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The Frederick S. Pardee Center for the Study of the Longer-Range Future

PARDEE CENTER RESEARCH REPORT MARCH 2017

The Risks of Multiple Breadbasket Failures in the 21st Century: A Science Research Agenda

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Executive Summary

This paper describes a science research agenda toward improved probabilistic modeling and prediction of multiple breadbasket failure events and their potential consequences for global food systems. A “breadbasket” is defined as an agricultural production area in which one of the world’s three main cereal crops — rice, wheat, or maize — is grown. “Breadbasket failure” is defined as a major yield reduction in annual crop cycle of a breadbasket region where there is a potential impact on global food systems because:

a) the production area is critical to global commodity trade;

b) the area provides food for a significant proportion of the population at local, regional, national, or global scales;

c) the area provides food such that a crop failure may have significant consequences in humanitarian, economic or political dimensions.

Gaps in the existing empirical foundation and analytical capabilities are highlighted together with general approaches to address these gaps. Improved capabilities will require fusion of diverse conventional and unconventional data sources, recent observations, and new suites of dynamic models capable of connecting agricultural outcomes to elements of the global food system. The goal of such improved capabilities is to provide better information concerning potential systemic risks to inform policies and decisions.

INTRODUCTION AND BACKGROUND

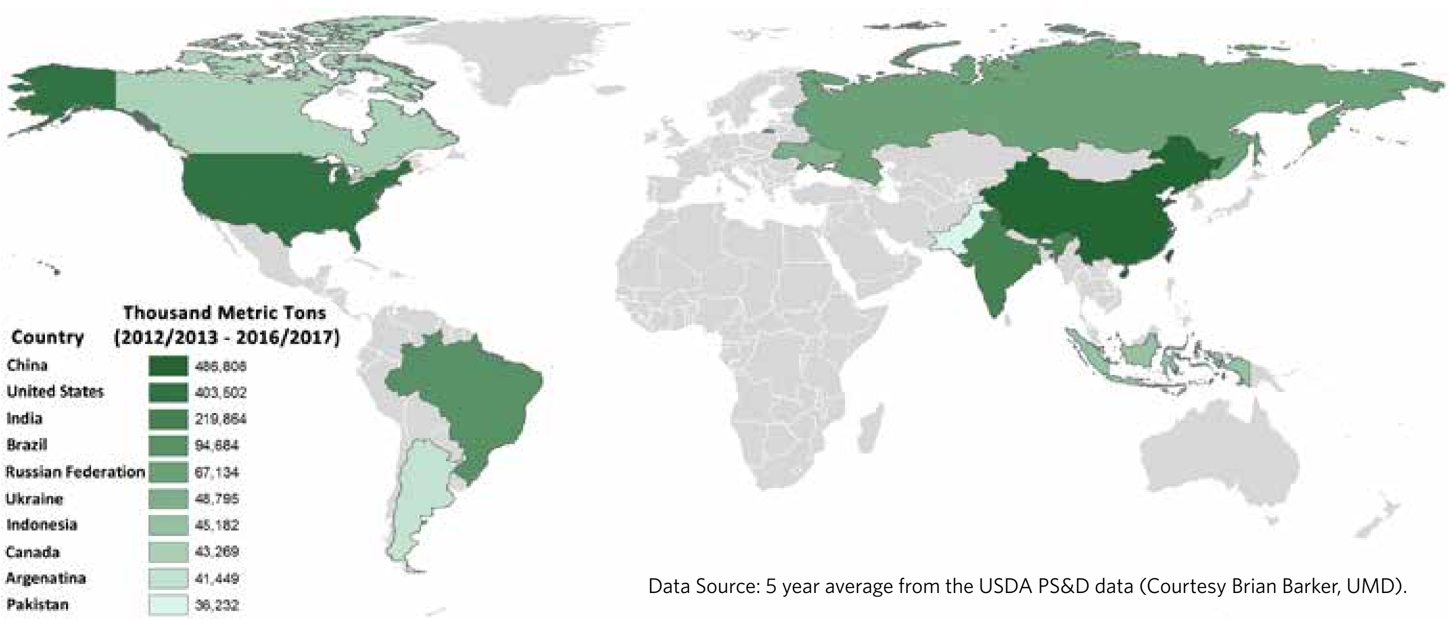
A relatively small area of the world, 23 percent of total cropland, accounts for a large proportion of total global cereal production, with most of the area devoted to the production of the world’s three major cereal crops: maize (70.3 percent), wheat (69.3 percent) and rice (84.5 percent) (Food and Agricultural Organization of the United Nations, Statistics Division 2016). In a recent study of global hotspots of heat stress due to climate change, Teixeira et al. (2013) showed areas of Central Asia, East Asia, South Asia and North America (40–60 degrees N.), which include the major grain producing areas of the world, as being particularly vulnerable. The structure of globalized food systems, with major constrictions in trade flows and highly concentrated areas of the world’s food production, creates obvious vulnerabilities. Systematic evaluation of the likelihood of disruptive events in relation to each other and their potential impacts has not been done.

