

Assessing the evolving fragility of the global food system

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Supplementary material for this article is available [online](#)

Abstract

The world food crisis in 2008 highlighted the susceptibility of the global food system to price shocks. Here we use annual staple food production and trade data from 1992–2009 to analyse the changing properties of the global food system. Over the 18 year study period, we show that the global food system is relatively homogeneous (85% of countries have low or marginal food self-sufficiency) and increases in complexity, with the number of global wheat and rice trade connections doubling and trade flows increasing by 42 and 90%, respectively. The increased connectivity and flows within these global trade networks suggest that the global food system is vulnerable to systemic disruptions, especially considering the tendency for exporting countries to switch to non-exporting states during times of food scarcity in the global markets. To test this hypothesis, we superimpose continental-scale disruptions on the wheat and rice trade networks. We find greater absolute reductions in global wheat and rice exports along with larger losses in network connectivity as the networks evolve due to disruptions in European wheat and Asian rice production. Importantly, our findings indicate that least developed countries suffer greater import losses in more connected networks through their increased dependence on imports for staple foods (due to these large-scale disturbances): mean (median) wheat losses as percentages of staple food supply are 8.9% (3.8%) for 1992–1996, increasing to 11% (5.7%) for 2005–2009. Over the same intervals, rice losses increase from 8.2% (2.2%) to 14% (5.2%). Our work indicates that policy efforts should focus on balancing the efficiency of international trade (and its associated specialization) with increased resilience of domestic production and global demand diversity.

1. Introduction

Studies of the global food system have typically focused on the challenges associated with matching supply to demand for future climate, environmental, and socio-economic scenarios [1–5]. These studies provide valuable insight into ‘equilibrium’ conditions, yet a critical knowledge gap continues to exist on how extreme disturbances or ‘shocks’ would impact the global food system. Shocks are relevant if they are widespread and severe, impact food-producing regions (especially any of the world’s major breadbaskets [6]), and ultimately lead to substantial reductions in global food supply.

Weather-related shocks are especially important because of crop sensitivity to weather extremes [7], including high [8] and low [9] temperatures, droughts [10], and floods [11]. Beyond these weather-related shocks, crop pests and pathogens [12, 13], regional nuclear wars [14–16], agroterrorism [17], and epidemics [18] (including the ongoing Ebola outbreak) all represent potential future disruptions to the global food system. Considering that society has been largely ineffective in coping with recent shocks [19], efforts focused on enhancing resilience in the global food system to such disruptions are critically needed.

All else being equal, a spike in global food prices would accompany any significant reduction in food

supply. Price shocks, which have long characterized global commodity prices [20, 21], alter global food trade [22], threaten global development, and exacerbate poverty [23], with particularly severe consequences for developing countries that are heavily dependent on food imports [20]. Despite the importance of preventing or at least mitigating these negative impacts, the short-run behaviour associated with price spikes (e.g., large-scale governmental intervention, hoarding, panic buying, and precautionary purchases) is poorly understood [3, 24].

A promising approach emerging in the economics literature to understand the impacts of extreme disturbances is focused on systemic complexity [25, 26]. In the context of the global food system, a key source of complexity at the global scale is international food trade because of its numerous interactions and inter-dependences. Similar systemic complexity is found across a variety of disciplines, where global networks have led to highly interdependent systems that are not understood and cannot be controlled well [27]. Yet understanding network characteristics and inter-dependences is crucial, as it allows us to gain insight into the susceptibility of globally interconnected systems to system-wide failures and the policies that would mitigate the likelihood and severity of such failures [25, 27].

Several studies have assessed the temporal evolution of trade networks using a complex systems approach, including recent work on world trade [28] and on the ‘virtual water’ trade associated with global agriculture [29, 30]. Although these studies did not specifically assess shocks, their insights into the topology of these complex networks are highly valuable. One study on world trade did go further, presenting an extinction analysis to evaluate trade network robustness [31]. Importantly, the authors found that the world trade network is moving towards a ‘robust-yet-fragile’ configuration, meaning that the network is resistant to random failures but fragile when key network components are either stressed or fail.

The interplay between international food trade and the stability of the global food system is multifaceted. International food trade helps balance supply and demand across different regions and provides protection against regional disturbances [3]. For example, international trade helped prevent a major food security challenge during Europe’s heat wave in 2003 [8], while its absence was a major reason why severe flooding initiated famine conditions in North Korea during the 1990s [32]. Enhanced local and regional resilience to food-supply disruptions as a result of international food trade is therefore invaluable. At the same time, we must consider whether the global food system is susceptible to catastrophic changes in state, due to its organization and related feedbacks [26]. We therefore argue that efficiency-maximising agricultural trade liberalization is not a panacea for the global food system, as its impacts on

food-supply resilience may be negative and require nuanced analyses [33].

Here we explore the fragility of the global food system using a complex-systems perspective with a particular focus on staple-food trade networks. We address two interrelated questions: (1) Does the global food system have characteristics that are consistent with one that is fragile (i.e., has ‘an accelerating sensitivity’ to harmful stressors [34])? (2) How has the global food system changed in terms of global trade flow and inter-connectivity? In particular, we hypothesise that the global food system has characteristics consistent with one that has a threshold beyond which a critical change in state could occur. To test this hypothesis, we evaluate the evolving properties of the global food system between 1992–2009 to understand its susceptibility to self-propagating changes [35] that could interrupt global food trade and threaten country-level staple food supplies. As part of our evaluation, we also use a parsimonious approach to understand the potential impacts of extreme disturbances on the global trade of staple foods. Finally, we discuss strategies that can be used to enhance both local and systemic resilience in the global food system.

2. Methods

We assess basic network characteristics—including network connectivity, trade flow, and homogeneity of network components—to explore whether the system is conducive to a self-propagating state shift [35] or ‘multiplier effect’ [36]. We argue here that a critical mechanism for a self-propagating state shift in the global food system is widespread imposition of trade policy interventions due to a severe spike in food prices. In the subsections below, we describe the metrics, data, analyses, and limits of the methodology.

2.1. Network metrics

In our global network analysis, individual countries are nodes and trade between any two countries is a link with an associated weight (defined as trade flows measured in crop equivalents) [28, 31, 37]. We focus on wheat and rice as they are (together with maize) the most critical staple food crops of the global food system. Adapting the nomenclature presented in [37], global trade of these grain commodities is represented as a weighted, directed network designated as the matrix G_D . Each element $g_{i,j}^D$ of this matrix contains the export flow from node i to node j . The elements of the principal diagonal for G_D are zero, because a country cannot trade with itself. The total global grain trade is then computed as $G_{\text{total}} = \sum_{i,j} g_{i,j}^D$.

When we are only concerned about the trade connections (and not the weights), we simplify to matrix A_D (the so-called directed adjacency matrix). Its elements $a_{i,j}^D$ are equal to one if an export connection exists (and zero otherwise). A further simplification is

to ignore direction for both of these matrices, yielding undirected versions designated as G_U and A_U . Each element g_{ij}^U is the total trade between countries (i.e., the sum of exports from country i to country j and from country j to country i), while each element a_{ij}^U is equal to one if there is trade and zero if not.

With these matrices, we identify some standard metrics used in complex systems analysis. First, the degree of node i , k_i , refers to the number of connections of that node to other nodes and is computed as $k_i = \sum_j a_{ij}^U$. We then distinguish between the number of export connections (export node degree of node i : $k_{out,i} = \sum_j a_{ij}^D$) and the number of import connections (import node degree of node i : $k_{in,i} = \sum_j a_{ji}^D$). Likewise, we define metrics that take the amount of trade (i.e., weights) into account: the export node strength is $s_{out,i} = \sum_j g_{ij}^D$ and the import node strength is $s_{in,i} = \sum_j g_{ji}^D$.

