Safeguard global supply chains to protect food security during the COVID-19 pandemic

Importance of supporting middle income exporters and food insecure regions

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There are multiple challenges to global food security this year. Restrictions on mobility due to the COVID-19 pandemic have disrupted agricultural supply chains and reduced freight transportation, as well as limited farm labor availability (*1, 2*). At the same time, a locust upsurge is destroying harvests in East Africa and South Asia *(3)*, and worse-than-normal climate conditions threaten crop losses in Europe and South America (*4, 5*). With COVID-19, markets are already under pressure, so any additional stress such as adverse weather events, which inevitably will happen in some regions during the upcoming growing period, or a second wave of COVID-19 outbreaks, might result in a compound event requiring immediate responses to protect the food system. But in sharp contrast to the crisis years of 2007/08 and 2010/11, global stocks of the main staple foods are currently high. With these high stock levels, there is no reason for panic. However, in response to market uncertainties surrounding the COVID-19 pandemic, some major food producing countries have restricted

exports in the past few months *(6)* to ensure domestic food security, and more are pondering the idea; at the same time, affluent import-dependent countries are making precautionary purchases.

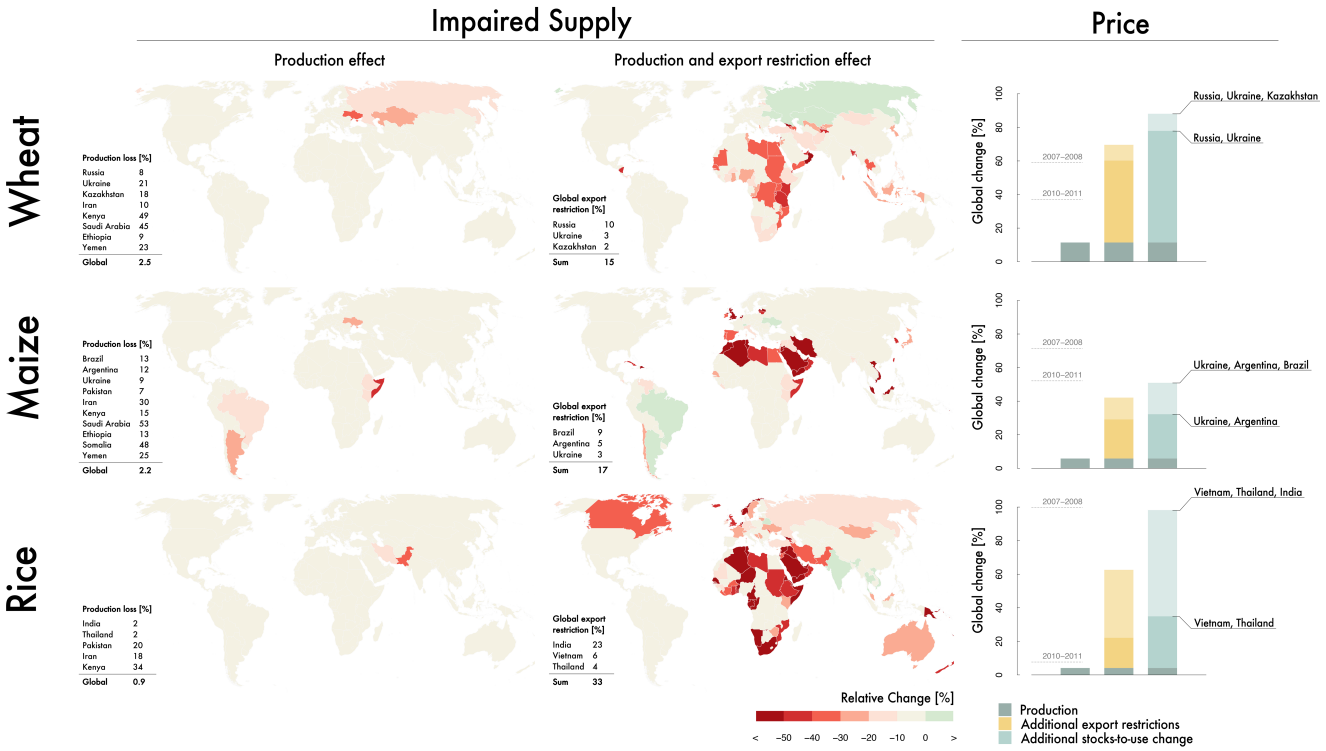
To help underline the importance of uninterrupted supply chains, we quantify the impact of these various threats to world food supply and prices for the three major food crops – wheat, rice and maize – using a global model for agricultural commodity markets *(7)* accounting for trade policies and storage. With food stocks at record levels, our analysis suggests that local production declines have only moderate effects on food supply and world market prices. However, prolonged trade restrictions and precautionary purchases by only a few countries would be sufficient to create global food price spikes comparable to those observed during the 2007/2008 and 2010/2011 world food price crises (*8*), with widespread disruptions in international supply chains. Critically, we show that trade restrictions disrupting global supply chains threaten food prices and security more than COVID-19 labor disruptions to agri-food systems, predicted climate hazards, or estimated insect outbreaks (together or in isolation).

Production shortfalls are manageable

While major local production shortfalls are expected for a combination of COVID-19 and other weather-related reasons, global supplies of the major staples are abundant. The locust infestation endangers food security and livelihoods in the Horn of Africa and parts of the Middle East. In East Africa, widespread spring rainfall created good breeding conditions for desert locusts. Large swarms have already devastated crops in parts of East Africa and are now moving into the Arabian Peninsula and South Asia, infesting expansive areas from Yemen to India *(3)*. Keeping the damages at a minimum will require rapid and coordinated responses by national governments and the international community *(9)*. At the world scale, the COVID-19 crisis is unlikely to substantially impact mechanized staple grain production in the major producing countries (*1*). While less essential for food security, labor shortages have already impacted fruit and vegetable harvesting and packaging in

many countries (*1*). Additionally, regions with high employment in agriculture may be impacted more by lock-downs. For example, the Ebola outbreak in West Africa in 2014 reduced labor availability for farming and led to a 20% decline in rice production *(10)*.

To understand the potential impacts of crop failures, we developed scenarios that impose, for each of the three crops, i) a 1-in-5-year production decline due to drought and lock-down effects in three major exporting countries and ii) a 1-in-20-year decline in production in the countries currently most affected by the locust infestations (see supplementary material (SM) for details and methods). We find that these production failures would drive up the world market prices of wheat by roughly 10%, of maize by about 7%, and of rice by less than 5% (see bar plots in figure) compared to a baseline scenario accounting for FAO supply and demand forecasts for 2020/21, which do not factor in these production shortfalls. Importantly, the stock-to-use (S/U) ratios of wheat and rice are at historically high levels; although the maize S/U has been falling for several years, it is still about twice as high as ten years ago (SM-2). Therefore, even massive production shortfalls of the same size as those preceding the recent world food price crises are unlikely to create a global shortage, though local food insecurities may arise in some countries with little integration in global markets.



Food security impacts of production failures and unilateral trade policies for wheat, maize, and rice.

World maps: Domestic supply changes due to potential production declines (**left panel**) and due to additional export restrictions (**middle panel**). Supply changes do not consider changes in reserves; inset tables detail production and export assumptions. **Bar plots:** Expected changes in world market prices (**right panel**) arising from production declines (gray bars), additional export restrictions (yellow bars), and additional consumer stock-up attempts (green bars). Dashed lines indicate price levels during the 2007/08 and 2010/11 food price crises. See supplementary material for details on data and methods.

We also highlight the impacts on food supplies in countries around the world for these scenarios. In particular, we find that crop losses of a plausible magnitude would cause food security problems locally in the affected countries by impairing domestic supply (see world maps in figure). For instance, a 1-in-20-year shortfall means a loss of about 15% of the average maize harvest in Kenya, or of around 7% of the average maize harvest in Pakistan. While Pakistan would be able to buffer trade-induced supply losses by tapping into domestic reserves, Kenya would face impaired availability without additional imports or food assistance (SM-1). However, stable world food prices will benefit net importing countries, allowing them to buy additional grain to compensate for domestic losses.

Increasing food imports will be especially critical for countries where food security is under immediate threat, and the international community has a responsibility to ensure that imports can actually reach those countries through functional international supply chains.

Trade restrictions would dramatically increase grain prices

The social distancing measures enacted during the COVID-19 pandemic are leading to labor shortfalls in agriculture and supply chains. Widespread lock-downs across the world have raised concerns about the stability of the global food system due to disruptions in the international as well as regional supply chains (*11*). On the demand side, surge purchases have temporarily emptied the shelves of supermarkets around the world (*2*), and wealthy importing countries have increased their imports of staple crops in an attempt to ensure domestic food security. Concerns about market uncertainty and ensuring domestic food supply have already prompted a number of exporting countries to issue export restrictions: Vietnam and Cambodia temporarily banned rice exports; Russia, Ukraine, and Kazakhstan restricted wheat exports *(6)*.

We explore the impacts of trade restrictions through a set of stylized scenarios. We select three major exporting countries for each of the three main staple crops that together account for over 13%, 16%, and over 33% of global production and for over 34%, 59%, and 55% of global exports for wheat, maize, and rice, respectively (see figure, and SM-2). Because these crops represent 43% of the calories consumed around the world and provide 37% of the global supply of protein (*12*), these countries form the backbone of global trade in stable crops, with high importance for food security. Although, the World Trade Organization prohibits export restrictions except to prevent or relieve critical domestic shortages of foodstuffs, major exporters have frequently employed such policies to insulate their domestic markets from world market price volatility and as a precautionary measure to protect domestic food supply when harvest failures loom (*13*). Similarly, wealthier importing countries that

decide to pile up larger-than-usual amount of grains in times of crises have put world markets under unnecessary pressure during the last two world food price crises in 2007/08 and 2010/11.

