Assessing the evolving fragility of the global food system: *Supplementary data*

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1. Overview

The following *Supplementary Data* document includes additional details on the analyses described in the printed version of the paper: *Assessing the evolving fragility of the global food system*. This document has four figures and four tables.

2. Additional network information

2.1. Basic information

The main data source for our analysis of the global food trade network is the Statistics Division of the Food and Agriculture Organization of the United Nations (FAOSTAT, http://faostat.fao.org). We obtain the following data from FAOSTAT: 1) food balance sheets and 2) bilateral trade datasets for the period 1992 to 2009 to quantify self-sufficiency and trade, respectively. Table S1 presents the list of countries and their

three-letter country codes that are used in Figures 2 and 6 to help the reader visualise interdependencies in the global food system. The asterisk (*) indicates that the country is affected by the one of the simulated disturbances (i.e. "Year Without a Summer" or the Great Drought).

We explore network connectivity by investigating bilateral trade data for wheat and rice commodities over the period 1992 to 2009. Wheat and rice were selected, because these crops, along with maize, are the most important cereals for the global food system. The following wheat commodities are aggregated: wheat, flour, macaroni, bread, bulgur, pastries, and breakfast cereals. For rice, we aggregate: paddy rice, husked rice, milled rice from imported husked rice, millled paddy rice broken rice, and rice flour. In particular, we aggregate these commodities to either wheat or rice equivalents using factors from the FAO's commodity trees [1] and sum the values. Table S2 presents the crop equivalency factors used to convert to either wheat or paddy rice equivalent.

2.2. Evidence for systemic fragility

We evaluate the homogeneity of the network using self sufficiency, because food import dependency has a major influence on the response of countries to actual (or perceived) food scarcity in the global markets. The self-sufficiency ratio (SSR) is a measure of a country's ability to meet its own food requirements without imports. It is computed as the ratio of domestic production to domestic consumption as defined in the main text. The distributions of SSR are presented in Figure S1, where we see a distinct shift away from marginal self sufficiency (SSR ≈ 1) for 2005–2009 relative to 1992–1996. It is clear from both of these distributions that the vast majority of countries have either low or marginal self sufficiency (SSR ≤ 1), suggesting a substantial dependence on imports during both periods and hence on the global food trade network.

We next assess changes in connectivity within the global food system focusing specifically on wheat and rice as shown in Figure S2. Between 1992 and 2009, globally traded wheat and rice amounts have risen by 42% and 90%, respectively, with the bilateral trade links approximately doubling over this period.

2.3. Additional Network Metrics

The main text describes key network metrics including the node degree, k, and node strength, s, along with directed versions of each (i.e., exports and imports). In Table S3, we present a ranking of top-10 countries according to their export strength for the wheat and rice networks for two individual years (1992 and 2009) to help clarify nodal importance. For wheat, we find that top-10 countries affected by the "Year Without a Summer" disturbance include France, Germany, and United Kingdom. (Italy and Belgium-Luxembourg are in the top 10 for the 1992–1996 network but are of less importance in the later network.) For the "Great Drought" disturbance affecting Asian rice, we find that Thailand, Vietnam, China and India are top-10 countries in the earlier network.

Table S1. List of countries and their three-letter country codes (standard "ISO 3166-1 alpha-3" codes) used in Figures 2 and 6. The asterisk (*) indicates that the country is affected by the one of the simulated disturbances (i.e. "Year Without a Summer" or the Great Drought).