2.2. Network data

To analyze the global food trade network for the period 1992 to 2009, we obtain bilateral trade and food supply data from the Statistics Division of the Food and Agriculture Organization (FAOSTAT, <http://faostat.fao.org>). We aggregate by converting to either wheat or paddy rice equivalent using factors from the FAO's commodity trees [38] and summing the values to obtain the trade matrix G_D . (The conversion factors are presented in table S2 of the supplementary data document, available at stacks.iop.org/erl/10/024007/mmedia.) For wheat, we aggregate the following commodities: wheat, flour, macaroni, bread, bulgur, pastries, and breakfast cereals. The rice commodities used here are paddy rice, husked rice, milled rice from imported husked rice, milled paddy rice broken rice, and rice flour. If any discrepancies exist in the trade amounts between two countries, the average is used [37]. However, if one of the two countries reported that no trade occurred, we simply use the single reported value [37].

Although bilateral trade data are available starting in 1986 from FAOSTAT, we focus on data after the dissolution of the Soviet Union (i.e., 1992 onward). From a trade-network perspective, we focus on this post-cold war era as it has been dominated by the rise of globalization. 1992 is also a convenient start year for comparative purposes, as there are only small changes to the set of nodes (i.e., countries) after this point. The analysis ends with 2009 data, because FAOSTAT's commodity balance data were available only through that year at the time of this analysis. These and other data that follow are available at <http://data.giss.nasa.gov/impacts/fragile/>.

2.3. Network properties

In networks where nodes can flip between two possible states and the interactions are susceptible to a

multiplier effect, high heterogeneity and low connectivity tend to impede changes [35, 39]. This means, for example, that countries decide whether to export at different prices, and the imposition of export restriction by one country only affects a relatively small number of countries. Conversely, for a network in which most countries are similar and are highly connected, countries impose export restrictions at similar prices, and these restrictions impact many countries throughout the network. Such a network would be susceptible to a self-propagating trade disruption.

To understand the interconnectivity of the global food trade network, we present the network 'backbone' [37] in figure 1, which shows the largest trade links that together account for 80% of total trade in 2009 for each network. The importance of a handful of wheat producers (USA, Canada, France, Germany, Russia, Ukraine, etc) and rice producers (Thailand, USA, Pakistan, Vietnam, India, etc) is evident. Also, we see the expected influence of geopolitics on the trade connections. For example, we find substantial interconnectivity among traditional trade partners of the USA and Russia, among European countries, and between European and African countries in the wheat trade network.

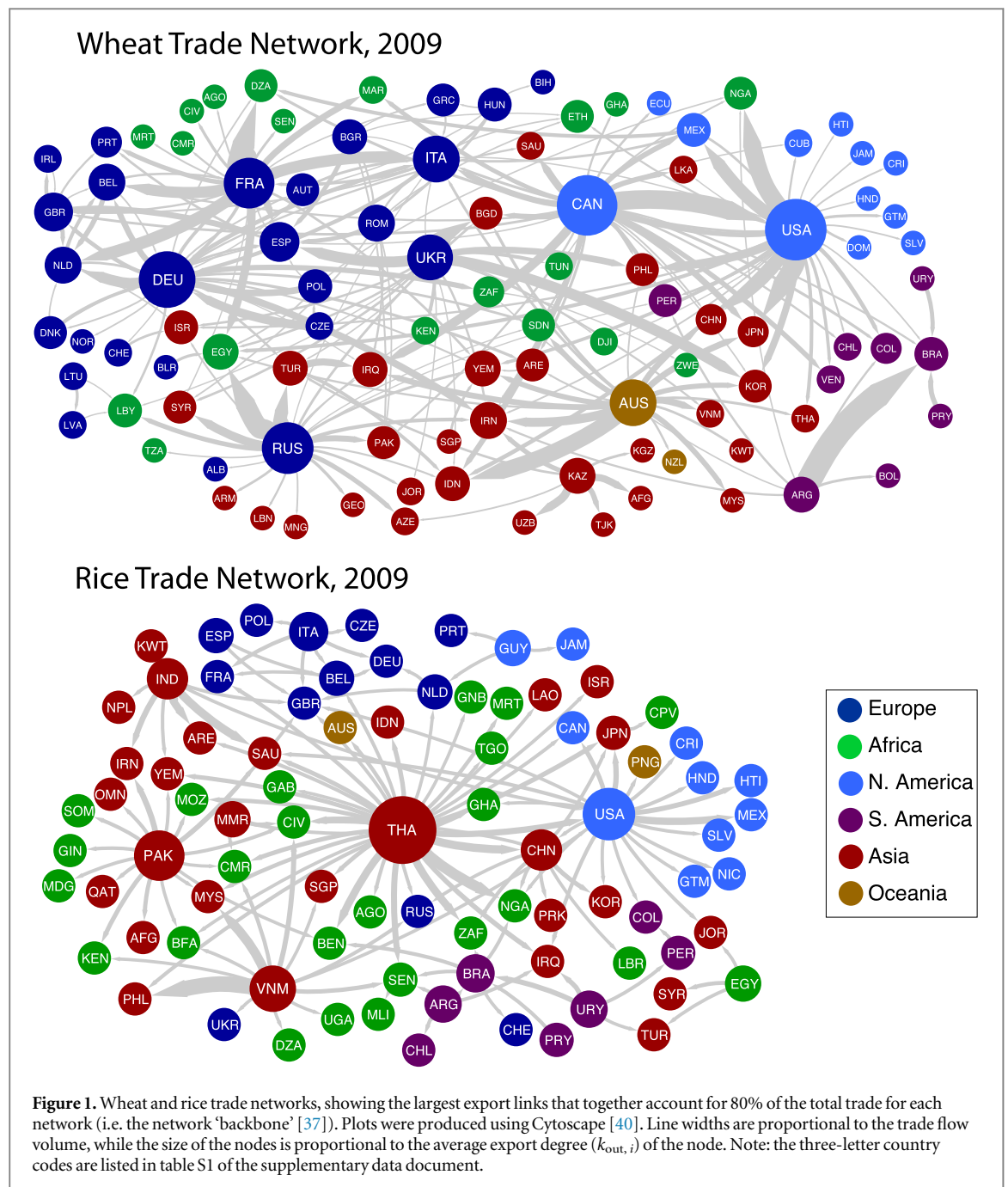
We next want to understand how similar (i.e., homogeneous) countries are in terms of their dependencies on other countries to assess whether the global food system is vulnerable to self-propagating trade disruptions. The self sufficiency ratio (SSR)—a measure of a country's ability to meet its own food requirements without imports—is useful in this regard. That is, we are particularly interested in the similarity of countries during times of food scarcity on the global food markets, as this similarity provides insight into their trade-policy behaviour for those times. We expect that most countries, especially those with low or marginal self-sufficiency, would be under substantial pressure to impose trade interventions to protect their domestic markets.

SSR is computed as the ratio of domestic production to domestic consumption [41, 42], so we have for country i :

$$SSR_i = \frac{P_i}{P_i + I_i - E_i + \Delta R_i}, \quad (1)$$

where P_i is production, I_i is imports, E_i is exports, and ΔR_i is change in reserves (or stocks) for country i . To be consistent with FAOSTAT's designation, we take ΔR_i to be positive if a commodity was consumed from country's i reserves in a given year (leading to a net stock decrease).

