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2016 Environ. Res. Lett. 11 035007

(http://iopscience.iop.org/1748-9326/11/3/035007)

Environmental Research Letters

CrossMark

OPEN ACCESS

RECEIVED
10 November 2015

REVISED
18 January 2016

ACCEPTED FOR PUBLICATION
15 February 2016

PUBLISHED
29 February 2016

LETTER

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Keywords: food security, trade shocks, vulnerability, climate change, teleconnections

Supplementary material for this article is available online

Abstract

The 2008–2010 food crisis might have been a harbinger of fundamental climate-induced food crises with geopolitical implications. Heat-wave-induced yield losses in Russia and resulting export restrictions led to increases in market prices for wheat across the Middle East, likely contributing to the Arab Spring. With ongoing climate change, temperatures and temperature variability will rise, leading to higher uncertainty in yields for major nutritional crops. Here we investigate which countries are most vulnerable to teleconnected supply-shocks, i.e. where diets strongly rely on the import of wheat, maize, or rice, and where a large share of the population is living in poverty. We find that the Middle East is most sensitive to teleconnected supply shocks in wheat, Central America to supply shocks in maize, and Western Africa to supply shocks in rice. Weighing with poverty levels, Sub-Saharan Africa is most affected. Altogether, a simultaneous 10% reduction in exports of wheat, rice, and maize would reduce caloric intake of 55 million people living in poverty by about 5%. Export bans in major producing regions would put up to 200 million people below the poverty line at risk, 90% of which live in Sub-Saharan Africa. Our results suggest that a region-specific combination of national increases in agricultural productivity and diversification of trade partners and diets can effectively decrease future food security risks.

Introduction

The future of food security in a changing climate is of global concern. Existing analyses of the impacts of climate change on food security focus typically on food production by quantifying to what extent changing temperature and precipitation patterns affect global or country-specific crop yields (Jones and Thornton 2003, Lobell and Field 2007, Nelson *et al* 2010, Lobell 2011). Models have advanced substantially in refined consideration of CO_2 fertilizing effects as well as nonlinearities in heat stress (Schlenker and Roberts 2009, Schlenker *et al* 2013, Challinor *et al* 2014, Asseng *et al* 2015). Most works conclude that, globally, average crop yields will decrease as the positive fertilizing effect is more than offset by unfavorable climate conditions. But, global warming not only influences mean total yields; recent work also highlights that crop yields become more variable (Asseng *et al* 2011, Urban 2012, Porter *et al* 2014) as climatic extremes become more frequent (Rahmstorf and Coumou 2011). Supply shocks due to adverse weather conditions may therefore become more common.

Variability in production is not per se a threat to food security. Grain storage and international trade are important tools to stabilize food supply by influencing grain supply inter-temporally or spatially. Many governments hold grain reserves for emergency or price stabilization purposes. But past efforts to liberalize grain markets (Galtier 2013), high costs, and governance problems of public storage (Rashid *et al* 2008, Rashid and Jayne 2010) have led to a substantial reduction of public grain stocks. This reduction has only

Table 1. Export shares of top five exporters on globally traded grains. The top five exporters of maize, rice and wheat account for more than two third of the total export volume (average for 2000–2012; source: FAOSTAT 2015).

Maize		Rice		Wheat	
Country	Share	Country	Share	Country	Share
United States	50%	Thailand	27%	United States	21%
Argentina	13%	Vietnam	16%	France	13%
Brazil	7%	India	14%	Canada	13%
France	7%	United States of America	10%	Australia	11%
China	5%	Pakistan	9%	Russia	8%
Top 5	82%	Top 5	77%	Top 5	66%

partially been compensated by speculative grain storage by private sector corporations (Fraser *et al* 2015). Contrary to public storage, speculative grain storage has relatively modest stabilizing effects on price volatility as only low stock levels are profitable (Gouel 2013). Due to missing insurance markets between consumers and stockholders, speculative grain storage tends to be too low from a social welfare perspective (Gouel 2013).

Apart from storage, international trade is able to diversify idiosyncratic production risks at comparably low costs. But, trade makes importing countries also vulnerable to teleconnected supply shocks resulting from e.g. harvest failures in distant producing regions, which limits their scope of domestic policy intervention. These supply shortages would mostly be mediated by price-effects. Several works study the transmission of prices and price volatility from international to domestic markets (Kornher and Kalkuhl 2013, Baquedano and Liefert 2014, Kalkuhl 2014). Such spatially disconnected climate events and market reactions, combined with the governance obstacles to adequately respond, are considered to have played an important role in the Arab Spring (Sternberg 2012, Werrell and Femia 2013). Weather-related production shocks in far-distant producer regions alone have not been exceptional in 2010. However, their impact on food prices in food importing countries, exacerbated by a cascade of counter-cyclical trade policies may have altered the conditions for political change. Political and economic motives are still dominant forces of political instability, and must be addressed directly (De Châtel 2014). But taken together, events like these can create a mixture of conditions that could provide a window of opportunity for riots and revolution in the Arab world and other countries (Bellemare 2015).

