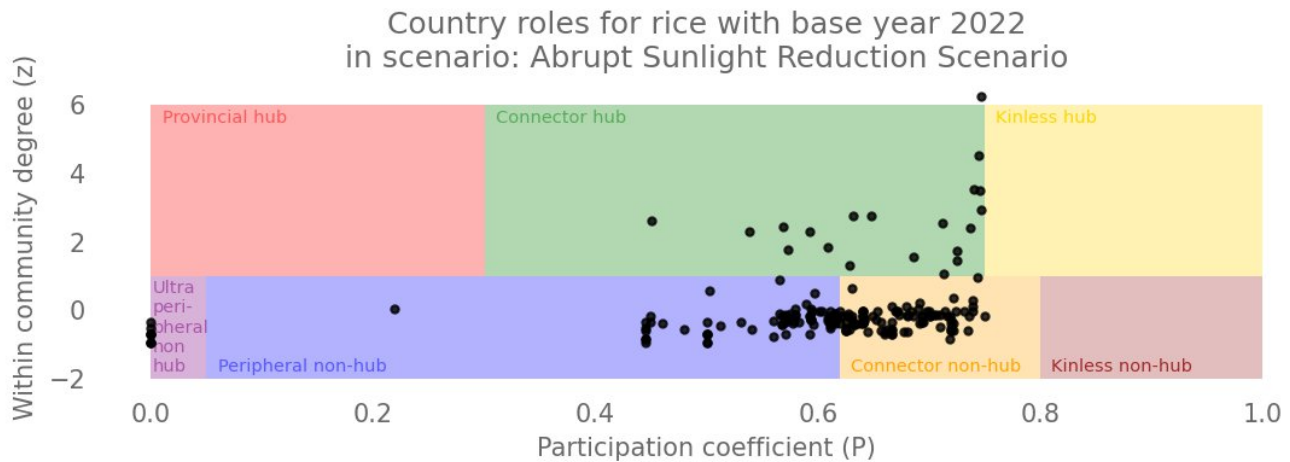
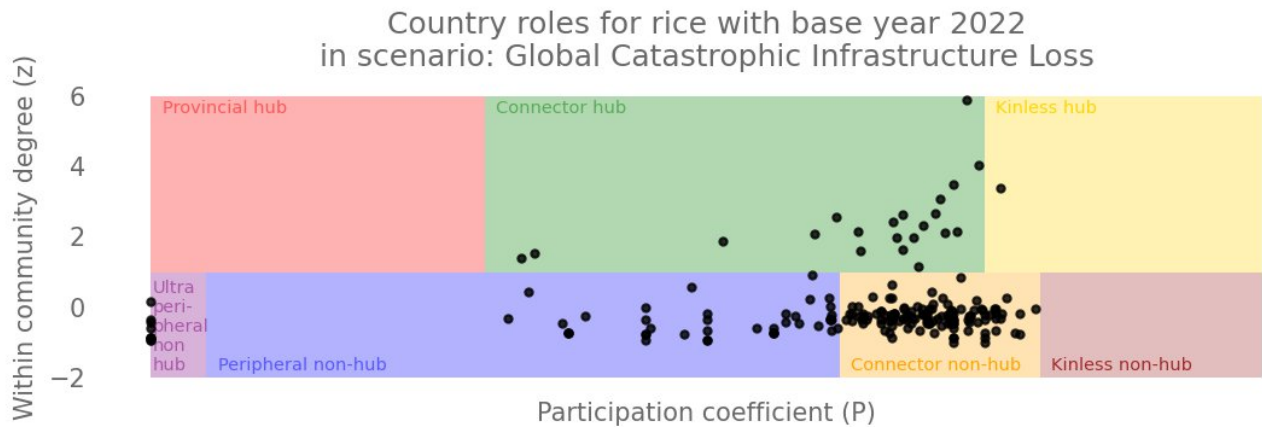
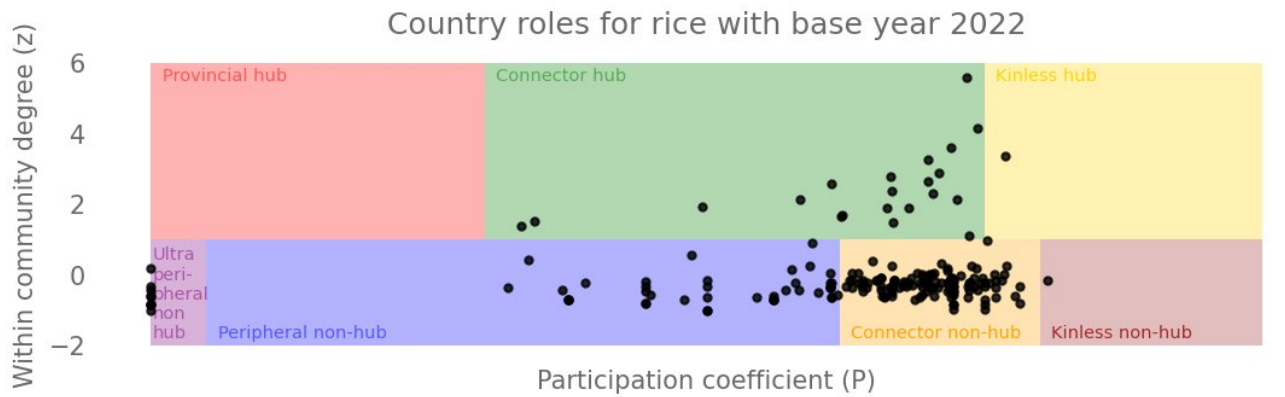
Jaccard distance for rice with base year 2022  
in scenario: Abrupt Sunlight Reduction Scenario



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**Figure S7: Changes in rice trade communities are plotted in comparison to the communities in 2022 after yield reduction due to global catastrophic infrastructure loss as well as abrupt sunlight reduction. Colours indicate how much the trade community of a country has changed. Yellow means the trade community of a country has changed completely, and dark blue means the trade community has not changed.**

