Improving the Resilience of African Countries to Food Shocks

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ABSTRACT

Most African countries are poorly positioned to deal with unanticipated shocks to the global food system. To mitigate vulnerabilities to this systemic risk, a new perspective on food security is needed that both supports diverse trade relationships for staple foods and promotes some degree of self sufficiency in domestic food production in African countries. Here we use a network-based shock propagation model to explore the sensitivity of African countries to short-term production shocks in the global food system. We examine the global cereals trade network for two periods, 1996–2000 and 2006–2010. Our results reveal two trends in African food status: an intensifying dependence on imported cereals complemented by a decline in intra-African trade. We find that maintaining stable intra-African trade links is a critical and effective strategy for absorbing and mitigating food-supply disruptions. Although intra-African trade represents 5.4% and 4.1% of African trade in the 1996–2000 and 2006–2010 time periods respectively, stabilizing intra-African trade links reduces individual African countries exposure to supply shocks by 26% and 20% and to consumption shocks by 22% and 14%, respectively.

Introduction

Mounting pressures on the global food system have renewed interest in governmental and institutional food policies[1]. These pressures include demand side pressures such as increasing population and changing diets as well as supply-side pressures such as changing agricultural production patterns due to climate change[2] and depleting groundwater due to unsustainable agricultural practices[3]. Africa is particularly vulnerable to these pressures as forcefully demonstrated by the global food crisis in 2007-2008[4,5]. Steep increases in international cereal prices, where wheat and corn doubled over two years and rice tripled over just a few months[6], initiated riots, with 14 out of 53 countries in Africa experiencing mass disturbances[7]. These events demonstrate that in the modern global economy, food-price spikes and supply deficits can lead to local political instability[8,9].

Food self sufficiency in Africa has declined in the decades since the 1960s[10]. While shifting away from staple food production may have economic benefits, it exposes African countries to systemic risk. In this context, *systemic risk* refers to threat associated with food production disruptions that could initiate a cascading failure in the food system[11]. African food policy makers therefore face a dilemma. International trade in the global food system provides new channels to meet food demand[12] but also may enhance the possibility of shock diffusion across borders[6] and a decline in national food security independence. This threat of shock diffusion highlights the need for a new way of thinking about national food policies both within and outside of Africa.

Presently, the African Union is moving forward to promote economic integration at the continental scale[13]. This proposed restructuring will likely have substantial implications for vulnerability of African countries to sudden disruptions. These disruptions or "shocks" can be weather-related: extreme droughts, floods, heat waves, and cold spells could all dramatically reduce crop yields depending on the timing, duration, and intensity of the weather event. Non-environmental disruptions – including economic crises, policy shifts, trade agreements, cyber-attacks, and civil conflict – could also lead to food system shocks.

Here we explore the response of the global food trade network to shocks, using a food shock propagation model[14] to understand the relative exposure of African countries to such disruptions. We examine the historical global cereals trade network for two periods, 1996–2000 and 2006–2010, to assess the implications of increased dependence on extra-Africa cereals imports and declining intra-African trade. We modify the simulation logic of the base model to (1) understand the contribution of intra-African trade and extra-African trade to African exposure to food shocks, (2) understand the relative importance of intra-African trade to systemic risk in African food security, and (3) investigate the impact of policies aimed at continental level stability in intra-African trade.

Methods

Model

We use the food shock propagation model introduced by Marchand et al.[14]. In this model, the global food trade network is represented as a graph in which each country is represented as a node with associated production, consumption, supply and reserves attributes, and bilateral trade is represented as directed edges from exporter to importer. The model simulates the network response to an exogenously induced shock to the production of a given country. The shock is initiated at a selected country and is given by the *production fraction* of the country's production.