Several decades ago, before the distribution and consumption of the major cereal crops became globalized, the failure of any one of the major global breadbaskets would have been expected largely to affect the regions that immediately surrounded it. The global trade in agricultural goods was more restricted and slower than is the case today (Porkka et al. 2013). Over the past several decades, however, trade and distribution of many, if not most of the globally important crops (and other foods) have effectively become both global and rapid (Carr et al. 2013; MacDonald et al. 2015). This has had some obvious benefits in terms of consumer choice, and in terms of the rapidity with which the food distribution system can respond to changes in availability and price. But it also means that productivity failures in an important cereal producing region have implications that can spread rapidly, with potentially large, non-linear consequences.

For this study we define “globally important breadbaskets” as those regions whose failure to produce would have important global consequences. Such regions have at least one of three characteristics:

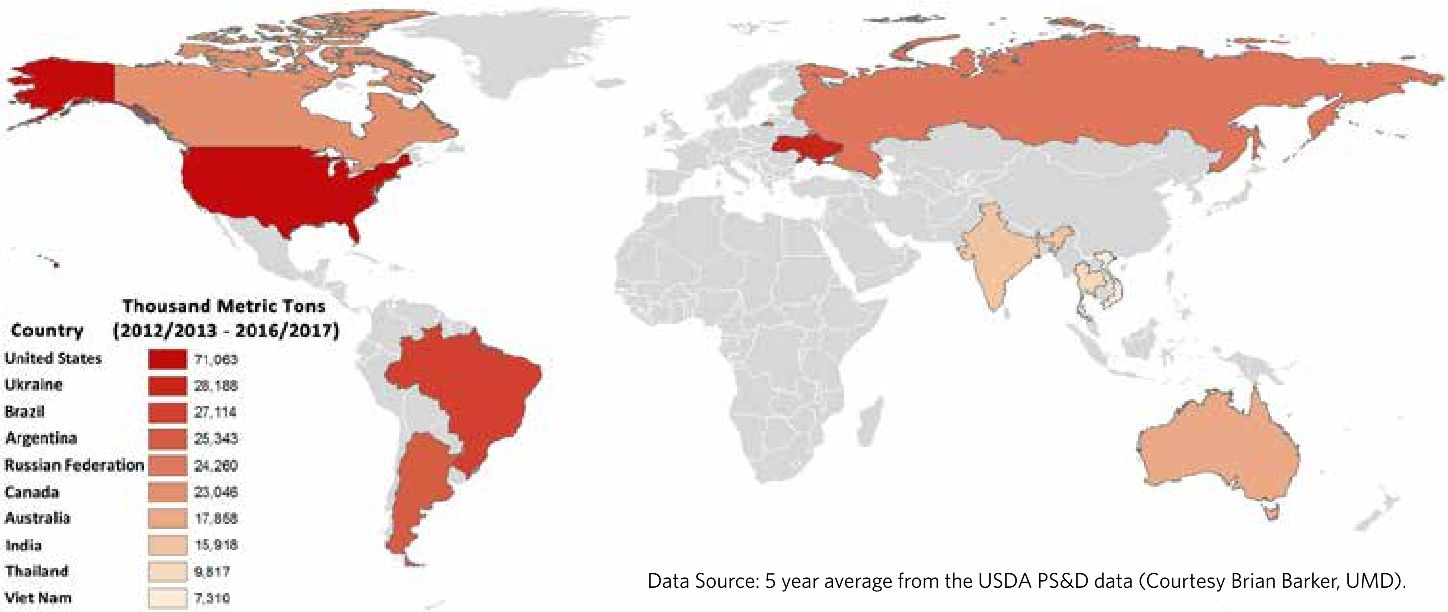
- Regions that characteristically produce large amounts of grain for both domestic consumption and export. Commodity crop failure or significant yield reduction in such regions would impact global markets for grain, e.g. the U.S., Canada, Australia, and Russia for wheat (Figure 1).
- Production regions that contribute to the diets of many people, but are not strong exporters to global markets, e.g. India for rice or wheat, China for rice (Figure 2).
- Cereal production regions that are large contributors to the diets of people in parts of the world that are strategically important for other reasons, or whose failure could result in humanitarian, political or other crises, e.g. donor countries to food insecure regions around the world (Figure 3).