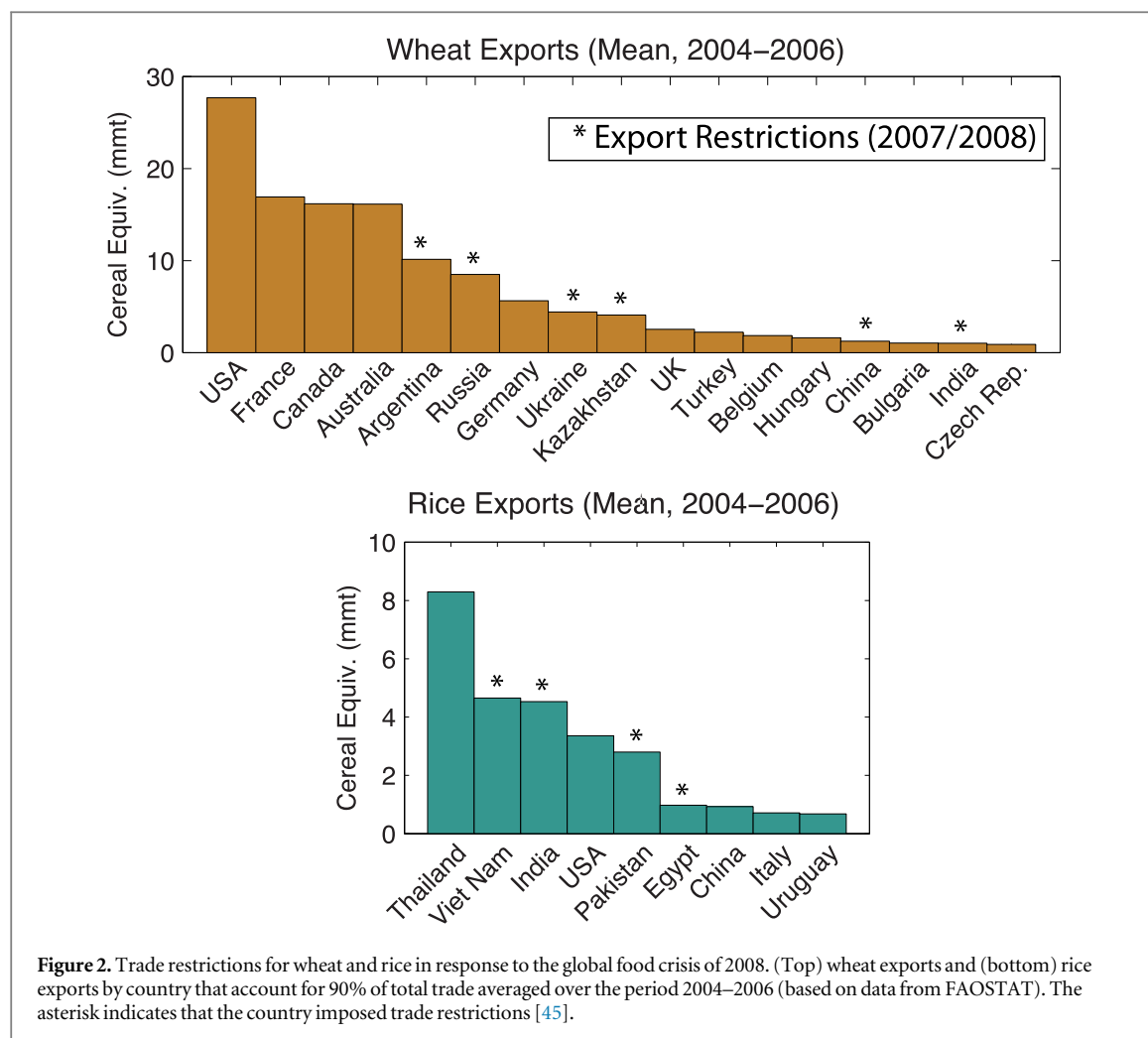
To compute SSR, we expand our analyses to consider other major staple foods in addition to the aforementioned wheat- and rice-derived commodities, because we use this metric to understand the self-sufficiency status of individual countries (nodes) in the network. (In contrast, we are interested in *network*



connectivity and trade flows in our analyses with global wheat and rice trade data.) Specifically, we include other staple cereals as well as starchy roots following [42], because these crops are the foundation of most diets throughout the world. FAOSTAT has prepared two aggregated items that are useful in this regard: ‘cereals—excluding beer’ and ‘starchy roots’. The cereals group includes wheat, maize, rice (milled equivalent), barley, rye, sorghum, oats, millet, and an ‘other cereals’ category, while the starchy roots group consists of potatoes, sweet potatoes, yams, cassava, and an ‘other roots’ category. Starchy roots are converted to cereal equivalent assuming 0.26 tonnes of cereals are equivalent to 1 tonne of starchy roots [42, 43].

2.4. Trade restrictions as a disruption mechanism

The events of the 2008 global food crisis provide (circumstantial) evidence that food trade interventions may result in a fragile global food system. For example, in response to the 2008 food-price spike, 6 out of the top 17 wheat exporters (accounting for 90% of total trade) imposed some degree of trade restrictions, while 4 out of the top 9 rice exporters did so (figure 2). Such trade interventions to protect domestic markets represent a collective-action problem that amplifies food-price volatility [44]. A recent analysis referred to this amplification as a ‘multiplier effect’ [36]. A multiplier effect, in this context, refers to the situation where a country imposes export restrictions,



which lead to higher global prices that trigger additional export restrictions by other countries and, therefore, further price increases in the global markets [36]. Those authors analysed data on 29 food products for the period 2008–2010, finding empirical evidence to support the existence of this multiplier effect.

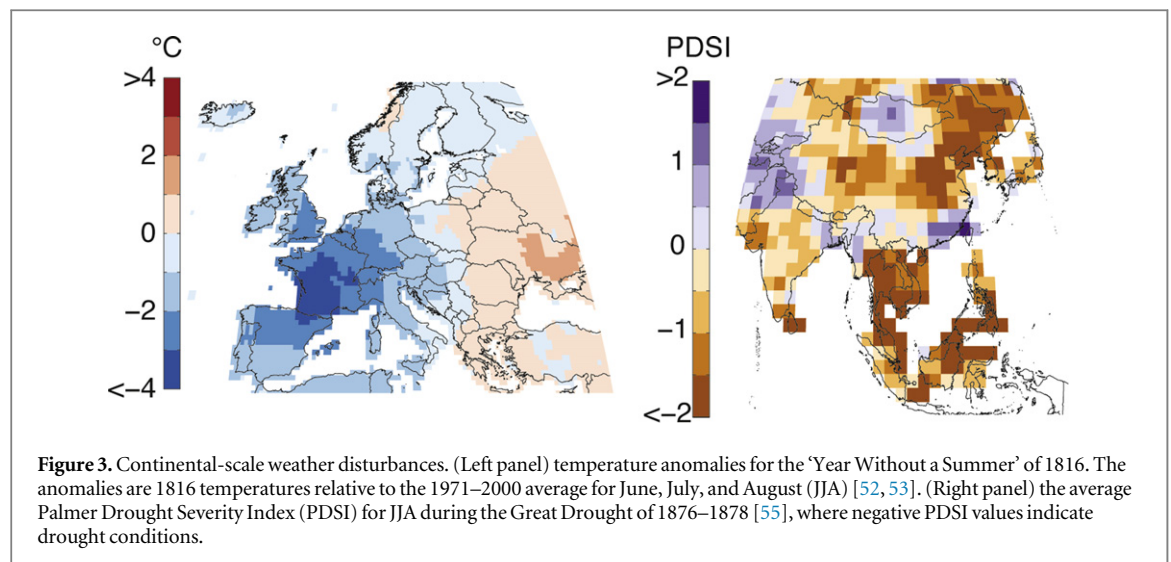
Export restrictions, together with import subsidies, represent trade policy interventions that governments traditionally have used to shield domestic agricultural markets from extreme fluctuations in international prices [36, 46]. Studies have shown that trade interventions accompanied recent surges in food prices, including the food spike of 2008 global food crisis [24, 36, 44, 46, 47] and afterwards in 2011 and 2012 [46]. In complex networks like the global food system, such interventions may ultimately be ineffective and may actually contribute to price spikes (as indicated by recent empirical findings [24, 36]).