Country	ISO code	Country	ISO code
Europe			
Austria*	AUT	Latvia*	LVA
Belgium*	BEL	Lithuania	LTU
Bosnia and Herzegovina*	BIH	Netherlands*	NLD
Bulgaria	BGR	Norway*	NOR
Czech Republic *	CZE	Poland*	POL
Denmark	DNK	Portugal*	PRT
France*	FRA	Romania	ROM
Germany*	DEU	Russian Federation	RUS
Greece	GRC	Spain*	ESP
Hungary*	HUN	Switzerland*	CHE
Ireland*	IRL	Ukraine	UKR
Italy*	ITA	United Kingdom*	GBR
Asia			
Afghanistan	AFG	Mongolia	MNG
Armenia	ARM	Myanmar*	MMR
Azerbaijan	AZE	Nepal	NPL
Bangladesh	BGD	Oman	OMN
China*	CHN	Pakistan	PAK
Democratic People's Republic of Korea*	PRK	Philippines*	PHL
Georgia	GEO	Qatar	QAT
India*	IND	Republic of Korea*	KOR
Indonesia*	IDN	Saudi Arabia	SAU
Iran (Islamic Republic of)	IRN	Singapore*	SGP
Iraq	IRQ	Sri Lanka*	LKA
Israel	ISR	Syrian Arab Republic	SYR
Japan*	JPN	Tajikistan	TJK
Jordan	JOR	Thailand*	THA
Kazakhstan	KAZ	Turkey	TUR
Kuwait	KWT	United Arab Emirates	ARE
Kyrgyzstan	KGZ	Uzbekistan	UZB
Lao People's Democratic Republic*	LAO	Viet Nam*	VNM
Lebanon	LBN	Yemen	YEM
Malaysia*	MYS		
Americas			
Argentina	ARG	Guyana	GUY
Bolivia (Plurinational State of)	BOL	Haiti	HTI
Brazil	BRA	Honduras	HND
Canada	CAN	Jamaica	JAM
Chile	CHL	Mexico	MEX
Colombia	COL	Nicaragua	NIC
Costa Rica	CRI	Paraguay	PRY
Cuba	CUB	Peru	PER
Dominican Republic	DOM	United States of America	USA
Ecuador	ECU	Uruguay	URY
El Salvador	SLV	Venezuela (Bolivarian Republic of)	VEN
Guatemala	GTM		
Oceania			
Australia	AUS	Papua New Guinea	PNG
New Zealand	NZL		

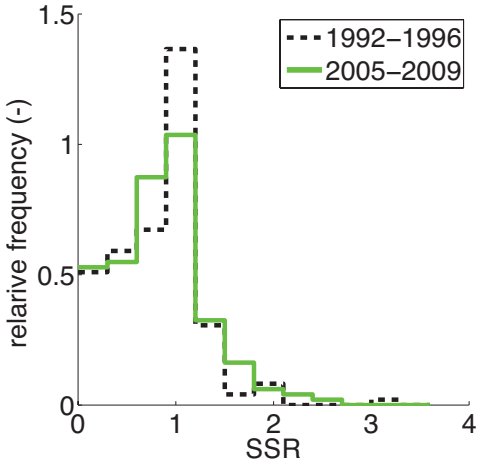

Figure S1. Normalized histogram of the self-sufficiency ratio for the global food system in 1992–1996 compared to 2005–2009.

Another network metric to assess the importance of any particular node in the network is betweenness centrality, B. This measure provides insight into how important a node is in connecting other network nodes and is defined as [2, 3]

$$B = \frac{(N-1)(N-2)}{2} \cdot \sum_{i,j} \frac{\sigma(i,u,j)}{\sigma(i,j)} \tag{S1}$$

where N is the number of active nodes, $\sigma(i,u,j)$ is the number of shortest paths between nodes i and j passing through node u, and $\sigma(i,j)$ is the total number of shortest paths between nodes i and j. The first term in the equation above is used to normalise B so that its range is between 0 and 1 [4, 3]; the summation accounts for all node pairs i and j [5, 3]. Here we compute B as an undirected and unweighted metric with the

Table S2. Crop equivalency factors used to convert to either wheat or paddy rice equivalent from the FAO's commodity trees [1].

Commodity	FAO Code	Crop Equivalency Factors
wheat	15	1.00
flour wheat	16	1.27
macaroni	18	1.27
bread	20	1.10
bulgur	21	1.05
pastry	22	1.10
wheat,starch	23	1.49
breakfast cereals	41	1.18
rice, paddy	27	1.00
rice,husked	28	1.30
milled rice from imported husked rice	29	1.11
millled paddy rice	31	1.49
rice,broken	32	1.49
rice,starch	34	1.76
rice flour	38	1.57