FIGURE 1. MAP OF TOP 10 GRAIN PRODUCING COUNTRIES (5 year average, 2012/2013 – 2016/2017)



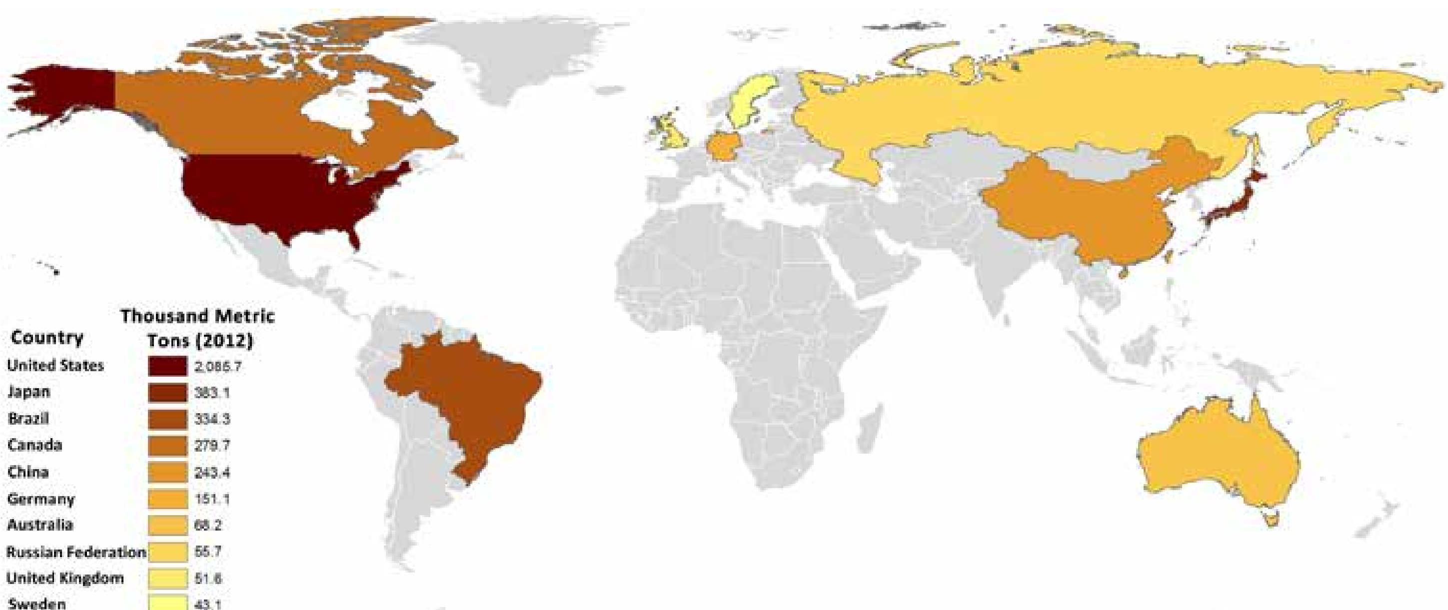
Data Source: 5 year average from the USDA PS&D data (Courtesy Brian Barker, UMD).

FIGURE 2. MAP OF TOP 10 GRAIN EXPORTING COUNTRIES (5 year average, 2012/2013 – 2016/2017)



Data Source: 5 year average from the USDA PS&D data (Courtesy Brian Barker, UMD).

FIGURE 3. MAP OF TOP 10 FOOD-AID DONOR COUNTRIES (2012)



Data Source: The International Food Aid Information System (INTERFAIS) database from WFP (Courtesy Brian Barker, UMD).

Over the next several decades, four major drivers are likely to collide, putting pressures on the global food system that are potentially troubling. The food system is defined as the system by which food is delivered (or not) to every person every day.

DRIVER #1: POPULATION GROWTH AND URBANIZATION

Global human population continues to increase, and is likely to reach somewhere between 9 and 10 billion in mid-century, before it stabilizes (Lee 2011; United Nations 2015a). Most of this growth is projected in what is now the developing world, and it is accompanied by an increasing trend towards urbanization and affluence (Cohen 2006). More than half of today's global population lives in cities, and this fraction is expected to continue to increase (United Nations 2015b). These developing countries are often challenged to be food self-sufficient and often rely on imported food to meet their national needs (Valdes and Foster 2012). Cereal imports to the Middle East and North Africa have increased markedly in recent years (Nigatu and Motamed 2015).

DRIVER #2: INCREASING TRANSITION TO MEAT-BASED DIETS

With increasing global affluence, grain-based and locally-based diets tend to transition to diets that are more meat-based, have higher caloric content, and are quicker to prepare (Drewnowski and Popkin 1997). While this driver is not universal, it is extremely common in the developing world and seems to accompany economic development, as consumers' time for food preparation becomes more valuable and scarcer, and as increasingly urban populations become more geographically distant from the resources that sustain them (Delgado 2003; Prentice 2006). To the extent that these dietary shifts rely on grain-fed animal products, their net effect is to magnify the demand for grains, i.e. the demand will grow more rapidly than population growth *per se* would suggest, which will put additional pressure on the global food system.