The simulation execution proceeds in discrete time steps. On each time step, each shocked country attempts to absorb the shock by first consuming up to the *reserve fraction*, f_r, of its reserves. If the reserves do not fully absorb the shock, then the country consumes up to the *consumption fraction*, f_c, of its reserves. If there is any remaining shock, then the country attempts to pass the remaining shock through to its trade partners by increasing its imports and decreasing its exports, with the restriction that it cannot increase imports from a trade partner that has absorbed a shock to its consumption. The remaining shock is distributed among its partners in proportion to their trade volumes. Each trade link thus limits its trade adjustment to its current trade volume. Finally, any remaining shock is simply absorbed by consumption. The *production fraction*, *reserve fraction*, and *consumption fraction* are global model parameters that are fixed before simulation begins. See Marchand et al.[14] for further details.

We modify the Marchand model to implement a pan-continental African shock absorption strategy of maintaining stable trade links. In the modified model, when an African country adjusts the trade volumes associated with its trade partners, it excludes other African countries from this adjustment. Thus, the total amount of shock an African country may pass on to its trade partners is the sum total of its trade volumes with extra-African partners, and shock is distributed in proportion to this amount.

Data

We initialized the network using historical data on cereals reserves, production, consumption and trade[14]. We also used the same data sources and processed the data when possible in the same way. We obtained trade, production and consumption data from the Food and Agriculture Organization (FAO) of the United Nations. Trade data is extracted from the Detailed Trade Matrix (DTM) published by the FAO Statistics division (FAOSTAT). The DTM is organized into rows structured by a *reporter country*, *partner countries*, *item*, *element*, and *unit* with a value and flag for the years 1986 to 2013.

The export volumes over a directed trade link between two countries from x to y is derived from the rows that have x as the *reporter country*, y as the *partner countries*, *Export Quantity* as the *element* and any of *item*s for the majority of cereals in the FAOSTAT database (see Appendix for the list). The values for all of the cereals *item*s extracted from the detailed trade matrix are provided in units of tons. To derive the final export volumes associated with each trade link, each commodity is converted into its kilocalorie equivalent and summed.

Production and consumption data are extracted from the Food Balance Sheet (FBS) published by FAOSTAT. The FBS is organized into rows structured by an *Area*, *Item*, *Element*, and *Unit* with a value and flag for the years 1961 to 2013. We derive the production of a country, c, from the rows that have c as their *Area*, *Production* as their *Element* and their *Item* (see Appendix for the list of FBS cereals). The values for all of the cereals *item*s extracted from the food balance sheet are given in units of 1000 tons. To derive the final production, and consumption values associated with each node, commodities are converted to their kilocalorie equivalent and summed.

Reserves data are extracted from the Production, Supply and Distribution (PSD) database published by the United States Department of Agriculture (USDA). The PSD is organized into rows structured by *commodity*, *country*, *market year*, *calendar year*, *attribute*, *unit* and *value*. We derive the reserves of a country, c, from the rows that have c as their *country*, *Ending Stocks* as their *attribute* and any of the *commodities* that correspond to the study cereals.

Time Periods

After processing the raw data, we further restricted the values for each initial network configuration to those from two fixed 5-year contiguous windows, 1996–2000 and 2006–2010, after considering all 5-year periods in the 1992-2013 time period. These time periods were chosen by a combination of the completeness of their reported data and their historical significance (see Appendix). The period 2006–2010 was selected, because it was the most recent 5-year window with relatively complete data; we therefore take this periods as our best approximation to the current state of the global food trade network. We selected the time period 1996–2000 because of its historical significance to Zimbabwean agricultural production and trade. The year 2000 marked the beginning of a violent and destabilizing phase of land reform in Zimbabwe, which saw Zimbabwean cereals production decrease by 50% (see Figure 1) and the country change from being the only African country that was a net exporter of cereals to a net importer.