2.5. Simulated disturbances

As our interest is in fragility of the global food system, we investigate network interactions when a shock causes a reduction in the global food supply. We are less interested in the specifics of the disturbance (aside from the countries affected) and more focused on the

response of our highly interconnected global food system to the shock—whatever the origin. In the complex systems literature, a disturbance affecting a critical network node (i.e., a major food producing region) has been referred to as a ‘targeted network attack’; in contrast, a ‘random network attack’ affects a node of random importance [31]. We focus on the former, because, although such events are rare, their impacts are potentially catastrophic.

Plausible shocks, as mentioned earlier, include weather extremes, epidemics, civil conflict, or the spread of a major crop disease (e.g., wheat stem rust, known as Ug99, is present in African and Middle Eastern wheat fields and can lead to 100% crop losses in most modern varieties [13]). In this study, we select large-scale weather anomalies as our example ‘disturbances’, because crop production, and hence our global food system, is particularly sensitive to weather extremes [7]. In particular, we assess how two pan-continental weather anomalies, 1816’s ‘Year Without a Summer’ and the Great Drought of 1876–1878, would impact wheat and rice trade, respectively, for the 1992–2009 networks. The spatial extent of these events is comparable to more recent events including the European heat wave of 2003 [8] and 2012s pan-



continental drought in the United States during the summer of 2012 [48], respectively. However, the impacts of 1816’s cold temperatures were more severe due to widespread crop failure [50], while the Great Drought was a particularly intense drought that extended over multiple years (unlike the 2012 US drought) [54, 55].

For these two disturbances, we characterize nodes (i.e., countries) as being in one of two alternate states, exporting or non-exporting. We then impose export bans only in directly affected countries (rather than in all exporting countries). Thus, we are conservative in this estimate, as we do not consider the more severe case where trade restrictions propagate throughout the entire network (i.e., the ‘multiplier effect’). (Additional limits of the methodology are discussed in the following section.)

The ‘Year Without a Summer’ of 1816 (figure 3, left panel), a result of the 1815 Mount Tambora volcano eruption in Indonesia [49–51], had abnormally low daily average temperatures from late spring through early fall, which led to severe drops in crop yield and a devastating famine in Europe [50]. We simulate a disturbance impacting most of Europe based on this event by overlaying the temperatures experienced in the ‘Year Without a Summer’ of 1816 and computing the differences between 1816 temperatures and the 1971–2000 averages for June, July, and August (JJA) [52, 53]. Wheat exports are then set to zero for European countries (in the 1992–2009 networks) with a cooling anomaly in half or more of their present-day territory.

The other disturbance, the late Victorian Great Drought of 1876–1878 (figure 3, right panel), was associated with one of the most severe El Niño events of the last 150 years. It affected most of Monsoon Asia, with particularly catastrophic impacts (more than 30 million famine deaths worldwide) [54, 55]. We use the Palmer Drought Severity Index (PDSI) [55] during JJA to identify the extent of drought during this event. As

with the European disturbance, we simulate a shock affecting most of monsoon Asia based on this event by overlaying PDSI for the Great Drought. Rice exports in the 1992–2009 networks are set to zero for Asian countries with a negative PDSI in half or more of present-day countries.

Our approach is a parsimonious one for simulating network response to disturbance, as exports are banned only in the directly affected countries. We assess imports lost from each country using two end-member scenarios:

- (1) *Static accounting*: no reallocation of remaining commodities on the global market.
- (2) *Dynamic accounting*: reallocation using a gross domestic product (GDP) ranking.

The static approach is used to understand the baseline vulnerability to disturbances that exists through trade connections. This baseline allows us then to assess the relative impacts of commodity reallocation. For dynamic accounting, we approach the reallocation problem from the perspective that wealthier countries will use their financial resources and influence to obtain additional food in times of scarcity on the global markets (at the expense of other nations). That is, we preferentially allocate the remaining commodities to wealthy countries using a GDP ranking based on data from the United Nations’ National Accounts Main Aggregates Database (<http://unstats.un.org/unsd/snaama/introduction.asp>). The underlying assumption is that higher GDP countries have more financial resources and influence to mitigate both supply losses and spikes in domestic food prices. In contrast, poor countries have neither the financial resources nor the influence to obtain commodities during times of food scarcity on the global markets.

Lastly, we quantify the ratio of lost wheat or rice commodities (due to each disturbance) to the total staple food supply consumed. This ratio is helpful for understanding how important the lost imports are relative to the total amount of staple foods consumed in each country. Total staple food supply consumed for country i ($S_{\text{food},i}$) is computed as

$$S_{\text{food},i} = P_i + I_i - E_i + \Delta R_i, \quad (2)$$

where $S_{\text{food},i}$ is expanded to include aggregated cereals and starchy roots data as done with the SSR computations. We pay particular attention to losses of least developed countries (LDCs), because they are the most vulnerable to disruptions given their limited financial resources. The latest FAOSTAT list of least developed countries (LDCs) (as of February 2014, the list includes 48 countries) is used here. We note, however, that South Sudan and Djibouti are excluded from the LDC assessment. South Sudan is excluded, because our analyses end before it was established. Djibouti is excluded due to major discrepancies in wheat trade between the food balance sheets and the bilateral trade data in FAOSTAT.

2.6. Limits of methodology

Here, the analyses of global food system are focused on staple foods, with the assessment of trade further limited to wheat and rice commodities. This subset of food commodities is relevant, as our interest is (1) in quantifying connectivity and trade flows within the network, (2) in assessing homogeneity of network nodes (to understand vulnerability to self propagating disruptions), and (3) in basic accounting of staple foods during shocks in the global food markets. Importantly, we also assessed global maize trade and found similar interdependencies and fragility but with the USA playing a larger role (not shown). For brevity's sake though, we limit the presented analyses to wheat and rice.

As noted in an extended discussion by [24], existing global agriculture simulation models (developed by the FAO, Organization for Economic Co-operation and Development, US Department of Agriculture, and others) are limited in their skill at modelling short-run supply and demand. That is, without realistic representation of processes like large-scale governmental intervention, hoarding, panic buying, and precautionary purchases [24], these widely used models have a limited capacity to provide insight when extreme disturbances affect the global food system.

In light of these challenges, we use an accounting approach similar to efforts that have used basic calculations to understand price shocks [24, 56, 57]. We emphasize that our calculations with static and dynamic accounting are end-member scenarios that do not capture the actual reallocation dynamics expected during a shock to the global food system. Multiple factors influence these reallocation dynamics including existing buyer-seller relationship within the global

network (as discussed by [58] and shown in figure 1), the response of private corporations to disruptions, the logistics of bulk grain trade [59], and differing tendencies of individual governments to intervene in trade. For example, the proactive intervention of the Philippines in 2008 [24] suggests that countries with limited financial means might, in fact, aggressively purchased commodities if food was scarce or perceived to be scarce on the global markets. Additionally, these simulations of single-commodity shocks do not account for the likelihood of commodity substitution by trade, which may dampen impacts if a disturbance only affects one commodity. At the same time, we also ignore the possible pressures in one commodity market that could be associated with a shock in another. For example, pressures in the rice markets during the 2008 global food crisis were initiated, to some extent, by price increases in the wheat markets [24].