DRIVER #3: CLIMATE CHANGE

The third driver is the continuing change in the physical climate system, driven for the most part by anthropogenic emissions of greenhouse gases. As the IPCC (2014) and many studies in the recent scientific literature have documented, there are substantial vulnerabilities of crop production systems to diminished agricultural productivity and yield losses as the climate continues to change, in spite of the direct positive effects of increases in atmospheric CO_2 concentrations (Schlenker and Roberts 2009; Lobell and Field 2007; Elbehri, Elliott, and Wheeler 2015; Senthold Asseng, Foster, and Turner 2011; S. Asseng et al. 2015; Tubiello, Soussana, and Howden 2007; Long et al. 2006; Leakey et al. 2006; Leakey et al. 2009). Mechanisms are often crop-specific, and depend in large part on how extremes in climate (e.g. droughts, heat waves) are manifested. But

> *"...if the world continues on a high GHG emissions pathway that fails to hold equilibrium warming to under 2 degrees C, there are almost no parts of the world where agriculture will be unaffected..."*

there is a strong consensus that parts of the world in which agriculture is already constrained by water availability or heat waves will become even more challenged by mid-century (Coumou and Rahmstorf 2012; Elliott et al. 2014; Hanjra and Qureshi 2010). Moreover, if the world continues on a high GHG emissions pathway that fails to hold equilibrium warming to under 2 degrees C, there are almost no parts of the world where agriculture will be unaffected, and agriculture in the developing world will be especially vulnerable (Parry et al. 2004).

A global study showed that recent droughts and extreme heat decreased national cereal production by 9-10 percent with a bigger impact in developed countries (Lesk, Rowhani, and Ramankutty 2016). With increasing global temperatures, we are likely to see an increase in the frequency of extreme weather events (IPCC 2014). The impact of extreme regional drought events in the last decade provides insights into the development and potential impacts of future extreme events, and on the resultant volatility in grain markets and perturbations in distribution. It should be noted, however, that the relationship between production variability and prices is not a simple one (Greenfield and Abbassian 2011). In the past, the impact of single drought events in one region could be reduced by normal or above average conditions in other regions. Similarly, the impacts of one bad year could potentially be ameliorated by reserve stocks and by a return to average conditions the next year. With an increased frequency of extreme events, there is the possibility of multiple regions being affected by drought in one year, and by continued drought events in the following years.

DRIVER #4: INCREASED TRADE, GLOBALIZATION, AND MERGING OF AGRICULTURAL COMMODITY MARKETS

In the past couple of decades, previously independent trading systems for each major global grain commodity have merged as deregulation and intensified global trade stream consolidation has reduced the extent to which one commodity may be used to hedge another. Today, food systems are highly optimized for efficiency in peacetime under relatively stable environmental conditions. However, the impact of increased trade liberalization on long-term food system resilience remains unknown.

Trade can impact the price of agricultural commodities in a multitude of ways. In the long run, increased trade tends to lower prices globally and possibly price volatility as well. However, under some conditions, for example when domestic consumption policies have large effects on other regions, global price volatility can increase. And while global prices might decline, the same is not necessarily true in local markets. In competitive markets, production should be allocated to geographies where it is most suited and the costs of production are low. As trade grows, one would also expect the allocation of production to the most suitable places to grow as well.

Core breadbaskets are typically characterized by lower production volatility. Less volatility suggests overall greater system resilience due to lower risk of supply interruption and greater flexibility through trade. That said, as trade continues to increase, breadbaskets become more concentrated, with a possible reduction in resiliency. These core production centers could be hit by an irregularly occurring hazard.

For short-run market phenomena, more trade means more inter-dependency among trading partners. More trade and more trading partners leads to increased overall diversification and higher resilience to absorb local production shocks. However, a system with a large number of trading partners appears more volatile when a systemic risk hits the network. For example, during the last food price crisis a multitude of countries — including Argentina, Russia and Thailand — simultaneously closed their borders for food exports while many countries with idle production resources could not leverage their own supply capacities early enough, leading to a marked price spike.

The impact of trade on food system resilience is not fully understood, and it remains a focal area to be explored by the research agenda moving forward.

This paper is a synthesis of a workshop and current research in which the authors have sought to lay out a research agenda that explores the most potentially damaging consequences of the intersection of these drivers .

SCOPING OF THE RESEARCH AGENDA

The research agenda we propose in this paper explores the potentially damaging consequences of the intersection of the drivers discussed above. In our view, the problems of most concern are threefold:

- What would be the regional/global impacts of simultaneous and successive failures of crop production in the major grain producing regions of the world?
- What are amplifiers and mitigation elements of risks associated with such events, which are subject to change in the future?
- What are (proactive) policy measures to increase the robustness of a global food system subject to such large-scale shocks?

In order to understand where research priorities should be assigned, we use a classical definition of risk:

Risk = Magnitude of Impact x Probability of Occurrence

A research agenda is, therefore, required to primarily address four things:

1. **Evaluate the likelihood** of occurrence of such events;
2. **Assess the potential impacts** of multiple breadbasket failure as they ripple through both food and energy systems;
3. **Quantify the risks** associated with the failure of multiple breadbaskets; and
4. **Explore the scientific foundation of potential interventions** and solutions to ameliorate the risk.