Our article is motivated by the observation that exports of major food commodities are concentrated in few countries (table 1). For maize, for example, the global export market is largely dominated by the United States (Lobell *et al* 2014), with Central American countries depending on US imports. This raises the general question whether countries that heavily rely on imports are increasingly vulnerable to localized extreme events in supplying regions, especially since trade flows have become less reliable in past years and exporting countries often applied restricting trade policies to stabilize their domestic supply at the expense of world market supply (Headey and Fan 2008, Martin and Anderson 2012, Fellmann *et al* 2014, Jensen and Anderson 2014).

The aim of this study is to develop a methodology to identify most vulnerable countries to teleconnected food-supply shocks. There is a broad range of literature on the concept of vulnerability (see e.g. Adger 2006 for a review and Fraser *et al* 2013 for an exemplarily application). In this study, vulnerability is measured by two dimensions: (1) the extent to which a shock on the international grain market translates to the domestic grain market and (2) the number of poor people affected. The first dimension is relevant for policy makers as disruptions in food supply can induce turmoil and political instabilities (von Braun *et al* 2014). The second dimension is important for an appropriate understanding of the aggregate relevance of global market interruptions. By focusing on abrupt market shocks rather than slowly changing long-term dynamics, we take an explicit short-term perspective on events lasting several months up to one year.

Vulnerability is related to supply shocks in export markets as follows: supply shocks can be caused by harvest failures but also by policy interventions that can be partly understood as endogenous reactions to the domestic and international supply situation (von Braun *et al* 2014). The extent to what supply shocks in exporting countries transmit to the caloric food availability in importing countries depends on several factors, like market share of the exporter, import deficit, diet composition and possible secondary equilibrium responses at the international market. We identify countries with critical caloric trade dependency and map these countries to the total number of people living in poverty. We then determine trade dependencies for the countries identified, by linking them to their major suppliers. Finally, we calculate the calorie-supply implications for stylized supply shock scenarios, resulting in (i) a 10% reduction in availability of grains at world export markets, and (ii) export bans of maize in the US, of wheat in Russia, and of rice in Thailand. We conclude by pointing to measures that could reduce vulnerabilities. Our analysis complements previous climate impact studies on food availability by incorporating trade-related aspects.

Methods

We define country j's vulnerability V_j to teleconnected trade shocks as two-dimensional vector $V_j = (\nu_j, \rho_j)$ of a supply shock transmission indicator υ_j and the number of people living below the international poverty line ρ_j. The transmission of a relative (exogenous) supply shock of crop c from exporter i on domestic calorie availability of importer j, is expressed by

$$\tilde{\upsilon}_{ijc} = \theta_{jc}\, s_{ijc}\, \mathrm{IDR}_{jc}\, w_{jc}. \qquad (1)$$

Parameter θ_{jc} indicates the endogenous market adjustment of the world export market of crop c and importer j to an exogenous relative total supply shock[7]. The exogenous relative supply shock can be driven by a production shock (harvest) or policy shock (in particular, trade policy). The share country i holds on all imports of crop c of country j is given by s_{ijc}. The import dependency ratio IDR_{jc} represents that part of the domestic supply of crop c that has been produced outside country j itself. Finally, w_{jc} measures the share crop c holds on country j's total calorie consumption. The higher $\tilde{\upsilon}_{ijc}$, the more vulnerable country j is to teleconnected trade shocks. To the contrary, $\tilde{\upsilon}_{ijc} \approx 0$ implies independence on teleconnected shocks.

While s_{ijc}, IDR_{jc} and w_{jc} can be directly obtained from available data, θ_{jc} is a behavioral response parameter that is related to the underlying economic structure of exporting and importing countries. For iso-elastic supply and demand functions

$$\theta_{jc} = \frac{-\eta_j}{\varepsilon - \eta_j}$$

holds with $\eta_j < 0$ being the price elasticity of demand in the importing country j and ε being the price elasticity of supply in the exporting countries (see SI). Because of the uncertainties associated with the estimation of θ_{jc} and its relatively low impact on moderating teleconnected shocks in the short-run (see SI), we abstract from its role and focus in our vulnerability analysis on the simplified version of (1) that considers only first-round effects of trade shocks:

$$\upsilon_{ijc} = s_{ijc}\, \mathrm{IDR}_{jc}\, w_{jc}.$$

The crops considered here are wheat, maize and rice. The IDR is calculated from FAOSTAT's Food Balance Sheets (FAOSTAT 2015) as ratio of imported crops to total domestic supply (sum of production and import, net of export); the trade shares s are calculated by averaging annual export data from the FAO database for the years 2007–2011. In case there are no data available for a country, we derive the information from the GTAP 8.1 dataset for 2007 (Narayanan *et al* 2012)[8]. The calorie share w of crop c on total food consumption and, alternatively, on total cereals consumption is calculated from FAO's Balance Sheets. The poverty index ρ is defined as the number of people living on less than \$1.90 a day, based on World Bank data (The World Bank 2015).

In the following analysis, we decompose this transmission indicator into several components: the factor s_{ijc} measures to what extent a supply shock in exporter country i affects country j; the product $\mathrm{IDR}_{jc} \cdot w_{jc}$ measures the impact on the domestic calorie base. The different components can be addressed by different policies (see discussion).