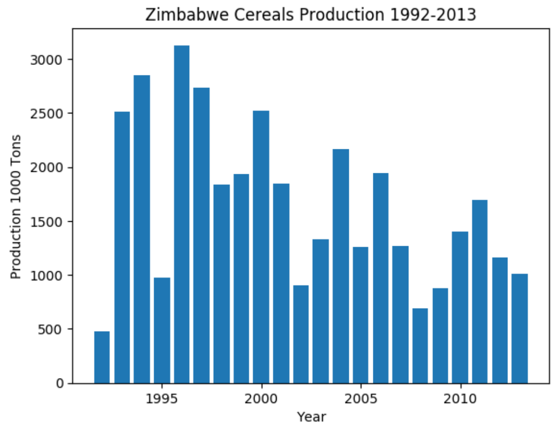

Figure 1. Zimbabwe cereals production in 1000 tons by year.

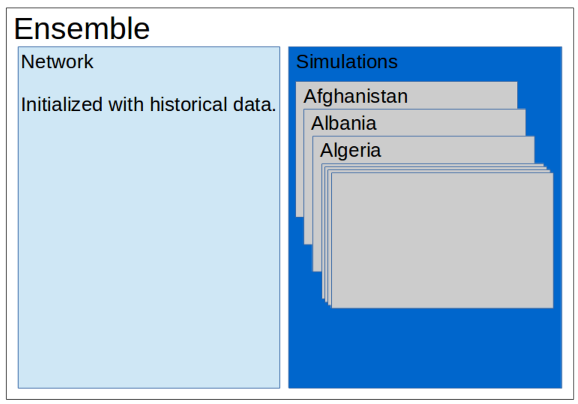

Figure 2. Structural representation of an ensemble run. Each ensemble has a fixed initial network state which is the same at the beginning of every simulation. One simulation is executed for as many countries as there are in the network with each country set as the epicenter in turn.

Simulation Design and Response Variables

We ran two ensembles of simulations for each initial network configuration, one for the original model logic ("Control") and the other for the modified model logic that would maintain African trade links ("Stable-Africa"). For each simulation, one country is selected to be the epicenter for a food production disruption and the shock propagation is simulated according to the ensemble logic. After convergence, data were collected on the final network state and then the network state was reset for the next simulation. The response variables are computed over the data from all the simulations in each ensemble run. The organization of the ensemble runs is shown in Figure 2.

We apply several of the response variables from Marchand et al. In particular we report the number of simulations in an ensemble run, N_c. We also compute several country level metrics. The number of *hits*, N_h, a country experiences across all simulations, that is the number of simulations in which a country receives a shock. We also count the number of simulations in which a country receives a *consumption hit*, N_{hc}. We record the total changes in supply and consumption for a country j as ΔS_j and ΔC_j respectively. The total changes are accumulated over all of the simulations in an ensemble run. We define the *relative change in net supply* of a country j to be

$$\Delta s_{\mathrm{rel},j} = \frac{\Delta S_j}{f_p S_{0,j}}$$

and the *relative change in net consumption* of a country j is defined similarly as

$$\Delta c_{\mathrm{rel},j} = \frac{\Delta C_j}{f_p S_{0,j}}$$

where $S_{0,j}$ is the initial supply of country j. The average over all countries gives the model run response variables *change in net supply* and *relative change in consumption*, Δ_s and Δ_c respectively. Finally, we also reapply the response variable of *evenness of*

Response Variable	1996-2000	2006-2010
N_c	162	166
N_h	48.0	61.6
N_h^A	35.8	48.8
N_{hc}	10.0	8.70
N_{hc}^A	17.2	10.7
Δ_s	-0.89	-1.16
Δ_s^A	-0.51	-0.74
Δ_c	-0.24	-0.22
Δ_c^A	-0.24	-0.24
J	0.29	0.35
J^A	0.31	0.35
G	934	1,200
A	139	210
A_i	7.51	8.51
A/G	0.15	0.17
A_i/A	0.05	0.04

Table 1. Response variable values for the Control ensemble run. The response variables G and A are reported in trillion kilocalories.

impact J so that the *evenness of impact* on a country j, J_j is

$$J_j = -\frac{1}{\log N_c}\Sigma_k \pi_{kj} \log \pi_{kj}$$

where π_{kj} is the fraction of ΔS_j that is contributed by the simulation in which country k is the epicenter.

