Supplementary Information

Grain export restrictions during COVID-19 risk food insecurity in many low and middle income countries

Theresa Falkendal[1,*], Christian Otto[1], Jacob Schewe[1], Jonas Jägermeyr[2,3,1], Megan Konar[4], Matti Kummu[5], Ben Watkins[6] and Michael J. Puma[2,3,*]

[1] Potsdam Institute for Climate Impact Research, 14473 Potsdam, Germany.

[2] NASA Goddard Institute for Space Studies, New York, NY 10025, USA.

[3] Center for Climate Systems Research, Earth Institute, Columbia University, New York, NY 10025, USA.

[4] Civil and Environmental Engineering Department, University of Illinois at Urbana-Champaign, Urbana, IL, USA.

[5] Water and Development Research Group, Aalto University, Tietotie 1E, 02150 ESPOO, Finland.

[6] Kimetrica, Brooklyn, NY 11225, USA.

[*] Corresponding authors

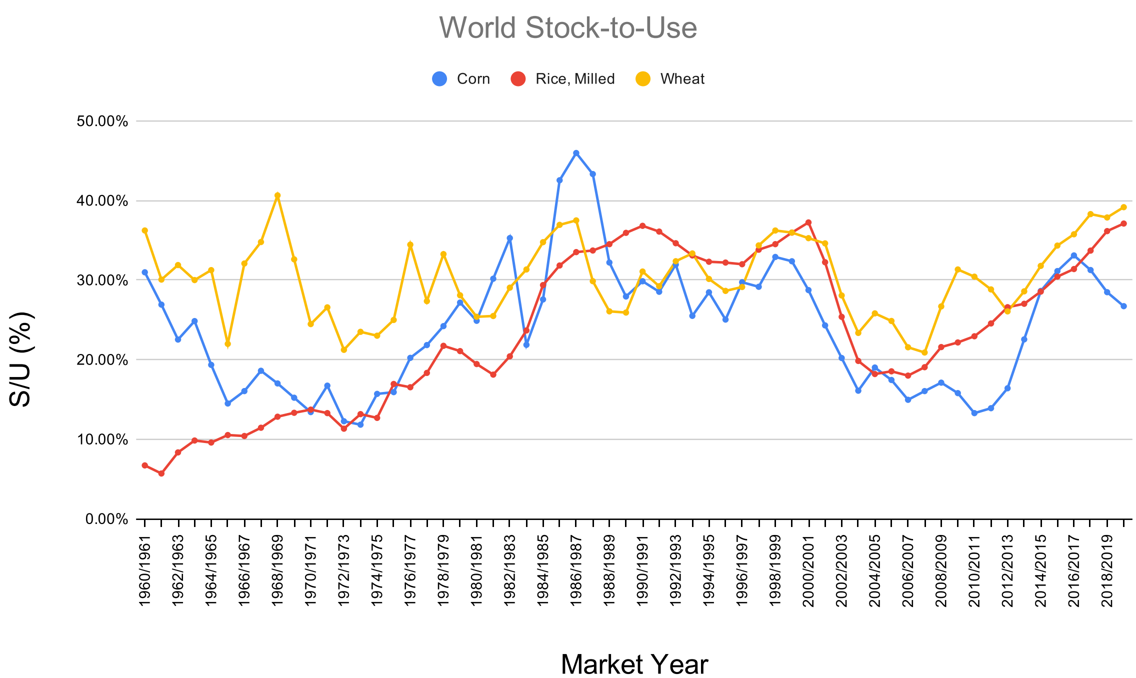
Email: theresa.falkendal@pik-potsdam.de and mjp38@columbia.edu

Table of Contents

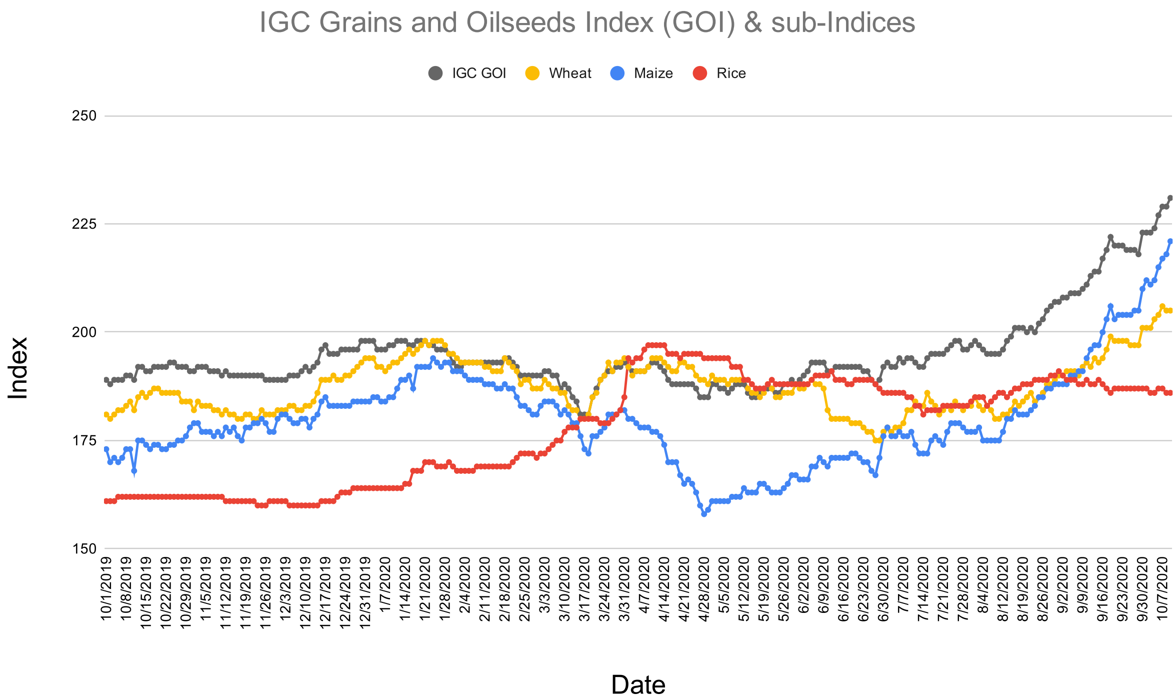
List of Supplementary Figures

List of Supplementary Tables

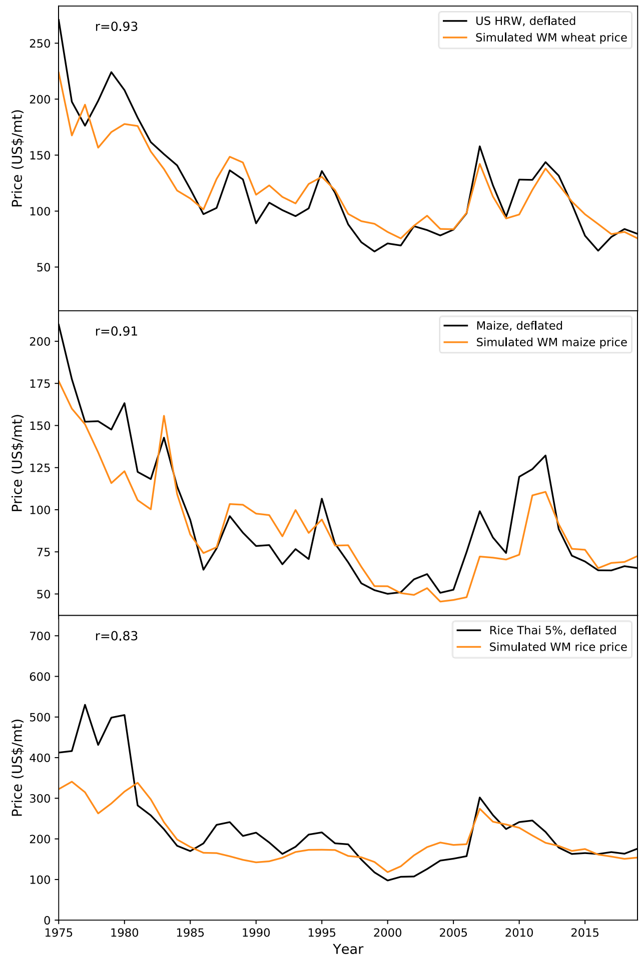
Supplementary Figures



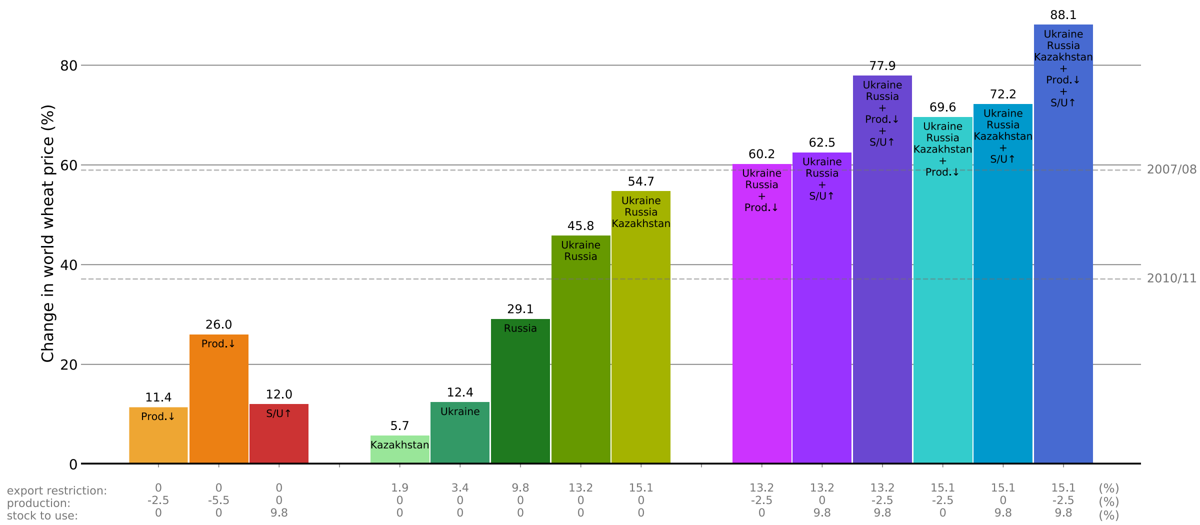
Supplementary Figure 1| World stock-to-use ratio. Derived values of S/U for wheat, rice and maize for 1960-2019, where S/U is the ending stock divided by domestic consumption. Data source: USDA PSD online.