Subsequently, we present results related to the following analysis:

(1) *Vulnerability due to caloric trade deficiency*: we identify countries with $\mathrm{IDR}_{jc} \geqslant \frac{1}{4}$ and $w_{jc} \geqslant \frac{1}{4}$ (figures 1 and 2) and add the poverty population index;

(2) *Trade dependency*: the countries selected by (1) are linked to their major exporter (i.e. $\max_i\{s_{ijc}\}$) (figure 3) as well as the three major exporting countries (figures S1–S3 in SI);

(3) *Continuous vulnerability mapping for specific trade shock scenarios*: we map aggregate values and variants of υ_{ijc} to population below the poverty line ρ_j. Here, we include all countries with available World Bank data on poverty.

Results

The results of this study show that there are many countries with both a high dependency on a single staple crop for supply of calories and a high dependency on imports, often from a very small supplier base. Our findings indicate that countries vulnerable to supply shocks of a specific crop are often clustered geographically.

Countries vulnerable due to large caloric trade deficits

We find that the most vulnerable countries are mainly located in Africa. The number of vulnerable countries varies by staple crop, i.e. we identify a total of 33 vulnerable countries, 21 of which depend on wheat, seven on maize and five on rice (figure 1). Since countries with similar vulnerabilities pattern cluster geographically, major supply disruptions are likely to affect entire regions rather than just single countries.

[7] The endogenous market adjustment rate θ_{jc} measures to what extent an exogenous relative shock in supply of exporting countries is moderated by market reactions. For example, consider a 10% aggregate supply shock in all exporting countries due to harvest failures. Reducing exports by 10% would lead to a price increase on the international market which, in turn, would increase profitability of exports. As a response, exports increase and the original supply shock of 10% is moderated to 10 θ_{jc} %.

[8] Please note in this case data refer to the year 2007 only as GTAP does not provide annual time series.

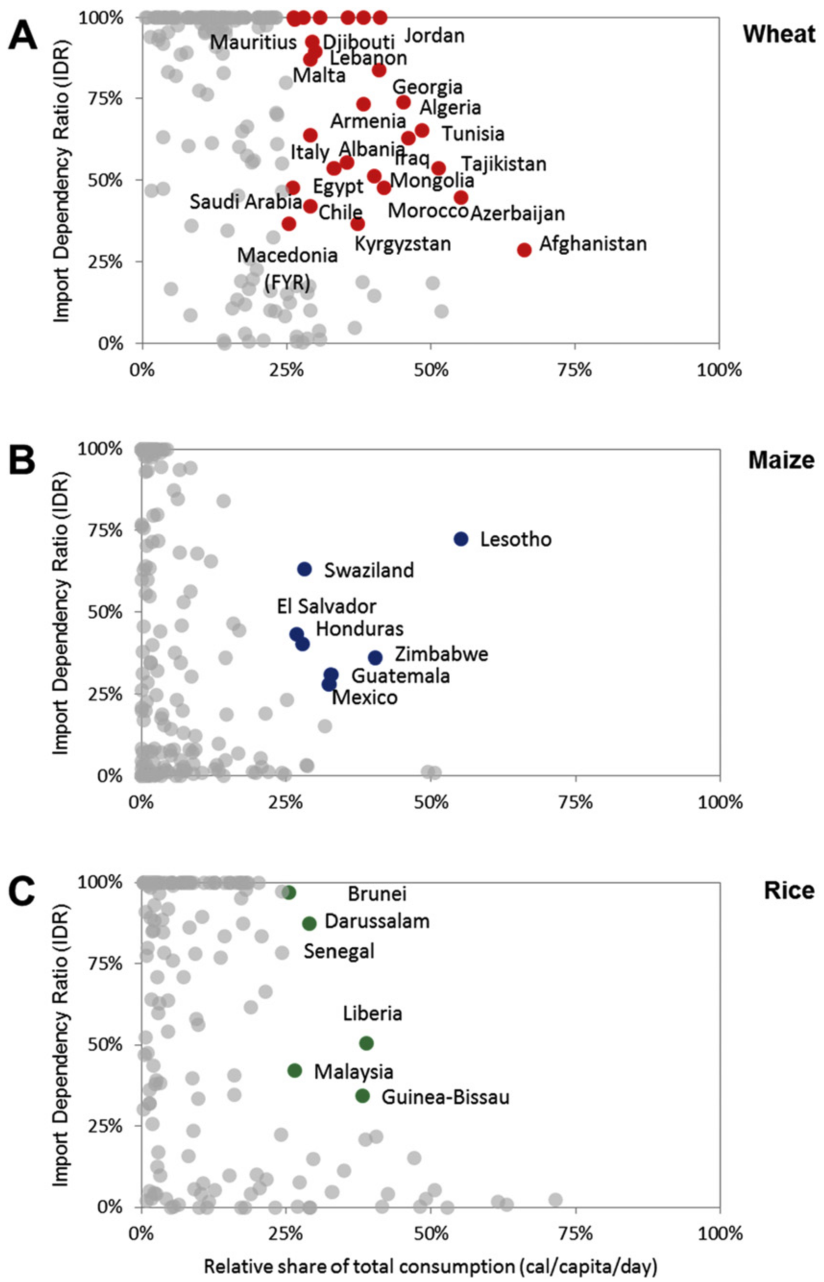

Figure 1. *Caloric trade dependency panels.* The horizontal axis indicates a country's reliance on a specific crop (w_{jc}), the vertical axis its import dependency ratio (IDR_{jc}). Analyzed crops are wheat (A), maize (B), and rice (C). Countries where both ratios are ⩾25% are highlighted.