The risks of precautionary stock piling and export restrictions are significant and real. Exporters such as Russia, Ukraine, Kazakhstan, Argentina, India, and Vietnam temporarily banned grain exports; while major importers like the Philippines, Saudi Arabia, Indonesia, Egypt, Algeria, or Iran purchased larger-than-normal quantities in 2007/08. Together with harvest-failures in several bread-baskets in the years leading up to the 2007/08 crisis, these measures contributed to escalating world market prices, which eventually caused consumer prices to skyrocket in import-dependent, low-income countries in the Middle East, Northern Africa and South-East Asia, sparking political turmoil and endangering food security (*14*)

While stock levels are much higher today than before the last crises, export restrictions and aggressive stock up attempts still have the potential to send world grain prices soaring. For instance, the International Grains Council's rice commodity price index increased by 15% between January and May 2020, while wheat and maize prices have decreased (SM-2). Assuming that three major exporters of each main staple grain ban exports in the current agricultural year, we estimate that the price for wheat would rise by 70% between the current and next agricultural year, which is an even larger price hike than during 2007/08 (see bar plots in figure). For maize and rice, prices would rise by over 40% and over 60%, respectively. Countries that normally depend on imports from these large exporters would need to find substitutes (world maps in figure). Many countries in Asia and Africa, would be suddenly stripped of more than a third of their annual supply, and not all of them keep sufficient reserves to buffer such a sharp drop in imports (SM-1). From all countries that reported reserves in 2015-2017, most of the countries that cannot buffer a decline in supply due to production losses and export bans are low-income and lower-middle-income countries in Africa and Asia (77.3%, 87%, and 66.6% for wheat, rice, and maize, respectively) (SM-1). These countries would need to rely on other exporters or international food aid to ensure domestic food security. Low-income countries

with high import dependencies for grain are especially vulnerable to increased trade restrictions, compounding their domestic agricultural production challenges during the COVID-19 pandemic, because they may be outbid by wealthier importers in times of high world market prices. Devaluation of domestic currencies during the COVID-19 crises could aggravate this problem.

Focus on the vulnerable

During the COVID-19 pandemic a two-pronged approach is required to prevent a major decline in food security: a proactive strategy to maintain food availability and accessibility in food insecure regions and a concerted effort to enable continued exports from key food producers. The first prong is generally known, as international institutions like the World Food Program are focused on raising awareness on the plight of food-insecure countries in Africa and Asia and the risks to their food supply chains. Indeed, the estimated peak number of people in need of emergency assistance is up 25% from the pre-COVID-19 level of 113 million people earlier in 2020, and far higher than the last three years, which had 84 million (2017), 80 million (2018) and 86 million people (2019) *(15)*. Fortunately, stock levels of the major grains are high, and the upcoming harvests are likely to be sufficient to meet this year's world demand, even if substantial production shortfalls arise. Thus, the focus should be on demand side policies such as cash transfers to maintain food accessibility for those whose incomes have been lost due to COVID-19 restrictions, as well as protection of the critical stages of food supply chains.

In contrast, the second prong is less well recognized. Considering Ukraine and Argentine, two middle-income exporting countries that are crucial for the global food system yet have domestic instabilities; Ukraine was the 5th largest wheat exporter and 4th largest maize exporter, while Argentine was the 6th largest wheat exporter and 3rd largest maize exporter in 2018/19 (SM-2). Besides the COVID-19 crisis, these countries are grappling with domestic instabilities, including underlying political, economic, and security pressures, which may threaten their export capacity. For example, Ukraine heavily depends on foreign credit and is struggling with an ongoing low-intensity war in the Eastern part of

the country. Likewise, Argentina has experienced severe increases in poverty, currency devaluation, high inflation rates and now bankruptcy. Furthermore, these countries have relatively little reserves compared to their domestic consumption. A back-of-the-envelope calculation suggests that they would not be able to buffer the moderate 1-in-5-year production declines that we computed for our analyses (SM-1). However, the impact of complete export restrictions would not only put the stability of the global food web at risk, but also harm local producers by reducing their sales opportunities at world markets. On the other hand, moderate consumer support policy measures, as for instance, a temporary reduction of import tariffs or moderate restrictions in export volumes changing the import-export balance of those countries by only a few percent, would likely be sufficient to ensure domestic food security and help avoid the spread of precarity from these countries to the rest of the world through international commodity markets and trade. Thus, the international community, including international institutions, agri-businesses, and countries, must cooperate to bolster vulnerable countries, importers and exporters alike, to keep trade flowing in order to ensure affordable staple grains for the world's poor and avert a humanitarian crisis.

Reference and notes

1. J. Schmidhuber, J. Pound & B. Qiao, "COVID-19: Channels of transmission to food and agriculture", Food and Agriculture Organization of the United Nation (FAO), Rome (2020) https://doi.org/10.4060/ca8430en
2. Yaroslav Trofimov and Lucy Craymer "Soaring Prices, Rotting Crops: Coronavirus Triggers Global Food Crisis", Dow Jones & Company, Inc., 13 May 2020 https://www.wsj.com/articles/coronavirus-global-food-crisis-shortages-11589385615
3. Food and Agriculture Organization of the United Nation (FAO) "Desert Locust Bulletin" FAO Situation Report No. 500 (2020). http://www.fao.org/ag/locusts/common/ecg/562/en/DL500e.pdf
4. European Commision "Crop monitoring in Europe", RC MARS Bulletin Vol. 28 No 5, (May 2020). https://ec.europa.eu/jrc/sites/jrcsh/files/jrc-mars-bulletin-vol28-no5.pdf
5. Agricultural Market Information System (AMIS) "AMIS Market Monitor" No. 78, May 2020
6. IFPRI COVID-19 Food Trade Policy Tracker, accessed May 2020 https://www.ifpri.org/project/covid-19-food trade-policy-tracker

7. J. Schewe, C. Otto and K. Frieler, The role of storage dynamics in annual wheat prices. *Environ. Res. Lett.* **12** (2017), doi:10.1088/1748-9326/aa678e.

8. Martin, W. & Anderson, K. "Export Restrictions and Price Insulation during Commodity Price Booms" The World Bank (May 2011) http://documents.worldbank.org/curated/en/583201468337175309/Export-restrictions-and-price-insulation-during-commodity-price-booms.

9. Maximo Torero Cullen "COVID-19 and the risk to food supply chains: How to respond?", Food and Agriculture Organization of the United Nation (FAO), March 2020 http://www.fao.org/3/ca8388en/CA8388EN.pdf

10. Food and Agriculture Organization of the United Nation (FAO) and World Food Programme "Crop and Food Security Assessment - Liberia, Sierra Leone and Guinea" Special Report Synthesis 5 January 2015 http://www.fao.org/emergencies/resources/documents/resources-detail/en/c/276089/

11. M. J. PuLato;sans-serifma, S. Bose, S. Y. Chon, B. I. Cook, Assessing the evolving fragility of the global food system. *Environ. Res. Lett.* **10** (2015), doi:10.1088/1748-9326/10/2/024007.

12. Food and Agriculture Organization of the United Nation (FAO) "Save and Grow in practice: maize, rice, wheat A guide to sustainable cereal production", FAO (2016) http://www.fao.org/ag/save-and-grow/MRW/index_en.html

13. Food and Agriculture Organization of the United Nation (FAO) "Agricultural export restrictions" FAO, Trade Policy Briefs No. 27 (October 2017) http://www.fao.org/3/a-i8006e.pdf

14. M. F. Bellemare, Rising Food Prices, Food Price Volatility, and Social Unrest. *Am. J. Agric. Econ.* **97**, 1-21 (2015).

15. The Famine Early Warning Systems Network (FEWS NET) "Global needs increase sharply as indirect impacts of COVID-19 pandemic threaten food access" FEWS NET and USAID version 3 April 28 2020 https://fews.net/sites/default/files/Food_Assistance_Peak_Needs_April2020.pdf

Acknowledgments

This work was supported by the Defense Advanced Research Project Agency (DARPA) under the World Modelers program (grant W911NF1910013), the CASCADES (grant agreement no. 821010) and RECEIPT (grant agreement no. 820712) projects within the Horizon 2020 framework program of the European Union, and the German Federal Ministry of Education and Research (BMBF) under the research project SLICE (FKZ: 01LA1829A).

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Supplementary Materials for

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Supplementary Materials (SM)

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SM-1: Materials and Methods

SM-1.1: Data

We use annual world wheat, rice and maize production as well as domestic consumption data from the United States Department of Agriculture (USDA) Foreign Agricultural Service's Production, Supply and Distribution (PSD)[1] database over the time period 1975-2018. 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) are used to project world production, consumption and ending-stock for the agricultural year 2020/2021. Annual nominal world market price for US hard red winter wheat, Thai 5% rice and maize are taken from the Commodity Markets online database "pink sheet" of the World Bank[3], 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[4]. Further, 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.

For country level commodity supply balances, we require data on country-to-country trade as well as country level production and reserves. First, we identify a list of 195 countries for our analyses given in Tab. S1.

Table S1: List of the 195 countries included in the "Impaired Supply" analyses.

Afghanistan	Ghana	Nicaragua
Albania	Guinea	Netherlands
Netherlands Antilles	Gambia	Norway
Aruba	Guinea-Bissau	Nepal

1 https://apps.fas.usda.gov/psdonline/app/index.html#/app/advQuery, accessed April 2020
2 WASDE-599 published 9 April 2020 https://usda.library.cornell.edu/concern/publications/3t945q76s?locale=en#release-items
3 http://www.worldbank.org/en/research/commodity-market accessed April 2020
4 https://www.bls.gov accessed April 2020

United Arab Emirates	Equatorial Guinea	New Zealand
Argentina	Greece	Oman
Armenia	Grenada	Pakistan
Antigua and Barbuda	Greenland	Panama
Australia	Guatemala	Peru
Austria	Guyana	Philippines
Azerbaijan	Hong Kong SAR, China	Papua New Guinea
Burundi	Honduras	Poland
Belgium	Croatia	Democratic People's Republic of Korea
Benin	Haiti	Portugal
Burkina Faso	Hungary	Paraguay
Bangladesh	Indonesia	Occupied Palestinian Territory
Bulgaria	India	French Polynesia
Bahrain	Ireland	Qatar
Bahamas	Iran (Islamic Republic of)	Romania
Bosnia and Herzegovina	Iraq	Russian Federation
Belarus	Iceland	Rwanda
Belize	Israel	Saudi Arabia
Bermuda	Italy	Sudan
Bolivia (Plurinational State of)	Jamaica	Senegal
Brazil	Jordan	Singapore
Barbados	Japan	Solomon Islands
Brunei Darussalam	Kazakhstan	Sierra Leone
Bhutan	Kenya	El Salvador
Botswana	Kyrgyzstan	Somalia
Central African Republic	Cambodia	Serbia
Canada	Kiribati	South Sudan
Switzerland	Saint Kitts and Nevis	Sao Tome and Principe
Chile	Republic of Korea	Suriname
China (mainland)	Kuwait	Slovakia

Cote d Ivoire	Lao People's Democratic Republic	Slovenia
Cameroon	Lebanon	Sweden
Democratic Republic of the Congo	Liberia	Swaziland
Congo	Libya	Seychelles
Cook Islands	Saint Lucia	Syrian Arab Republic
Colombia	Sri Lanka	Chad
Comoros	Lesotho	Togo
Cape Verde	Lithuania	Thailand
Costa Rica	Luxembourg	Tajikistan
Cuba	Latvia	Turkmenistan
Cyprus	Macao SAR, China	Timor-Leste
Czech Republic	Morocco	Tonga
Germany	Republic of Moldova	Trinidad and Tobago
Djibouti	Madagascar	Tunisia
Dominica	Maldives	Turkey
Denmark	Mexico	Tuvalu
Dominican Republic	The former Yugoslav Republic of Macedonia	Taiwan
Algeria	Mali	United Republic of Tanzania
Ecuador	Malta	Uganda
Egypt	Myanmar	Ukraine
Eritrea	Montenegro	Uruguay
Spain	Mongolia	United States of America
Estonia	Mozambique	Uzbekistan
Ethiopia	Mauritania	Saint Vincent and the Grenadines
Finland	Mauritius	Venezuela (Bolivarian Republic of)
Fiji	Malawi	Vietnam
France	Malaysia	Vanuatu
Faroe Islands	Namibia	Yemen

Gabon	New Caledonia	South Africa
United Kingdom	Niger	Zambia
Georgia	Nigeria	Zimbabwe

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)[5]. Additionally, we use country level production data from FAOSTAT[6] and reserves data from the PSD database[7]. For all of these 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 the trade and production data.