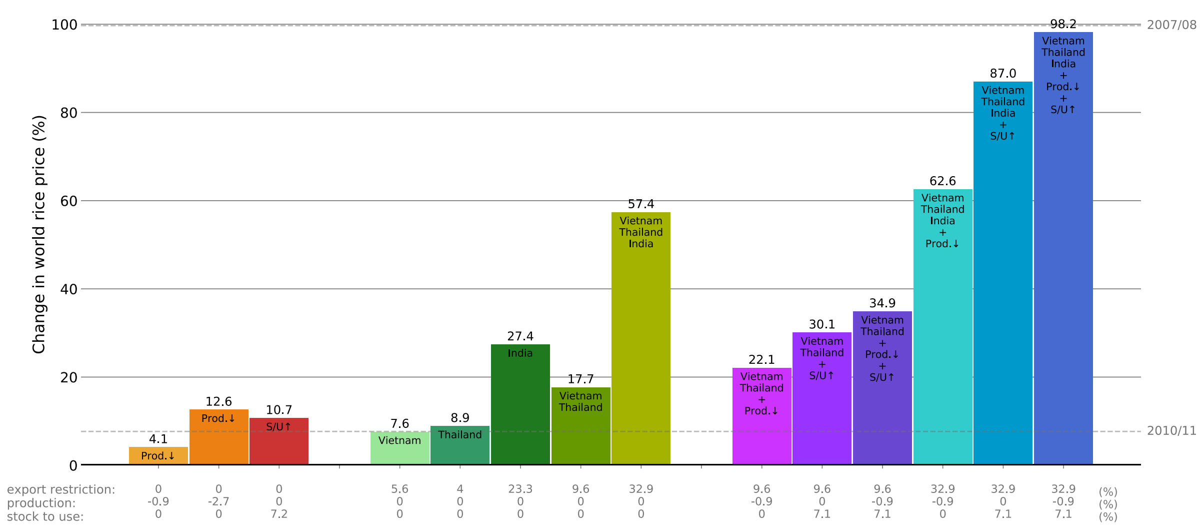
Supplementary Figure 2| Food price indices. Grain and Oilseeds index (GOI) and sub-indices for wheat, rice, and maize reported on a daily basis between October 2019 and October 2020. Normalized to January 2000 = 100. Data source: IGC.



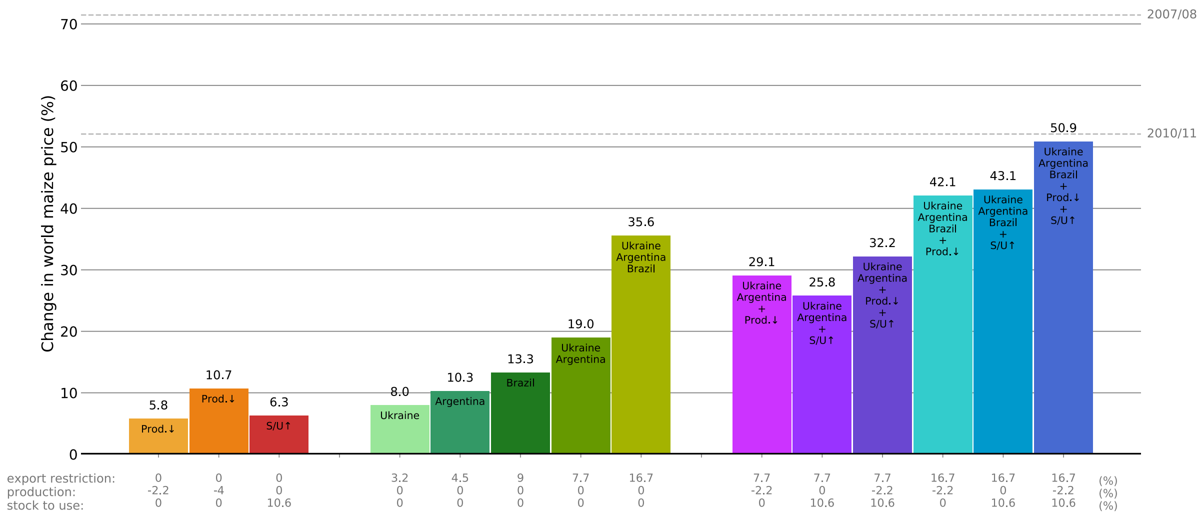
Supplementary Figure 3| Calibration to historic observed price. Simulated world market price (orange) for wheat (upper panel), maize (middle panel), and rice (lower panel) and time series of observed real prices (black). The model is calibrated individually for each crop to reproduce the historic price time series, where r denotes the Pearson's correlation coefficient.



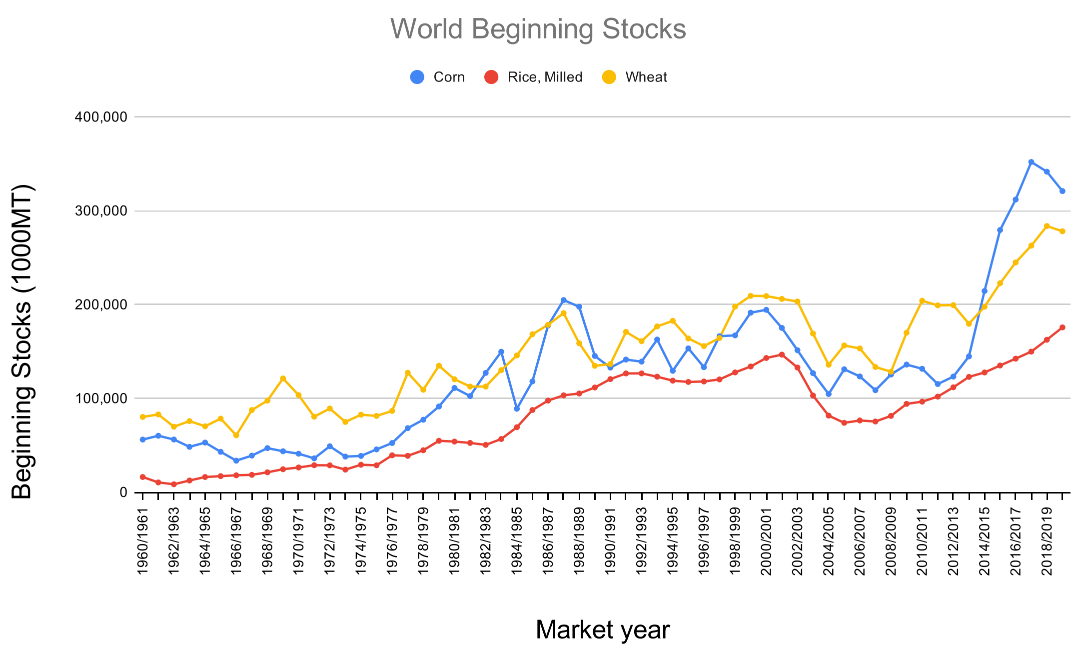
Supplementary Figure 4| Change in wheat price. Estimated scenario prices compared to the baseline price for 14 different scenarios. The results are grouped into 3 categories. Orange/red bars: Simulations with only a decrease in production or only an increase in stock-to-use ratio, first bar: combined world shock (cf. Supplementary Table 12), second bar: a 5th percentile total world production decline (cf. Supplementary Table 19), third: 80th percentile increase of stock-to-use ratio (cf. Supplementary Table 14). Green bars: Export restrictions only for individual/multiple countries (see labels in figure for country specifications). Purple/blue bars: Multiple combined shock scenarios. The size of the shocks is given below the bars. The dashed lines indicate the price changes during the previous world food price crises (see text for details).



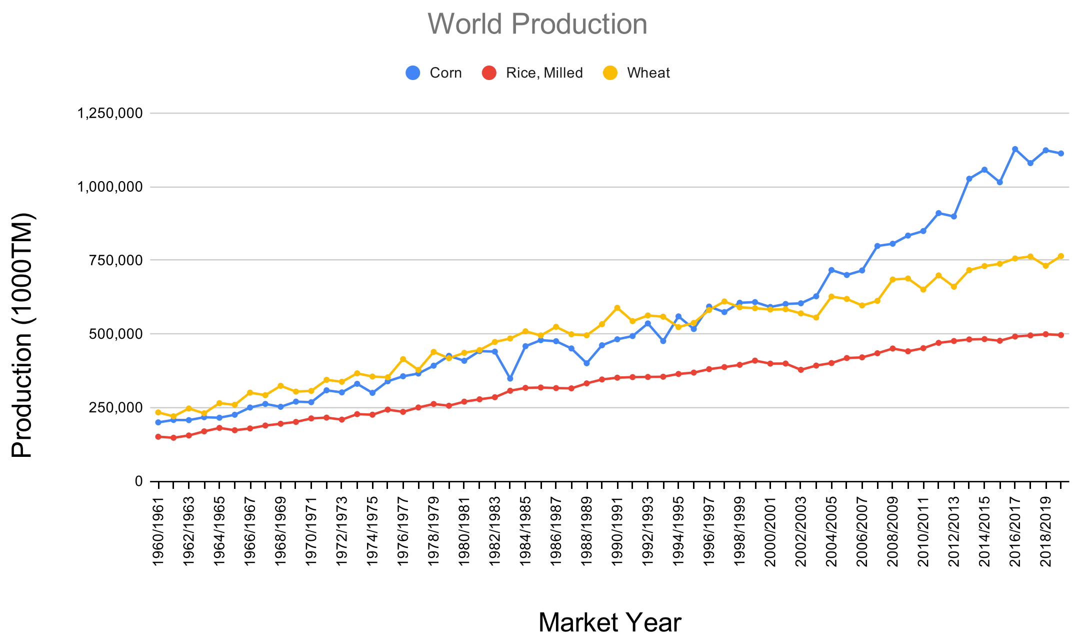
Supplementary Figure 5| Change in rice price. See caption of Supplementary Figure 4 for further details about the scenarios.