Wheat is particularly important for diets in the Middle East and Northern Africa (MENA region) as well as some regions in Central Asia (figure 2). As most of these regions are characterized by arid desert climate and have very little suitable croplands, import dependencies are often high (>50%). Maize is an important staple crop in Central America and Southern African countries (figure 2). Both regions neighbor major producing countries (the USA and South Africa). With the exception of Malaysia and Brunei Darussalam, there are no countries in Asia that import more than 25% of their rice supply, even though rice is by far the most important staple crop of the region. The rice-consuming countries that qualify under our definition as vulnerable are instead mostly located in Western Africa.

Trade dependencies

Our results show that most of the countries identified receive their imports from just a few dominant producing countries, in some cases only a single one (figure 3). Wheat is mainly sourced from former Soviet republics (Russia, Kazakhstan, and Ukraine), Western Europe, and North America. Most MENA countries obtain the largest share of their imports from Russia and Western Europe (mostly France). The US and Canada are important suppliers for some of the Gulf States while Kazakhstan is a very important supplier

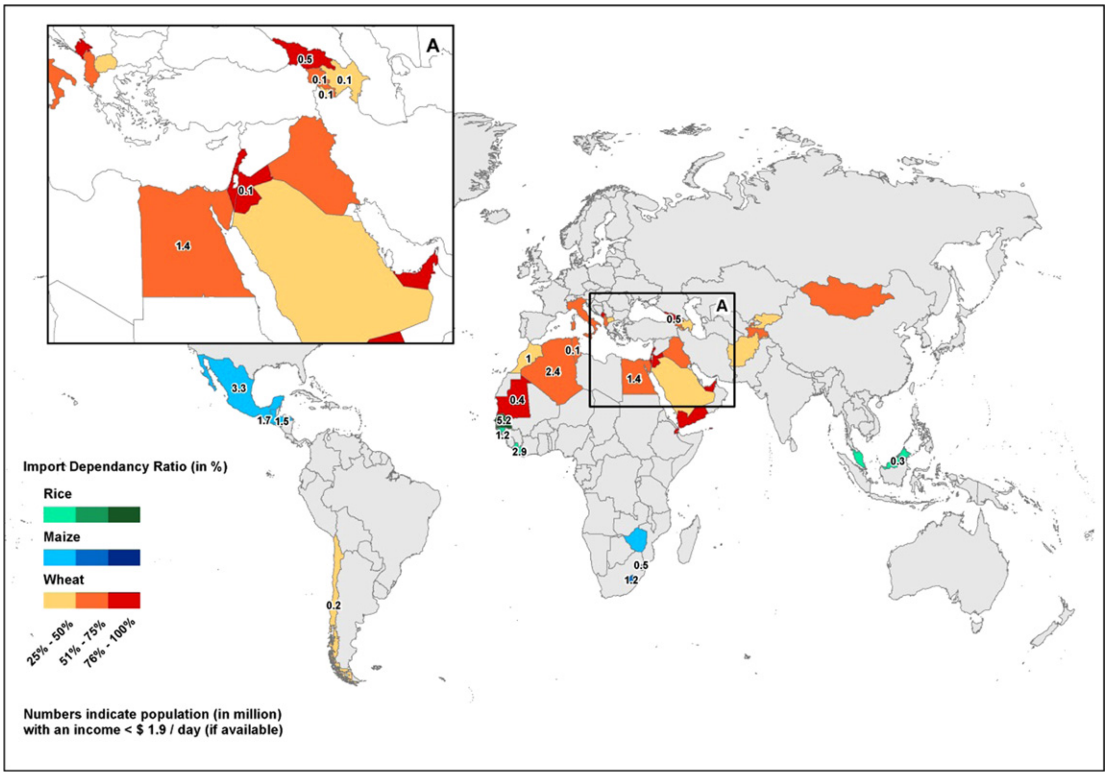

Figure 2. *Caloric trade deficits and poverty levels.* Countries with an import dependency ratio and dietary reliance on wheat, maize, or rice of at least 25%, respectively, are highlighted. Black numbers indicate the number of people (in million) living on less than US $1.90 a day. Panel (A) provides a close up of the Middle Eastern region.