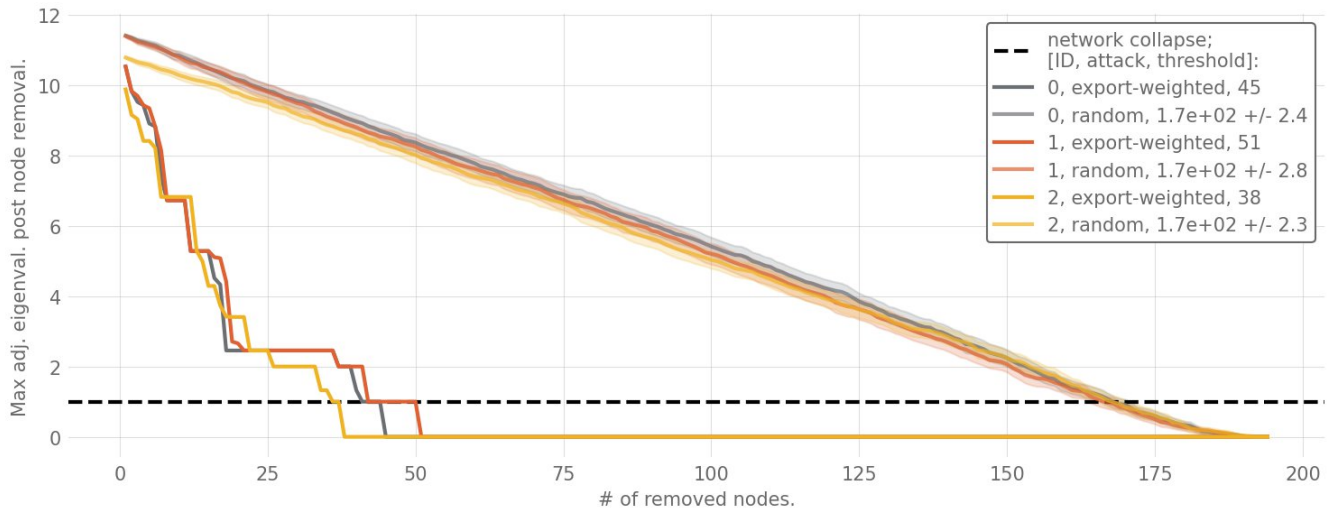




206

207 **Figure S8: Distribution of country roles in the global rice trade network in 2022 and after yield reduction due to global catastrophic**  
 208 **infrastructure loss as well as abrupt sunlight reduction based on within community degree and participant coefficient (see 2.4.1 in**  
 209 **main manuscript).**

210



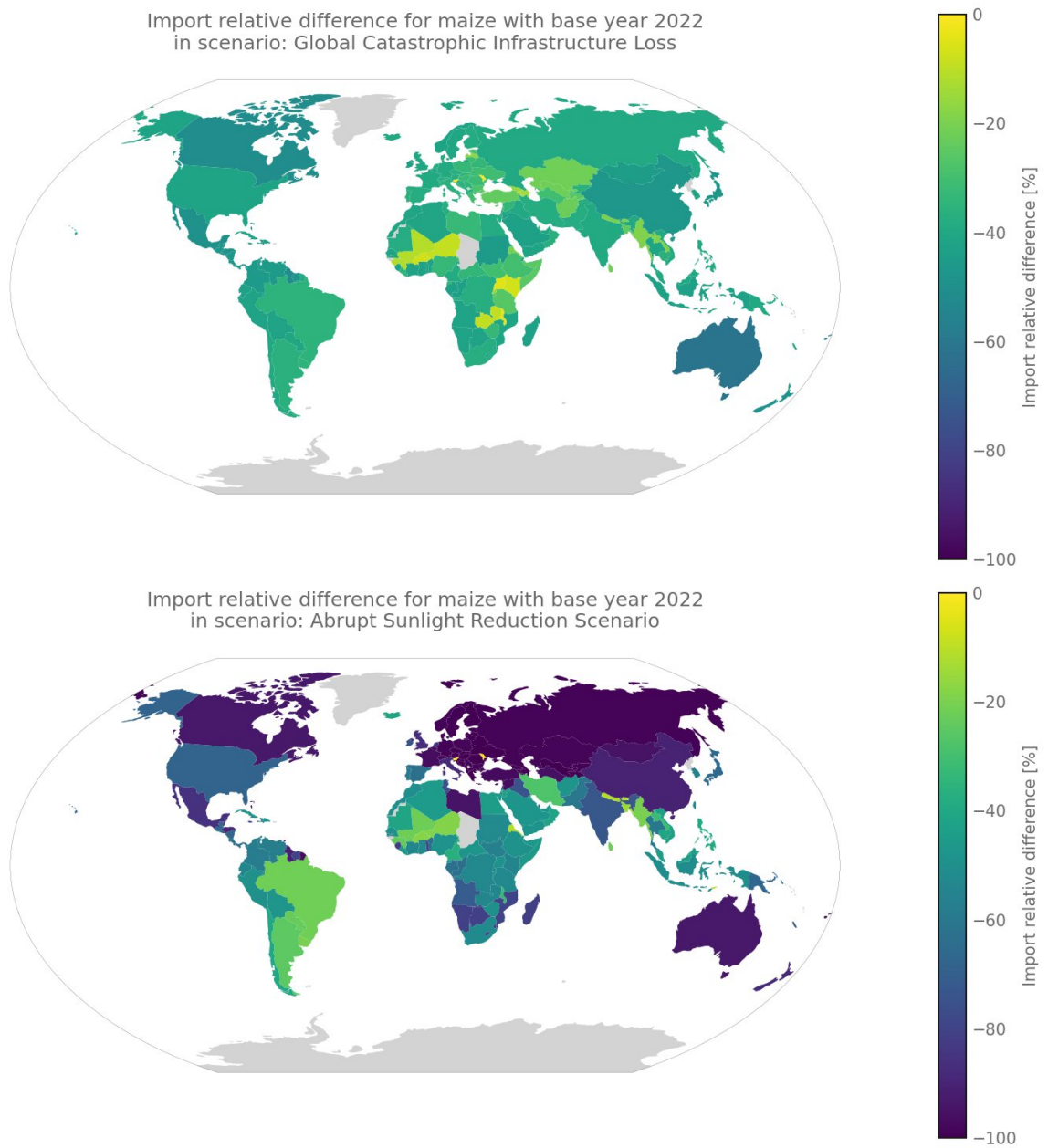
211

212 **Figure S9: Vulnerability of the different scenarios for rice to the removal of nodes. ID 0 = rice trade today, ID 1 = global catastrophic**

213 **infrastructure loss, ID 2 = abrupt sunlight reduction scenario. Dotted line marks the collapse threshold of the network.**