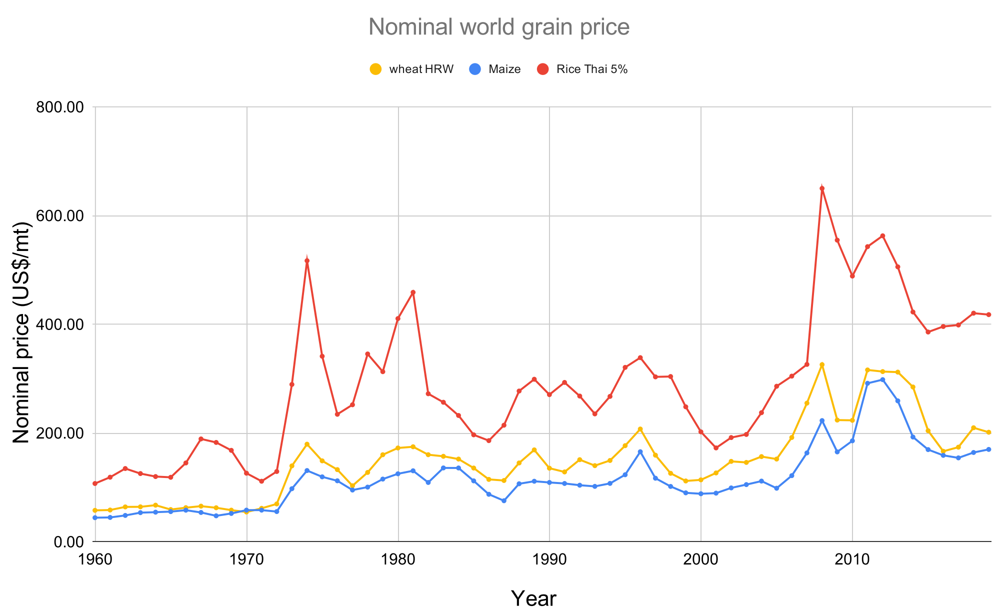
Supplementary Figure 6| Change in maize price. See caption of Supplementary Figure 4 for further details about the scenarios.



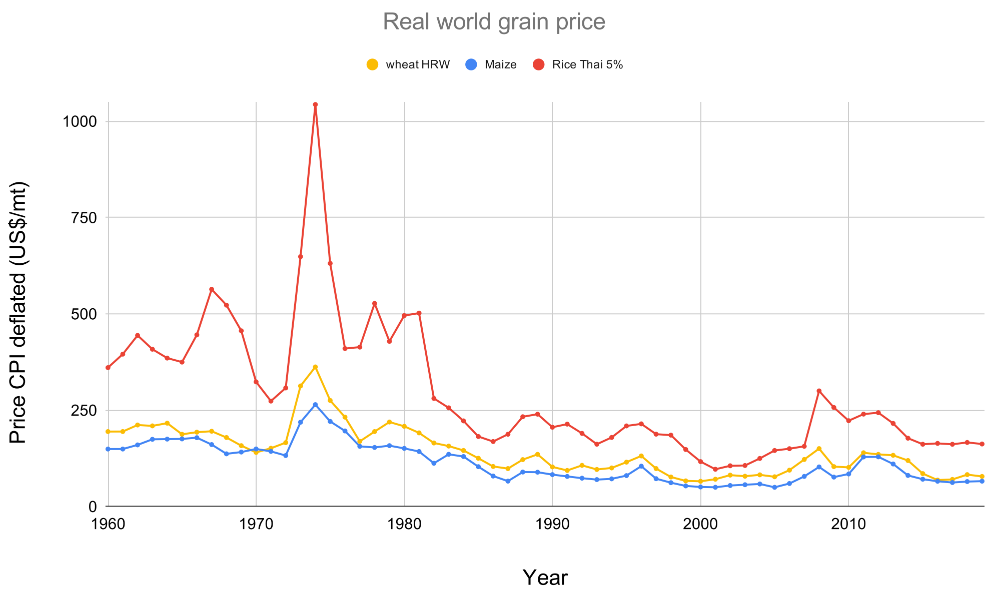
Supplementary Figure 7| World's grain stock. Beginning stocks from wheat, rice and maize from 1960-2019. The current world stock levels are historically high for rice, wheat and maize. Data source: USDA PSD online.



Supplementary Figure 8| World production of wheat, rice and maize. Data source: USDA PSD online.



Supplementary Figure 9| Annual nominal world market price. Historic prices for wheat HRW, rice Thai 5% and maize for 1960-2019. Data source: "pink sheet" of the World Bank.



Supplementary Figure 10| Annual real world market price. Historic prices for wheat HRW, rice and Maize for 1960-2019, deflated by the CPI normalized to June 1983=100. Data source: World Bank "pink sheet" and CPI from US Bureau of Labor Statistics.

Supplementary Tables

Supplementary Table 1| Result of impaired supply calculations for wheat with production losses. Applied values of wheat production decline in selected countries (Supplementary Methods: Production Decline) and the resulting change in impaired supply due to production losses (given in percent and kcal) and domestic reserves. The last column shows the ratio of the decline in supply (due to production losses and export bans) to the domestic reserve. Data Source: FAOSTAT.

Country	Change in production due to production decline	Change in Impaired Supply due to P loss (fraction)	Change in Impaired Supply due to P loss (kcal)	Reserves (kcal)	Exports (kcal)	Ratio of decline in Impaired Supply to Reserves
Kazakhstan	-18.18%	-23.90%	-1.61E+13	5.97E+12	2.16E+13	269.40%
Russian Federation	-7.68%	-10.23%	-2.58E+13	3.13E+13	8.57E+13	82.45%
Ukraine	-20.50%	-39.78%	-2.25E+13	4.52E+12	5.33E+13	496.77%
Ethiopia	-8.74%	-7.65%	-1.86E+12	1.54E+12	1.38E+10	120.82%
Iran (Islamic Republic of)	-10.24%	-9.54%	-6.67E+12	2.28E+13	9.93E+11	29.29%
Kenya	-49.16%	-8.56%	-5.93E+11	6.06E+11	2.60E+10	97.94%
Pakistan	-9.76%	-9.94%	-1.14E+13	9.37E+12	2.20E+12	121.66%
Saudi Arabia	-44.83%	-8.98%	-1.21E+12	1.03E+13	4.17E+11	11.80%
Yemen	-23.35%	-1.29%	-1.46E+11	1.35E+12	3.63E+09	10.82%

Supplementary Table 2| Result of impaired supply calculations for rice with production losses. Applied values of rice production decline in selected countries (Supplementary Methods: Production Decline) and the resulting change in impaired supply due to production losses (given in percent and kcal) and domestic reserves. The last column shows the ratio of the decline in supply (due to production losses and export bans) to the domestic reserve. Data Source: FAOSTAT.

Country	Change in production due to production decline	Change in Impaired Supply due to P loss (fraction)	Change in Impaired Supply due to P loss (kcal)	Reserves (kcal)	Exports (kcal)	Ratio of decline in Impaired Supply to Reserves
India	-1.92%	-2.06%	-1.11E+13	1.05E+14	3.87E+13	10.57%
Thailand	-2.10%	-3.08%	-2.25E+12	1.40E+13	3.43E+13	16.06%
Viet Nam	-0.12%	-0.13%	-1.73E+11	3.84E+12	1.52E+13	4.50%
Iran (Islamic Republic of)	-18.83%	-12.60%	-1.60E+12	2.06E+12	3.15E+09	77.66%
Kenya	-34.25%	-6.37%	-1.65E+11	3.23E+11	4.76E+08	51.19%
Pakistan	-19.70%	-31.06%	-7.38E+12	3.70E+12	1.37E+13	199.41%

Supplementary Table 3| Result of impaired supply calculations for maize with production losses. Applied values of maize production decline in selected countries (Supplementary Methods: Production Decline) together with the resulting change in impaired supply (due to production losses (given in percent and kcal) and domestic reserves. The last column shows the ratio of the decline in supply (due to production losses and export bans) to the domestic reserve. Data Source: FAOSTAT.

Country	Change in production due to production decline	Change in Impaired Supply due to P loss (fraction)	Change in Impaired Supply due to P loss (kcal)	Reserves (kcal)	Exports (kcal)	Ratio of decline in Impaired Supply to Reserves
Argentina	-11.90%	-21.92%	-1.97E+13	1.09E+13	7.60E+13	181.87%
Brazil	-13.28%	-17.42%	-4.65E+13	2.24E+13	8.88E+13	207.96%
Ukraine	-8.78%	-21.70%	-9.29E+12	4.28E+12	6.32E+13	217.00%
Ethiopia	-13.01%	-13.01%	-4.67E+12	2.94E+12	3.89E+10	158.63%
Iran (Islamic Republic of)	-29.75%	-4.63%	-1.50E+12	4.59E+12	3.58E+10	32.78%
Kenya	-15.21%	-13.76%	-3.15E+12	1.79E+12	2.37E+10	175.57%
Pakistan	-7.17%	-7.19%	-1.81E+12	3.20E+12	1.99E+11	56.50%
Saudi Arabia	-52.81%	-1.12%	-1.41E+11	2.72E+12	2.42E+11	5.16%
Somalia	-48.44%	-45.43%	-3.74E+11	not reported	1.32E+07	n/a
Yemen	-25.18%	-3.11%	-7.58E+10	9.37E+10	1.02E+10	80.91%

Supplementary Table 4| Number of countries experiencing a decline in supply. Total number of countries included in the analysis of the FAOSTAT data (Supplementary Methods: Impaired Supply) and number of countries which experience a decline in impaired supply due to export bans and production losses. Listed is also the number of countries with a decline of more than half, a third and a quarter of their supply. Data source: FAOSTAT.