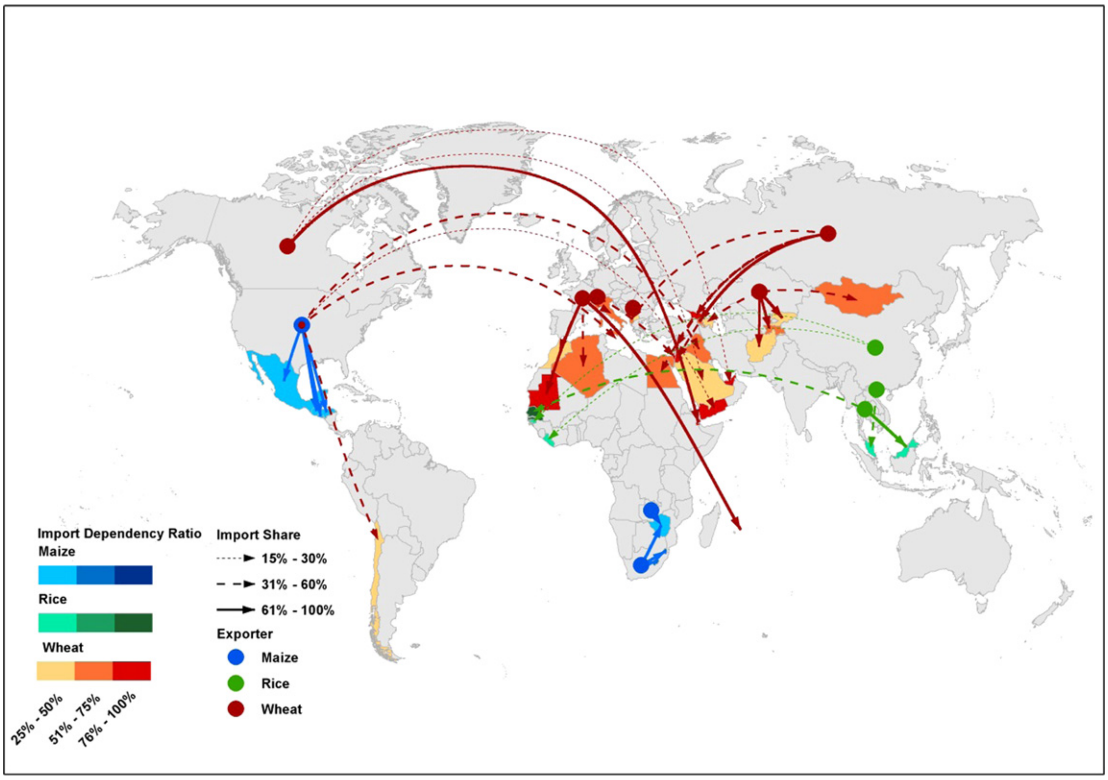

Figure 3. *Major crop import flows for caloric trade dependent countries.* Countries are colored according to the crop they are importing. The color intensification signifies the import dependency ratio. Each country is linked to its major supplier via an import arrow. The thicker the arrow, the higher the share the exporting country has on the import volume of that country.