We stress that the particulars of the disturbances are of secondary importance to the analyses. Rather, we are performing an accounting exercise to assess the impacts of node removal (i.e., export bans in major exporting regions) on the global food system. Consequently, the impacts of the weather anomalies on actual production are not explicitly modelled. Instead, the 'Year Without a Summer' and the Great Drought are used for illustrative purposes to show that intense and spatially extensive disturbances have occurred in the recent past in major food-producing regions. Additionally, considering that disturbance-induced shortage would lead to global food-price shocks, we view these weather-related disturbances as useful surrogates for many other types of disturbances. That is, even though other possible perturbations have different spatial characteristics, we might expect somewhat similar impacts on the entire global food network through spikes in global food prices.

While the occurrence of these historical weather anomalies highlights the fact that widespread and severe conditions have occurred in the past, we are arguably more interested in whether such disruptions might occur in the future. Any future cold episode like the 'Year Without a Summer' would most likely to be linked to volcanic activity (consider the 2010 eruption of Iceland's Eyjafjallajökull volcano), nuclear conflict, or any other event that affects the Earth's radiation balance through increases in atmospheric aerosols [60]. Heat waves, at the other end of the spectrum, are a major future concern, especially considering that warming of the Earth's climate is projected to be very widespread [61]. Furthermore, the likelihood of continental-scale drought will be amplified if this future warming of the Earth's climate is widespread and homogenous as expected [48]. It is important to clarify however that we do not have the skill to predict *specific* extreme climate anomalies, despite significant efforts to understand our changing climate (e.g., the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, <http://ipcc.ch/report/ar5/>).

Table 1. Complex-network metrics for the global wheat and rice trade networks for 1992–1996 and 2005–2009. Each value is an average value for the respective time period (i.e., 1992–1996 or 2005–2009). (Note: mmt stands for million metric tonnes.)

Network metric	Symbol	Wheat		Rice	
		1992–1996	2005–2009	1992–1996	2005–2009
Global trade, mmt yr ⁻¹	G_{total}	116	157	24.6	42.7
Number of links, -	L	3925	6415	1671	2731
Number of active export nodes, -	N_{out}	154	175	125	151
Number of active import nodes, -	N_{in}	226	209	210	208
Average active export degree, -	$\langle k_{\text{out}}^{\text{act}} \rangle$	25.5	36.8	13.4	18.1
Average active import degree, -	$\langle k_{\text{in}}^{\text{act}} \rangle$	17.4	30.7	7.97	13.2
Average active export strength, mmt yr ⁻¹	$\langle s_{\text{out}}^{\text{act}} \rangle$	0.75	0.90	0.20	0.28
Average active import strength, mmt yr ⁻¹	$\langle s_{\text{in}}^{\text{act}} \rangle$	0.51	0.75	0.12	0.21
Max. export degree, -	$k_{\text{out}}^{\text{max}}$	168	177	135	159
Max. import degree, -	$k_{\text{in}}^{\text{max}}$	72	105	36.2	54.2
Max. export strength, mmt yr ⁻¹	$s_{\text{out}}^{\text{max}}$	34.0	28.0	7.98	12.5
Max. import strength, mmt yr ⁻¹	$s_{\text{in}}^{\text{max}}$	14.2	7.69	2.48	2.89

We therefore emphasize that these events are only example disturbances and not representative of some ‘probable maximum’ extremes (as we have neither the skill nor data to estimate accurately such values for either past or future climate).

3. Results

3.1. Evidence for increased fragility in the undisturbed network

We first assess changes in connectivity within the global food system, focusing specifically on wheat and rice, arguably the two most important crops in the world’s food supply. These networks evolve over the period 1992–2009, with the number of countries active in trade (importing or exporting) ranging from 191 to 233 for wheat and from 173 to 218 for rice. The number of bilateral trade links has approximately doubled over this period with globally traded wheat and rice amounts rising between 1992 and 2009 by 42 and 90%, respectively (see figure S2).

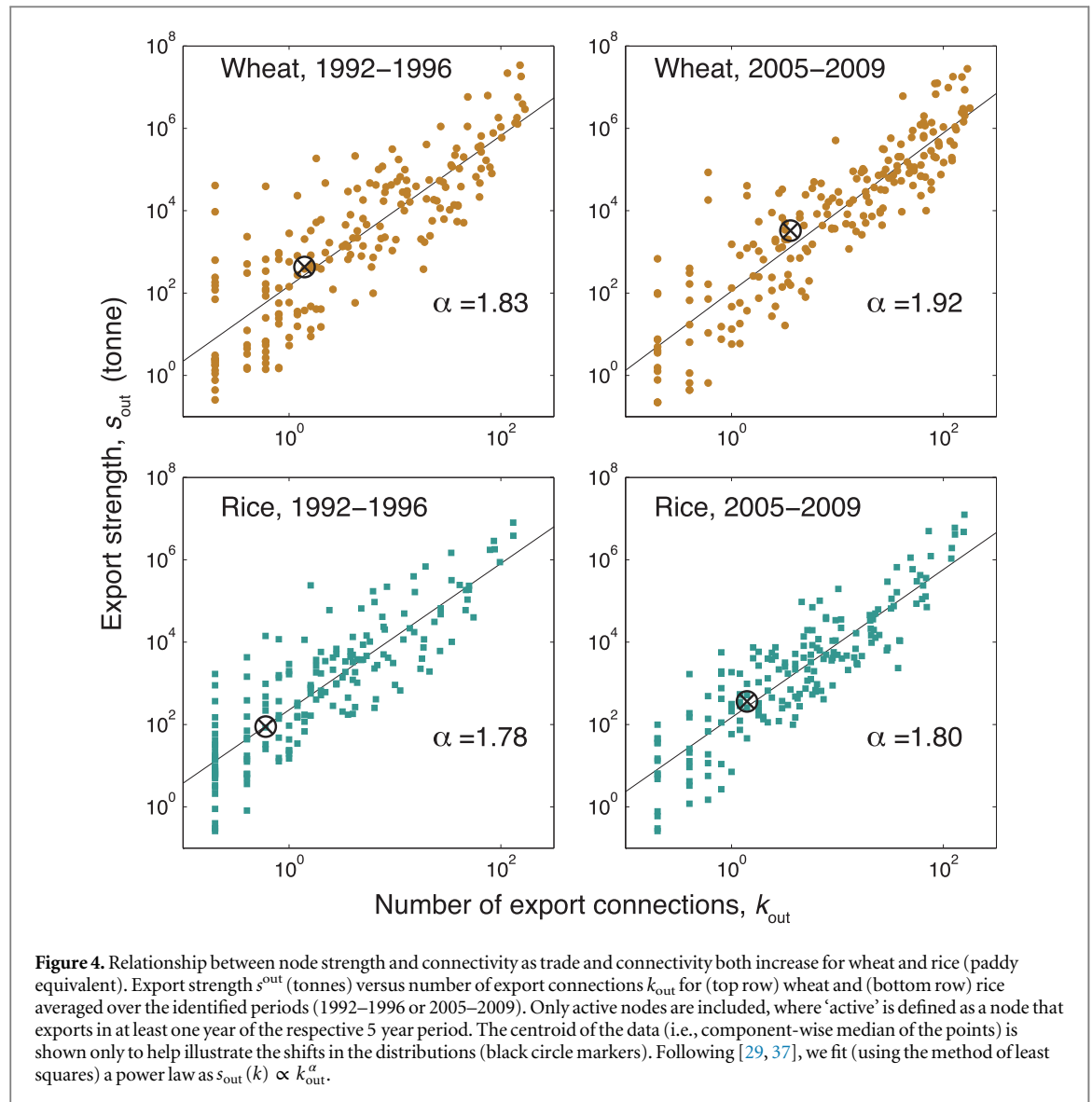
Table 1 presents key metrics for the global wheat and rice trade networks focused on the average values for two time periods: 1992–1996 and 2005–2009. We average over these 5 year intervals to compare mean changes (given the year-to-year network variability). Wheat trade for 2005–2009 is 157 million metric tonnes (mmt), up from 116 mmt in 1992–1996; rice trade is 42.7 mmt for the latter period up from 24.6 mmt. While the volumes of wheat trade are much higher than rice trade for both periods, this does not mean that rice trade is inconsequential. Wheat trade, as a percentage of total production, was 21% for 1992–1996 increasing to 25% for 2005–2009. In comparison, rice trade was 7 and 10% of total production, respectively, for these same two periods (see figure S3).