As for the world-level balances, we also consider three groups of commodities – wheat, rice, and maize – for the supply balances at the country level. 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 (FAO, 2001). 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 (Konar et al. 2011; Puma et al. 2015).

5 Version date: 10 September 2019, http://www.fao.org/faostat/ accessed May 2020
6 Version date: 04 March 2020, http://www.fao.org/faostat/ accessed May 2020
7 file "psd_grains_pulses.csv", https://apps.fas.usda.gov/psdonline/app/index.html#/app/downloads accessed May 2020

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 converting 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 (Marchand et al. 2016).

SM-1.2: Supply-Demand Model

We use the global Trade WIth STorage (TWIST) model, which is a dynamic agent based supply-demand model including producer and consumer storage (Schewe et al. 2017). 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. We calibrated the model for each crop individually and extended it to include exogenous production declines.

SM-1.2.1: Baseline

The baseline price for 2020/2021 is calculated by prescribing both production and consumption between 1975 and 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 provide one-decade long projections, which is the reason we use their estimate for 2020/2021.

SM-1.2.2: 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 from the world supply function. 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 (Tab. S2). 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 (Tab. S2) 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, the countries are Russia, Ukraine and Kazakhstan; for rice, they are: Vietnam, Thailand and India; and, for maize, they are Ukraine, Argentina and Brazil. (see Tab. S2 for details about the applied limits to world supply and demand for the export simulations.)

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%

Table S2: World share of production and domestic consumption 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 Tabs. S14-S16 for further information).

SM-1.2.3: 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, of the frequency of one in every 20 years. The country level production declines are used to calculate the impaired domestic supply (cf. Sec. SM-1.3) for the production loss scenarios (Tab. S3). 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 (Tab. S4).

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%

Table S3: 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 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%

Table S4: Sum of the world production decline of the 3 selected export countries (green), the locust threatened countries (yellow) and all countries (white) listed in Tab. S3.

SM-1.2.4: Import policies

Changes in import strategies can result from increases in supply and demand. Importing countries attempting to restock or increase their inventories would increase the demand, but strategic or significant stock reductions by certain countries would decrease the demand. We represent major changes in consumer-side buying/selling behavior as changes of the consumer-side "target" inventory level. 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 stock-to-use ratio is calculated as ending stocks divided by the domestic consumption (see Tab. S5 for the adopted values for wheat, rice and maize).

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

Table S5: World increase in stock-to-use based on the year-to-year variation for the period 2000-2019.

SM-1.2.5: 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. Sec. SM-1.2.1). 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, Tab. S4 (see Sec. SM-1.2.3) 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 (Sec. SM-2.2.3, Tab. S18). The change in import policy only scenario is based on a 1-in-5-year increase in S/U (Sec. SM-1.2.4, Tab. S5). The export ban only scenarios are based on the values in Tab. S2, and include both, the impact of individual countries and combinations of 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 together, in a total of 6 different combinations.

The change in price for wheat, rice and maize is given in Figs. S1, S2 and S3, respectively, and the dashed lines indicate the observed price change during the 2007/08 and 2010/11 food price crises, computed from annual real prices (Sec. SM-2.3). Overall, the price increases for all three commodities, 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 policy changes where increases in import (increase of target S/U levels) take place. The effects of export bans get increasingly severe when more countries are included, and the cumulative effects can be very high. Also, the impacts are not linear, meaning that the price increases more if two countries impose export bans at the

same time than adding up the price increase of them separately. 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%. Largest price increases are seen when there are multiple impacts in the same year (purple and blue bars in Figs. S1-S3).

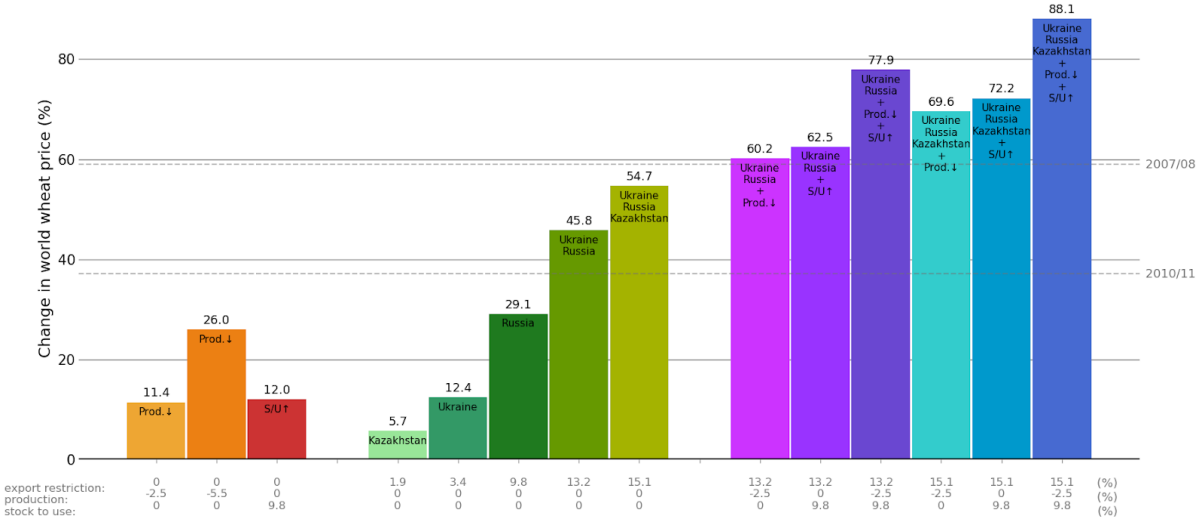

Figure S1: Change in wheat price compared to baseline for 14 different scenarios. The results are grouped in 3 categories. *Orange/red bars*: Simulations with only decrease in production or increase in stock-to-use ratio, first bar: combined world shock (cf. Tab. S4), second bar: a 5th percentile total world production decline (cf. Tab. S18), third: 80th percentile increase of stock-to-use ratio (cf. Tab. S5). *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).

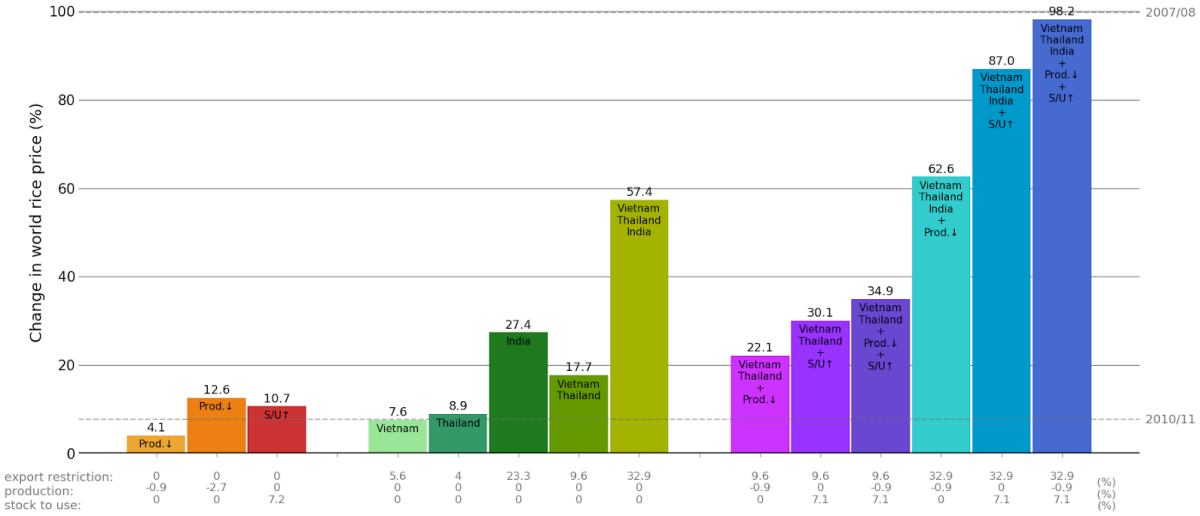

Figure S2: Change in rice price compared to baseline for 14 different scenarios. See caption of Fig. S1 for further details about the scenarios.

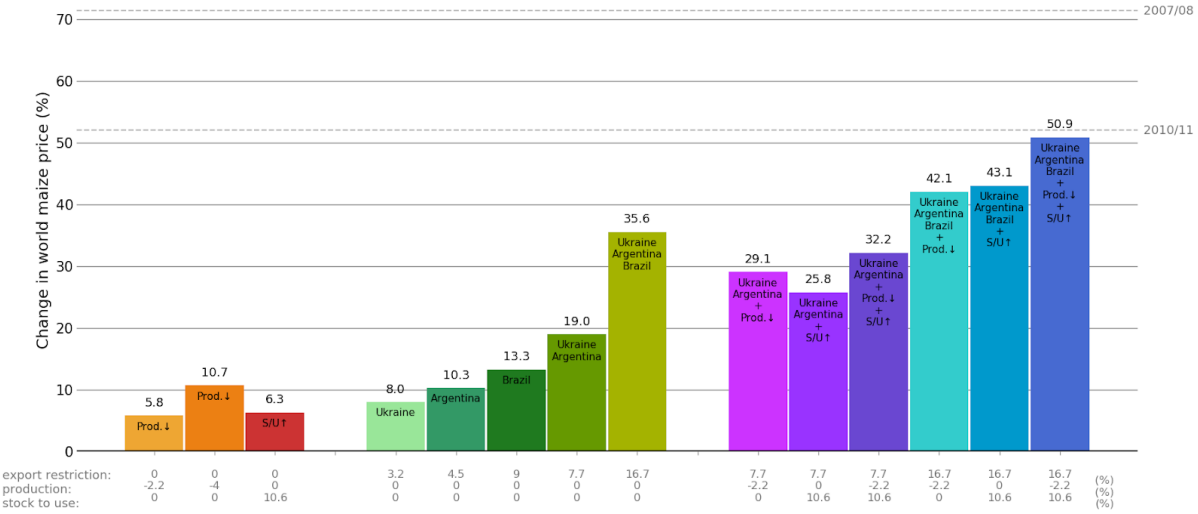

Figure S3: Change in maize price compared to baseline for 14 different scenarios. See caption of Fig. S1 for further details about the scenarios.