We adapt several of these response variables to better understand the food security situation of the African countries within the context of global food security. In an ensemble run, we define the number of *African supply hits*, N_h^A, to be the average number of African countries that experience a supply hit in any simulation. We analogously define *African consumption hits*. In order to understand which countries represent the most risk to African supplies and consumption, we define the number of *induced African hits* of country k, $N_h^{A_k}$, which is the number of African countries that experience a supply hit when k is the epicenter of the simulation. The number of *induced African consumption hits* of country k is defined analogously. We make similar adaptations for Δs_{rel} and Δc_{rel} to define the *relative change in African supply* and the *relative change in African consumption*, Δ_s^A and Δ_c^A, respectively. Also, for *evenness of impact*, we define the specific *African evenness of impact*, J^A.

We also compute the total global trade volume G as well as the total African trade volumes A, which is the sum of all export volumes where at least one trade partner is an African country. We define intra-African trade volumes A_i to be the sum of all export volumes where both trade partners are African countries.

Results

The results of executing ensemble runs using the Control logic for the two time periods are shown in Table 1. The results of executing the model runs using the Stable-Africa logic on both time periods are shown in Table 2. Plots of *induced African supply hits* and *induced African consumption hits* are shown in Figures 3 and 4. For both time periods, we also plot a heat map showing the change in *induced African supply hits* and *induced African consumption hits* by epicenter in Figures 5 and 6. We omit corresponding figures for the Stable-Africa logic as they do not differ significantly from the Control logic figures.

Discussion

Our results on the two time periods using the original logic of the food shock propagation model ("Control") highlight the vulnerability and exposure of African countries to shocks in the global food system. In 1996–2000, a food shock with an epicenter anywhere in the world would, on average, impact the supplies of more than 70% of all African countries as well as the consumption of more than 30% of all African countries. By 2006–2010 we see that a food shock anywhere in the world would, on average, impact the supplies of almost every African country. Interestingly, however, at the same time as the Control model predicts that African and global exposure to supply hits should increase, it also predicts that African and global exposure

Response Variable	1996-2000	2006-2010
N_c	162	166
N_h	44.6	58.4
N_h^A	26.4	39.1
N_{hc}	8.78	8.22
N_{hc}^A	13.3	9.26
Δ_s	-0.87	-1.14
Δ_s^A	-0.46	-0.65
Δ_c	-0.24	-0.23
Δ_c^A	-0.25	-0.25
J	0.27	0.33
J^A	0.24	0.29
G	934	1,200
A	139	210
A_i	7.51	8.51
A/G	0.15	0.17
A_i/A	0.05	0.04

Table 2. Response variable values for Stable-Africa ensemble run. The response variables G and A are reported in trillion kilocalories.

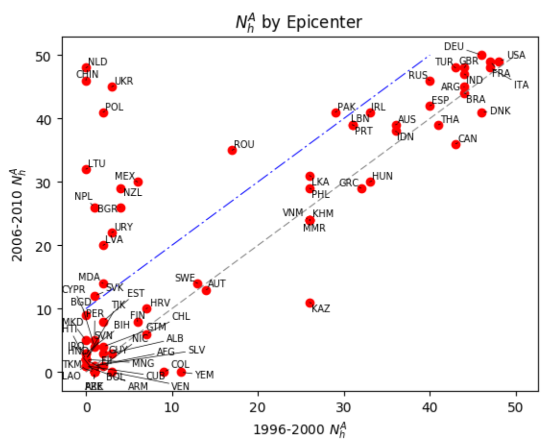

Figure 3. A plot of *induced African supply hits* for each epicenter in the 1996-2000 time period against the 2006-2010 time period using Control ensemble run. The dashed gray line marks the line $y = x$; a country that falls on this line caused the same number of African supply hits in both periods. The dotted dashed blue line is $y = x + 10$; a country that falls on this line or above caused at least 10 more African supply hits in the 2006-2010 time period than in the 1996-2000 time period.