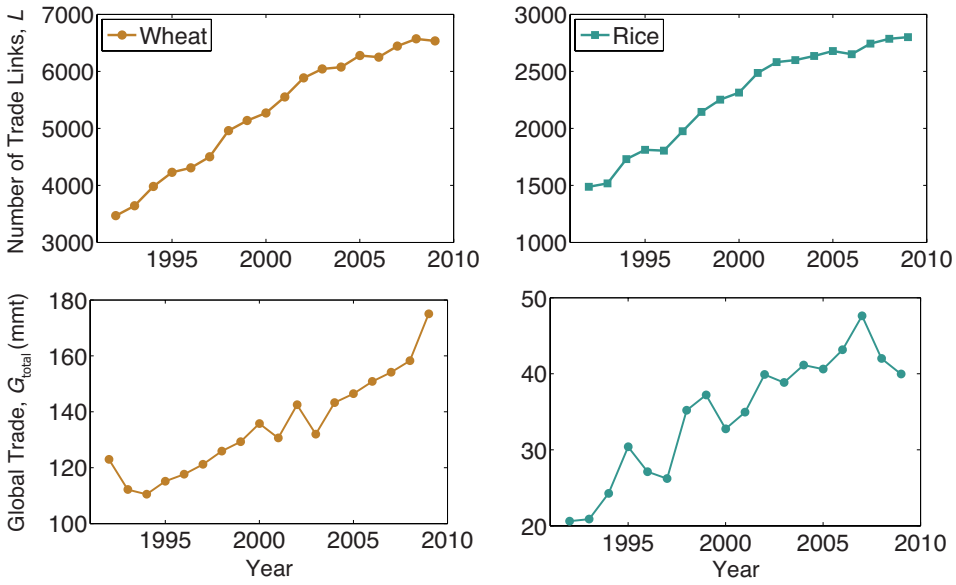

Figure S2. Increasing network connectivity. Wheat and rice (paddy equivalent) trade networks, showing the total number of links in each network and total commodity flow in million metric tons (mmt) for 1992 to 2009.

algorithm of [6], using code developed by [7].

As with the export-strength ranking, the B ranking confirms the importance of the United Kingdom (UK), France, and Germany in the wheat network. Other European

Table S3. Ranking of top 10 countries by export strength for the (top) wheat and (bottom) rice networks for 1992 and 2009.

Wheat 1992			Wheat 2009		
Rank	Country	s_{out} (mmt)	Rank	Country	s_{out} (mmt)
1	USA	35.8	1	USA	23.4
2	Canada	26.7	2	Canada	20.1
3	France	20.1	3	France	18.5
4	Germany	6.03	4	Russian Federation	15.6
5	Argentina	5.95	5	Australia	15.6
6	United Kingdom	4.24	6	Ukraine	12.5
7	Turkey	3.69	7	Germany	11.9
8	Australia	3.65	8	Argentina	6.62
9	Italy	3.61	9	Kazakhstan	5.66
10	Belgium-Lux.	1.78	10	United Kingdom	3.40
Rice 1992			Rice 2009		
Rank	Country	s_{out} (mmt)	Rank	Country	s_{out} (mmt)
1	Thailand	7.48	1	Thailand	12.6
2	USA	3.14	2	Viet Nam	5.72
3	Pakistan	1.84	3	USA	4.26
4	China	1.67	4	Pakistan	3.64
5	Viet Nam	1.07	5	India	3.63
6	Italy	1.07	6	China	1.44
7	India	0.99	7	Uruguay	1.43
8	Uruguay	0.54	8	Italy	1.04
9	Egypt	0.29	9	Brazil	0.89
10	Spain	0.29	10	Argentina	0.85

countries have an elevated importance as indicated by this top-10 list, including Italy, the Netherlands, Belgium-Luxembourg (1992 only), and Denmark (1992 only). This highlights their key role linking countries in the trade network. For rice, Thailand, China and India have high B, but importantly Vietnam does not. Then we might expect, for example, that the removal of Vietnam from the trade network would not be as disruptive as the removal of one of the other three countries.

Table S4. Betweenness centrality of top 10 countries in the (top) wheat and (bottom) rice networks for 1992 and 2009.

Wheat 1992			Wheat 2009		
Rank	Country	B	Rank	Country	B
1	USA	0.209	1	USA	0.130
2	Italy	0.181	2	Italy	0.114
3	UK	0.177	3	UK	0.091
4	France	0.171	4	China	0.087
5	Australia	0.123	5	Netherlands	0.080
6	Netherlands	0.117	6	Germany	0.073
7	Belgium-Luxembourg	0.101	7	France	0.069
8	Canada	0.099	8	Canada	0.063
9	Denmark	0.099	9	Turkey	0.062
10	Germany	0.094	10	Malaysia	0.059
Rice 1992			Rice 2009		
Rank	Country	B	Rank	Country	B
1	USA	0.565	1	USA	0.387
2	Thailand	0.341	2	Thailand	0.329
3	Italy	0.260	3	Pakistan	0.152
4	China	0.200	4	China	0.142
5	Pakistan	0.111	5	India	0.105
6	Australia	0.095	6	Italy	0.095
7	UK	0.077	7	France	0.066
8	France	0.069	8	Canada	0.052
9	India	0.066	9	UK	0.047
10	Spain	0.066	10	Brazil	0.041