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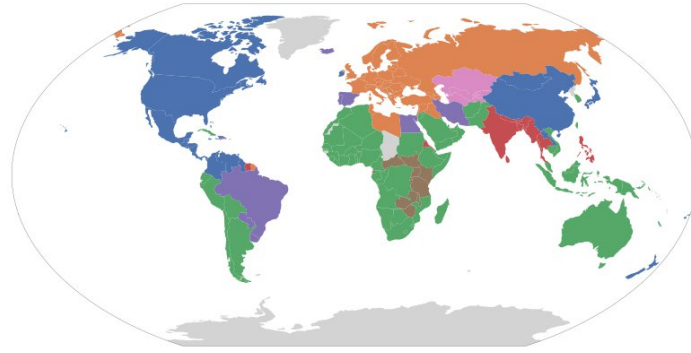


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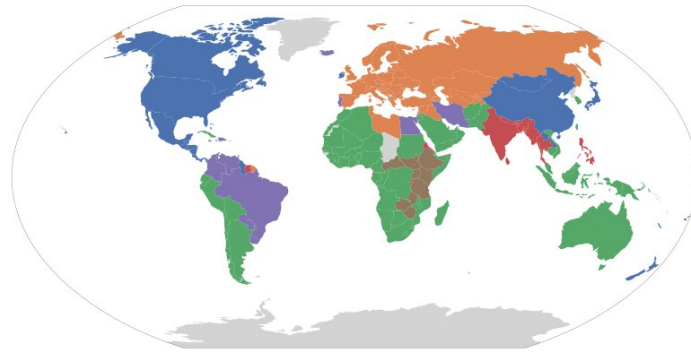
218 **Figure S10: Relative changes in maize imports after global catastrophic infrastructure loss and abrupt sunlight reduction scenarios**  
219 **in comparison to today.**

220

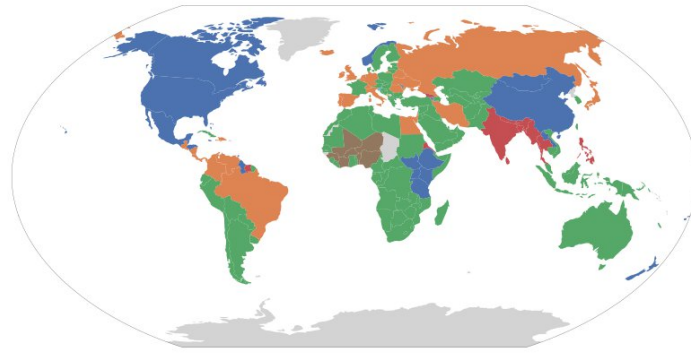
Trade communities for maize with base year 2022



Trade communities for maize with base year 2022  
in scenario: Global Catastrophic Infrastructure Loss



Trade communities for maize with base year 2022  
in scenario: Abrupt Sunlight Reduction Scenario



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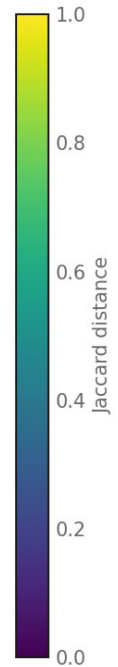
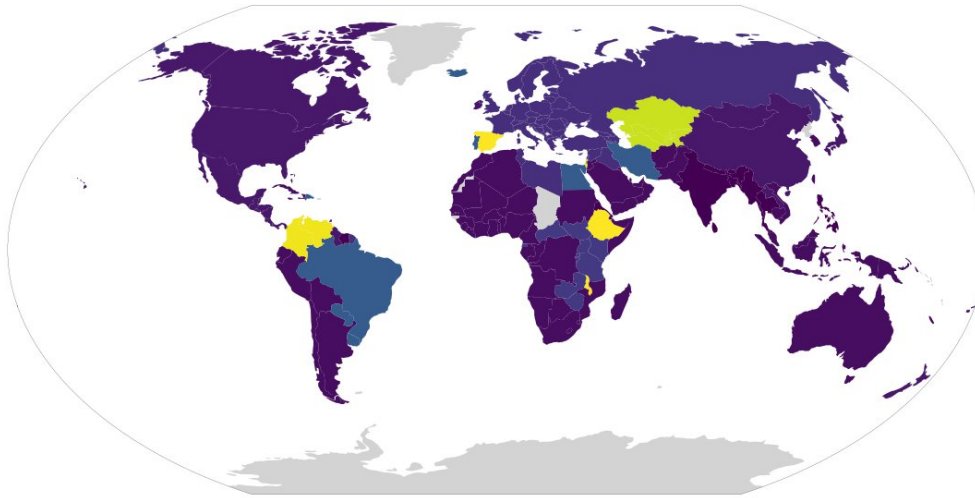
**Figure S11: Trade communities for maize in 2022 and after yield reduction due to global catastrophic infrastructure loss as well as abrupt sunlight reduction. The colours show which countries belong in which trade communities.**

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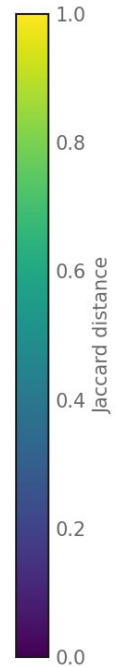
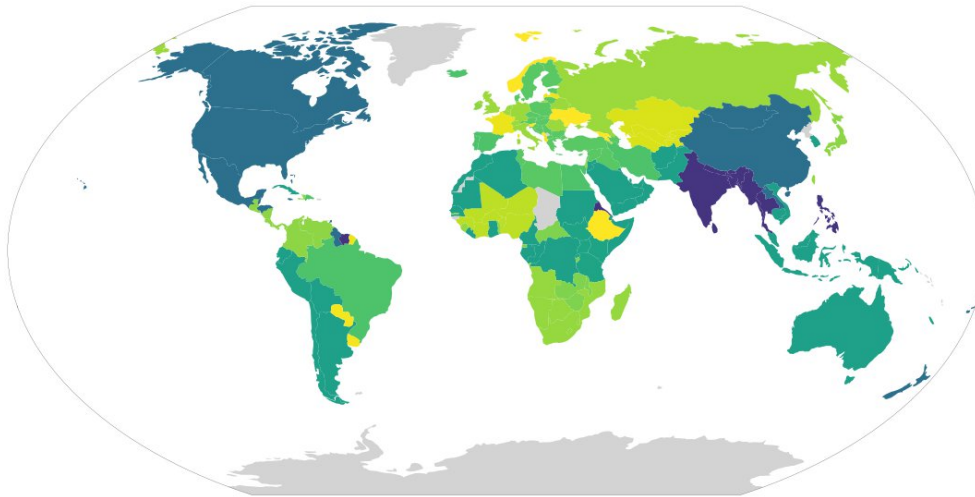
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Jaccard distance for maize with base year 2022  
in scenario: Global Catastrophic Infrastructure Loss