SM-1.2.6: Caveats of simulated prices

The prices are modeled on an annual basis and are average yearly prices. This means that short-term price changes are averaged out and that the most extreme price changes may not be reproduced. Another limitation of the simulated scenario prices is that the export bans are activated for one timestep, i.e., one full year. We limit the amount of supply available for trade at the international market by the production share for the given country/countries; that is, a complete export ban for 12 months. The country's harvest and domestic reserve is not available for trade in the selected timestep. This is in some cases not completely realistic, since many countries impose only partial export restrictions and not complete bans, and 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.

SM-1.3: Impaired Supply

To complement the global level supply-demand analyzes with the TWIST model, we examine the supply balances at the country level for the export-restriction and production-decline scenarios described in Secs.1.2.2 and 1.2.3, respectively. We consider the annual food balance in kilocalories for each country as

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

where S is domestic supply, P 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 productions 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.

SM-1.3.1: Domestic reserves and decline of Impaired Supply

The impact of domestic production losses and/or decline in imports due to exterior export bans depends on how import dependent a country is, the share of domestic crop production and the size of the grain reserves. Looking at declines in domestic supply due to production failures only (Tabs. S6-S8), a country like Ethiopia, which has a relatively large share of domestic production and low reserves, is especially vulnerable. If Ethiopia would face a 1-in-20-years production decline of 7% (13%) in wheat (maize) they would need to increase their import to compensate and which would increase their dependence on the world market price and trade accessibility. Saudi Arabia would, on

the other hand, have sufficient reserves to cover a 1-in-20-year production decline. This is due to the fact that Saudi Arabia import 80%, 100% and 99% of their wheat, rice and maize, respectively. Another example is Kenya, which imports 83%, 81% and 10% of their wheat, rice and maize, respectively, and would only need to increase imports of maize since their reserves only cover 57% of the change in supply due to a 1-in-20-year harvest failure. The value of the resulting change in impaired supply due to production loss for the three major exporters and the locus threatened countries, as well as the ratio of decline in impaired supply to reserves, are given in Tabs. S6 (wheat), S7 (rice) and S8 (maize). The ratio shows which countries have reserves large enough to cover the change in supply. A value of 100% means that the supply deficit and reserves are equal in size, and a value above 100% means that the country's reserve is smaller than the supply deficit. Several of the major export countries would not have reserves large enough to cover the decline due to a 1-in-5-year production failure, but since they export a large share of their production (Tabs. S14-S16) they have the possibility to decrease their export 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 (Tab. S9). The decline in supply can be compensated by either releasing grains from their domestic reserves or increasing imports. In order to check how many countries would be dependent on international import 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. The majority of these countries are low- and

middle-income countries and Africa and Asia account for the largest share (Tab. S9). We use 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[8] (Tabs. S11-S13). Tabs. S11-S13 contain country specific values for the change in impaired supply and its ratio to domestic reserves. The countries are grouped into three categories, i) focus countries (selected exporters and locust threatened countries (Sec. SM-3)), ii) countries which experience more than 50% decline in imports due to export bans but have large enough reserves and iii) 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 more secure if sudden export bans are imposed, since they have enough reserves or domestic production to cover any short-term decline in import. Many countries which have high shares of imports would not have enough reserves to compensate for declines in imports due to export bans (Tabs. S11-S13). Ecuador is an exception in the sense that even though they only import 4.3% of their maize supply, they would not be able to buffer a decline in imports by 68.5% because their reserves are extremely small. Also vulnerable to sudden 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 import stop, and they would not have enough reserves to buffer such a decline in imports.

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 dependence. If there are periods of extensive export bans, then it is a burden to be dependent on imports since the world market price will increase (Sec. SM-1.2.5) or it might be difficult to import the amount needed at all if a substantial fraction of

[8] World Bank database https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups accessed June 2020. "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."

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 would experience 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 case, 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.

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%

Table S6: Wheat production decline in selected countries (Sec. SM-1.2.3) 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%

Table S7: Rice production decline in selected countries (Sec. SM-1.2.3) 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
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%

Table S8: Maize production decline in selected countries (Sec. SM-1.2.3) 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.

Commodity	Number of countries	Number of countries with decline in imparied 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

Table S9: Summary of table of the total number of countries included in the analysis of the FAOSTAT data (see Sec. SM-1.3) 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 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%

Table S10: Summary table of the total number of countries included in the analysis of the FAOSTAT data (Sec. SM-1.3), 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 (Tabs. S11-S13). 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.

Country	Production Decline	Share of import compared to domestic supply	Share of reserves compared to domestic supply	Change in Imports due to Export Ban	Change in Impaired Supply due to P loss and Export	Change in Impaired Supply due to P loss and	Reserves (kcal)	Ratio of decline in Impaired Supply to Reserves	Country Classification based on GNI per capita

					ban (fraction)	Export Ban (kcal)			
Focus countries									
Kazakhstan	18.18%	0.6%	8.9%	-95.0%	7.6%	5.09E+12	5.97E+12	n/a	Upper middle income
Russian Federation	7.68%	0.8%	12.5%	-63.0%	23.2%	5.87E+13	3.13E+13	n/a	Upper middle income
Ukraine	20.50%	0.3%	8.1%	-15.4%	54.5%	3.08E+13	4.52E+12	n/a	Lower middle income
Ethiopia	8.74%	12.6%	6.4%	-25.0%	-10.8%	-2.62E+12	1.54E+12	170.0%	Low income
Iran (Islamic Republic of)	10.24%	8.2%	32.5%	-49.8%	-13.6%	-9.54E+12	2.28E+13	41.9%	Upper middle income
Kenya	49.16%	83.3%	8.8%	-39.3%	-41.2%	-2.85E+12	6.06E+11	471.2%	Lower middle income
Pakistan	9.76%	0.1%	8.5%	-10.6%	-9.9%	-1.14E+13	9.37E+12	121.7%	Lower middle income
Saudi Arabia	44.83%	80.2%	73.6%	-0.8%	-9.6%	-1.30E+12	1.03E+13	12.6%	Lower middle income
Yemen	23.35%	96.9%	12.3%	-33.7%	-33.2%	-3.74E+12	1.35E+12	277.2%	High income
Afghanistan	0.00%	25.8%	4.7%	-69.2%	-17.8%	-5.36E+12	1.42E+12	377.9%	Low income
United Arab Emirates	0%	118.0%	42.1%	-34.4%	-40.5%	-2.02E+12	2.11E+12	96.0%	High income
Iraq	0%	37.0%	15.6%	-0.2%	-0.1%	-1.93E+10	3.28E+12	0.6%	Upper middle income
Jordan	0%	97.6%	32.6%	-22.1%	-21.5%	-8.62E+11	1.30E+12	66.2%	Upper middle income
Oman	0%	159.0%	21.0%	-32.0%	-50.1%	-8.15E+11	3.36E+11	242.3%	High income
Sudan	0%	73.4%	8.9%	-42.5%	-30.9%	-3.12E+12	8.90E+11	350.7%	Lower middle income
Uganda	0%	98.1%	8.8%	-37.5%	-36.9%	-6.25E+11	1.50E+11	417.0%	Low income
Countries with >50% decline in import but large reserves									
India	0%	2.0%	14.4%	-51.6%	-1.1%	-4.43E+12	6.04E+13	7.3%	Lower middle income
Republic of Moldova	0%	5.7%	43.2%	-88.9%	-5.1%	-1.63E+11	1.38E+12	11.8%	Lower middle income
Belarus	0%	4.1%	22.8%	-94.6%	-3.7%	-4.23E+11	2.51E+12	16.9%	Upper middle income

Countries where the reserves < decline in impaired supply									
Albania	0%	44.2%	17.1%	-52.9%	-22.9%	-5.14E+11	3.76E+11	136.6%	Upper middle income
Armenia	0%	40.4%	4.6%	-97.1%	-38.5%	-9.03E+11	1.06E+11	854.2%	Upper middle income
Azerbaijan	0%	36.6%	7.0%	-98.3%	-35.3%	-4.31E+12	8.38E+11	515.0%	Upper middle income
Burkina Faso	0%	99.5%	2.7%	-10.2%	-10.2%	-8.56E+10	2.23E+10	384.6%	Low income
Bangladesh	0%	76.7%	24.4%	-55.6%	-42.0%	-1.02E+13	5.84E+12	175.1%	Lower middle income
Cameroon	0%	97.0%	0.7%	-19.7%	-19.4%	-4.39E+11	1.67E+10	2630.0%	Lower middle income
Democratic Republic of the Congo	0%	91.4%	1.3%	-33.4%	-31.3%	-3.97E+11	1.67E+10	2380.0%	Low income
Cyprus	0%	93.8%	2.2%	-25.0%	-23.2%	-1.27E+11	1.18E+10	1076.6%	High income
Egypt	0%	51.5%	19.7%	-71.8%	-37.2%	-2.66E+13	1.42E+13	187.2%	Lower middle income
Spain	0%	46.7%	4.5%	-11.2%	-5.2%	-2.41E+12	2.06E+12	116.8%	High income
Georgia	0%	74.8%	13.6%	-98.3%	-74.2%	-1.84E+12	3.41E+11	539.0%	Upper middle income
Greece	0%	42.5%	5.4%	-17.5%	-7.4%	-6.63E+11	4.79E+11	138.4%	High income
Haiti	0%	104.0%	7.7%	-11.3%	-11.3%	-1.18E+11	7.68E+10	153.0%	Low income
Indonesia	0%	103.0%	18.4%	-21.7%	-22.2%	-7.17E+12	5.88E+12	122.0%	Lower middle income
Israel	0%	90.5%	22.3%	-32.2%	-29.0%	-1.84E+12	1.41E+12	130.9%	High income
Italy	0%	54.9%	4.9%	-10.0%	-5.4%	-2.52E+12	2.26E+12	111.6%	High income
Kyrgyzstan	0%	27.0%	9.0%	-99.2%	-26.6%	-1.15E+12	3.87E+11	298.0%	Lower middle income
Lebanon	0%	86.1%	13.4%	-76.3%	-65.6%	-2.56E+12	5.24E+11	489.0%	Upper middle income
Libya	0%	78.1%	5.2%	-42.5%	-33.0%	-1.93E+12	3.01E+11	640.0%	Upper middle income
Latvia	0%	48.2%	13.9%	-31.7%	-15.3%	-7.03E+11	6.41E+11	109.7%	High income
Mali	0%	80.2%	3.7%	-11.4%	-9.0%	-1.28E+11	5.23E+10	244.0%	Low income
Mozambique	0%	98.6%	7.7%	-38.1%	-37.9%	-8.65E+11	1.77E+11	489.0%	Low income