Commodity	Number of countries	Number of countries with decline in impaired supply due to export bans and P loss	Number of countries with a decline >50%	Number of countries with a decline >33.3%	Number of countries with a decline >25%
Wheat	195	145	3	20	33
Rice	195	175	37	58	68
Maize	195	155	18	30	34

Supplementary Table 5| Share of countries that experience a decline in supply for different parts of the world and for different income levels. Total number of countries included in the analysis of the FAOSTAT data (Supplementary Methods: Impaired Supply), number of countries which have reported values of reserves and the total number of countries which cannot buffer a supply shock due to production losses and export restrictions (Supplementary Tables 6, 7 and 8). Columns 5 to 8 show the fraction of the countries with low reserves located in Africa, Asia, South America, and Europe. The two last columns indicate the share between high-, upper-middle-, lower-middle- and low-income countries for which the domestic reserves are lower than the decline in impaired supply. Data Source: FAOSTAT and World Bank. Supplementary Methods:

Commodity	Number of countries	Number of countries with reported value of reserve	Number of countries where decline in impaired supply due to P loss and export ban > reserves	Share of African countries	Share of Asian countries	Share of South American countries	Share of European countries	Share of low-income countries	Share of lower-middle-income countries	Share of upper-middle-income countries	Share of high-income countries
Wheat	195	127	44	45.5%	31.8%	6.8%	15.9%	27.3%	31.8%	20.5%	20.5%
Rice	195	70	24	41.7%	45.8%	0%	12.5%	21%	25%	29.2%	25%
Maize	195	113	36	22.2%	44.4%	16.7%	16.7%	8.3%	25%	30.6%	26.1%

Supplementary Table 6| Result of impaired supply calculations for wheat with production losses and export ban. Wheat production decline (Supplementary Methods: Production Decline), share of imports compared to domestic supply calculated from 2015-2018 averages, change in imports due to export bans in Russia, Ukraine and Kazakhstan (given in percent and kcal) and domestic reserves 2015-2018 average. The second last column shows the ratios of the decline in supply (due to production losses and export bans) to the domestic reserve. The last column lists the country classification based on GNI per capita done by the World Bank for the current 2020 fiscal year. Data Source: FAOSTAT and World Bank.

Supplementary Table 6 is included as a separate .xlsx file.

Supplementary Table 7| Result of impaired supply calculations for rice with production losses and export ban. Rice production decline (Supplementary Methods: Production Decline), share of imports compared to domestic supply calculated from 2015-2018 averages, change in imports due to export bans in India, Thailand and Vietnam (given in percent and kcal) and domestic reserves 2015-2018 average. The second last column shows the ratio of the decline in supply (due to production losses and export bans) to the domestic reserve. The last column lists the country classification based on GNI per capita done by the World Bank for the current 2020 fiscal year. Data Source: FAOSTAT and World Bank

Supplementary Table 7 is included as a separate .xlsx file.

Supplementary Table 8| Result of impaired supply calculations for maize with production losses and export ban. Maize production decline (Supplementary Methods: Production Decline), share of imports compared to domestic supply calculated from 2015-2018 averages, change in imports due to export bans in Argentina, Brazil and Ukraine (given in percent and kcal) and domestic reserves 2015-2018 average. The second last column shows the ratio of the decline in supply (due to production losses and export bans) to the domestic reserve. The last column lists the country classification based on GNI per capita done by the World Bank for the current 2020 fiscal year. Data Source: FAOSTAT and World Bank

Supplementary Table 8 is included in a separate .xlsx file.

Supplementary Table 9| List of the 195 countries included in the “Impaired Supply” analyses.

Supplementary Table 9 is included as a separate .xlsx file.

Supplementary Table 10| Calibrated free parameters. The best fitted value of free parameters for wheat, maize and rice, fitted using ordinary least mean squares.

Commodity	**Exponent of supply curve, e_s**	**Producers' maximum price, $P_{max,p}$ (US $)**	**Exponent of demand curve, e_d**	**Consumers' maximum price, $P_{max,c}$ (US $)**	**Consumer storage capacity in excess of annual demand, $I_{max,c}$ (%)**
Wheat	0.15	110	0.7	577	91
Maize	0.15	250	1.3	1770	30
Rice	0.12	220	0.7	1490	68

Supplementary Table 11| Exporters share of world production and domestic consumption. Values for the selected export countries that are applied to the supply-demand model to simulate export bans for different scenarios. The values are derived from USDA data (see Supplementary Tables 15, 16 and 17 for further information).

Country	Commodity	World supply	World demand
Kazakhstan	Wheat	-1.9%	-0.9%
Ukraine	Wheat	-3.4%	-1.2%
Russia	Wheat	-9.8%	-5.5%
Russia and Ukraine	Wheat	-13.2%	-6.7%
Russia, Ukraine and Kazakhstan	Wheat	-15.1%	-7.6%
Vietnam	Rice	-5.6%	-4.4%
Thailand	Rice	-4%	-2.4%
India	Rice	-23.3%	-20.4%
Vietnam and Thailand	Rice	-9.6%	-6.8%
Vietnam, Thailand and India	Rice	-32.9%	-27.2%
Ukraine	Maize	-3.2%	-0.5%
Argentina	Maize	-4.5%	-1.2%
Brazil	Maize	-9%	-6%
Ukraine and Argentina	Maize	-7.7%	-1.7%
Ukraine, Argentina and Brazil	Maize	-16.7%	-7.7%

Supplementary Table 12| Production decline in export and locust threatened countries. Size of domestic production decline for the selected exporters (green) with 20th percentile decline and locust threatened countries (yellow) with 5th percentile decline, based on the year-to-year variation in production in the period 2000-2019. The corresponding world production decline of individual countries is calculated by scaling the domestic decline with their world production share. The country's share of total world production is calculated for the production in 2018/2019.

Country	Commodity	Percentile	Domestic production decline	Domestic share of world production	Corresponding World production decline
Kazakhstan	Wheat	20th	-18.18%	1.91%	-0.35%
Russia	Wheat	20th	-7.68%	9.80%	-0.75%
Ukraine	Wheat	20th	-20.50%	3.43%	-0.70%
Ethiopia	Wheat	5th	-8.74%	0.66%	-0.06%
Iran	Wheat	5th	-10.24%	1.98%	-0.20%
Kenya	Wheat	5th	-49.16%	0.05%	-0.02%
Pakistan	Wheat	5th	-9.76%	3.43%	-0.34%
Saudi Arabia	Wheat	5th	-44.83%	0.07%	-0.03%
Yemen	Wheat	5th	-23.35%	0.02%	0.00%
India	Rice	20th	-1.92%	23.34%	-0.45%
Thailand	Rice	20th	-2.10%	4.08%	-0.09%
Vietnam	Rice	20th	-0.12%	5.48%	-0.01%
Iran	Rice	5th	-18.33%	0.40%	-0.07%
Kenya	Rice	5th	-34.25%	0.02%	-0.01%
Pakistan	Rice	5th	-19.70%	1.46%	-0.29%
Argentina	Maize	20th	-11.90%	4.54%	-0.54%
Brazil	Maize	20th	-13.28%	8.99%	-1.19%
Ukraine	Maize	20th	-8.78%	3.19%	-0.28%
Ethiopia	Maize	5th	-13.01%	0.74%	-0.10%
Iran	Maize	5th	-29.75%	0.11%	-0.03%
Kenya	Maize	5th	-15.21%	0.36%	-0.05%
Pakistan	Maize	5th	-7.17%	0.54%	-0.04%
Saudi Arabia	Maize	5th	-52.81%	0.01%	-0.004%
Somalia	Maize	5th	-48.44%	0.01%	-0.004%
Yemen	Maize	5th	-25.18%	0.004%	-0.001%

Supplementary Table 13| Aggregate world decline. Sum of the world production decline of the 3 selected exporting countries (green), the locust threatened countries (yellow) and all countries (white) listed in Supplementary Table 12.

Country selection	Commodity	Aggregated global shock
All exporters	Wheat	-1.80%
All locust threatened	Wheat	-0.65%
Complete combined shock	Wheat	-2.45%
All exporters	Rice	-0.54%
All locust threatened	Rice	-0.37%
Complete combined shock	Rice	-0.91%
All exporters	Maize	-2.01%
All locust threatened	Maize	-0.22%
Complete combined shock	Maize	-2.23%

Supplementary Table 14| Increased world demand. World increase in stock-to-use based on the year-to-year variation for the period 2000-2019.

Commodity	Percentile	World S/U increase
Wheat	80th	9.82%
Rice	80th	7.02%
Maize	80th	10.58%

Supplementary Table 15| World's largest wheat producers. Wheat production and export (per trade year) for the 13 largest wheat producing countries/regions and their market shares in 2018/2019. The shaded boxes indicate the 5 countries which are the largest exporters, and together make up 72% of all wheat exports. The first column lists the current 2020 fiscal year, country classification based on GNI per capita done by the World Bank. Data source: USDA PSD online and the World Bank.