To address the four primary componets of the research agenda, we have identified the following over-arching features that will serve as important guidelines:

A focus on globally important risks

We are primarily interested in risks that are globally important; i.e. that are large enough, persistent enough, or frequent enough that they pose significant difficulties for significant numbers of people ("Global Risks 2016" 2016). This definition does not imply that the underlying phenomena must be global — it explicitly recognizes that global risk may be a consequence of regionally significant or regionally ephemeral phenomena. It also recognizes that there is a relatively small number of regions which produce the bulk of the grain for the global markets but we are not primarily laying out a research agenda for understanding short-term, regional events. Such events are clearly important, but they are already the focus of many important programs, such as the Famine Early Warning System Network (USAID FEWS NET) and the Agricultural Market Information System (AMIS) (Ross et al. 2009; Verdin et al. 2005; AMIS 2015). We are more concerned with larger systemic risks, even if they originate on a regional basis (Helbing 2013; Haldane and May 2011).

A focus on biophysical shocks that may be able to be forecast through continuous monitoring and early warning systems

The shocks of primary interest that result in crop failure are generally natural [biophysical], i.e. those that are an integral part of the food production system that goes awry, e.g. large and persistent regional droughts, heat waves, other extreme weather events, or pest and pathogen epidemics. These shocks should in principle be amenable to research that builds a predictive capacity. They should also be amenable to being forecast through early warning systems, and continuous monitoring programs, as they develop. However, we are currently unable to predict future extreme climate events across breadbaskets with any accuracy.

"The research agenda needs to diagnose and build understanding of the causes, consequences, and likelihoods of multiple breadbasket failure, but it must also be effective in providing the underpinning for policy interventions that reduce the risk of occurrence and mitigate its consequences."

We recognize that there are also human-driven shocks, driven by policy or societal actions that may occur, e.g. creation of large biofuel markets from crops, which can help drive up food prices globally through price changes in the transport fuel market. These shocks and ripple effects through seemingly unrelated markets may be inherently unpredictable, although their consequences become ex post measurable. Management of such risks originating from risk-enhancing policies can best be informed by anticipative scenario analysis of appropriate risk abatement measures (e.g. grain storage).

Research that provides the scientific foundation underlying effective policy interventions that reduce the risk of multiple breadbasket failure

We are interested not only in understanding the risks that potential multiple breadbasket failure may present, but also in the underlying research that can inform effective interventions to either avoid those collapses, or recover from them more rapidly. The research agenda needs to diagnose and build understanding of the causes, consequences, and likelihoods of multiple breadbasket failure, but it must also be effective in providing the underpinning for policy interventions that reduce the risk of occurrence and mitigate its consequences. Understanding that the risks extend beyond simply changes in the food system, and may involve effects that ripple through other sectors, is crucial in this respect.

Research that is multi-disiplinary, transparent, and directed toward improving the resiliency of the food system and societies in case of unavoidable shocks triggering multiple breadbasket failures
We argue that research must be directed towards improving the resiliency of the food system and society to such shocks (Suweis et al. 2015; UK-US Taskforce on Extreme Weather and Global Food System Resilience 2015). We define resilience in this case as actions that reduce the probability of multiple breadbasket failure, reduce the magnitude of the effects if such failure occurs, or reduce the time it takes for society to recover. In this way, we believe that the concept of resilience can be operationalized, at least for this particular topic. Importantly, we also argue that such research must involve investigation in the decision and behavioral sciences and economics as much as it must integrate advancements in the physical, biological, chemical, and ecological sciences. Data and information must be effectively managed, and transparently available to all important stakeholders (Zaks and Kucharik 2011; Carollo et al. 2009).

Core Research for Evaluating the Risk of Multiple Breadbasket Collapse

As discussed above, we have used a classical definition of risk to establish the four major areas that most need additional research in order to establish a firmer foundation for understanding the risks of multiple breadbasket collapse, and for the science that should underlie potential policy interventions. These are explored in turn below.

EVALUATING THE LIKELIHOOD OF OCCURRENCE

The research agenda to explore MBBF should be grounded in the current baseline food system with its patterns of agricultural production, distribution, stockpiling and trade — but with an understanding that the system is dynamic, e.g. due to changing supply and demand and associated market forces. Recent trends to increase agricultural productivity are likely to continue, and the current distribution and productivity of agricultural land are likely to undergo change related to the availability of water for irrigation and a changing climate (Nelson et al. 2014). As a result, research that develops future scenarios will be needed to model agricultural land use change dynamically.

Understanding how regional extreme climate events happen will require an understanding of global weather patterns and processes, and retrospective analysis of meteorological data (Easterling et al. 2000; Coumou and Rahmstorf 2012). Different global and mesoscale processes impact different regions. For example, the El Nino Southern Oscillation (ENSO) can have agricultural drought impacts in South and Eastern Africa, Central America, and Southeast Asia, depending on the its strength and timing. In North America and Eurasia, agricultural droughts are associated with static high pressure systems and the position of the jet stream (Ropelewski and Halpert 1989). Understanding the different underlying synoptic conditions that result in regional drought, how droughts develop, and whether there are any trends in frequency of occurrence or teleconnections will provide important input to this study.