Jaccard distance for maize with base year 2022  
in scenario: Abrupt Sunlight Reduction Scenario



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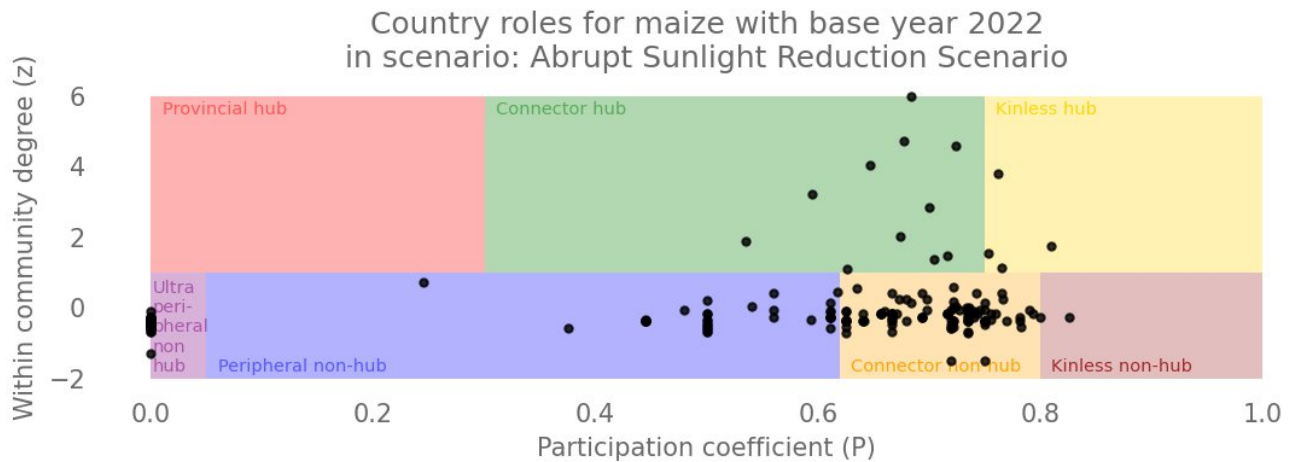
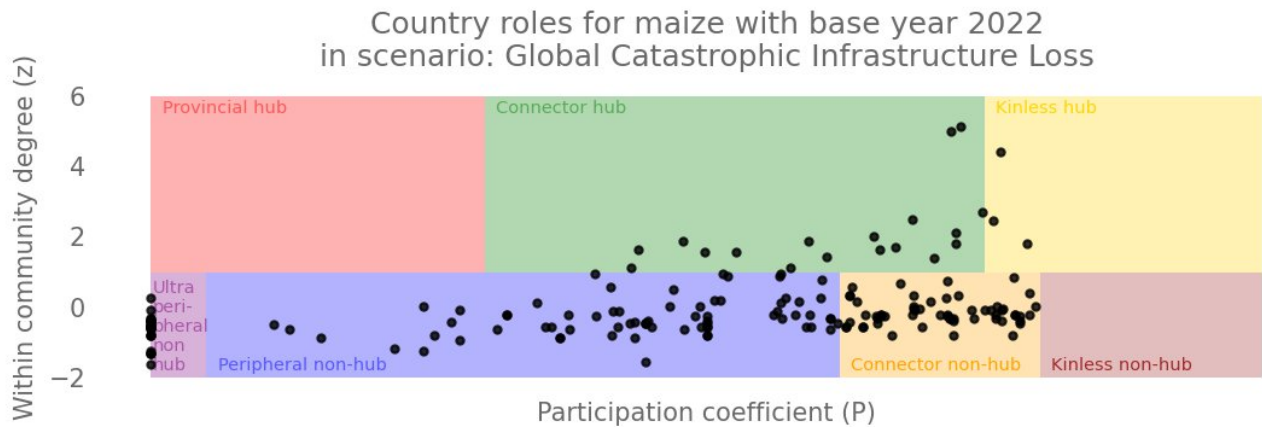
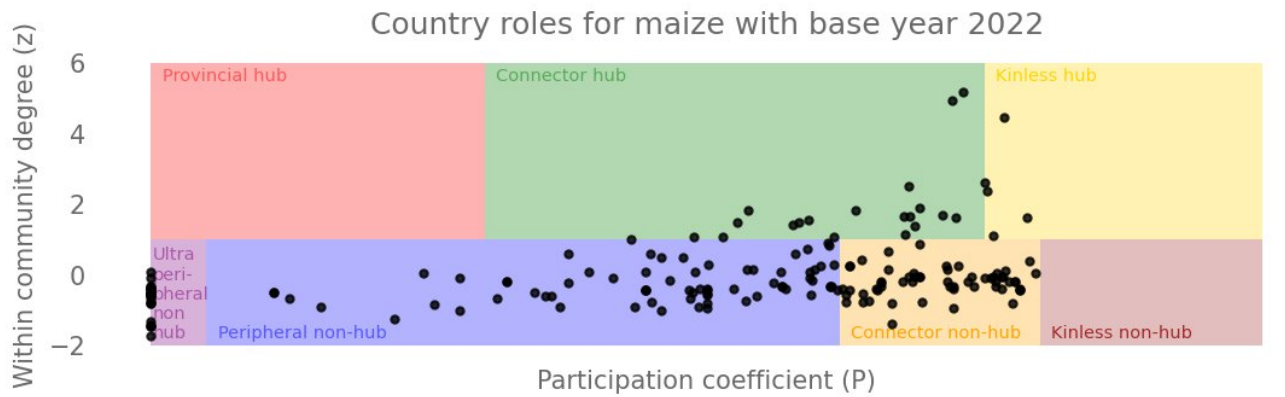
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**Figure S12: Changes in maize trade communities in comparison to the communities in 2022 after yield reduction due to global catastrophic infrastructure loss as well as abrupt sunlight reduction. Colours indicate how much the trade community of a country has changed. Yellow meaning the trade community of a country has changed completely, dark blue meaning the trade community has not changed.**