Country	Country Classification	Production 2018/2019 (1000 MT)	Export 2018/2019 (1000 MT)	Share of total consumption	Share of total production	Export share of dom. production	Share of total export
European Union	High income	136863	23310	16.78%	18.71%	17.03%	13.29%
China	Upper middle income	131430	1006	17.02%	17.97%	0.77%	0.57%
India	Lower middle income	99870	494	13.02%	13.65%	0.49%	0.28%
Russia	Upper middle income	71685	35838	5.52%	9.80%	49.99%	20.44%
United States	High income	51306	26069	4.09%	7.01%	50.81%	14.86%
Canada	High income	32201	24476	1.22%	4.40%	76.01%	13.96%
Pakistan	Lower middle income	25100	1649	3.45%	3.43%	6.57%	0.94%
Ukraine	Lower middle income	25057	16019	1.20%	3.43%	63.93%	9.13%
Argentina	Upper middle income	19500	12680	0.82%	2.67%	65.03%	7.23%
Turkey	Upper middle income	19000	6215	2.56%	2.60%	32.71%	3.54%
Australia	High income	17298	9835	1.25%	2.36%	56.86%	5.61%
Iran	Upper middle income	14500	320	2.19%	1.98%	2.21%	0.18%
Kazakhstan	Upper middle income	13947	8780	0.90%	1.91 %	62.95%	5.01%
World	n/a	731460	175372	100.00%	100.00%	23.98%	100.00%

Supplementary Table 16| World's largest rice producers. Rice production and export (per trade year) for the 12 largest rice producing countries and their market share in 2018/2019. The shaded boxes indicate the 5 countries which are the largest exporters, and together make up 73% of all rice exports. The first column lists the current 2020 fiscal year, country classification based on GNI per capita done by the World Bank. Data source: USDA PSD online and the World Bank.

Country	Country Classification	Production 2018/2019 (1000 MT)	Export 2018/2019 (1000 MT)	Share of total consumption	Share of total production	Export share of dom. production	Share of total export
China	Upper middle income	148490	2720	29.36%	29.74%	1.83%	6.29%
India	Lower middle income	116480	9790	20.40%	23.33%	8.40%	22.62%
Indonesia	Lower middle income	36700	2	7.84%	7.35%	0.01%	0.00%
Bangladesh	Lower middle income	34909	4	7.28%	6.99%	0.01%	0.01%
Vietnam	Lower middle income	27767	6581	4.42%	5.56%	23.70%	15.21%
Thailand	Upper middle income	20340	7562	2.43%	4.07%	37.18%	17.48%
Burma	Lower middle income	13175	2500	2.14%	2.64%	18.98%	5.78%
Philippines	Lower middle income	11732	0	2.90%	2.35%	0.00%	0.00%
Japan	High income	7657	60	1.75%	1.53%	0.78%	0.14%
Pakistan	Lower middle income	7300	4600	0.68%	1.46%	63.01%	10.63%
Brazil	Upper middle income	7140	953	1.54%	1.43%	13.35%	2.20%
United States	High income	7107	3135	0.94%	1.42%	44.11%	7.24%
World	n/a	499372	43273	100.00%	100.00%	8.67%	100.00%

Supplementary Table 17| World's largest maize producers. Maize production and export (per trade year) for the 12 largest maize producing countries/regions and their market share in 2018/2019. The shaded boxes indicate the 5 countries which are the largest exporters, and together make up 90% of all maize exports. The first column lists the current 2020 fiscal year, country classification based on GNI per capita done by the World Bank. Data source: USDA PSD online and the World Bank.

Country	Country Classification	Production 2018/2019 (1000 MT)	Export 2018/2019 (1000 MT)	Share of total consumption	Share of total production	Export share of dom. production	Share of total export
United States	High income	364262	49194	27.56%	32.43%	13.51%	28.61%
China	Upper middle income	257330	19	24.32%	22.91%	0.01%	0.01%
Brazil	Upper middle income	101000	38807	5.95%	8.99%	38.42%	22.57%
European Union	High income	64440	3629	7.81%	5.74%	5.63%	2.11%
Argentina	Upper middle income	51000	32879	1.22%	4.54%	64.47%	19.12%
Ukraine	Lower middle income	35805	30321	0.51%	3.19%	84.68%	17.64%
India	Lower middle income	27715	482	2.53%	2.47%	1.74%	0.28%
Mexico	Upper middle income	27600	718	3.91%	2.46%	2.60%	0.42%
Canada	High income	13885	1719	1.35%	1.24%	12.38%	1.00%
Indonesia	Lower middle income	12000	2	1.15%	1.07%	0.02%	0.00%
South Africa	Upper middle income	11824	1183	1.07%	1.05%	10.01%	0.69%
Russia	Upper middle income	11415	2770	0.75%	1.02%	24.27%	1.61%
World	n/a	1123332	171918	100.00%	100.00%	15.30%	100.00%

Supplementary Table 18| Change in stock-to-use ratio. The change in S/U is calculated by comparing a given year's value with the values of the previous year. The 95th and 80th percentiles are reported for four different time periods. Data source: USDA PSD online.

Commodity	95th percentile	80th percentile	min	max	mean	STD
1961-2019						
Corn	27.6%	16.3%	-38.0%	54.3%	1.3%	18.0%
Rice, Milled	19.1%	9.9%	-21.8%	46.4%	3.5%	11.2%
Wheat	22.2%	10.7%	-29.6%	45.9%	1.2%	14.6%
1980-2019						
Corn	27.5%	17.1%	-38.0%	54.3%	1.5%	18.2%
Rice, Milled	13.4%	7.1%	-21.8%	24.1%	1.8%	8.7%
Wheat	18.0%	10.6%	-20.4%	27.7%	1.4%	10.8%
2000-2019						
Corn	27.5%	10.6%	-20.3%	37.4%	0.2%	15.9%
Rice, Milled	8.6%	7.1%	-21.8%	13.3%	0.6%	9.6%
Wheat	17.9%	9.8%	-18.9%	27.7%	1.0%	11.5%
2004-2019						
Corn	29.6%	18.0%	-15.9%	37.4%	4.2%	15.2%
Rice, Milled	9.6%	7.3%	-8.3%	13.3%	4.1%	4.9%
Wheat	20.0%	10.5%	-13.3%	27.7%	3.8%	10.5%

Supplementary Table 19| Change in world production. The change is calculated by comparing a given year's value with the values of the previous year. The 5th, 10th and 20th percentile is reported for four different time periods. Data source: USDA PSD online.

Commodity	5th percentile	10th percentile	20th percentile	min	max	mean	STD
	1961-2019						
Corn	-9.49%	-4.42%	-2.49%	-20.81%	31.57%	3.28%	8.27%
Rice, Milled	-3.10%	-2.28%	-0.42%	-5.33%	8.97%	2.09%	3.19%
Wheat	-6.37%	-5.53%	-3.37%	-8.81%	17.50%	2.24%	6.70%
	1980-2019						
Corn	-11.16%	-5.41%	-3.32%	-20.81%	31.57%	2.83%	7.09%
Rice, Milled	-2.12%	-0.67%	0.14%	-5.33%	7.73%	1.69%	3.62%
Wheat	-5.53%	-4.90%	-2.86%	-7.70%	12.79%	1.65%	5.89%
	2000-2019						
Corn	-4.04%	-2.86%	-1.46%	-4.23%	14.25%	3.22%	9.17%
Rice, Milled	-2.56%	-2.14%	-0.71%	-5.33%	4.25%	1.00%	2.40%
Wheat	-5.45%	-4.25%	-2.68%	-5.48%	12.79%	1.45%	5.10%
	2004-2019						
Corn	-4.08%	-3.18%	-1.25%	-4.23%	14.25%	3.81%	6.16%
Rice, Milled	-1.38%	-0.88%	0.24%	-2.10%	4.25%	1.49%	1.89%
Wheat	-5.46%	-4.79%	-3.58%	-5.48%	12.79%	2.16%	5.69%

Supplementary Table 20| Extreme change in annual world price. Price increase during the two recent food crises 2007/08 (price in 2008 compared to 2006) and 2010/11 (price in 2011 compared to 2010) in real price, deflated by CPI normalized to June 1983=100.

food crisis	Wheat HRW	Maize	Rice Thai 5%
2007/08	58.96%	71.45%	99.69%
2010/11	37.12%	52.09%	7.67%

Supplementary Table 21| Output dataset generated for the impaired supply analysis. Table includes the complete output dataset for all 195 countries (Supplementary Table 9) included in the study for wheat, rice and maize. The file contains country level impaired supply and impaired inventory due to production decline, impaired supply and impaired inventory due to production decline and export bans, initial supply, initial inventory and change in production due to production declines, as well as ranked lists of largest producers, largest exporters and largest domestic reserves. For details about the impaired supply calculations see Supplementary Methods: Impaired Supply. Data source: FAOSTAT.

Supplementary Table 21 is included as a separate .xlsx file.

Supplementary Methods

Data

In this paper, we use data from two complementary databases, one provided by the United States Department of Agriculture (USDA) and another provided by the Food and Agricultural Organization of the United Nations (FAO).

For the modeling of world market prices and associated movements of global stocks with the Trade WIth Storage (TWIST) Model (cf. Supplementary Methods: Supply-Demand Model with Storage), we use annual world wheat, rice and maize production, domestic consumption data, and ending-stocks from USDA Foreign Agricultural Service's Production, Supply and Distribution (PSD)[1] database over the time period 1975-2018. These data are reported in million metric tons of grains and do not include grain products (e.g. pasta). This makes the USDA times series preferable when modeling the world market price of grains, because the price of processed goods differ from the grain price. Further, only the USDA PSD database contains data on stock levels. For the agricultural year 2019/2020, we use estimates published in the USDA's World Agricultural Supply and Demand Estimates (WASDE) report[2]. Further, annual forecasts from the OECD-FAO Agricultural Outlook 2019-2028 report (OECD-FAO, 2019)[3] are used to project world production, consumption, and ending-stock for the agricultural year 2020/2021. Annual nominal world market price for US wheat (Hard Red Winter, export price delivered at the US Gulf port), Thai rice (5% broken, white rice, milled, export transaction price, free on board Bangkok) and US maize (yellow, free on board US Gulf ports) are taken from the Commodity Markets online database "pink sheet" of the World Bank[4], and real prices are obtained by deflating with the US All Urban Consumers price index (June 1983=100) provided by the US Bureau of Labor Statistics[5].

For the calculations of historic year-to-year variations in production and stock-to-use, as well as share of export and production, we use country-level data of production, domestic consumption and exports from the PSD database, see Supplementary Notes, for further details.

For the country level network analysis (see Supplementary Methods: Impaired Supply), we require data on country-to-country trade as well as country level production and reserves. This is achieved by combining trade, production, and consumption data from FAO and storage data from USDA. For that, we first identify a list of 195 countries for our analyses given in Supplementary Table 9.