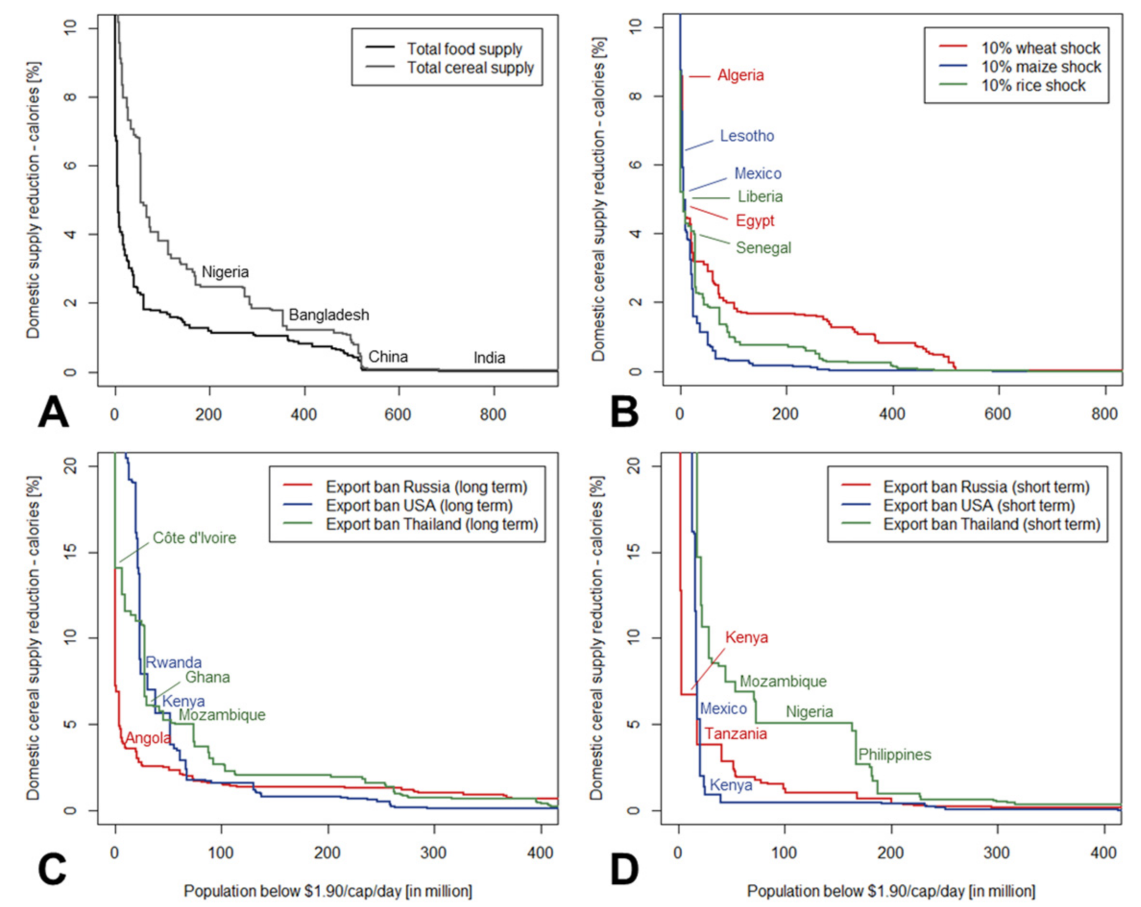

Figure 4. *Exposure of people living below the international poverty line to different supply shock scenarios*. Countries are sorted in descending order with respect to the size of the effect (y-axis). The horizontal length of the graphs indicates the number of poor people living in a particular country. We exclude transit from the analysis, i.e. use net imports in our calculations. (A) A 10% simultaneous reduction in trade cereals (rice, wheat maize) (formally: $V_j = (\nu_j, \rho_j)$ with $\nu_j := \sum_i \sum_c \upsilon_{ijc} \cdot 10\% = \sum_c \mathrm{IDR}_{jc}\, w_{jc} \cdot 10\%$). (B) A 10% reduction for individual grains ($V_{jc} = (\nu_{jc}, \rho_j)$ with $\nu_{jc} := \sum_i \upsilon_{ijc} \cdot 10\% = \mathrm{IDR}_{jc}\, w_{jc} \cdot 10\%$). (C) Long term impacts of export bans in important producing regions (a reduction of 8% in wheat, 27% in rice and 50% in maize): perfect compensation of trade flows leads to an equal distribution of shocks among all importing countries affecting all importers proportionally (formally $\bar{V}_{ij} = (\bar{\nu}_{ij}, \rho_j)$ with $\bar{\nu}_{ij} := \nu_j (1 - x_i)$). (D) Short term impacts of scenario (C) export bans affect only direct trade partners ($V_{ij} = (\nu_{ij}, \rho_j)$ with $\nu_{ij} := \sum_{l \neq i} \sum_c \upsilon_{ljc} = \sum_{l \neq i} \sum_c s_{ijc}\, \mathrm{IDR}_{jc}\, w_{jc}$). Included are all countries with available World Bank data on poverty. We highlight a sample of countries: (A) countries with the highest absolute poverty numbers; (B) countries from vulnerable regions (as identified in figure 1); (C, D) countries with poor population > 5 million and relevant cereal supply reduction.

for the countries in Central Asia (figure 3). Overall, Russia is the most important exporter for the countries identified (table S1).

The world market for maize is largely dominated by the US. Virtually all imports of the Central American countries come from the US. The countries in Southern Africa are the exception in that they receive almost all of their imports from the regional hegemon South Africa, the most important producer of the region (figure 3). Thailand and Vietnam dominate rice exports[9].

Continuous vulnerability mapping for specific trade shock scenarios

We now analyze how many poor people would be affected by supply-side shocks in food-producing countries. To this end we investigate the import-effects of a climate hazard that reduces global exports of maize, of wheat, and of rice by 10%, respectively, and map the cumulative effect on the population below the international poverty line (figure 4). Note that the 10% reduction can be understood as either a 10% supply shock with no market adjustment on global markets, or as a supply shock greater than 10% with an endogenous market response that leads ultimately to 10% lower global exports. Such a reduction can have different underlying causes such as production shocks or restricting trade policies in important exporting countries. We chose a 10% reduction scenario as it is easily scalable and still realistic[10]. We find that a simultaneous 10% reduction in international market supply of the three crops reduces domestic calorie supply in total food by at least 5% for 6.3 million

[9] After lifting an export ban, India's exports exceeded those of Vietnam and Thailand in 2012. These recent shifts in global trade are not considered in our analysis which is based on the years 2007–2011.

[10] For example, rice exports collapsed by 12% in 2008 after various export bans (FAOSTAT 2015).

people below the poverty line in 19 countries. When considering cereals as most important staple group, calorie supply decreases at least by 5% in 58 countries and 55 million people are affected (figure 4A). The standalone impact on the poor population of a 10% supply reduction of each of the three crops separately is comparable: almost seven million people below the poverty line are impacted by at least 5% (6.8 million people for wheat, 6.5 for rice, and 6.8 for maize) (figure 4B).

Next, we consider export restrictions in major exporting countries with strong trade relations to import-dependent countries: i.e. an export restriction for wheat in Russia, for rice in Thailand, and for maize in the United States (figure 4C, D). We chose these three countries as illustration for our methodological approach which can be easily extended to other countries and scenarios[11]. In a first scenario, we model the immediate short term impacts by looking at the bilateral trade relations only (figure 4D, tables S1–3). An export ban in Russia would reduce cereal supply by more than 5% for 18 million people under the international poverty line. An export ban for maize in the USA would reduce cereal supply by at least 5% for 21 million people, mostly in the Central Americas or the Caribbean. An export ban on rice in Thailand would expose 163 million people in Sub-Saharan Africa (SSA) to a cereal supply reduction of more than 5%, 29 million of which to a reduction of 10% or more. Altogether, 200 million poor would be put at risk in the short term, most of which live in SSA (90%). Other vulnerable regions include South America (4%), Central America and the Caribbean (3%), and Northern Africa (3%).