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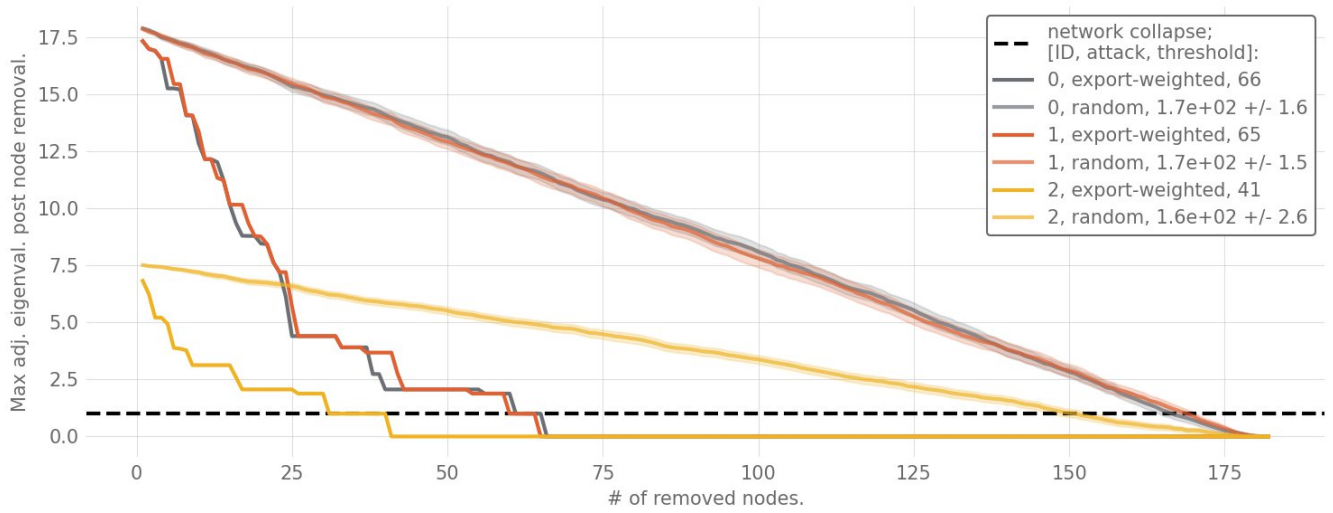
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**Figure S13: Distribution of country roles in the global maize trade network in 2022 and after yield reduction due to global catastrophic infrastructure loss as well as abrupt sunlight reduction based on within community degree and participant coefficient (see 2.4.1 in main manuscript).**



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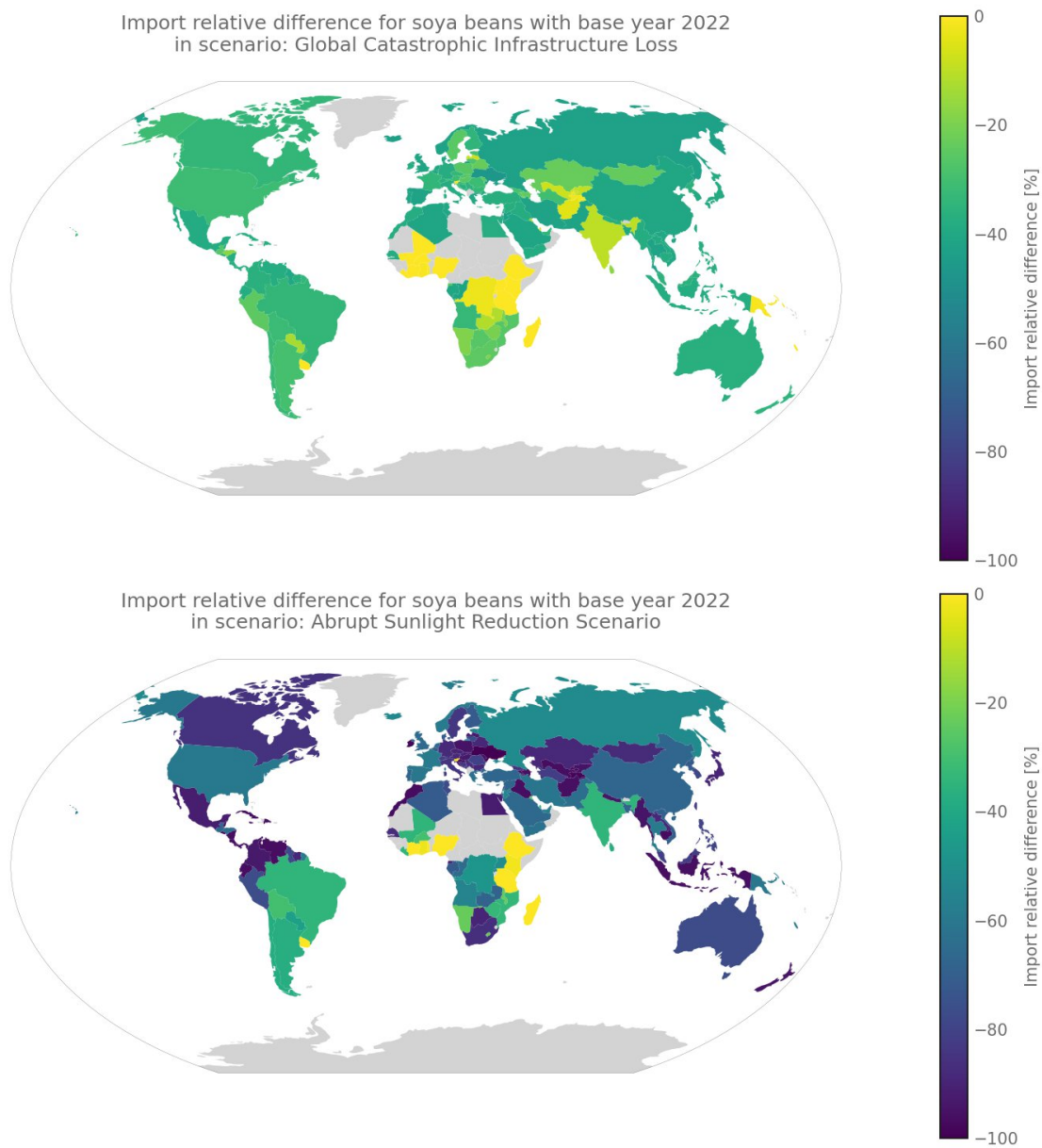
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**Figure S14: Vulnerability of the different scenarios for rice to the removal of nodes. ID 0 = maize trade today, ID 1 = global catastrophic infrastructure loss, ID 2 = abrupt sunlight reduction scenario. Dotted line marks the collapse threshold of the network.**