Mauritania	0%	93.8%	13.4%	-41.8%	-39.5%	-7.84E+11	2.68E+11	292.1%	Lower middle income
Malawi	0%	94.5%	3.9%	-30.8%	-28.9%	-2.15E+11	2.89E+10	743.9%	Low income
Namibia	0%	69.7%	2.1%	-16.1%	-11.2%	-7.19E+10	1.34E+10	536.6%	Upper middle income
Nigeria	0%	100.0%	4.2%	-26.9%	-26.2%	-4.30E+12	6.68E+11	644.0%	Lower middle income
Nicaragua	0%	109.0%	4.0%	-45.6%	-49.8%	-3.03E+11	2.45E+10	1238.0%	Lower middle income
Panama	0%	108.0%	6.2%	-10.3%	-11.1%	-7.39E+10	4.12E+10	179.3%	High income
Rwanda	0%	78.5%	15.4%	-51.4%	-40.5%	-2.02E+11	7.68E+10	263.0%	Low income
Senegal	0%	101.0%	8.9%	-34.8%	-35.9%	-7.75E+11	1.95E+11	398.0%	Lower middle income
Thailand	0%	108.0%	15.3%	-36.8%	-38.4%	-5.17E+12	1.99E+12	260.0%	Upper middle income
Tajikistan	0%	47.0%	23.7%	-99.9%	-47.1%	-3.66E+12	1.85E+12	197.8%	Low income
Tunisia	0%	54.9%	20.9%	-38.9%	-22.1%	-2.56E+12	2.51E+12	102.3%	Lower middle income
United Republic of Tanzania	0%	84.5%	8.8%	-47.0%	-40.1%	-1.39E+12	3.07E+11	453.0%	Low income
Uzbekistan	0%	22.6%	16.8%	-100.0%	-22.5%	-7.89E+12	5.89E+12	134.0%	Lower middle income
South Africa	0%	50.3%	19.0%	-39.9%	-19.6%	-2.41E+12	2.27E+12	106.0%	Upper middle income

Table S11: Wheat production decline (Sec. SM-1.2.3), 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.

Country	Production Decline	Share of import compared	Share of reserves compared	Change in Imports due to	Change in Impaired Supply	Change in Impaired Supply	Reserves (kcal)	Ratio of decline in Impaired	Country Classification

		to domestic supply	to domestic supply	Export Ban	due to P loss and Export ban (fraction)	due to P loss and Export Ban (kcal)		Supply to Reserves	based on GNI per capita
Focus countries									
India	-1.92%	0.0%	19.4%	-2.0%	5.1%	2.76E+13	1.05E+14	n/a	Lower middle income
Thailand	-2.10%	0.4%	19.2%	-3.5%	43.9%	3.21E+13	1.40E+13	n/a	Upper middle income
Viet Nam	-0.12%	0.1%	3.0%	-82.5%	11.6%	1.50E+13	3.84E+12	n/a	Lower middle income
Iran (Islamic Republic of)	-18.83%	32.4%	15.9%	-71.4%	-36.3%	-4.60E+12	2.06E+12	224.0%	Upper middle income
Kenya	-34.25%	81.3%	12.4%	-17.2%	-20.4%	-5.29E+11	3.23E+11	164.0%	Lower middle income
Pakistan	-19.70%	0.1%	15.4%	-9.7%	-31.1%	-7.38E+12	3.70E+12	199.0%	Lower middle income
Saudi Arabia	0%	101.0%	15.9%	-80.2%	-80.5%	-3.88E+12	7.62E+11	510.0%	High income
Ethiopia	0%	49.4%	n/a	-86.7%	-41.4%	-4.72E+11	not reported	n/a	Low income
Somalia	0%	91.2%	n/a	-88.2%	-82.6%	-1.13E+12	not reported	n/a	Low income
Yemen	0%	99.6%	n/a	-79.8%	-79.8%	-1.27E+12	not reported	n/a	Low income
Jordan	0%	100.0%	7.9%	-33.1%	-33.4%	-2.42E+11	5.76E+10	421.0%	Upper middle income
Oman	0%	107.0%	36.0%	-46.0%	-49.1%	-4.42E+11	3.24E+11	136.0%	High income
United Arab Emirates	0%	146.0%	5.4%	-79.0%	-113.4%	-3.22E+12	1.50E+11	2150.0%	High income
Iraq	0%	81.4%	8.5%	-69.2%	-56.3%	-2.31E+12	3.50E+11	659.0%	Upper middle income
Countries with >50% decline in import but large reserves									
Bangladesh	0%	1.65%	2.9%	-98.9%	-1.6%	-2.93E+12	5.30E+12	55.3%	Lower middle income
China (mainland)	0%	1.89%	59.1%	-80.7%	-1.5%	-1.05E+13	4.08E+14	2.6%	Upper middle income

Egypt	0%	1.63%	27.7%	-96.5%	-1.6%	-2.52E+11	4.43E+12	5.7%	Lower middle income
Cambodia	0%	0.36%	5.3%	-90.8%	-0.3%	-1.12E+11	1.79E+12	6.2%	Lower middle income
Sri Lanka	0%	8.99%	10.6%	-73.0%	-6.6%	-9.19E+11	1.48E+12	62.1%	Upper middle income
Myanmar	0%	0.07%	4.1%	-96.5%	-0.1%	-5.90E+10	3.62E+12	1.6%	Lower middle income
Nigeria	0%	3.76%	13.8%	-95.3%	-3.6%	-1.08E+12	4.13E+12	26.1%	Lower middle income
Philippines	0%	4.67%	15.7%	-95.9%	-4.5%	-3.05E+12	1.07E+13	28.5%	Lower middle income
United States of America	0%	11.50%	40.5%	-86.0%	-9.9%	-2.37E+12	3.99E+12	59.3%	High income
Countries where the reserves < decline in impaired supply									
Burkina Faso	0%	39.9%	5.6%	-75.5%	-30.5%	-7.53E+11	1.40E+11	538.0%	Low income
Switzerland	0%	118.6%	19.9%	-21.4%	-25.6%	-8.11E+10	6.36E+10	127.0%	High income
France	0%	91.9%	7.7%	-23.6%	-21.4%	-4.55E+11	1.61E+11	282.0%	High income
Ghana	0%	43.1%	19.2%	-95.0%	-40.9%	-1.92E+12	9.00E+11	214.0%	Lower middle income
Guinea	0%	15.8%	4.5%	-87.6%	-14.0%	-1.80E+12	5.78E+11	312.0%	Low income
Gambia	0%	60.0%	10.9%	-22.2%	-13.3%	-1.15E+11	9.36E+10	123.0%	Low income
Israel	0%	101.0%	15.5%	-57.9%	-58.0%	-2.80E+11	7.44E+10	376.0%	High income
Lao People's Democratic Republic	0%	4.2%	2.9%	-99.5%	-4.3%	-6.24E+11	4.40E+11	142.0%	Lower middle income
Liberia	0%	39.3%	5.1%	-85.7%	-33.6%	-8.76E+11	1.33E+11	659.0%	Low income
Mauritania	0%	19.8%	5.4%	-57.4%	-11.0%	-1.25E+11	5.88E+10	212.0%	Lower middle income
Malaysia	0%	24.1%	8.8%	-82.7%	-20.1%	-2.59E+12	1.14E+12	227.0%	Upper middle income
Russian Federation	0%	22.6%	8.0%	-52.3%	-12.0%	-4.98E+11	3.35E+11	149.0%	Upper middle income
Senegal	0%	64.0%	11.8%	-79.5%	-51.0%	-3.51E+12	8.15E+11	430.0%	Lower middle income

Syrian Arab Republic	0%	99.7%	6.2%	-51.1%	-51.1%	-1.48E+11	1.80E+10	820.0%	Low income
Turkey	0%	25.6%	7.9%	-51.2%	-13.2%	-5.25E+11	3.14E+11	167.0%	Upper middle income
South Africa	0%	110.0%	7.4%	-95.2%	-106.0%	-3.13E+12	2.22E+11	1410.0%	Upper middle income

Table S12: Rice production decline (Sec. SM-1.2.3), 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

Country	**Production Decline**	**Share of import compared to domestic supply**	**Share of reserves compared to domestic supply**	**Change in Imports due to Export Ban**	**Change in Impaired Supply due to P loss and Export ban (fraction)**	**Change in Impaired Supply due to P loss and Export Ban (kcal)**	**Reserves (kcal)**	**Ratio of decline in Impaired Supply to Reserves**	**Country Classification based on GNI per capita**
Focus countries									
Argentina	-11.9%	0.2%	12.1%	-3.2%	62.5%	5.63E+13	1.09E+13	n/a	Upper middle income
Brazil	-13.3%	2.1%	8.3%	-43.0%	14.9%	3.98E+13	2.24E+13	n/a	Upper middle income
Ukraine	-8.8%	0.4%	10.0%	0.0%	125.8%	5.39E+13	4.28E+12	n/a	Lower middle income
Ethiopia	-13.0%	0.1%	8.2%	-40.0%	-13.0%	-4.68E+12	2.94E+12	159.03%	Low income
Iran (Islamic Republic of)	-29.8%	84.5%	14.3%	-54.5%	-50.7%	-1.65E+13	4.59E+12	358.89%	Upper middle income
Kenya	-15.2%	9.6%	7.8%	-7.7%	-14.5%	-3.31E+12	1.79E+12	185.00%	Lower middle income
Pakistan	-7.2%	0.4%	12.8%	-13.4%	-7.3%	-1.82E+12	3.20E+12	56.90%	Lower middle income
Saudi Arabia	-52.8%	99.8%	21.0%	-49.4%	-50.4%	-6.32E+12	2.72E+12	231.81%	High income
Somalia	-48.4%	6.2%	n/a	-0.5%	-45.5%	-3.74E+11	not reported	n/a	Low income