For trade data of these countries, we use the bilateral trade matrix data (referred to as "detailed trade matrix" export data) from FAOSTAT, which is the online statistical database of the Food and Agricultural

Organization of the United Nations (FAOSTAT)[6]. Additionally, we use country level production data from FAOSTAT[7], because it includes data for the 27 member countries of the European Union (EU27), whereas the USDA database only aggregated data for the EU27; reserves data are taken from USDA's PSD database[8]. For all of the datasets, we focus on the period 2015 to 2017, because the year 2017 is the latest bilateral trade data available through FAOSTAT. Thus, we compute our baseline conditions for trade, production, and reserves by averaging over this three-year period to smooth out year-to-year fluctuations in trade and production data.

For the world-level balances, we consider three groups of commodities – wheat, rice, and maize – for the supply balances at the country level. However, in contrast to the global price modeling, we here account for unprocessed grains as well as for (derived) commodities to better capture the food security impacts of supply shortages. The commodities in the wheat group include: *wheat*, *flour of wheat*, *macaroni*, *germ of wheat*, *bread*, *bulgur*, and *pastry*. For the maize group, we include: *maize*, *germ of maize*, *flour of maize*, *maize oil*, and *green maize*. For rice, we include: *paddy rice*, *husked rice*, *milled/husked rice*, *rice milled*, *rice broken*, *rice bran oil*, and *rice flour*. The values for each of the commodities in these groups are aggregated after converting units from metric tons to kilocalories[9]. We note that if there are discrepancies in the trade values, harmonization is needed. To do this, we average the exports between countries based on reported exports and reported imports, unless one was reported as zero; in that case, we used the non-zero reported value[10,11].

We use the end-of-year reserves data from the PSD database for wheat, rice, and maize (referred to as "corn" in this database), also converted to kilocalories. In the PSD database, only aggregated data is available for European Union (EU); we therefore divide reserves among EU countries in proportion to each country's share of EU production[12].

Supply-Demand Model with Storage

We use the global Trade WIth STorage (TWIST) model, which is a dynamic agent based supply-demand model including producer and consumer storage[13]. It simulates year-to-year variations on the global grain market driven by supply and demand and changes in stocks. We assume that all produced grains are traded at a single common global market, and we model the annual world market export price of wheat, rice and maize. The equilibrium world market price (P) is calculated by assuming market clearance at each time steps and equating the supply (Q_s) and demand curve (Q_d), which are defined as

$$Q_s(t) = I_p(t) \cdot \delta_{trade} \cdot (P(t)/P_{max,p})^{e_s}, \tag{1}$$

$$Q_d(t) = (\delta_{demand} \cdot I_{max,c}(t) - I_c(t)) \cdot (1 - (P(t)/P_{max,c})^{e_d}), \quad (2)$$

where I_p is the producer storage, δ_{trade} is the size of the trade restrictions (share of the world market supply unavailable for trade), $P_{max,p}$ is the maximum producer price, δ_{demand} is the change in consumer stock-to-use (as a proxy for changes in consumer demand, e.g. stock-up-attempts in order to build up grain reserves), $I_{max,c}$ is the maximum size of consumer storage, I_c is the consumer storage, $P_{max,c}$ is the maximum consumer price, and e_s and e_d denote the price elasticities of supply and demand, respectively. The carryover of producer and consumer storages to the next timestep are defined as

$$I_p(t) = I_p(t-1) - Q_x(t) + H(t), \quad (3)$$

$$I_c(t) = I_c(t-1) + Q_x(t) - Q_{out}(t), \quad (4)$$

where Q_x is the quantity sold/bought, H is the production (harvest) and Q_{out} is the consumption (Ref. 13 for further details).

The TWIST model is designed to describe the price and storage dynamics for individual agricultural commodities and does not include any possible cross-market connections between different commodities. The model is calibrated for each crop individually, driven by exogenous annual time series of global production and consumption, where the free parameters are fitted to reproduce the observed world market price for the years 1975-2019 (Supplementary Figure 3), see Supplementary Table 10 for details. On a global level we are able to largely reproduce historic price time series of the three main staple crops without including cross-market interaction.

Baseline

The baseline price for 2020/2021 is calculated by prescribing both production and consumption for the period 1975-2021. For the period 1975-2019, we use available USDA data and, for the agricultural year 2020/2021, we combine it with the projections published in the OECD-FAO Agricultural Outlook 2019-2028 report. We extend the time series to the agricultural year 2020 by first calculating the projected relative change in production and consumption (2020 projection divided by 2019 values) and then multiplying the projected relative change with the values of year 2019/2020 of the USDA data. This computation creates a self-consistent time series for the whole period 1975-2020. The reason we use FAO projections is that USDA only provides estimates of the next agricultural year, which as of April

2020 only include 2019/2020. FAO provides one-decade long projections, which is the reason we use their estimate for 2020/2021.

Export Restrictions

From a world-market perspective, export restrictions effectively make part of the total supply unavailable for international trade. In our model, this can be represented by temporarily withholding parts of the producer-side stocks (δ_{trade}) from the world supply function, see Eq. (1). The size of the export ban is based on the production share of major exporters. We lower the available global producer-side stocks by a fraction of the production from selected countries (Supplementary Table 11). We lower the producer-side stocks by the total share of a specific country; this represents a complete export ban, effective for the whole market year. We assume that the country imposing an export ban is able to satisfy domestic demand. That is, the country does not import any grains while the ban is effective, and the consumer demand of the country is fulfilled by direct domestic consumption. We simulate this by lowering the world demand by the share of total consumption (Supplementary Table 11) for the country imposing an export ban. After trade has taken place and the equilibrium price has been calculated for the given time step, we reduce the producer-side storage by the absolute consumption of the country imposing export restrictions, to account for direct domestic consumption.

In this paper, we consider three major exporters that have historically imposed export restrictions for each commodity. For wheat, these are Russia, Ukraine and Kazakhstan; for rice, they are Vietnam, Thailand, and India; and, for maize, they are Ukraine, Argentina, and Brazil (see Supplementary Table 11 for details about the applied limits to world supply and demand for the export simulations.).

Production Decline

We account for production declines by reducing the projected world production in the agricultural year 2020/2021 by a hypothetical, yet plausible amount. The production declines are defined as the 20th or 5th percentile of the year-to-year change in production during 2000-2019 for countries restricting exports and countries affected by the locust infestation, respectively. The change in production is calculated by dividing the production of a given year with the production of the previous year. The 20th percentile is chosen as a representative value of a bad weather event, which happens, on average, every

5 years. The 5th percentile is assumed to represent an extreme production failure, with a frequency of one in every 20 years. The country level production declines are used to calculate the impaired domestic supply (cf. Supplementary Methods: Impaired Supply) for the production loss scenarios (Supplementary Table 12). In the demand-supply model, we use the aggregated world production declines. These declines are calculated by scaling the domestic production decline by the country's share of total world production in 2018/2019 (Supplementary Table 13).

Import Policies

Changes in import strategies can result from increases in supply and demand. While importing countries attempting to restock or increase their inventories would increase the demand, strategic or significant stock reductions by certain countries would decrease the demand. We represent major changes in consumer-side buying/selling behavior as changes (δ_{demand}) in the consumer-side "target" inventory level, see Eq. (2). This changes the steepness of the demand curve and an increase in target inventory level results in a higher equilibrium price if the supply curve remains constant. We assume an 80th percentile increase in the stock-to-use (S/U) ratio with regard to the period 2000-2019. The S/U ratio is calculated as ending stocks divided by the domestic consumption (see Supplementary Table 14 for the adopted values for wheat, rice and maize).

Simulated Wheat, Rice and Maize World Market Price

We compute the world market export price for 14 different scenarios for each commodity (wheat, rice, maize). For the scenarios, the impact (export restrictions, production decline and change in import policies) are all applied to the agricultural year 2020/2021, and the simulated price in 2020/2021 is compared to the baseline price in the same year (cf. Supplementary Methods: Baseline). We thus calculate the change in price compared to the unperturbed baseline projection, which does not consider any effects related to the pandemic. Among the 14 scenarios, there are two accounting for production declines only, one with increased import only, five with export bans only, and six combined scenarios with at least two impacts (export bans with production decline and/or increased demand). The production decline scenarios consist of:

1) a 1-in-20-year production failure in locust threatened countries together with a 1-in-5-year in export countries, (Supplementary Methods: Production Decline, Supplementary Table 13) and

2) an extreme world production decline “worst case” corresponding to a 5th percentile (1-in-20-year) decline in world production based on the reported values for 2000-2019 (Supplementary Notes: World Production, Supplementary Table 19).

The “change in import policy only” scenario is based on a 1-in-5-year increase in S/U (Supplementary Methods: Import Policies, Supplementary Table 14). The “export ban only” scenarios are based on the values provided in Supplementary Table 11, and include both, the impact of export bans issued by individual countries as well as export bans issued simultaneously by two or three countries. The combined scenarios consist of export restrictions of two or three countries, together with either production decline or increased S/U or both (6 different combinations in total).

The change in the world market prices for wheat, rice, and maize are depicted in the Supplementary Figures 4, 5 and 6, respectively, and the dashed lines indicate the observed price changes during the 2007/08 and 2010/11 food price crises (cf. Supplementary Notes: Historic World Price of Wheat, Rice and Maize). Overall, the prices for all three commodities increase, but to different degrees. A production decline in isolation is not enough to cause severe changes in price levels (max. 12% increase). The same applies to those policy changes accounting for increases in demand due to restocking attempts. The effects of export bans get increasingly severe when the number of countries issuing bans increases, and the cumulative effects on prices can be fairly severe. Also, the price impacts are not linear, meaning the price hike resulting from bans in two countries is more than the sum of the price hikes caused when each country separately bans exports. For example, wheat export bans of Ukraine or Russia alone correspond to a price increase of 12.4% or 29.1%, respectively, but export bans of Ukraine and Russia at the same time leads to a change of 45.8%. The largest price increases are seen when there are multiple impacts in the same year (purple and blue bars in Supplementary Figures 4, 5 and 6).