Comparing the two time periods, we find increases in average and maximum node degree for exporting and importing for both wheat and rice (table 1 and figure 4). Likewise, we find increases in average and maximum node strength for exporting and importing

between the two periods, with the only exceptions being decreases in maximum export and import strength for wheat. We also note the entry of new major exporters into the wheat markets since 1992 and declines in the relative importance of European countries in wheat exports (see country rankings for export strength in table S3 and betweenness centrality in table S4). In particular, one of the most notable changes in global wheat trade is the dramatic increase in the exports of Russia and Ukraine. Combined, their wheat and flour exports were 31 mmt (in wheat equivalent) in 2009 rising from just 0.77 mmt in 1992. Importantly, we note that Ukraine’s wheat exports have been highly variable ranging from 0.20 to 13 mmt since the year 2000.

The relationship between the export strength s_{out} and the number of export connections k_{out} (averaged over the indicated time period) is presented in figure 4. We find a power law relationship of the form $s_{\text{out}}(k) \propto k_{\text{out}}^{\alpha}$, with parameter α ranging from 1.78 to 1.92. These high values indicate that as countries increase their number of export connections, the amount of their exports increase much faster. As observed by [37] for the global ‘virtual water’ trade, the more export connections that a country has, its trade activity increases in a highly nonlinear fashion. These power-law relationships reinforce the observation from figures 1 and 2 that a small number of key countries are important in the global export of wheat and rice.

Beyond the dominant influence of major exporting countries, we want to know whether the majority of countries in the network have similar characteristics in terms of their trade dependency. Using SSR as a metric, the network is relatively homogeneous in the sense that the vast majority of countries either depend on imports for their staple-food supply or would immediately look to imports to meet any supply shortfalls (figure 5). SSR is marginal ($\text{SSR} \approx 1$) or low ($\text{SSR} < 1$) in 83% of countries for 2005–2009, with an average of 85% over the the entire period 1992–2009.



Notable declines in self sufficiency (North and Central America, Western Europe, and parts of South America and Africa) are evident together with improvements in Eastern Europe, China, countries of the former Soviet Union, Australia, and part of South America. Consistent with increasing specialization (a basic feature of trade), we also find a shift away from SSR ≈ 1 to both higher and lower values over this period (see figure S1).

3.2. Disturbance impacts

In table 2, we present the decreases in wheat and rice network metrics using the static accounting averaged over the periods 1992–1996 and 2005–2009 for the ‘Year Without a Summer’ and the Great Drought disturbances, respectively. That is, we impose export restrictions in the countries affected by the relevant disturbance and assess losses without reallocation. We find greater absolute reductions in global wheat exports of 38 and 46 mmt for the 1992–1996 and 2005–2009 networks, respectively, while reductions

for the global rice exports are 15 and 26 mmt, respectively. Considering widespread increases in population over this period, we might expect that the losses from the later network would be accompanied by a larger vulnerable population. In terms of complex-network metrics (degree and strength), the losses between the earlier and later networks are comparable for wheat. This result is in line with our finding that the relative importance of European wheat exports has declined somewhat between the two periods. For rice, however, these metric generally indicate larger losses for the 2005–2009 network.

The major network connections between European wheat exporters and LDCs and between Asian rice exporters and LDCs are presented in figure 6 (left panels) for the year 2009. Key exporters of European wheat to LDCs include France and Germany, while Thailand is critical for Asian rice exports to LDCs. Some countries, like Senegal and Haiti, receive over 96% of their wheat imports from France alone, while the average for the ten LDCs linked to France in