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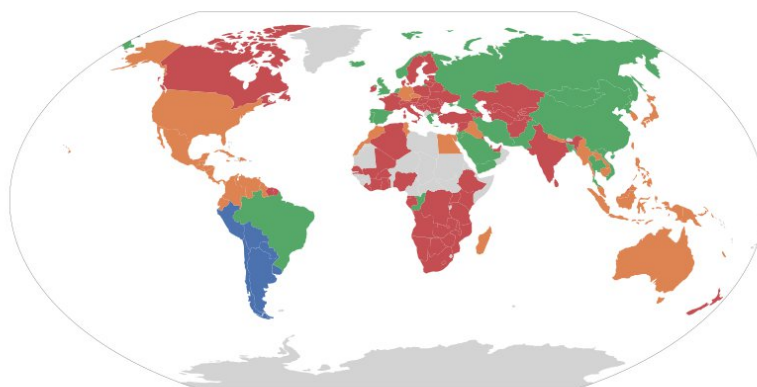
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244 **Figure S15: Relative changes in soya beans imports after global catastrophic infrastructure loss and abrupt sunlight reduction**  
245 **scenarios in comparison to today.**

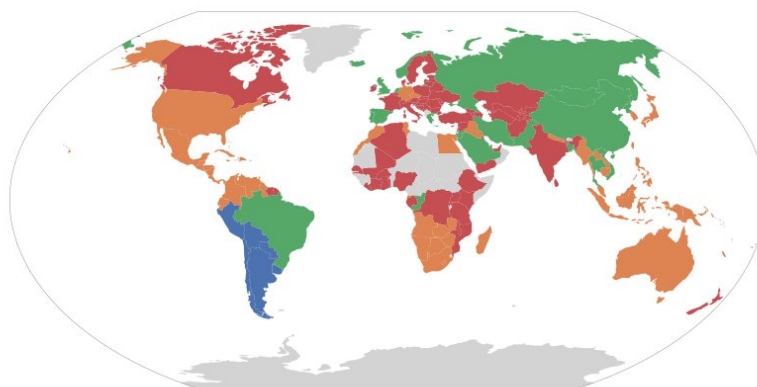
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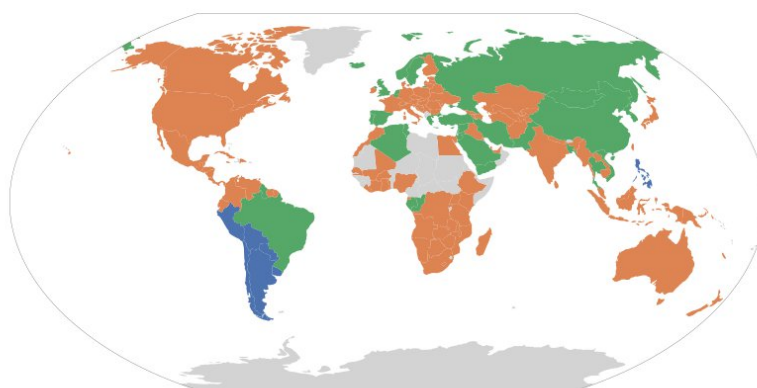
Trade communities for soya beans with base year 2022



Trade communities for soya beans with base year 2022  
in scenario: Global Catastrophic Infrastructure Loss



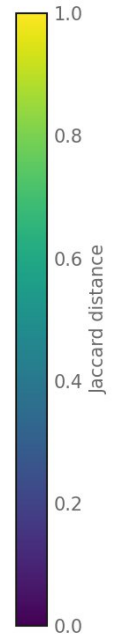
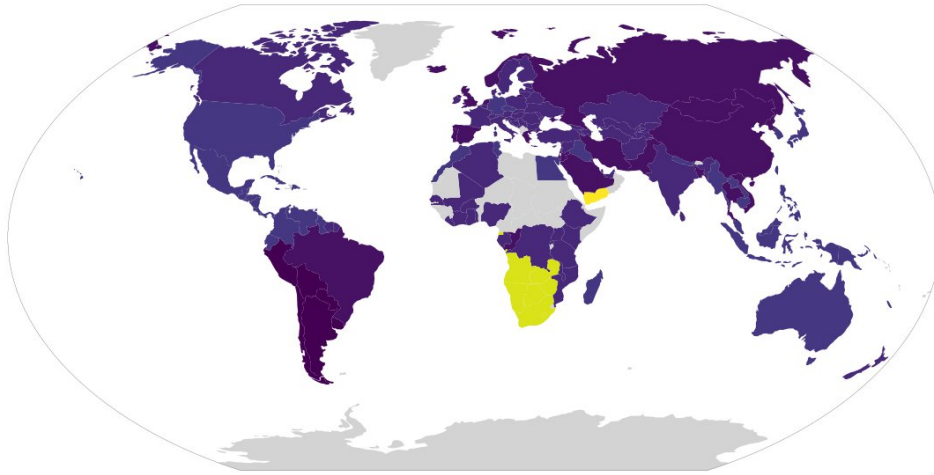
Trade communities for soya beans with base year 2022  
in scenario: Abrupt Sunlight Reduction Scenario



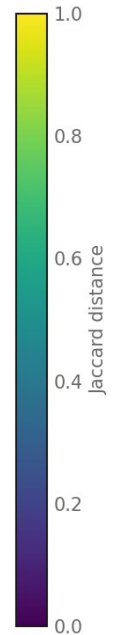
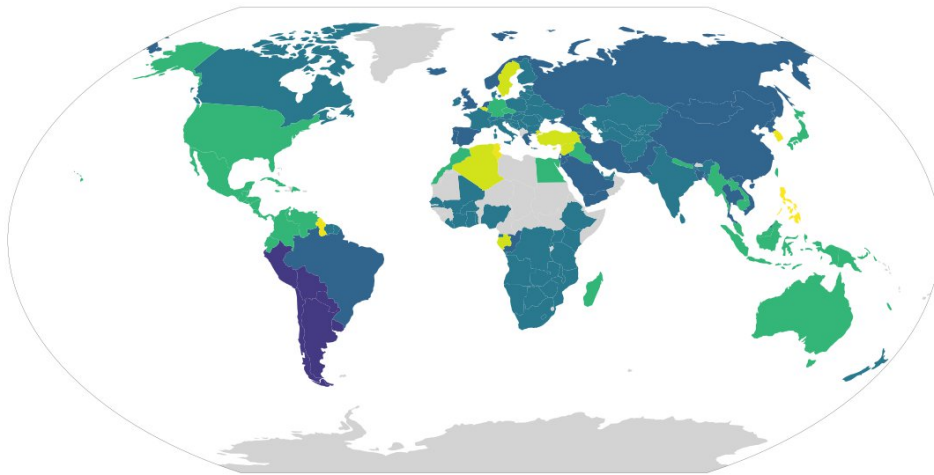
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**Figure S16: Trade communities for soya beans in 2022 and after yield reduction due to global catastrophic infrastructure loss as well as abrupt sunlight reduction. The colours show which countries belong in which trade communities.**