Caveats of Simulated Prices

The prices are modeled on an annual basis and are average yearly prices implying that price changes on shorter time scales cannot be resolved. Another limitation of the simulated scenario prices is that the export bans are activated for one timestep, i.e., one full year. For that, we limit the amount of supply available for trade at the international market by the production share for the given country/countries corresponding to a complete export ban for a full year. The country’s harvest and domestic reserve is not available for trade in the selected timestep. This is, in some cases, not completely realistic, because many countries impose only partial export restrictions or impose export tariffs leading only to a reduction in exports. It is also common that export bans are only active for a few months at a time. Our simulated price changes should therefore be regarded as upper limits of the possible impact on price changes during one year. Further, the TWIST model abstracts from factors such as crude oil prices, speculations, devaluation of currencies, labor shortfalls, or cross-market interactions. However, as shown in Supplementary Fig. 1, the model is able to reproduce historical grain prices for an extended period of time rather well but does not closely reproduce prices during the oil crises in the 1970s.

Impaired Supply

To complement the global level supply-demand analysis with the TWIST model, we examine supply balances at the country level for the export-restriction and production-decline scenarios described in Supplementary Methods: Export Restrictions and Supplementary Methods: Production Decline, respectively. We consider the annual food balance in kilocalories for each country as

$$S = H + I - E + R$$

where S is domestic supply, H is production, I is imports, E is exports, and R represents reserves. (Note: To estimate consumption over some time period (here, a 3-year window), we assume that the reserve level remains constant.)

For the scenarios with production declines and export restrictions, we can then easily estimate the "impaired supply." For a country imposing export restrictions, we set all values in the row corresponding to that country in the export matrix to zero. Thus, partner countries will experience loss of imports from that exporter. In the case of production declines, supply will be directly impacted as described by the mass-balance equation above (import and export remain constant). We consider two indicators for assessing the country level impacts of the different scenarios: 1) the ratio of supply with production losses to initial supply and 2) the ratio of supply with production losses and export restrictions to initial supply.

Buffering Role of Domestic Reserves to Impaired Supply

Countries are especially vulnerable to supply failures when they have little reserve to buffer either domestic supply shocks (e.g., due to domestic crop failures) or trade related supply shocks (e.g., foreign supply failures due crop failures in main exporting countries or foreign export restrictions).
Looking at declines in domestic supply due to production failures only (Supplementary Table 1, 2 and 3), a country like Ethiopia, which has a high degree of self-sufficiency (i.e., has little world market

penetration) and low reserves, is especially vulnerable. If Ethiopia were to face a 1-in-20-year production decline of 7% (13%) in wheat (maize), the country would need to increase its imports to compensate, which would increase its sensitivity to world market prices and trade accessibility. On the other hand, a country like Saudi Arabia, which imports 80%, 100%, and 99% of its wheat, rice and maize, respectively, would be strongly affected by trade-related supply failures but would have sufficient reserves to cover a 1-in-20-year production decline. Kenya is an example of a country that is vulnerable to both foreign and domestic supply shocks. Though it has strong import dependencies (importing 83%, 81%, and 10% of its domestic consumption of wheat, rice, and maize, respectively), it does not have sufficient domestic reserves to buffer a 1-in-20-year domestic harvest failure.

For the three major exporting countries for each crop as well as for the locus threatened countries, the value of the resulting change in impaired supply due to production loss and the ratio between the reduced impaired supply compared to size of domestic reserves are given in Supplementary Table 1 (wheat), Supplementary Table 2 (rice) and Supplementary Table 3 (maize). The ratio shows which, among these countries, have reserves large enough to absorb the supply shock. A value of 100% means that the supply deficit exactly equals the reserves, and a value above 100% means that the country's reserves are smaller than its supply deficit. Several of the major export countries do not have reserves large enough to cover a 1-in-5-year production failure, but, because they export a large share of their production (Supplementary Tables 15, 16 and 17), they have the capacity to decrease their exports in order to ensure that the domestic demand is met.

When export bans are put in place by major exporters (wheat: Russia, Ukraine, and Kazakhstan, rice: India, Vietnam, and Thailand, maize: Brazil, Argentina, and Ukraine) 145, 176, and 155 out of 195 countries experience a negative change in their supply for wheat, rice, and maize, respectively. However, most countries are not severely impacted and only 3, 37, and 18 countries would experience a decline of their impaired supply by more than 50 percent in wheat, rice, and maize, respectively (Supplementary Table 4). The decline in supply can be compensated for by either releasing grains from domestic reserves or increasing imports. In order to check how many countries would be dependent on international imports, we look at the size of the domestic reserves and whether they are large enough to cover the decline in supply. Out of the 195 countries included in this analysis, 127, 70, and 113 countries have reported values of wheat, rice, and maize reserves, respectively. Out of these, 35%, 34%, and 32% of the countries have too little reserves to completely compensate for the decline in supply of wheat, rice, and maize, respectively.

Using the country income classification based on gross national income (GNI) per capita for the 2020 fiscal year published by the World Bank to categorize the countries[14] (Supplementary Tables 6, 7 and 8), we find that the majority of these countries are low- and middle-income countries mainly located in Africa and Asia (Supplementary Table 5). Supplementary Tables 6, 7 and 8 contain country specific values for the change in impaired supply and its ratio to domestic reserves. The countries are grouped into three categories:

1) focus countries (selected exporters and locust threatened countries (Supplementary Methods: Impaired Supply)),
2) countries which experience more than 50% decline in imports due to export bans but have large enough reserves and
3) countries which have too small reserves to buffer a potential shock in supply.

In general, the countries which have a weak import dependence (import is < 20% of domestic supply) and experience no domestic harvest failure are less vulnerable to foreign export bans, because they have enough reserves or domestic production to cover any short-term decline in import. Many countries that have high shares of imports would not have enough reserves to compensate for declines in imports due to export bans (Supplementary Tables 6, 7 and 8). Ecuador is an exception in the sense that even though it only imports 4.3% of its maize supply, it would not be able to buffer a decline in imports by 68.5% because its reserves are extremely small. Also vulnerable to export bans are countries with a small supplier base. For example, Kyrgyzstan imports 27% of its wheat, and 99% of these imports come from Russia and Kazakhstan. This means that the country would experience an almost complete disruption of imports, and the country would not have enough reserves to buffer such an import shortfall.

The sensitivity of a country's food supply to production failures or export bans depends on the country's own production share and its import dependency. If there are periods of extensive export bans, then it is a burden to be dependent on imports because the world market price will increase (Supplementary Methods: Simulated Wheat, Rice and Maize World Market Price) or it might be difficult to import the amount needed at all if a substantial fraction of the world supply is not available for international trade. On the other hand, if a county has a very large share of domestic production and experiences large scale harvest failures, then this would result in an immediate decline in supply, which of course could be mitigated by increased imports. In many cases, domestic reserves have the possibility to mitigate sudden decline in supply and can make the country less sensitive to both domestic and international supply shocks.

Example of Major Medium-Income Exporters

Several of the world's largest exporters are medium income countries according to the World Bank country classification based on GNI per capita[15] (Supplementary Tables 15, 16 and 17). Argentina and Ukraine are two examples of such countries. Both countries are important exporters playing a central role in the stability of the world food system. For instance, in the agricultural year 2018/19, Argentina was the 6th largest wheat exporter and 3rd largest maize exporter, and Ukraine was the 5th largest wheat exporter and 4th largest maize exporter (Supplementary Tables 15 and 17). Both countries have relatively small reserves compared to their domestic consumption (production + imports - exports). Ukraine's wheat reserve is 8%, 10% of its domestic consumption in wheat and maize, respectively, and Argentina's maize reserve is 12.1% of its domestic consumption (Supplementary Tables 6 and 8). As shown in Supplementary Methods: Buffering Role of Domestic Reserves to Impaired Supply, the reserves of both countries would not be sufficient to buffer a 1-in-5-year production decline, if trade (both import and exports) is kept constant. Therefore, export bans might be an intriguing option to secure domestic food security. However, because both countries are large exporters, complete export restrictions would strongly overcompensate the decline in supply (impaired supply) they are facing due to production losses. To show this, we compute the ratio of impaired supply from production failure plus reserves to exports,

$$r = \frac{|\, imparied\ supply\ due\ to\ production\ loss + reserves \,|}{exports}.$$

Using the values given in Supplementary Tables 1 and 3, we obtain r=0.34 for wheat in Ukraine, and r=0.08 and r=0.11 for maize in Ukraine and Argentina, respectively. Thus, in the case of maize, it would be sufficient for both countries to reduce export only by a few percent, while Ukraine would need to reduce its wheat export by roughly one third, in order to ensure domestic food security. For that, mild forms of export restrictions (e.g., restriction in export volumes) or an adjustment of tariffs would be sufficient. In contrast, complete export restrictions would probably harm producers in Ukraine and Argentina by stripping them of sales opportunities and would have the potential to create severe food shortages for import dependent low-income countries as discussed in the main text.

Supplementary Notes

Major Producers and Export Countries

Production of main staple grain crops are dominated by a few major producing breadbasket regions/countries. In 2018/2019, the production of the top 5 producers accounted for 67%, 73%, and 75% for the total world production for wheat, rice, and maize, respectively. However, when it comes to international trade and the importance of individual countries, the largest producer is not necessarily the largest exporter. When identifying the most important countries with respect to global supply of staple crops, we instead consider the countries which are major exporters. For example, China was, in 2018, the world's largest rice producer, accounting for almost 30% of the total production. But China exported only 1.8% of its domestic harvest, which accounted for 6.3% of international rice exports. Thailand, on the other hand, produces only 4% of all rice but its share of world total rice export is 17.5%, and Thailand was in 2018/2019 the second largest exporter of rice. The top 5 exporters account for 72%, 73%, and 90% of all exported wheat, rice and maize, respectively (Supplementary Table 15, 16 and 17).