In a second scenario, we model the impacts of such a reduction on the world markets. We consider them to be long term impacts as the supply reductions are mediated proportionally among all importing countries, independent of actual trade relations. The export ban in Russia translates into an 8% reduction in global wheat exports which in turn impacts 4.2 million people under the poverty line by at least 5%. An export ban in Thailand reduces global rice exports by 27%. We find that this reduction decreases cereal supply of 74 million by at least 5%. The impact in terms of population affected is particularly strong in SSA while we observe the highest supply reduction rates on small island states. Due to the high market concentration, an export ban on maize in the United States would curtail global exports of maize by 50%. We find that this reduction decreases cereal supply by at least 5% for 52.4 million people below the poverty line, which can be attributed to spillover effects into Africa where most of the poor live. Still, the highest reduction rates are in Middle America and the Caribbean. Cereal supply would, for instance, decrease by 25% in Mexico and by 45% in Panama. A total of 120 million poor people would be affected in this instance. We find that 76% of these people live in SSA, 11% in Central America and the Caribbean, 7% in South America, and 4% in Northern Africa.

Of the five countries with the highest absolute population below international poverty lines, namely India, China, Nigeria, Bangladesh, and the Democratic Republic of the Congo (DRC; excluded from analysis due to lack of data), which together account for about 70% of the world's poor, only Nigeria and Bangladesh show marginal impacts. India and China are not affected by teleconnected supply shocks due to their strong self-sufficiency.

Discussion

In this paper, we reported the exposure of caloric trade dependent countries to supply-side shocks. If global exports were simultaneously reduced by 10%, we find that cereal supply in 58 countries would decrease by at least 5%. Considering poverty levels, we find that—dependent on the scenario—up to 200 million poor people are potentially vulnerable to trade-related food supply shocks. While some of these supply reduction numbers seem to be small on the first sight, their implications can be substantial. Own-price elasticities of cereal demand range from −0.5 to −0.3 for low and middle income countries (Seale *et al* 2003). A 5% supply reduction can therefore imply a price increase in the range of 10%–17%[12]. In the following we will first discuss potential future implications of our results for specific staple crops, rice, wheat and maize, and will then discuss policy implications that could generally reduce vulnerability to trade-related supply shocks.

Rice appears as essential crop in our vulnerability analysis. It provides up to 50% of the calories for Asia's poor population and matures into a major staple of African diets (Muthayya *et al* 2014). Our findings indicate that supply shortages have severe implications for African countries, especially in the short term. West African rice importers suffer most from unreliable international markets, notably in the short term as exemplified by an export ban in Thailand. The international rice market has historically always been dominated by few exporters, notably Thailand,

[11] Russia is a large exporter and several countries' imports depend strongly on Russian exports; additionally, Russia used export bans in the past to insulate domestic markets from global markets. Thailand has been the largest rice exporter in 2000–2012 (see table 1) with a fragile political system. The US is the largest exporter of maize; although the country is unlikely to use export bans in the future, a strong reduction of exports can also result from an ambitious biofuel policy in addition to a positive oil price shock (which makes ethanol production from maize highly profitable).

[12] An own-price elasticity of −0.3 implies a 0.3% demand reduction in reaction to a 1% price increase. In turn, a 5% reduction in demand would lead to a 17% price increase (or 10% increase for an own-price elasticity of −0.5). Contrary, supply elasticities for food crops range from 0.02 (rice) to 0.27 (maize) (Haile *et al* 2016).

Vietnam and, India, that often apply restricting trade policies to stabilize domestic markets (Dawe 2002).

Wheat has the lowest market concentration of the three staple crops and has a relatively diverse supplier base (table 1). Yet, import dependencies are high for many countries that rely on wheat as most important calorie source (figure 1A). These preconditions lead to a high level of vulnerability to teleconnected supply shocks in the wheat market. While the yields in the major producing regions in the US and Western Europe are close to their maximum potential (West *et al* 2014), wheat production in Russia remains below its high potential. Recurring droughts cause high fluctuations in actual and potential yields, especially under rainfed conditions (Schierhorn *et al* 2014). In times of bad harvests, Russia is likely to introduce export restrictions to keep domestic prices stable (Fellmann *et al* 2014). Global warming may further reduce wheat yields in Russia and Eastern Europe and increase their volatility (Alcamo *et al* 2007). At the same time, diet shifts towards a higher relevance of meat in China (and potentially other Asian regions) accompanied by reduced food production areas due to urbanization are likely to induce a redirection of Russian wheat exports from the Middle East to China. In this scenario, the Middle East and especially Egypt would suffer dramatically from food price spikes, and food shortages.

As maize use can be flexibly directed into the food, feed or ethanol sector, demand shocks on oil markets translate stronger to food markets (Abbott 2013, Serra and Zilberman 2013). Ethanol mandates further constitute an inelastic demand factor which amplifies the relative magnitude of harvest shocks in terms of maize availability for non-biofuel use (Abbott 2013). Thus, particularly Central American countries, such as Mexico and El Salvador, become more susceptible to supply-side shocks in the US[13]. Additionally, global warming is projected to reduce US maize yields by up to 40%–80% compared to a scenario of no warming by the end of this century (Schlenker and Roberts 2009), affecting Central American countries even further. Not only do yields decrease, variability in harvests also increases due to the highly non-linear response of plant growth to temperature shocks.