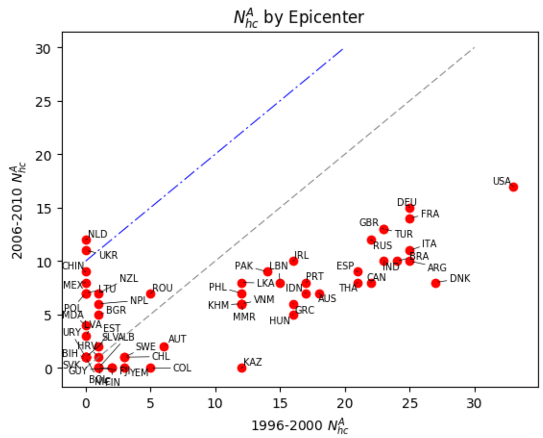

Figure 4. A plot of *induced African consumption hits* for each epicenter in the 1996-2000 time period against the 2006-2010 time period using Control ensemble run. The dashed gray line marks the line $y = x$; a country that falls on this line caused the same number of African consumption hits in both periods. The dotted dashed blue line is $y = x + 10$; a country that falls on this line or above caused at least 10 more African consumption hits in the 2006-2010 time period than in the 1996-2000 time period.

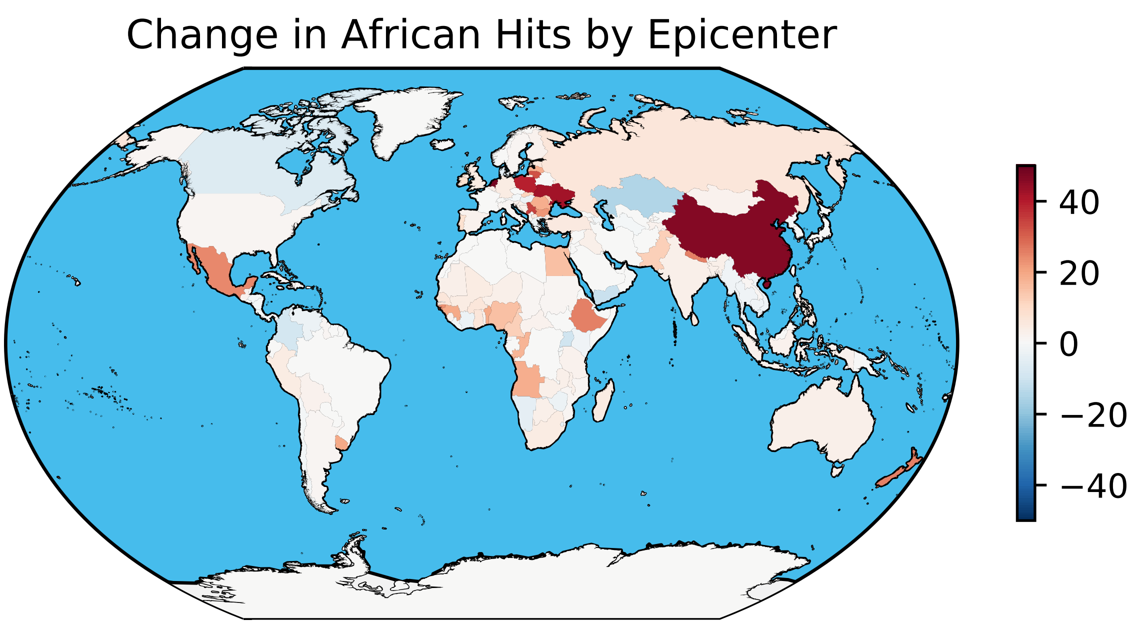

Figure 5. A heat map showing the change in the number of *induced African supply hits* from the 1996-2000 time period to the 2006-2010 time period using Control ensemble run.