Yemen	-25.2%	88.1%	3.9%	-94.7%	-86.5%	-2.11E+12	9.37E+10	2248.62%	Low income
Jordan	0%	76.4%	1.2%	-79.5%	-60.7%	-2.43E+12	4.75E+10	5111.52%	Upper middle income
Iraq	0%	52.7%	2.0%	-23.5%	-12.4%	-2.83E+11	4.63E+10	610.18%	Upper middle income
Uganda	0%	0.1%	5.8%	0%	0%	0	7.54E+11	n/a	Low income
Countries with >50% decline in import but large reserves									
Bolivia (Plurinational State of)	0%	4.1%	24.0%	-99.1%	-4.1%	-2.15E+11	1.25E+12	17.2%	Lower middle income
China (mainland)	0%	1.2%	69.1%	-76.6%	-0.9%	-9.99E+12	7.61E+14	1.3%	Upper middle income
India	0%	0.3%	5.0%	-94.2%	-0.3%	-3.70E+11	5.96E+12	6.2%	Lower middle income
Kazakhstan	0%	1.1%	12.9%	-58.1%	-0.7%	-2.27E+10	4.50E+11	5.0%	Upper middle income
Paraguay	0%	0.3%	30.9%	-97.5%	-0.3%	-4.11E+10	4.02E+12	1.0%	Upper middle income
South Africa	0%	11.2%	16.8%	-66.6%	-7.4%	-3.78E+12	8.57E+12	44.1%	Upper middle income
Countries where the reserves < decline in impaired supply									
Belgium	0%	82.7%	3.9%	-22.2%	-18.3%	-1.41E+12	3.01E+11	468.2%	High income
Bangladesh	0%	24.0%	4.1%	-74.0%	-17.8%	-2.50E+12	5.71E+11	437.9%	Lower middle income
Chile	0%	49.5%	6.2%	-43.6%	-21.6%	-2.29E+12	6.79E+11	337.8%	High income
Costa Rica	0%	96.7%	5.4%	-10.5%	-10.1%	-3.11E+11	1.67E+11	186.0%	Upper middle income
Cuba	0%	61.5%	3.7%	-80.1%	-49.2%	-2.56E+12	1.90E+11	1349.9%	Upper middle income
Dominican Republic	0%	94.6%	11.2%	-56.1%	-53.1%	-2.60E+12	5.48E+11	475.0%	Upper middle income
Algeria	0%	99.2%	10.8%	-86.8%	-86.1%	-1.29E+13	1.62E+12	798.4%	Upper middle income
Ecuador	0%	4.3%	2.1%	-68.5%	-2.9%	-2.05E+11	1.48E+11	138.1%	Upper middle income
Egypt	0%	46.5%	9.8%	-84.6%	-39.3%	-2.40E+13	6.00E+12	399.5%	Lower middle income

Spain	0%	62.6%	4.8%	-52.3%	-32.8%	-1.32E+13	1.93E+12	684.6%	High income
Indonesia	0%	5.5%	2.7%	-84.5%	-4.6%	-5.01E+12	2.97E+12	168.8%	Lower middle income
Israel	0%	82.3%	7.3%	-36.7%	-30.2%	-2.14E+12	5.17E+11	414.5%	High income
Italy	0%	39.6%	7.2%	-30.6%	-12.1%	-5.18E+12	3.10E+12	167.1%	High income
Japan	0%	99.5%	9.4%	-20.2%	-20.1%	-1.08E+13	5.08E+12	212.6%	High income
Republic of Korea	0%	99.4%	19.0%	-41.2%	-41.0%	-1.45E+13	6.64E+12	218.0%	High income
Kuwait	0%	75.7%	4.0%	-59.1%	-44.8%	-5.08E+11	4.39E+10	1158.1%	High income
Lebanon	0%	94.3%	4.5%	-37.2%	-35.0%	-9.13E+11	1.17E+11	780.0%	Upper middle income
Libya	0%	96.7%	5.7%	-47.1%	-45.5%	-1.36E+12	1.70E+11	798.7%	Upper middle income
Lithuania	0%	59.9%	5.2%	-71.3%	-42.7%	-2.29E+11	5.57E+10	411.0%	High income
Morocco	0%	90.6%	5.2%	-68.7%	-62.3%	-5.34E+12	4.44E+11	1202.5%	Lower middle income
Malaysia	0%	98.1%	6.0%	-89.9%	-88.2%	-1.22E+13	8.38E+11	1456.6%	Lower middle income
Netherlands	0%	125.4%	0.6%	-47.5%	-59.5%	-8.76E+12	9.63E+10	9096.7%	High income
Portugal	0%	68.2%	4.0%	-56.1%	-38.3%	-3.77E+12	3.91E+11	965.7%	High income
Senegal	0%	33.4%	7.1%	-67.9%	-22.7%	-5.98E+11	1.84E+11	325.2%	Lower middle income
Syrian Arab Republic	0%	55.8%	8.2%	-27.8%	-15.5%	-2.50E+11	1.31E+11	191.5%	Low income
Tunisia	0%	103.8%	4.0%	-78.7%	-81.7%	-3.51E+12	1.73E+11	2023.4%	Lower middle income
Taiwan	0%	94.4%	18.5%	-44.1%	-41.6%	-6.69E+12	2.96E+12	226.0%	High income
Venezuela (Bolivarian Republic of)	0%	48.5%	2.9%	-21.5%	-10.4%	-1.27E+12	3.51E+11	362.6%	Upper middle income
Vietnam	0%	55.1%	7.3%	-92.3%	-50.8%	-2.57E+13	3.74E+12	686.5%	Lower middle income

Table S13: Maize production decline (Sec. SM-1.2.3), 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

SM-1.3.2: 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[9] (Tabs. S14-S16). Argentina and Ukraine are two examples of such countries. Both countries are important exporters playing a central role for the stability of the world food system. For instance, in the agricultural year 2018/19 Argentine was the 6th largest wheat exporter and 3rd largest maize exporter, and Ukraine was the 5th largest wheat exporter and 4th largest maize exporter (Tabs. S14 and S16). Both countries, have relatively small reserves compared to their domestic consumption (production + imports - exports). Ukraine's wheat reserve is 8%, 10% of their domestic consumption in wheat and maize, respectively, and Argentina's maize reserve is 12.1% of their domestic consumption (Tabs. S11 and S13). As shown in Sec. SM-1.3.1, 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, since 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,

$$r = \frac{|\text{impaired supply due to produciton loss} + \text{reserves}|}{\text{exports}}.$$

Using the values given in Tabs. S6 and S8, 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

9 https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups accessed June 2020

reduce their 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 Argentine 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.

SM-2: Supporting data

All production, domestic consumption, export and ending stock data used in this subsection are published by the United States Department of Agriculture and are available from USDA's PSD online database[10]. The figures and content of the tables are all produced using data from 1960-2019. Annual nominal world market price for US hard red winter wheat, Thai 5% rice and Maize are published by the World Bank and are taken from the Commodity Markets online database "pink sheet"[11].

SM-2.1: 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 their domestic harvest, which accounted for 6.3% of international rice exports. Thailand on the other hand, produces only 4% of all rice but their share of world total rice export is 17.5% and Thailand was in 2018/2019 the second largest exporter of rice.

10 https://apps.fas.usda.gov/psdonline/app/index.html#/app/advQuery accessed April 2020
11 http://www.worldbank.org/en/research/commodity-market accessed April 2020

The top 5 exporters account for 72%, 73% and 90% of all exported wheat, rice and maize, respectively (Tabs. S14-S16).

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 US. 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.

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%

Table S14: 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
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%

Table S15: 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
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%

Table S16: 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.

SM-2.2: Historic USDA data

SM-2.2.1: Stocks

Global beginning stocks of grains are at a very high level, record high for rice, but also historically high for wheat and maize. The 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. Maize stock-to-use is at 27% and has been declining since 2016 when it reached 33% but is still at a relatively high level for a historic point of view. 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 Tab. S17 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.

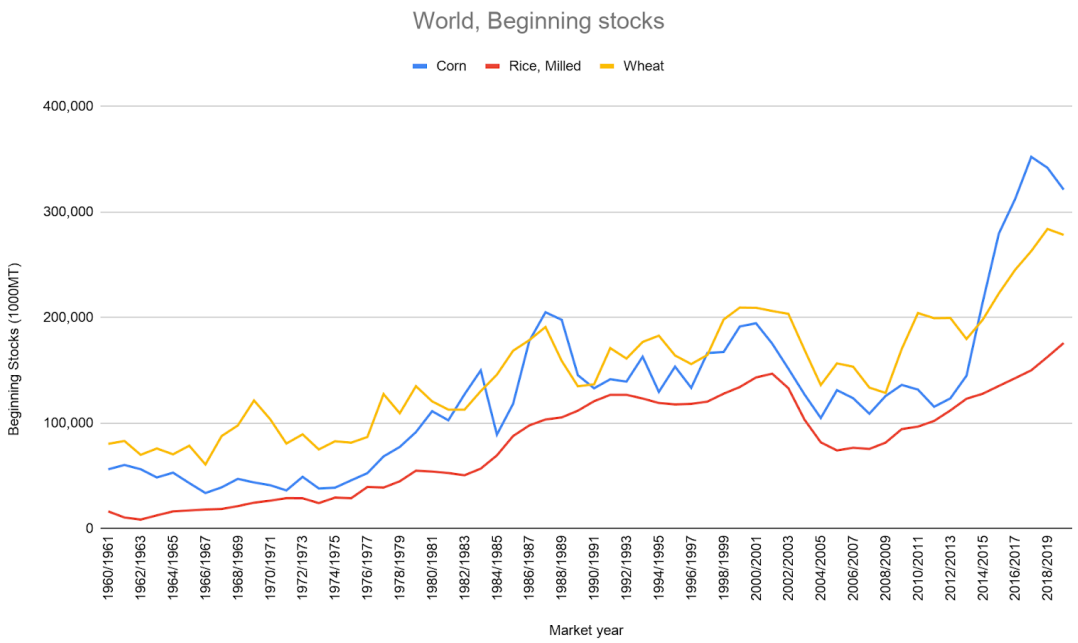

Figure S4: World beginning stocks from wheat, rice and maize from 1960-2019. The current world stock is historically high for rice, wheat and maize. Data source: USDA PSD online.