Generally, besides natural harvest variability, sudden trade restrictions like export bans are considered to be an important factor explaining the price spikes in 2007/08 and 2010, in particular for rice in 2008 (Abbott 2012, Headey 2011) and wheat (Fellmann *et al* 2014). So far, neither the international community, nor the WTO, nor the G20 have developed an effective mechanism to prevent such beggar-they-neighbor behavior (Bouet and Laborde 2016). Hence, there remain substantial risks of future trade disruptions by exporting countries, depending on domestic and world market prices as well as their prevailing political situation.

Different measures besides poverty reduction could reduce this vulnerability: (i) reducing the scale of supply shocks in exporting countries, (ii) increasing the endogenous market response to shocks, (iii) reducing the trade share from volatile exporting countries, (iv) diversifying diets away from internationally traded and volatile grains, and (v) reducing import dependency. All of these measures are associated to additional costs and benefits. While equation (1) allows to systematically address these measures, a full discussion and assessment lies beyond the scope of this paper. A brief discussion is provided in the following.

The use of food crops or agricultural land for biofuel production has been identified as a major concern for food security (Tilman *et al* 2009, Creutzig *et al* 2015, Fraser *et al* 2016), reducing the supply of major exporting countries (ad i). Biofuel policies are considered to have contributed to price increases of several food crops in 2007/08 (Wright 2014).

Endogenous market response (ad ii) can be augmented with increased use of multi-seasonal cropping regimes, in particular in tropical and subtropical regions (potentially facilitated by irrigation). Multiple harvesting seasons enable a relatively quick response to global scarcities. An additional measure would be higher storage capacities which would increase intertemporal flexibility.

Diversification of imports (ad iii) can substantially reduce vulnerability to bi-lateral trade shocks but is of little effectiveness for global supply shocks. Also, diversification can be costly if it implies imports from far-distant exports. With respect to diets (ad iv), increasing incomes are expected to lead to more dietary diversification, i.e. towards higher protein consumption (ad iv). However, recent trends of wheat, maize, and rice consumption point to continuous demand growth for these crops and a streamlining of diets in developing regions at the cost of scarcely traded crops such as millet (Kearney 2010). This could imply an increasing exposure to world market volatility.

The scarcity of water and arable land is one reason for the high import dependency (ad v) in the MENA region. A good fiscal situation in many of the mostly oil exporting Gulf States allows to cover potentially harmful consequences of these problematic preconditions (Lampietti *et al* 2011). Countries with fiscal deficits however, which are mostly found in Northern Africa, have shown to be very vulnerable to food price increases (Werrell and Femia 2013) even though the region has a low share of population living below international poverty lines.

Finally, even though most of the global poor live in SSA, it has not been identified to be particularly vulnerable in our study (with the exception of rice in Western African countries). It however constitutes a

[13] As biofuel production diverts crops and agricultural land away from food production to non-food uses, it tends to reduce total availability of food which might also have adverse distributional impacts (Fraser *et al* 2016).

special case as the three crops analyzed in this study contribute only 31% to the calories consumed by the poor in SSA (Lobell *et al* 2008) whereas they represent roughly half of the calories consumed by the world's poor in general. The most important calorie providers in most of SSA are other cereals like millet and sorghum, starchy roots, and pulses, which are almost exclusively grown domestically. Hence, major trade dependencies do not exist yet. However, as income levels rise, per capita consumption of wheat, maize, and rice is expected to increase rapidly in SSA, while the consumption of e.g. millet is expected to decrease (Kearney 2010). Most of the increase in wheat consumption is expected to come from non-SSA countries (Mason *et al* 2012). At the same time, research indicates that SSA and South Asia will likely suffer from negative climate impacts on several crops that are important for food security (Lobell *et al* 2008), which could also lead to higher reliance on imported staples.

Conclusion

This study indicates that the problematic confluence of strong and mostly bilateral import dependence and a high dietary reliance on specific crops is a common occurrence and is often regionally concentrated. Climate change is likely to further aggravate the situation.

Import dependent countries can implement measures to prevent extreme food shortages, and mediate food import dependency, some of which have been discussed. First, closing yield gaps can reduce reliance on international markets especially for African countries (West *et al* 2014), but may also involve high costs and face limitations by land and water constraints as, for example, in Egypt. Second, diversification of trading partners but also of diets can reduce risks to sudden supply shocks. Third, regional trade agreements combined with regional grain emergency reserves can be a promising tool to stabilize food supply at low costs (Kornher and Kalkuhl 2016). It depends on the specific characteristics of each country, which of these strategies, or which combination of strategies, will be optimal.

Acknowledgments

We thank Ulf Weddige for support with designing the figures. Jan Steckel and Leonie Wenz gratefully acknowledge financial support from Deutsche Forschungsgemeinschaft Collaborative Research Center 1026 and Deutsche Bundesstiftung Umwelt, Christopher Bren d'Amour financial support from Stiftung der Deutschen Wirtschaft. We thank Ottmar Edenhofer for his valuable comments and support.

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