Jaccard distance for soya beans with base year 2022  
in scenario: Global Catastrophic Infrastructure Loss



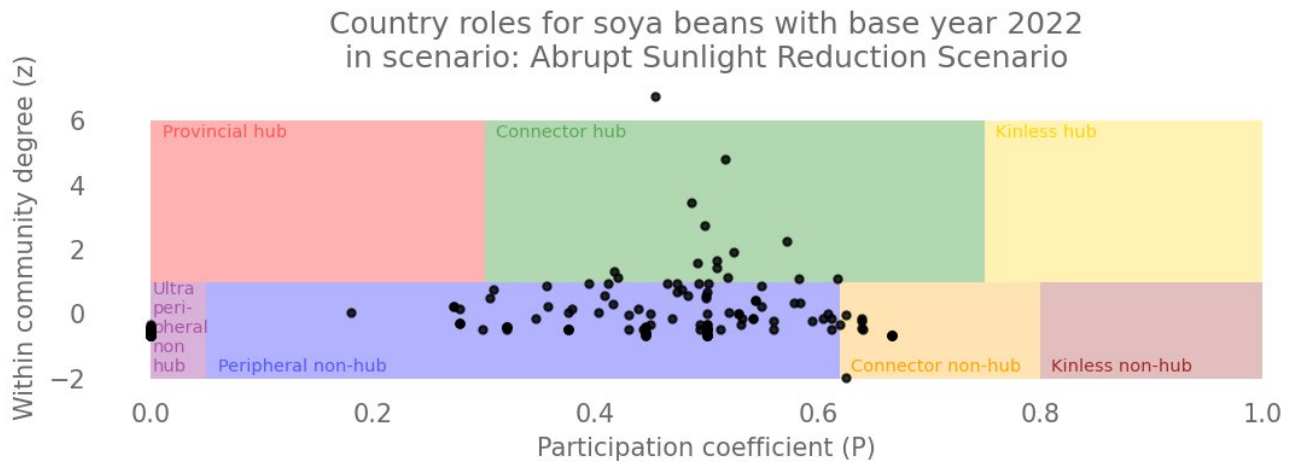
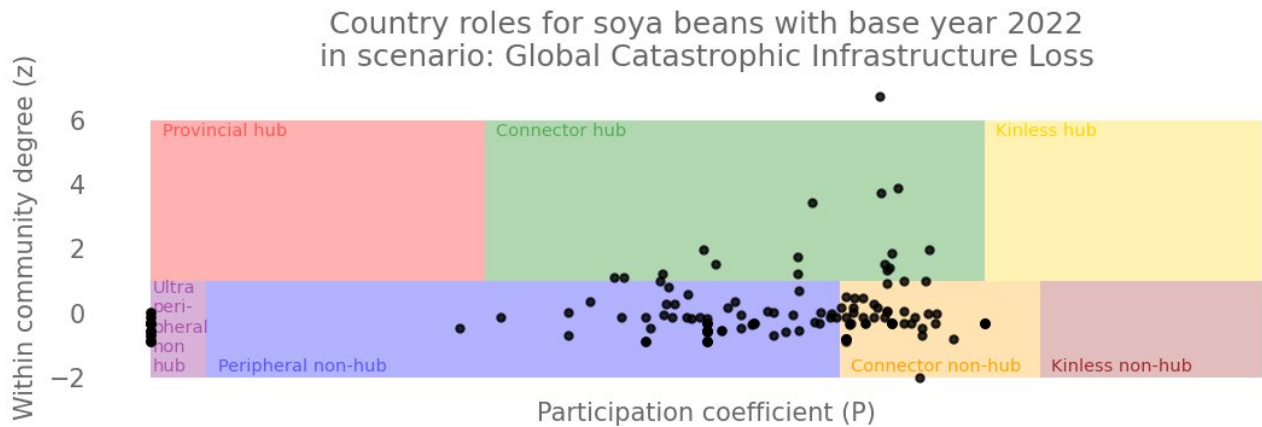
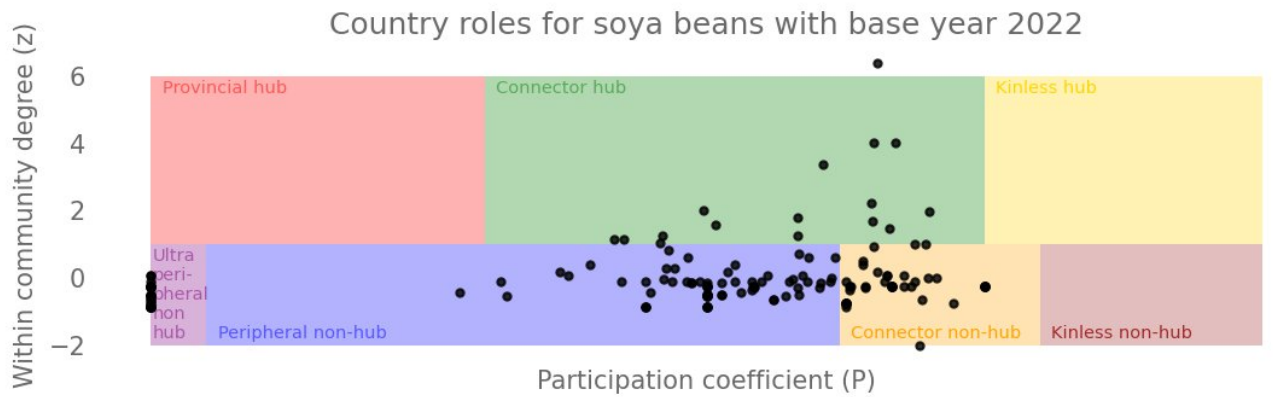
Jaccard distance for soya beans with base year 2022  
in scenario: Abrupt Sunlight Reduction Scenario