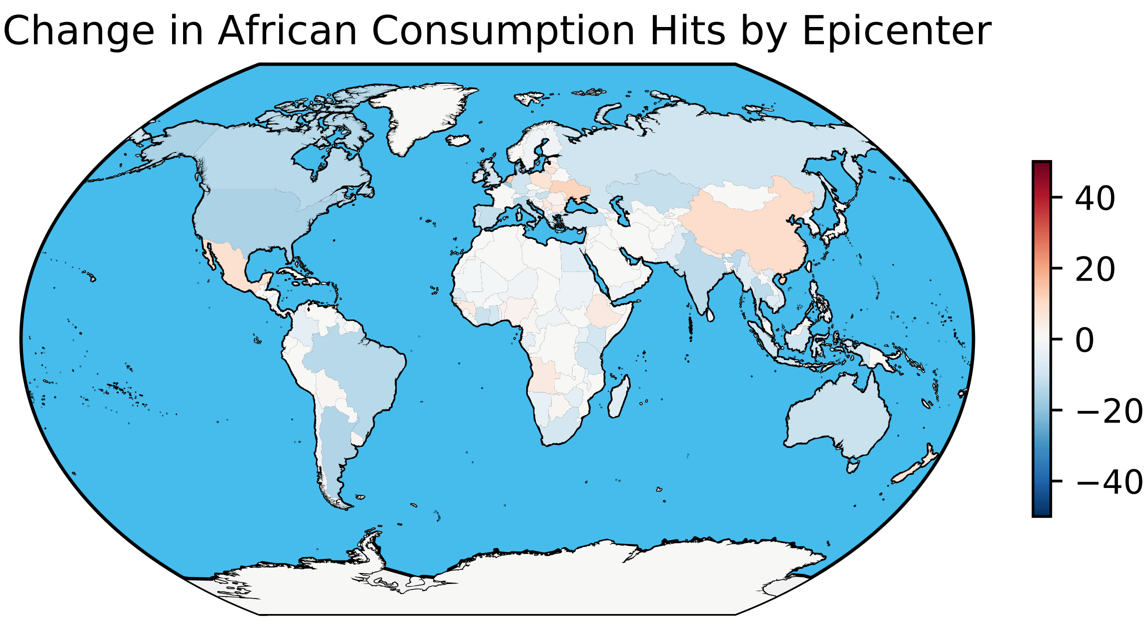

Figure 6. A heat map showing the change in the number of *induced African consumption hits* from the 1996-2000 time period to the 2006-2010 time period using Control ensemble run.

to consumption hits should decrease. This dynamic is captured by how the model allocates the supply of kilocalories between reserves and consumption and also treats them separately.

We identify two major trends in African food security in the context of the global food trade network. First, we observe an increasing dependence on extra-African cereals imports from 1996–2000 to 2006–2010. This is demonstrated by a nominal increase in African trade of 71 trillion kilocalories, a relative increase of 51%, indicating that the global trend of trade intensification is especially pronounced in Africa. However, only 1 trillion kilocalories comes from intra-African trade. Further, when we break down the increase in extra-African trade, we see that exports to extra-African countries have actually declined and so imports of cereals from extra-African countries have increased by an astounding 70 trillion kilocalories.

This intensification of African dependence on extra-African cereals imports is simultaneously complemented by a relative decline in intra-African trade. As mentioned, intra-African trade increased in nominal terms; however, relative to total African trade, it decreased to 4% of total African trade in 2006–2010 from 5% of total African trade in 1996–2000.

While the relatively small share of African trade accounted for by intra-African trade would seem to suggest that intra-African trade should be correspondingly small in shaping African exposure to supply and consumption hits, our results suggest the opposite, intra-African trade plays a vital and disproportionate role in the exposure of African food supplies and consumption. We see that, in the modified model, when intra-African trade links are held stable, African exposure to supply hits decreases by 26.3% from 35.8 to 26.4 in the 1996–2000 time period and by 19.9% from 48.8 to 39.1 in the 2006–2010 time period. Compared to the 5% and 4% share of African trade that is intra-African in the early and later time periods respectively, we see a disproportionate impact.