Largest producers:

- **Wheat:** EU, China, India, Russia, USA. These countries make up 67% of world production and 49% of world exports.
- **Rice:** China, India, Indonesia, Bangladesh and Vietnam. These countries make up 73% of world production and 44% of world exports.
- **Maize:** US, China, Brazil, EU and Argentina. These countries make up 73% of world production and 44% of world exports.

Largest exporters:

- **Wheat:** Russia, US, Canada, EU, Ukraine. These countries make up 43% of world production and 72% of world exports.
- **Rice:** India, Thailand, Vietnam, Pakistan and USA. These countries make up 36% of world production and 73% of world exports.
- **Maize:** US, Brazil, Argentina and Ukraine. These countries make up 55% of world production and 90% of world exports.

Historic USDA Data

World Beginning Stocks

Global beginning stocks of grains are at a very high level: a record high level for rice but also historically high levels for wheat and maize (Supplementary Figure 7). Stocks have been increasing since 2007-2008, which may be due to changes in stockholding strategies because of the previous food crises. In 2007/08, when the food crisis occurred, it happened at a time when stocks were at record low values and there had also been production problems in the years leading up to the crisis. Today, the world is in a different situation and the share of stock to consumption (stock-to-use, S/U) is also at a historically high level for wheat and rice with values of 39% and 37%, respectively (Supplementary Figure 1). Maize stock-to-use is at 27% and has been declining since 2016 when it reached 33%, but it is still at a relatively high level from a historic point of view (Supplementary Figure 1). The stock-to-use levels in 2019/20 are 86%, 95%, and 68% higher than they were in 2007/08 for wheat, rice and maize, respectively. The year-to-year change in stock-to-use is reported in Supplementary Table 18 for four different time periods and the 95th and 80th percentile corresponds to a 1-in-20 and 1-in-5-year increase in stock-to-use.

World Production

World production of the main staple crops have been increasing over the last 60 years and the increase in maize has been larger in the last 20 years compared to wheat and rice (Supplementary Figure 8). The year-to-year variation in production is given in Supplementary Table 19 for four different time periods and the 95th, 90th, and 80th percentile changes in production correspond to a 1-in-20, 1-in-10, and 1-in-5-year decline in production, respectively. The production variations are larger for wheat and maize than for rice. The worst global decline in rice production during the last 15 years was only 2.1%, while it was 5.5% and 4.2% for wheat and maize, respectively. However, a 1-in-20-year world production decline only corresponds to a 1.4%-5.5% decrease in total production based on data over the last 20 years. This is much smaller compared to domestic production declines, which vary much more (Supplementary Table 12). For example, a 1-in-20-year production failure in Kenya would result in a decline of 15%-49% for wheat, rice and maize. The total world production averages out local harvest failures and can hide the fact that production losses can be severe in certain regions. This is one reason why food insecurity can arise even though there is enough food globally to cover the world food demand. Food needs to be available and affordable for countries to mitigate regional declines in food production that may arise due to e.g. worse-than-normal weather, or changes in trade policies.

Historic World Price of Wheat, Rice and Maize

The world market price for food and grains has varied substantially over certain periods of time, especially during the oil crisis in the 1970s and the world food crises in 2007/08 and 2010/11 (Supplementary Table 20). These effects are seen both in nominal and real prices (Supplementary Figures 9 and 10). The nominal prices are taken from the Commodity Markets online database "pink sheet" of the World Bank[4] and real prices are obtained by deflating with the US All Urban Consumers price index (June 1983=100) provided by the US Bureau of Labor Statistics[5]. During the last 5 years the real world market price has been quite stable without large fluctuations, but, between 2006 and 2008, the price increased with 59%, 72%, and 100% in wheat, rice, and maize, respectively. Large price changes in export price increases the cost of food imports and can also transmit to domestic prices making food very expensive. This is especially harmful for low income populations spending a large fraction of their income on food. Large price drops can also have negative impacts, as e.g., smallholders in low-income countries might not be able to sell their food at a reasonable price and suffer economically.

The International Grain Council provides daily values of the change in export prices expressed in grain indices[16]. From 1 Jan 2020 to 29 May 2020 the index went up 15% for rice and stayed elevated in the following months (see Supplementary Figure 2). The wheat and maize index also increased during 2020 by 12% and 26%, respectively, from 1 Jan 2020 to 12 October 2020 (see Supplementary Figure 2). The early price increase in rice prices may be partly due to the temporary ban of rice by Vietnam. The initial decrease in maize prices (during March-April 2020) may be partly due to lowered demand of biofuel, since the oil price deceased during the COVID-19 pandemic and even turned negative in US[17].

Locust Infestation

Some parts of the world are currently facing the worst locust upsurge in decades. It started in 2018 when cyclones created wet and favorable conditions in the southern Arabian Peninsula. These conditions allowed for locust eggs to hatch and a few new generations of locusts occurred, which was unknown at the time and was therefore not controlled[18]. In 2019, the locusts spread to the Horn of Africa, Southwestern Asia and the Indo-Pakistan border. Widespread spring breeding took place, increasing the number of locusts and swarms began forming. In early 2020, Kenya and Ethiopia were particularly threatened by swarms of locusts and destruction of crops. In East Africa, widespread rainfall in March created good breeding conditions for desert locusts, which exacerbated the situation[19]. Because locusts are a significant threat to crop production, we explore the impact of a 1-in-20-year production decline in the countries classified as *Serious* or *Dangerous* in the 8th May 2020[19]. These countries are Kenya, Ethiopia, Somalia, Saudi Arabia, Yemen, Iran and Pakistan[20]. The countries classified *Threatened* in 8th of May were India, Afghanistan, Iraq, Sudan, South Sudan, Oman, United Arab Emirates, Qatar, Jordan, Eritrea, Djibouti and Uganda. Since then, the situation has deteriorated, especially in South Asia and India in particular, which is now facing an infestation of swarms. In the northern states[21] it is the first time since 1962 that any desert locusts threaten their land and crops[22].

Supplementary References

1. *Production, Supply and Distribution online* (USDA, accessed April 2020); https://apps.fas.usda.gov/psdonline
2. *World Agricultural Supply and Demand Estimates, WASDE-599* (FAO, 2020); https://usda.library.cornell.edu/concern/publications/3t945q76s?locale=en#release-items
3. *OECD-FAO Agricultural Outlook 2019-2028* (OECD/FAO 2019) OECD Publishing, Paris; https://doi.org/10.1787/agr_outlook-2019-en
4. *World Bank commodity markets database, "pink sheet"* (World Bank, accessed April 2020); https://www.worldbank.org/en/research/commodity-markets
5. *US Bureau of Labor Statistics* (BLS, accessed April 2020); https://www.bls.gov
6. *Food and Agriculture Organization Corporate Statistical Database.* Version date: 10 September 2019 (FAO, accessed May 2020); http://www.fao.org/faostat/
7. *Food and Agriculture Organization Corporate Statistical Database.* Version date: 04 March 2020 (FAO, accessed May 2020); http://www.fao.org/faostat/
8. *Production, Supply and Distribution online.* File "psd_grains_pulses.csv" (USDA, accessed April 2020); https://apps.fas.usda.gov/psdonline
9. *Food Balance Sheets: A Handbook* (FAO 2001), Rome; http://www.fao.org/3/X9892E/X9892E00.htm
10. Konar M, Dalin C, Suweis S, Hanasaki N, Rinaldo A and Rodriguez-Iturbe. Water for food: The global virtual water trade network. Water Resour. Res. 5,47 (2011), doi:10.1029/2010WR010307
11. Puma, M. J., Bose, S., Chon, S. Y., Cook, B. I. Assessing the evolving fragility of the global food system. *Environ. Res. Lett.* **10** (2015), doi:10.1088/1748-9326/10/2/024007.
12. Marchand, P., Carr, J. A., Dell'Angelo, J., Fader, M., Gephart, J. A., Kummu, M. & Rulli, M. C. Reserves and trade jointly determine exposure to food supply shocks. *Environmental Research Letters*, **11** (9), 095009 (2016), doi:10.1088/1748-9326/11/9/095009
13. J. Schewe, C. Otto, K. Frieler, The role of storage dynamics in annual wheat prices. *Environ. Res. Lett.* **12**, 54005–54005 (2017), doi:10.1088/1748-9326/aa678e.

14. *The World Bank, Country Classification* (World Bank, accessed June 2020); https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups Note: "For the current 2020 fiscal year, low-income economies are defined as those with a GNI per capita, calculated using the World Bank Atlas method, of $1,025 or less in 2018; lower middle-income economies are those with a GNI per capita between $1,026 and $3,995; upper middle-income economies are those with a GNI per capita between $3,996 and $12,375; high-income economies are those with a GNI per capita of $12,376 or more."
15. *The World Bank, Country Classification, World Bank Country and Lending Groups* (World Bank, accessed June 2020); https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups
16. *International Grains Council* (IGC, accessed June 2020); https://www.igc.int/en/markets/marketinfo-goi.aspx
17. Sundria, S and Longley, A. Oil Market Trading in Negative Territory After Record Crash. *Bloomberg* 21 April 2020
18. *Locust Watch, Desert Locust, Current upsurge 2019-2020* (FAO, 2020); http://www.fao.org/ag/locusts/en/info/2094/
19. *Desert Locust Bulletin, Situation Report No. 499* (FAO, 2020); http://www.fao.org/ag/locusts/common/ecg/562/en/DL499e.pdf
20. *FAO Locust Watch map update 8 May* (FAO, 2020); http://www.fao.org/ag/locusts/common/ecg/75/en/200507globalE.jpg
21. *FAO Locust Watch risk map updated 4 June* (FAO, 2020); http://www.fao.org/ag/locusts/common/ecg/75/en/200604forecastE.jpg
22. *Desert Locust Bulletin, Situation Report No. 500* (FAO, 2020); http://www.fao.org/ag/locusts/common/ecg/562/en/DL500e.pdf