Analysis of agricultural statistics will also be needed to understand the impact of recent past extreme events of different extent and severity on agricultural production and to identify production areas and timing for which the impact of severe drought would be the greatest. Analysis of the statistical probability of simultaneous and successive events will be needed to explore the likelihood of occurrence.

However, with a changing climate, the past is not necessarily a good predictor of the future. We are already experiencing increased climate variability, which is changing our view of normal conditions, and climate change is resulting in changes in agricultural land use (Thornton et al. 2014; Mendelson 2011). It is now quite clear that the frequency of heat waves and drought events is very likely to increase in a warming world (IPCC 2014; Melillo, Richmond, and Yohe 2014). Further, the National Academy of Sciences has concluded that there are clear links between increased frequency of extreme agrometeorological events, such as heat waves and drought events, and anthropogenic climate change (National Academies of Sciences, Engineering, and Medicine 2016). Studies of how the probabilities of these events will change in future decades will require both an emphasis on understanding interannual climate variability and an examination of spatial and temporal downscaling methods for translating global changes in physical climate to regional specificity.

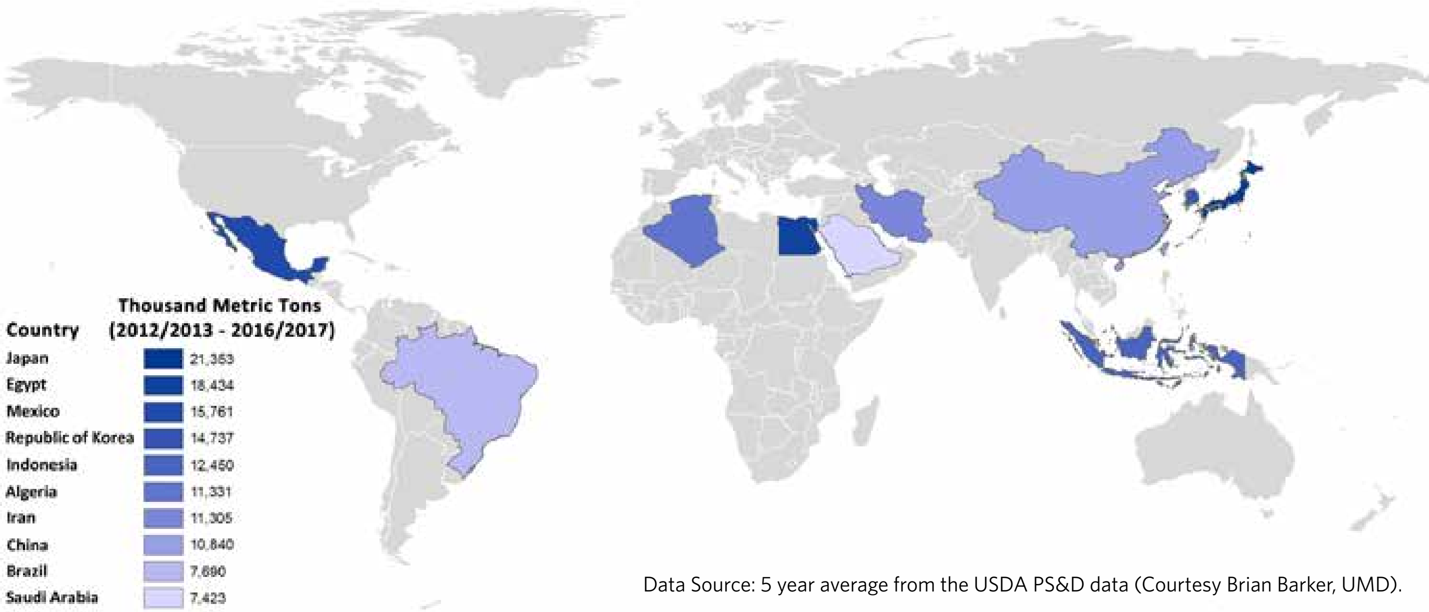
ASSESSING THE POTENTIAL IMPACTS

Potential impacts of multiple breadbasket failure can be estimated both empirically and through the use of models. Empirical, historical studies provide important insights into how the system as currently structured functions in the face of productivity shocks. These studies also provide important information about how the food system *per se* is linked to other important systems, e.g. the energy system or the transportation sector, or to other kinds of impacts, such as civil unrest.

The most obvious impacts of recent productivity failures are increases in food prices, and for failures that are large or persistent enough, actual food shortages. The impact of intense regional drought in Russia and the Ukraine in 2010, for example, contributed to a 27 percent increase in global wheat prices. So aside from a strict focus on food supply, it is immediately clear that we must consider the food system's interactions with economic systems, both domestically and internationally. Similarly, the rapid introduction of a large demand for maize through new U.S. policies promoting ethanol production resulted in upward pressure on maize prices globally (Roberts and Schlenker 2013). The latter shows the potential strengths of interactions with both energy and transportation sectors, and the need to understand such "knock-on" or "ripple effects."