2.4. Additional Metrics of Disturbance

Figure S3 presents the importance of wheat production and exports in Europe and rice production and exports in Asia relative to total global amounts. As mentioned in the main text, wheat is heavily traded but with production distributed over various regions with Europe responsible for roughly 20% of global production and 30% of global exports during both the 1992–1996 and 2005–2009 periods. Asia, on the other hand, produces more than 80% of the total global supply of rice and is responsible for about 60% of global exports during these same periods.

Figure S4 provides insight into the geographic distribution of the staple-food-supply losses. In the case of the European wheat export disruption, many African nations are

vulnerable to severe food supply impacts, which intensifies in the 2005–2009 network with dynamic accounting. For the disturbance affecting Asian rice exports, we also find that many African nations are vulnerable to such a disruption.

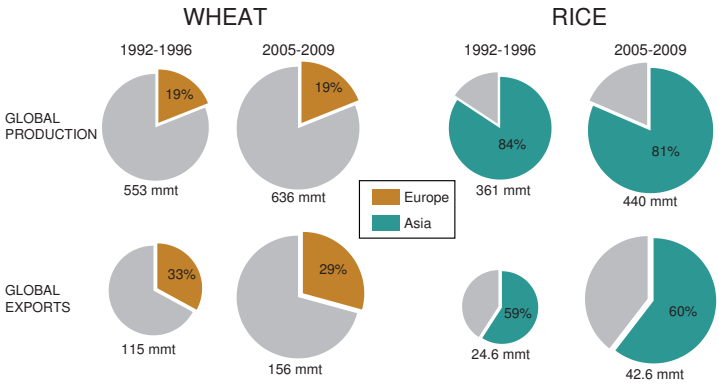

Figure S3. (Left) Wheat production and exports by European countries (affected in the simulation of the "Year without a Summer") as percentages of total global production and exports, respectively, for the 1992–1996 and 2005–2009 periods. (Right) Same but for rice production and exports of Asian countries affected in the simulation of the Great Drought of 1876 to 1878. The aggregated wheat data in the FAOSTAT database (FAO code 2511) include wheat, flour of wheat, macaroni, bread, bulgur, pastry, starch of wheat, breakfast cereals, and wafers. The aggregated rice data (FAO code 2805) include the milled equivalent of paddy rice, paddy, rice husked, milled/husked rice, rice milled, rice broken, starch of rice, and rice flour. Note that the pie charts sizes for each period are based on the ratio of global amounts (production or exports) between the periods.

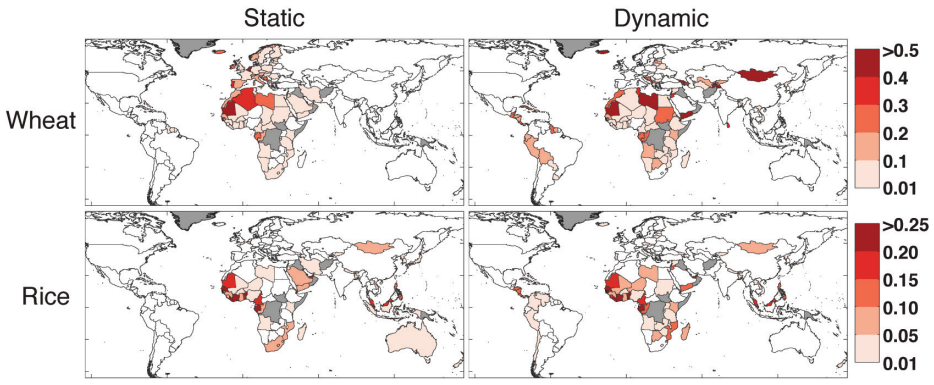

Figure S4. The median food supply losses as fraction of staple food supply due to weather-induced disruptions in European wheat and Asian rice exports. Losses are based on the static and dynamic approaches for the 2005–2009 period.

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