This has important implications for policy aimed at improving African food security as this suggests that policy targeting trade link stability or that indirectly work to stabilize trade links can yield substantial returns. Examples of such strategies may be pan-continental agreements and increasing production. In the context of a resource constrained environment, putting energy towards maximum impact efforts is paramount. Future work is needed to understand what strategies are available and their practicability.

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Appendix

The cereals extracted from the FAOSTAT detailed trade matrix are listed in Table 3. The FAOSTAT items in the food balance sheet corresponding to the study cereals are listed in Table 4. We define reporting completeness, or simply completeness, of each individual data source to be the ratio of reported values to the number of expected values. Given a time period of interest, in the detailed trade matrix and the food balance sheet we expect that a country should report a value for a commodity in every year in the period where there is a value for at least one year. Thus, in the food balance sheet and detailed trade matrix, we expect as many values as their are rows. The completeness of the reported detailed trade matrix data is shown in Figure 7 and the completeness of the reported data in the food balance sheet is shown in Figure 8. In the production, supply and distribution data, however, each row reports the value for only one year so we must aggregate the rows on the *commodity*, *country*, and *attribute*. The completeness of the production, supply and distribution data is shown in Figure 9.

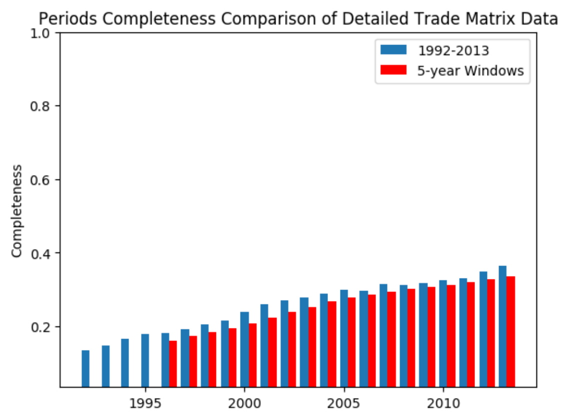

Figure 7. Completeness of the detailed trade matrix data. The blue bars are the completeness for the individual years within the entire 1992-2013 time period we considered for this study and the red bars are the completeness of the 5 year-windows where the bar is placed above the ending year on the x-axis. We see a strong increasing trend in completeness indicating that later periods in the detailed trade matrix have more complete data. Completeness is also fairly low in the earlier time periods, and even with the increasing trend are still fairly low at less than 0.4.

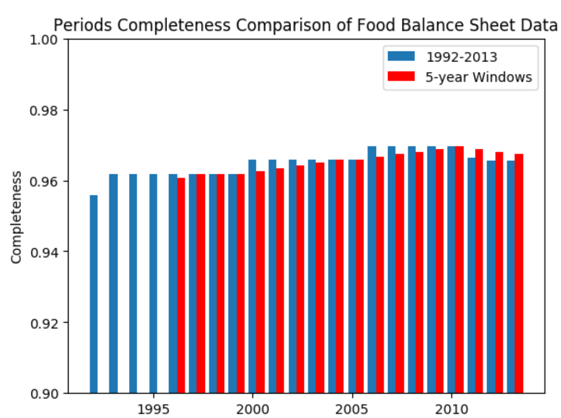

Figure 8. Completeness of the food balance sheet data. The blue bars are the completeness for the individual years within the entire 1992-2013 time period we considered for this study and the red bars are the completeness of the 5 year-windows where the bar is placed above the ending year on the x-axis. We see very consistent and high levels of reporting throughout the time periods indicating a high quality to the food balance sheet data.