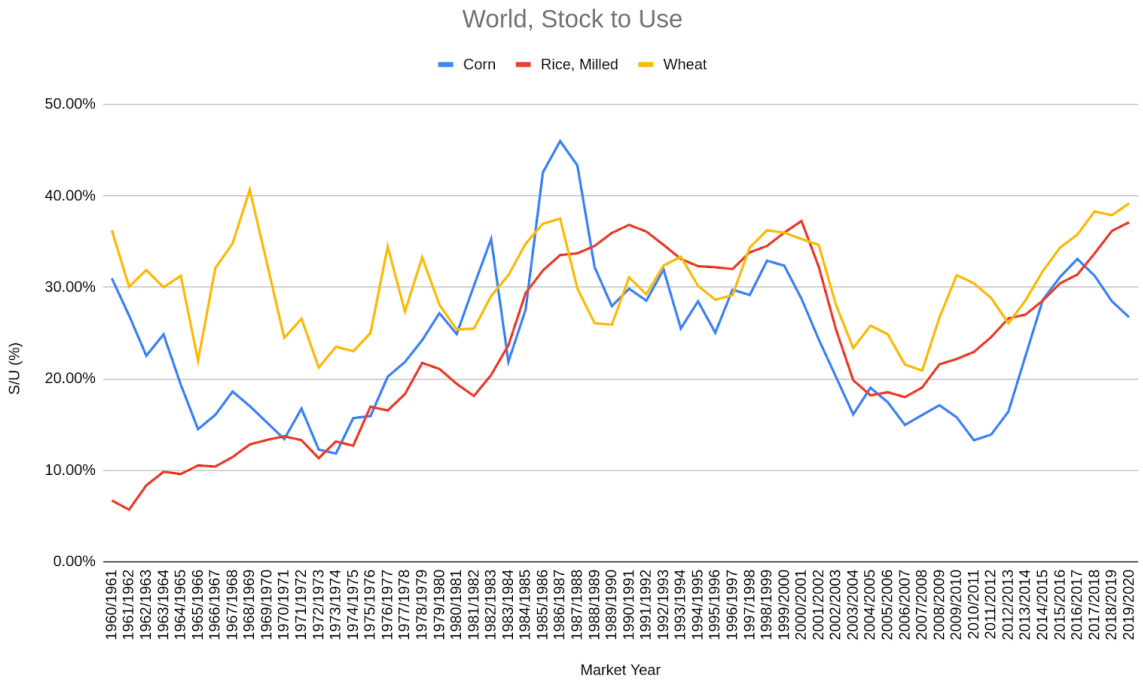

Figure S5: World stock to use ration for wheat, rice and maize for 1960-2019. S/U = Ending stock divided by domestic consumption. Data source: USDA PSD online.

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%

Table S17: Change in stock-to-use ratio compared to the previous year, for four different time periods. Data source: USDA PSD online.

SM-2.2.3: 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 (Fig. S6). The year-to-year variation in production is given in Tab. S18 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 variation is 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 base on data over the last 20 years. This is much smaller compared to domestic production declines, which vary much more (Tab. S3). 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 the certain regions. This is one reason why food insecurity can arise even though there is enough food globally to cover the world food demand. The 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.

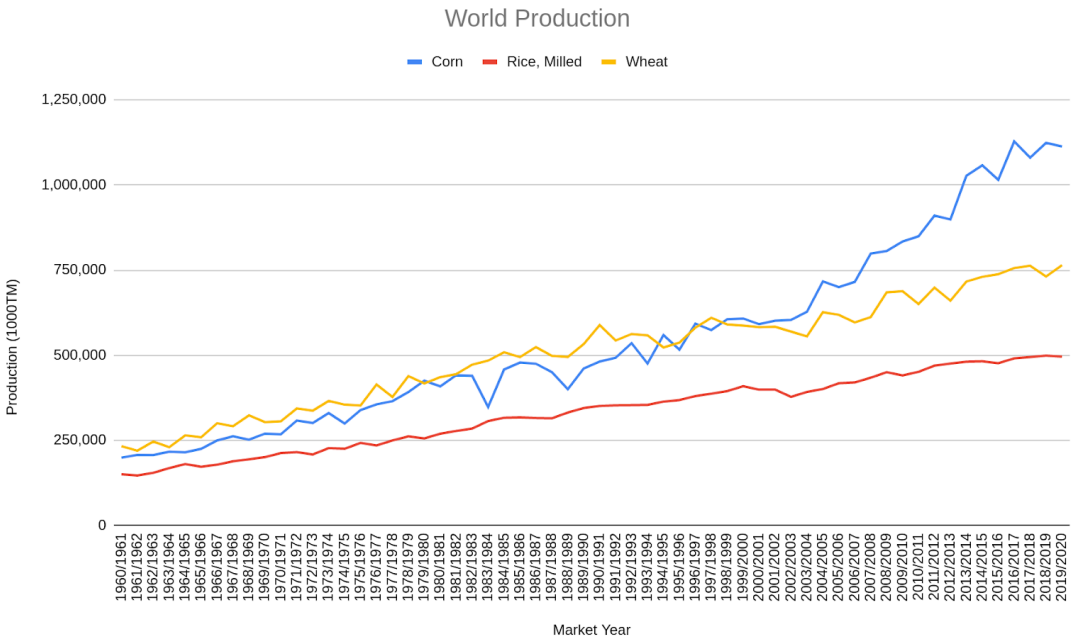

Figure S6: World production of wheat, rice and maize for 1960-2019. Data source: USDA PSD online.

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%

Table S18: Change in world production compared to the previous year. Data source: USDA PSD online.

SM-2.3: Historic World Price of wheat, rice and maize

The world market price for food and grains has varied substantially under certain periods of time. Especially during the oil crisis in the 1970s and the world food crisis in 2007/08 and 2010/11 (Tab. S19). These effects are seen both in nominal and real prices (Figs. S7 and S8). The nominal prices are taken from the Commodity Markets online database "pink sheet" of the World Bank[12] 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[13]. 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 people that spends a large fraction of their income on food.

12 http://www.worldbank.org/en/research/commodity-market accessed April 2020
13 https://www.bls.gov accessed April 2020

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.

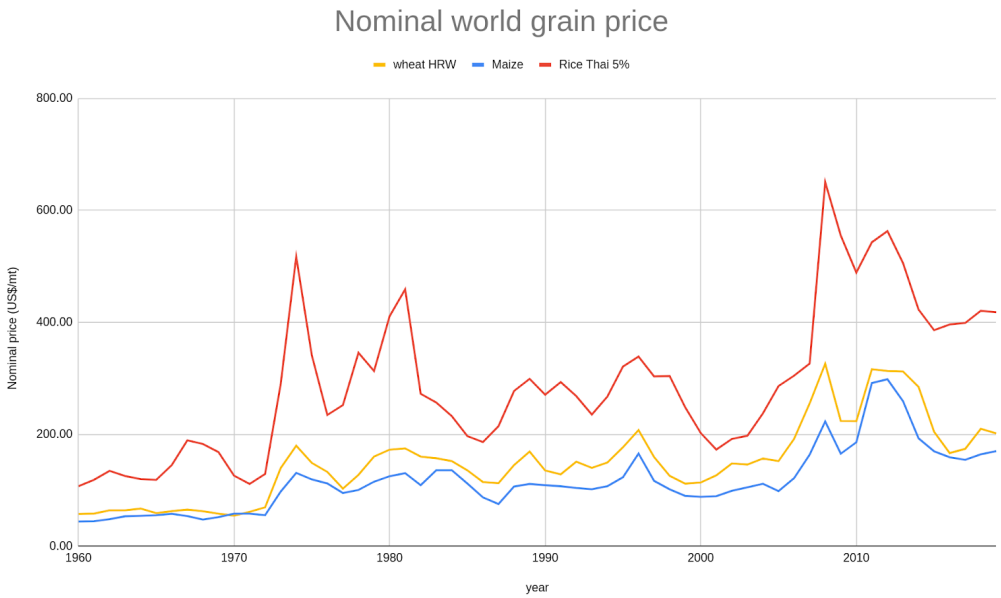

Figure S7: Annual nominal world market price for wheat HRW, rice Thai 5% and maize for 1960-2019. Data source: "pink sheet" of the World Bank.

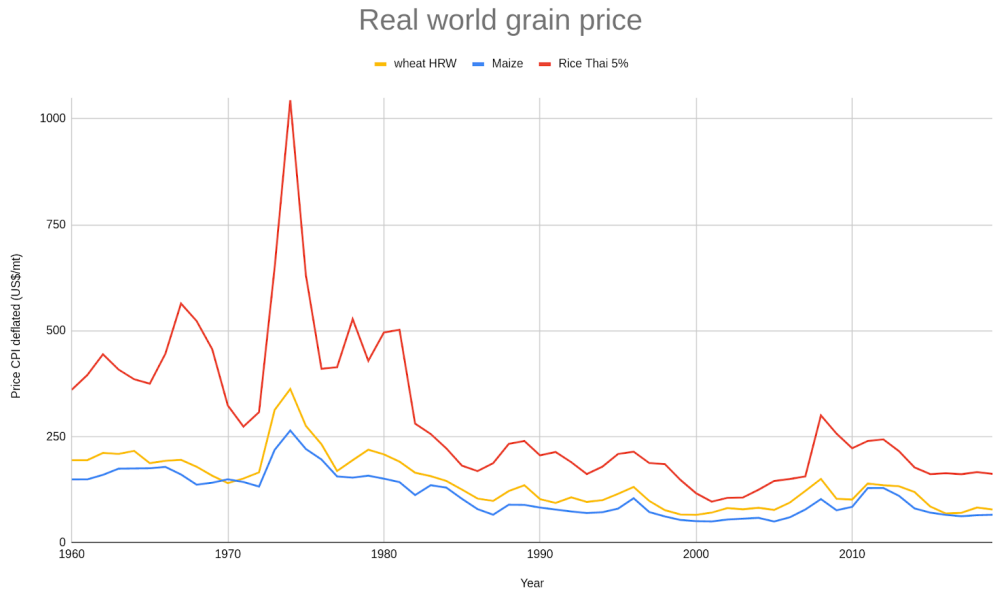

Figure 8: Annual world market price for wheat HRW, rice and Maize for 1960-2019, deflated by the CPI normalized to June 1983=100. Data source: World Bank "pink sheet" and CPI from US Bureau of Labor Statistics.

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

Table S19: Change in annual world price during the food crisis 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.