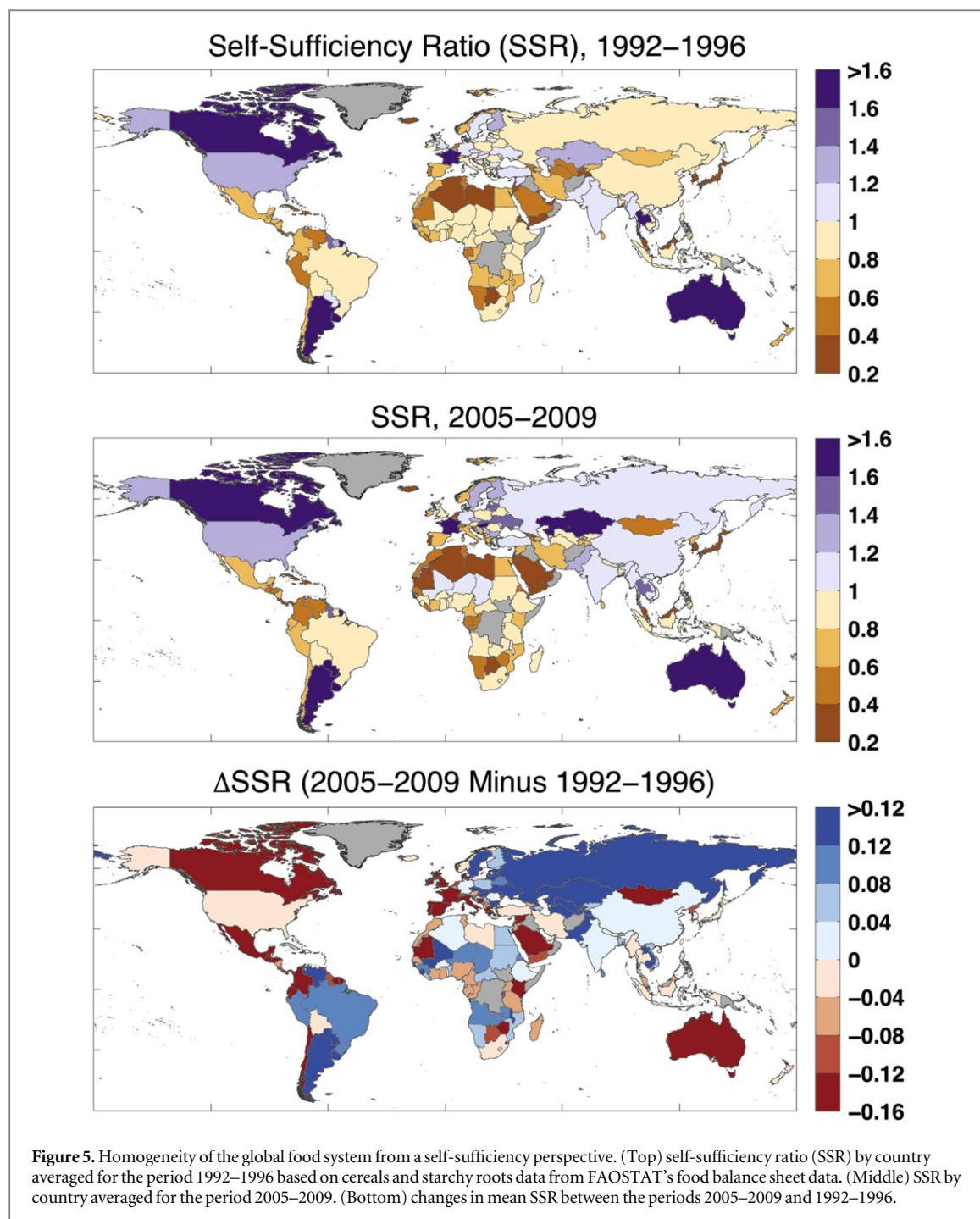


figure 6 is 73%. Thailand is even more important as the sole source of rice imports. Benin, Mozambique, Mauritania, Angola, Laos, Guinea, and Guinea-Bissau all receive over 96% of their rice imports from Thailand, while the average for all fourteen LDCs linked to Thailand is 80%. Overall, these results suggest that LDCs would not benefit from the increases in trade, as they tend to be depended on imports from only one or two countries.

We next assess losses as a percentage of the staple food supply due to the disturbances, comparing results from the static and dynamic accounting approaches. As expected, LDCs experience greater losses with the dynamic accounting compared to static

accounting due to preferential allocation to wealthier nations. More importantly, LDCs suffer greater losses due to the imposed disturbances in the more connected 2005–2009 network with dynamic accounting. In figure 6, median wheat losses are 3.8% for the 1992–1996 network increasing to 5.7% for the 2005–2009 network, while median rice losses increase from 2.2 to 5.2%. Interestingly, mean wheat losses are somewhat larger (8.9% for the earlier period increasing to 11% for the later period) as are mean rice losses (increasing from 8.2 to 14%). This difference between the median and mean changes suggests that LDCs with the greatest losses for 1992–1996 are worse off in the

Table 2. Losses in complex-network metrics for the global wheat and rice trade for the 1992–1996 and 2005–2009 networks. For each metric, the absolute loss for the disturbed network relative to the relevant undisturbed network is followed by the percentage change. All values are average for the respective time period (i.e., 1992–1996 or 2005–2009) using the static-accounting approach.

Network metric	Symbol	Wheat		Rice	
		1992–1996	2005–2009	1992–1996	2005–2009
Loss in global trade, mmt yr ⁻¹ (%)	ΔG_{total}	38 (33%)	46 (29%)	15 (59%)	26 (60%)
Loss in no. of links, - (%)	ΔL	1641 (42%)	2081 (32%)	466 (28%)	710 (26%)
Loss in no. of active export nodes, - (%)	ΔN_{out}	29 (19%)	28 (16%)	14 (12%)	17 (11%)
Loss in no. of active import nodes, - (%)	ΔN_{in}	6 (3%)	1 (1%)	14 (7%)	5 (3%)
Loss in avg. active export degree, - (%)	$\Delta \langle k_{\text{out}}^{\text{act}} \rangle$	7 (28%)	7 (20%)	2 (18%)	3 (17%)
Loss in avg. active import degree, - (%)	$\Delta \langle k_{\text{in}}^{\text{act}} \rangle$	7 (40%)	10 (32%)	2 (23%)	3 (24%)
Loss in avg. active export strength, mmt yr ⁻¹ (%)	$\Delta \langle s_{\text{out}}^{\text{act}} \rangle$	0.13 (17%)	0.14 (16%)	0.11 (54%)	0.16 (56%)
Loss in avg. active import strength, mmt yr ⁻¹ (%)	$\Delta \langle s_{\text{in}}^{\text{act}} \rangle$	0.16 (31%)	0.22 (29%)	0.07 (56%)	0.12 (59%)
Loss in max. export degree, - (%)	$\Delta k_{\text{out}}^{\text{max}}$	16 (10%)	9 (5%)	4 (3%)	3 (2%)
Loss in max. import degree, - (%)	$\Delta k_{\text{in}}^{\text{max}}$	20 (28%)	25 (23%)	8 (23%)	12 (22%)
Loss in max. export strength, mmt yr ⁻¹ (%)	$\Delta s_{\text{out}}^{\text{max}}$	0 (0%)	0 (0%)	4.2 (52%)	7.7 (61%)
Loss in max. import strength, mmt yr ⁻¹ (%)	$\Delta s_{\text{in}}^{\text{max}}$	1 (7%)	0.9 (12%)	1.5 (61%)	1.8 (63%)

2005–2009 network with the imposed disturbances (table 3).

Many island nations and African countries are especially vulnerable to the imposed shocks based on our findings (figure 6 and table 3). For example, countries in northern Africa and the Middle East lose substantial percentages of their staple food supply due to the wheat shock, with the greatest losses in Yemen and Mauritania. For rice, losses are especially substantial in the developing countries of western Africa. Haiti stands out as the country that is most severely impacted by both the wheat and rice shocks (table 3).

4. Discussion and conclusions

We show that the global food system does exhibit characteristics consistent with a fragile one that is vulnerable to self-propagating disruptions. That is, in a setting where countries are increasingly interconnected and more food is traded globally over the 18 year study period, a significant majority of countries are either dependent on imports for their staple-food supply or would look to imports to meet any supply shortfalls. A benefit of this dependency is that the global food system is generally robust to a shock impacting a random node, provided that the node is not a major one. However, we also highlight a mechanism for self-propagating trade disruptions: the tendency of countries to protect their domestic markets using trade restrictions. Empirical evidence suggests that such trade restrictions can propagate, because countries tend to flip between exporting and non-exporting states depending on the trade status of their neighbours [36].