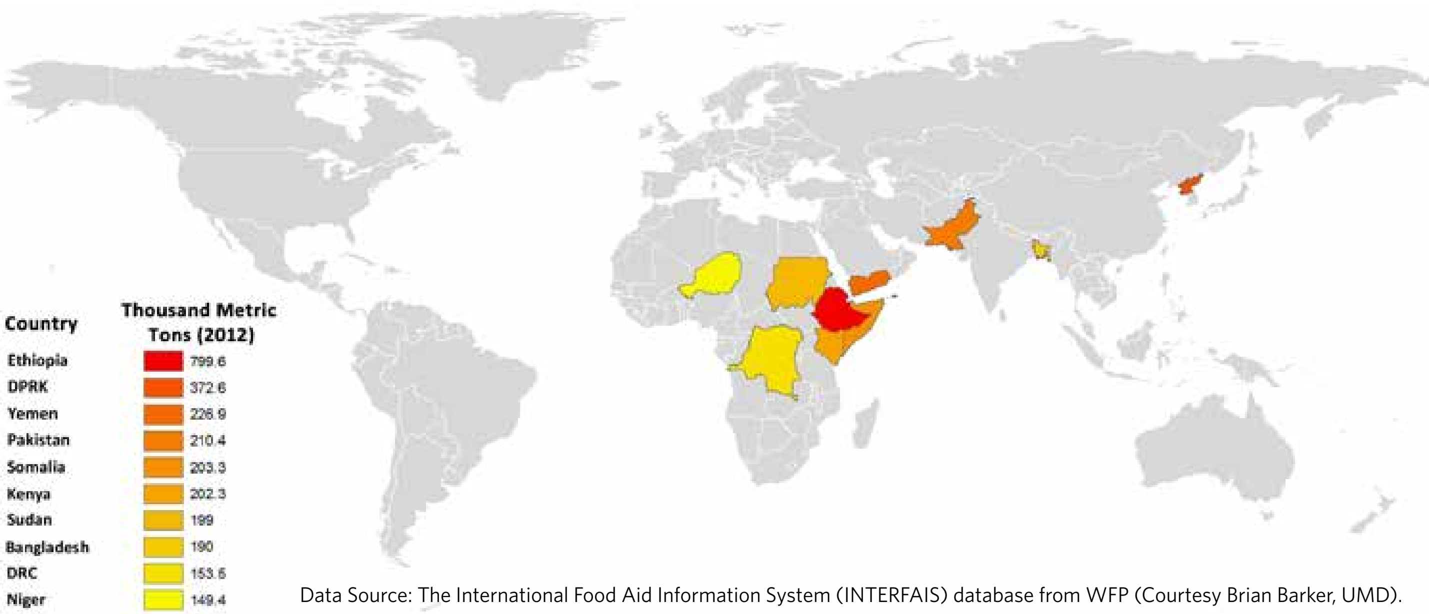
Food commodity price shocks impact different countries — and consumers in rural and urban settings — in different ways, depending on their net food trade and the share of household spending on food commodities (Halle 2016). The interactions of failures in crop production and associated food price increases with social and political unrest are of particular interest. Food shortages have long been associated with civil unrest and an impact of global shortages (UK-US Taskforce on Extreme Weather and Global Food System Resilience 2015). Social unrest in Morocco, Bangladesh, Egypt, and Indonesia was associated with the 2007–2008 food price increases (Halle 2016). The impact of food shortages will vary by country, with wealthier nations being more resilient to price volatility (Halle 2016). Food price increases will have a disproportionate effect on food insecure countries that are dependent on foreign imports (**Figure 4**) and will inevitably lead to greater hardship especially for those chronically food insecure countries which rely on routine food aid (Gustafson 2013) (**Figure 5).** It should be noted that countries already experiencing civil unrest may be more susceptible to food riots. Persistent multi-year drought in the Sahel in the 1970s lead to widespread food shortages and famine within the region, resulting in mobilization of substantial international relief efforts (Batterbury and Warren 2001).

FIGURE 4. MAP OF TOP 10 GRAIN IMPORTING COUNTRIES (5 year average, 2012/2013 – 2016/2017)



Data Source: 5 year average from the USDA PS&D data (Courtesy Brian Barker, UMD).

FIGURE 5. MAP OF TOP 10 FOOD-AID RECIPIENTS (2012)



Data Source: The International Food Aid Information System (INTERFAIS) database from WFP (Courtesy Brian Barker, UMD).

The current food system also has important information embedded within it about the strategies used by countries, international organizations, and the private sector to respond to productivity failures. For example, grain stocks provide a buffer for bad years of crop production (Bobenrieth, Wright, and Zeng 2012). However, grain storage has a limited lifespan, and there is considerable year-to-year variation. With persistent shortfalls in production, stocks can become depleted and no longer an option in mitigating reduced grain supply.