The International Grain Council provides daily values of the change in export prices expressed in grain indices[14]. From 1 Jan 2020 to 29 May 2020 the index went up 15% for rice, while it decreased by 3.1% and 9.3% for wheat and maize, respectively, for the same time period (see Fig. S9). The early price increase in rice prices may be partly due to the temporary ban of rice by Vietnam. The decrease in maize prices 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[15].

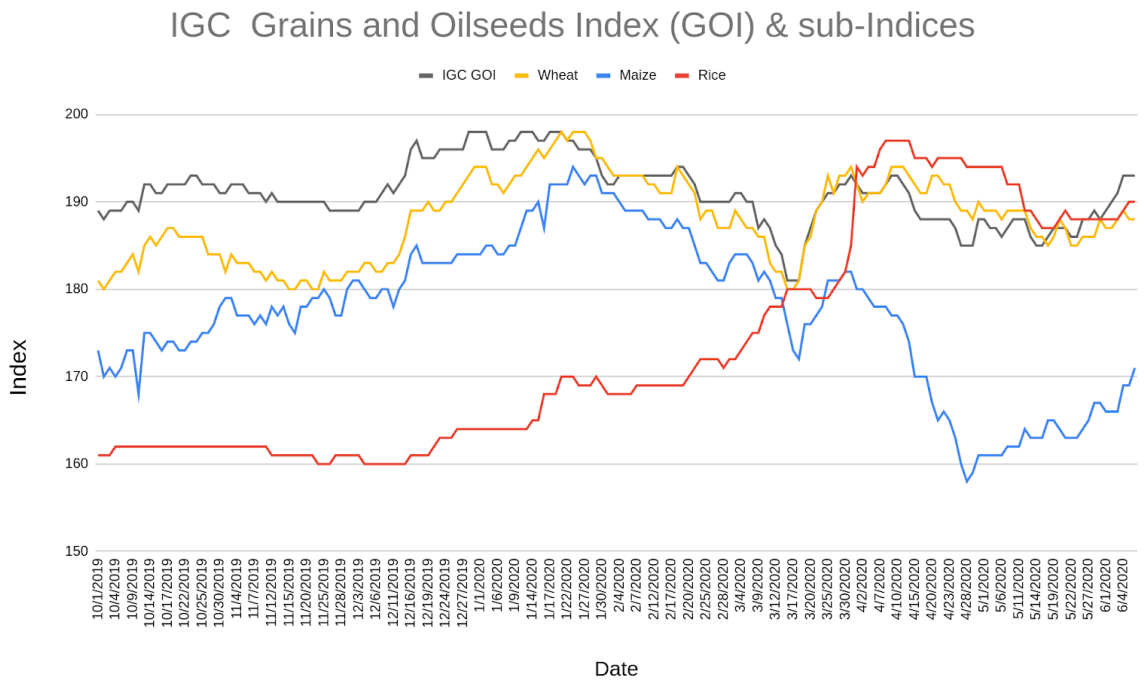

Figure S9: Grain and Oilseeds index (GOI) and sub-indices for wheat, rice and maize reported on a daily basis between October 2019 and June 2020. Normalized to January 2000 = 100 Data source: IGC.

14 https://www.igc.int/en/markets/marketinfo-goi.aspx accessed June 2020
15 https://www.bloomberg.com/news/articles/2020-04-20/negative-prices-for-oil-here-s-what-that-means-quicktake

SM-3: 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. This allowed for locust eggs to hatch and a few new generations of locusts occurred, which was unknown at the time and was therefore not under controlled[16]. 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 (FAO, 2020a). Since locusts are a huge 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 update (FAO, 2020a). These countries are Kenya, Ethiopia, Somalia, Saudi Arabia, Yemen, Iran and Pakistan (Fig. S10). 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 (see Fig. S11), it is the first time since 1962 that any desert locusts threaten their land and crops (FAO, 2020b).

[16] http://www.fao.org/ag/locusts/en/info/2094/index.html

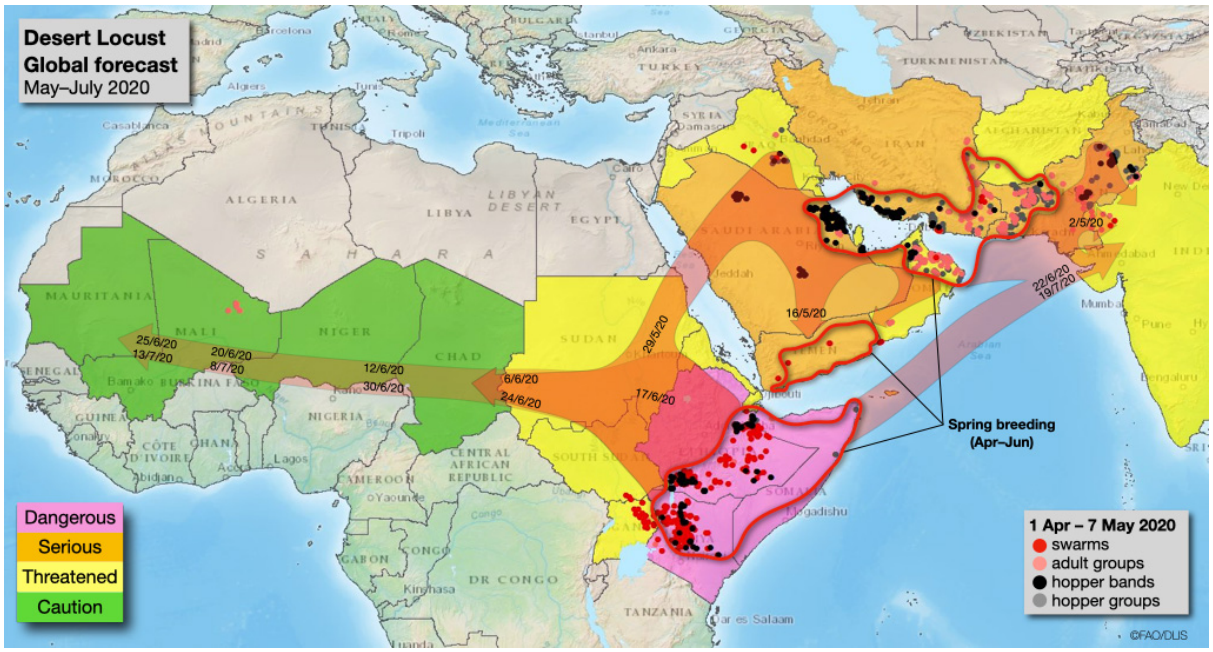

Figure S10: FAO Locust Watch map update 8 May. Reprinted from FAO[17].

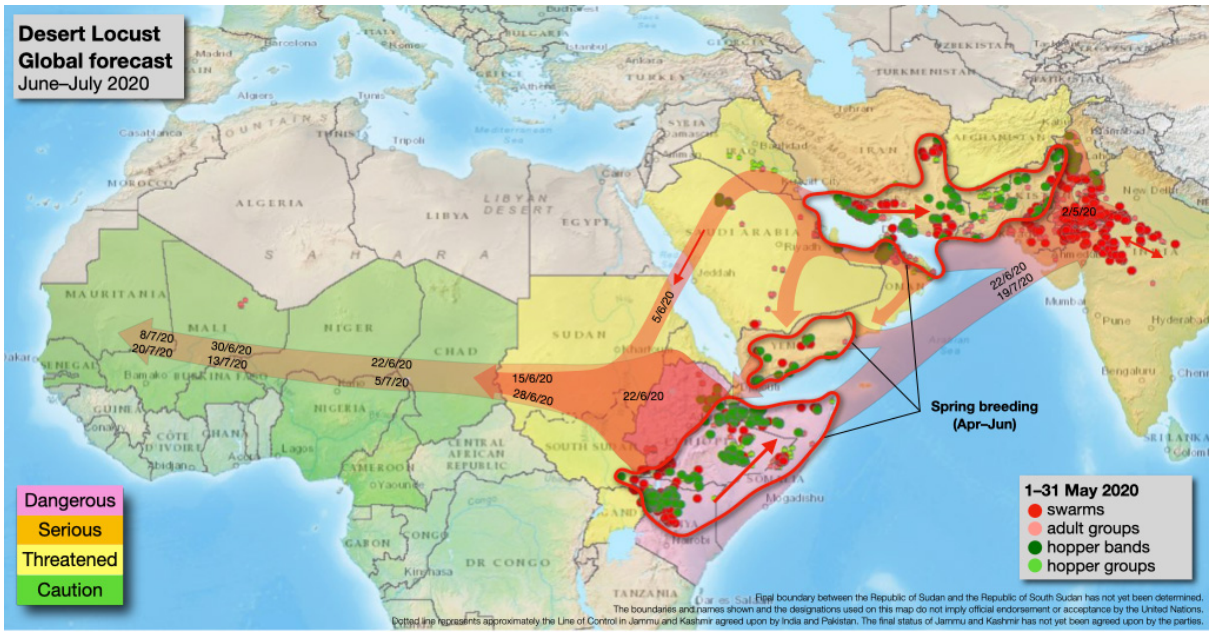

Figure S11: FAO Locust Watch risk map updated 4 June. Reprinted from FAO[18].

[17] http://www.fao.org/ag/locusts/common/ecg/75/en/200507globalE.jpg
[18] http://www.fao.org/ag/locusts/common/ecg/75/en/200604forecastE.jpg

References

OECD/FAO 2019, “OECD-FAO Agricultural Outlook 2019-2028, OECD Publishing”, Paris/Food and Agriculture Organization of the United Nations, Rome. https://doi.org/10.1787/agr_outlook-2019-en

FAO 2001, Food Balance Sheets: A Handbook (Rome: Food & Agriculture Organization of the United Nations) http://www.fao.org/3/X9892E/X9892E00.htm

FAO 2020a, Desert Locust Bulletin, FAO Situation Report No. 499

http://www.fao.org/ag/locusts/common/ecg/562/en/DL499e.pdf

FAO 2020b, Desert Locust Bulletin, FAO Situation Report No. 499

http://www.fao.org/ag/locusts/common/ecg/562/en/DL500e.pdf

Konar M, Dalin C, Suweis S, Hanasaki N, Rinaldo A and Rodriguez-Iturbe, *Water Resour. Res. 47* (2011)

Puma M J, Bose S, Chon S Y and Cook B, Assessing the evolving fragility of the global food system. *Environ. Res. Lett*. 10 024007 (2015)

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)

J. Schewe, C. Otto, K. Frieler, The role of storage dynamics in annual wheat prices. *Environ. Res. Lett.* **12**, 54005–54005 (2017).