FAOSTAT Item Code	Crop Name	Primary?	Conversion factor (10^6 kcal/ton)
15	Wheat	TRUE	3.34
16	Flour of Wheat	FALSE	3.64
18	Macaroni	FALSE	3.67
19	Germ of Wheat	FALSE	3.82
20	Bread	FALSE	2.49
21	Bulgur	TRUE	3.45
22	Pastry	FALSE	3.69
27	Rice, paddy	TRUE	2.80
28	Rice Husked	FALSE	3.57
29	Milled/Husked Rice	FALSE	3.57
31	Rice Milled	FALSE	3.60
32	Rice Broken	FALSE	3.60
38	Rice Flour	FALSE	3.66
41	Breakfast Cereals	FALSE	3.89
44	Barley	TRUE	3.32
45	Pot Barley	FALSE	3.48
46	Barley Pearled	FALSE	3.46
48	Barley Flour and Grits	FALSE	3.43
49	Malt	FALSE	3.68
50	Malt Extract	FALSE	3.67
56	Maize	TRUE	3.56
57	Germ of Maize	FALSE	3.73
58	Flour of Maize	FALSE	3.63
68	Popcorn	FALSE	3.56
71	Rye	TRUE	3.19
72	Flour of Rye	FALSE	3.41
75	Oats	TRUE	3.85
76	Oats Rolled	FALSE	3.84
79	Millet	TRUE	3.40
80	Flour of Millet	FALSE	3.40
83	Sorghum	TRUE	3.43
84	Flour of Sorghum	FALSE	3.43
89	Buckwheat	TRUE	3.30
90	Flour of Buckwheat	FALSE	3.44
92	Quinoa	TRUE	3.42
94	Fonio	TRUE	3.38
95	Flour of Fonio	FALSE	3.55
97	Triticale	TRUE	3.27
101	Canary seed	TRUE	3.88
103	Mixed grain	TRUE	3.40
104	Flour of Mixed Grain	FALSE	3.64
108	Cereals, nes	TRUE	3.40
109	Infant Food	FALSE	3.68
110	Wafers	FALSE	4.39
111	Flour of Cereals	FALSE	3.64
113	Cereal Preparations, Nes	FALSE	3.64
114	Mixes and Doughs	FALSE	3.93
115	Food Prep, Flour, Malt Extract	FALSE	3.77

Table 3. Table 2 from the supplementary data of Marchand et al.[14]. List of the FAOSTAT **item**s that correspond to the study cereals and that were extracted from the detailed trade matrix to initialize the network with trade links and export volumes.

FAOSTAT Item Code	Item Name
2511	Wheat and products
2805	Rice (Milled Equivalent)
2513	Barley and products
2514	Maize and products
2520	Cereals, other
2515	Rye and products
2516	Oats
2517	Millet and products
2518	Sorghum and products
2680	Infant food

Table 4. List of FAOSTAT **item**s used to initialize the nodes' production attribute in the network.

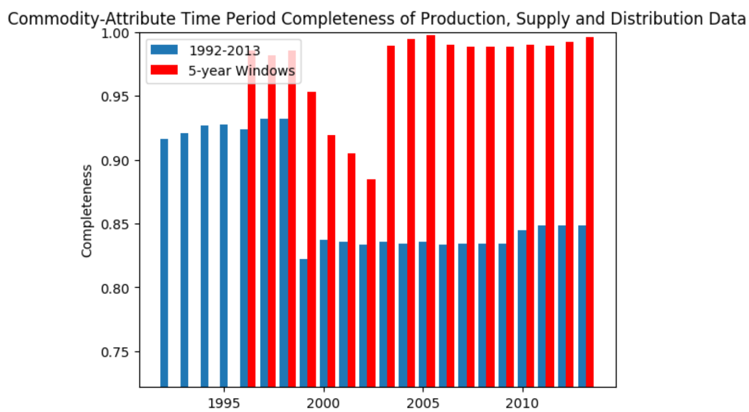

Figure 9. Completeness of the food balance sheet data. The blue bars are the completeness for the individual years within the entire 1992-2013 time period we considered for this study and the red bars are the completeness of the 5 year-windows where the bar is placed above the ending year on the x-axis. Interestingly, we see a divergence between the full 22 year window versus the rolling 5-year windows. This likely reflects high variability in the groups of commodities reported over time. If a commodity is only ever reported in 1992, for example, then it will bring down the completeness of every other year in the full window, but only the years 1993-1996 in the only 5-year window that contains 1992.