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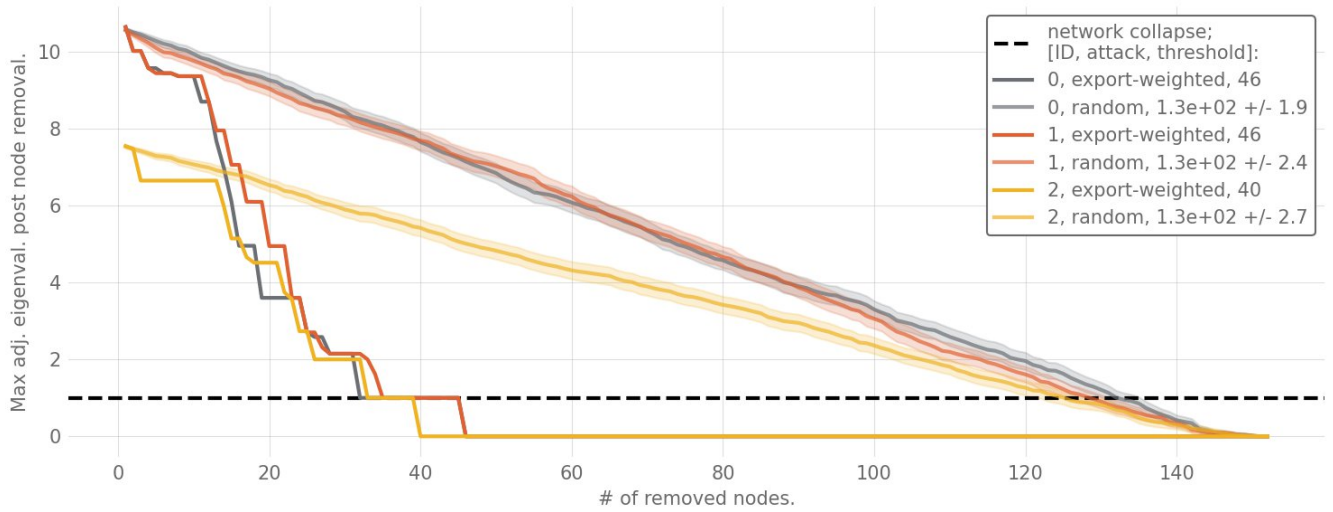
252 **Figure S17: Changes in soya beans trade communities in comparison to the communities in 2022 after yield reduction due to global**  
253 **catastrophic infrastructure loss as well as abrupt sunlight reduction. Colours indicate how much the trade community of a country**  
254 **has changed. Yellow meaning the trade community of a country has changed completely, dark blue meaning the trade community**  
255 **has not changed.**



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257 **Figure S18: Distribution of country roles in the global soya bean trade network in 2022 and after yield reduction due to global**  
 258 **catastrophic infrastructure loss as well as abrupt sunlight reduction based on within community degree and participant coefficient**  
 259 **(see 2.4.1 in main manuscript).**

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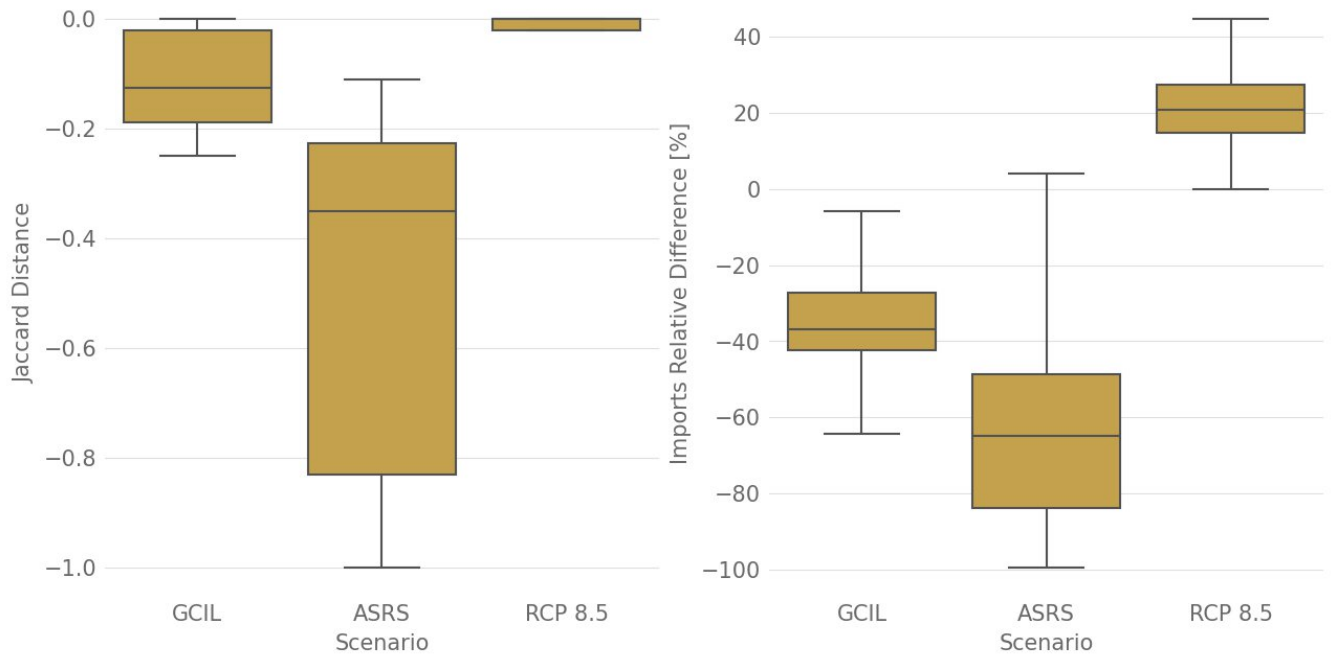


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262 **Figure S19: Vulnerability of the different scenarios for soya beans to the removal of nodes. ID 0 = soya bean trade today, ID 1 =**  
 263 **global catastrophic infrastructure loss, ID 2 = abrupt sunlight reduction scenario. Dotted line marks the collapse threshold of the**  
 264 **network.**

265

266 **5 Further supplemental analysis**



267

268 **Figure S20: Relative change in imports and Jaccard distance to compare the effects of global catastrophic infrastructure loss (GCIL),**  
269 **abrupt sunlight reduction scenarios (ASRS) and extreme climate change (RCP 8.5). The base year is 2018 to reflect that this**  
270 **comparison is to Hedlund et al. (2022) who based their analysis on that year.**

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