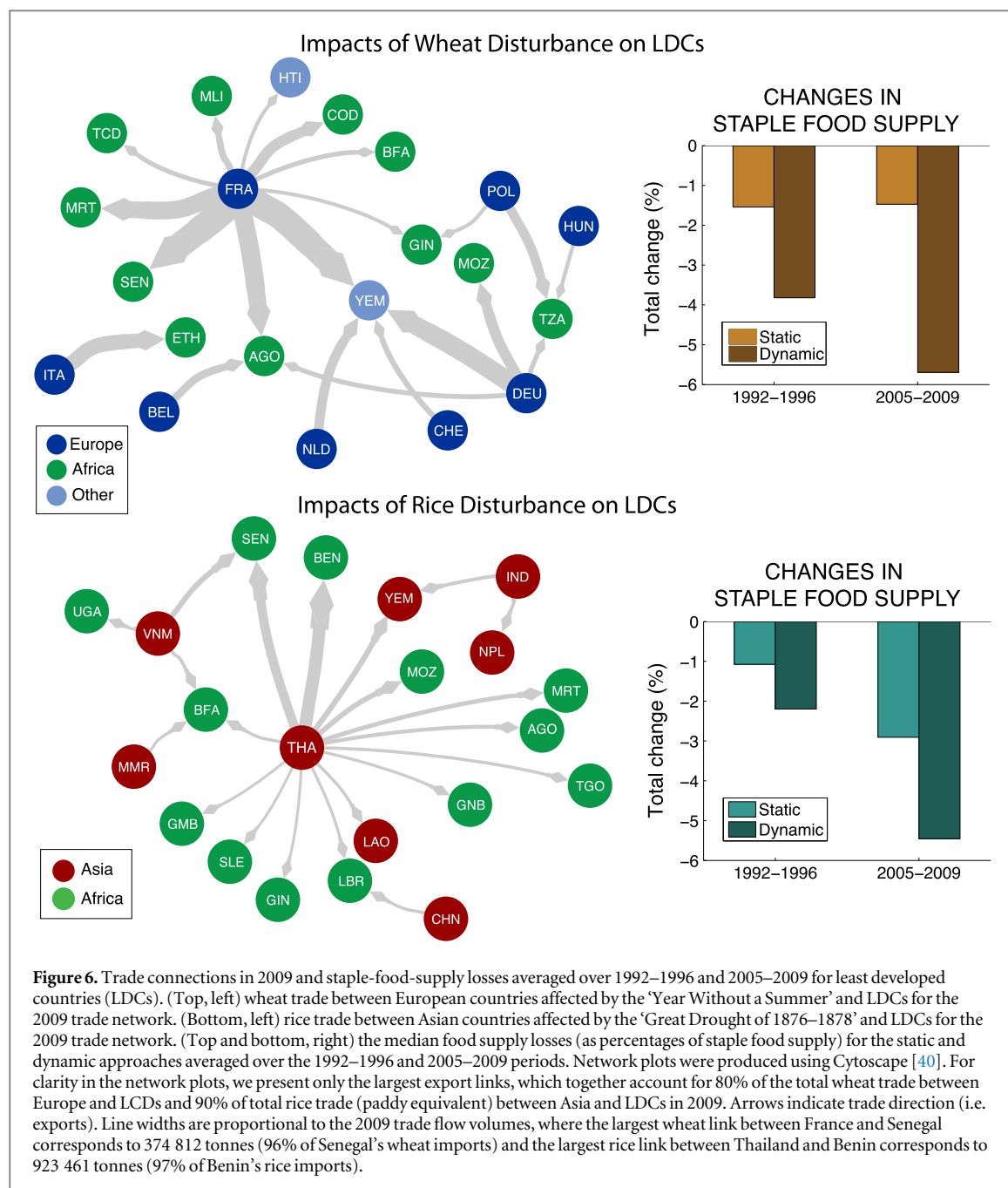
More generally, we demonstrate that fundamental, evolving characteristics of the global food system make it increasingly necessary to consider global systemic risk. Significant pressures from outside the system like the extreme weather anomalies (i.e., the ‘Year Without a Summer’ and Great Drought) could

be triggers for global systemic disruption. Other triggers could be related to food-reserve levels, speculative influences, rapid economic growth of developing economies, and depreciation of the US dollar [62]. Here we emphasize that fundamental network characteristics of the global food system—like high interconnectivity and homogeneity—influence how susceptible the system is to these triggers.

What then are our options going forward to mitigate global systemic risk and enhance the resilience of the global food system? As a starting point, we need to move away from a regional or component-oriented view of systemic risk in the global food system towards a network- and interaction-oriented view [27]. To do so, we look to a recent study that identified policy-relevant principles to enhance resilience of social-ecological system [63]. In particular, we focus on the following three principles [63]:

- (1) preservation/promotion of redundancy and diversity within the system
- (2) management of connectivity in the system
- (3) management of gradual changes and feedbacks impacting the system.

In the context of the global food system, redundancy means that, if production and/or trade of certain commodities are interrupted in one or more regions, other parts of the food system can make up for the losses. Creating redundancy is a major challenge as the world is now experiencing a tighter relationship between agricultural supply and demand—likely to be exacerbated in the future—due especially to climate change, a shift towards more affluent diets, growth in population, biofuels, and depletion of water resources [64]. Demand-side solutions involve exploring opportunities for diet diversification to help mitigate dependency on these major crops. In conjunction with diet diversification, supply-side solutions are critical.



From a supply-side perspective, our analyses of the wheat and rice networks demonstrate that fundamentally different approaches are needed to improve redundancy for wheat and rice. Wheat is heavily traded but with production distributed over various regions; conversely, rice trade is somewhat smaller but with production largely concentrated in Asia. Redundancy improvements for wheat might focus mainly on increases in domestic production in countries where (1) wheat makes up a large percentage of the nation’s diet and (2) the country depends heavily on imports to meet this demand. For rice, we might look to promote the expansion of production outside of Asia, as has been done with soya bean. However, this expansion would require that farmers profit from growing rice in new regions, which would be influenced by multiple

market factors and grade-trade logistics as well as the suitability of agricultural land and availability of water resources for rice production. These strategies would also have to be evaluated by both private corporations and government along with the various environmental costs of such changes (e.g. deforestation, water-resource depletion), so that the appropriate trade-off between efficiency and resilience is assessed.

Promoting diversity in the global food system is equally challenging. Over the past 50 years, we have seen a narrowing in diversity in crops with wheat, rice, and other globally common crop commodities becoming more important in national food supplies [65]. To counteract this trend, we might consider supply-side solutions that maintain the current supply portfolio but expand the genetic diversity of major

Table 3. Top five losses (based on the 1992–1996 network) as percentages of staple food supply in least developed countries for targeted (top) wheat disturbance (bottom) rice disturbance using dynamic accounting. Losses are presented for both the 1992–1996 and 2005–2009 networks.

Wheat disturbance		
Country	1992–1996	2005–2009
Yemen	55%	64%
Mauritania	40%	61%
Kiribati	32%	39%
São Tomé & Príncipe	28%	33%
Haiti	24%	21%
Rice disturbance		
Country	1992–1996	2005–2009 ^a
Comoros	45%	64%
Senegal	31%	53%
Haiti	23%	39%
Benin	23%	41%
Togo	22%	25%

^a The top five losses for the 2005–2009 network include Kiribati (51%) and Gambia (42%).

crops. That is, there is a critical need to continue to support and expand breeding and cultivation of varieties that have diverse genetic backgrounds [65–67].

‘Management of connectivity’ can be framed as the need to address the tradeoffs associated with local and global resilience, which requires that countries consider balancing food self sufficiency and import dependency. For example, the impasse on agricultural trade faced by the World Trade Organization’s Doha Development Round is linked to policies that protect domestic agriculture. (The main aim of the Doha round is to lower trade barriers in the global trade system.) Governments are reluctant to remove such protective policies, in part, because of an implicit recognition of the dangers associated with substantial dependence on the global markets for domestic food supply. Past behaviour suggests that countries are likely to adjust their trade policies in response to surges in food prices. We then should expect that, during the times of actual (or perceived) food scarcity in the global markets, each government’s priority would be the protection of domestic food supply and markets. Strategies to improve global food security should recognize and account for this behaviour. Overall, both private corporations and governments need to move beyond the traditional aggregate supply-demand approach to better understand the complex interdependencies of the global food system.

Lastly, ‘gradual changes and feedbacks’ include the aforementioned tighter relationship between food supply and demand, pressures related to climate variability and change [68], and depletion of critical groundwater resources that are used for irrigation in major agricultural regions [69]. To address gradual changes effectively, greater recognition of the

pressures from a network- and interaction-oriented perspective is needed. Then private corporations and governments must take concerted steps to adjust global food systems. Such steps may include new investments in food buffer stocks (avoiding the pitfalls associated with purely public food stocks [62]), increased domestic yield improvements [70], and protection of agriculturally productive lands [71]. Of these steps, buffer stocks are particularly important, considering that the global food system is particularly sensitivity to supply and demand shocks when stocks are low [72]. Ultimately, further analyses using the complex systems perspective are needed, so that the resilience of our global food system is improved in the coming years.

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