When governments of grain-producing countries impose trade restrictions and export bans in response to domestic food shortages, they can exacerbate a global food shortage, especially for countries dependent on foreign grain supply for food security (Porkka et al. 2013).

Given rapid globalization and the change in demand in recent years, analysis of trade-flows and modeling of scenarios of supply and demand will be needed (D'Odorico et al. 2014).

Monitoring and data analysis of known productivity shocks, and their consequences for multiple systems, is therefore a high priority. Better data and more sophisticated analysis is needed for areas including: analysis of trade-flows, mismatches of supply and demand, the strength of the economic response to productivity shocks, the role of stockpiles, and the effectiveness (or unanticipated side-effects) of response strategies.

A major challenge is that the food system of future decades is unlikely to look and behave exactly as today's food system does — similar to the novel characteristics expected of the climate regime of the future. We have already outlined the major reasons for this: population growth, dietary shifts, climate change, and continued economic globalization. But because the system itself is changing, along with the demands and stresses on it, the research agenda must incorporate a strong modeling component so that future sensitivities and responses can be evaluated.

> *"New models are needed that incorporate other sectors that impact the performance of the food sector, including investment in agricultural infrastructure, the financial system, and the changing behavior of decision-makers as they learn and adapt to new conditions."*

For example, linking agricultural production models with climate models provides a means to investigate agricultural production under a changing climate with projected changes in precipitation and temperature. There is a long tradition of such studies (IPCC 2014; Rosenzweig et al. 2013). The crop production models themselves differ considerably, and intercomparison of their results under different climate scenarios is relatively recent (Nelson et al. 2014; Rosenzweig et al. 2014). Similarly, the inclusion of extreme events in global climate, agricultural, and economic models is an area of ongoing research and development.

Existing production models based on biological and climatic factors need to be augmented with models that can describe the dynamics of economic aspects of the food system under current and future conditions.

Models that are capable of doing this include those that focus primarily or only on the agricultural sector (Antle et al. 2015; Rosegrant et al. 2012). However, understanding the ways in which the food system interacts with other economic sectors, e.g. energy or transportation, will require a new suite of models that are specifically designed to simulate such linkages. Some of the new Integrated Assessment Models (e.g. GCAM and EPPA) are capable of simulating interactions between agriculture and land use sectors and the energy sector, especially with respect to land-use allocation, food prices and demand, and terrestrial carbon emissions from land-use change (Kim et al. 2006; Paltsev et al. 2005). Simulations of simultaneous impacts among multiple crops and/or multiple regions have mostly not been done, but such scenarios of stresses are important to formulate so that the models can provide some understanding of the potential impacts of multiple failures (Stern 2016; Farmer et al. 2015).

New models are needed that incorporate other sectors that impact the performance of the food sector, including investment in agricultural infrastructure, the financial system, and the changing behavior of decision-makers as they learn and adapt to new conditions. Simulations of adaptation to climate change in the agricultural system, for example, are beginning to emerge, but new models will need to add value to the existing modeling infrastructure. Better treatment of data uncertainties, structural uncertainties, interactions among individual decision agents, and non-linearities, all need more attention in new models. Systems dynamics models, agent-based models, and hybrid models all have potentially important roles to play.

Model development, however, is only one part of assessing potential impacts in the food system and associated sectors. Because actual predictions of the frequency and magnitude of stresses are beyond our current capabilities, there is a strong need for the construction and application of appropriate scenarios for both the evolution of the food system, its governance, and demographic and climate stresses on the food system to quantify the relative contributions of risk drivers and adaptive capacities (Leclère et al. 2014).

QUANTIFYING THE RISKS

Many approaches are used to assess the likelihood of future events but all depend on three factors: event typologies that allow categorization of events of interest, data regarding the occurrence of such events in the past, and models that can be used to evaluate our understanding of the dynamics of the events in question. The frame described in this paper sets the scope of any analytical research agenda to include weather-related agricultural production shocks, such as heat waves occurring at crop flowering (anthesis), droughts that may or may not be primarily related to weather (e.g., the construction of an upstream dam may change vulnerabilities of extensive downstream production areas), and changes in crop condition or performance crucial to national production. Breadbasket failure, as defined by this paper, necessarily has impacts that can move risk profiles related to food availability and price, and can and does often move other categories of risk profiles, e.g., civil unrest, infrastructure choke points, or financial markets. These categories of risks to business were recently enumerated, using a qualitative "extreme but plausible" scenario published by Lloyd's of London (Maynard 2015; Lunt et al. 2016) and a recent report linking environmental stresses to sovereign risk via food price (Halle 2016).

This, and other evidence of uncharacterized risk — and obvious links between food prices and political stability, including the advance of non-state terror groups — has highlighted the need for new approaches to expand our understanding of the far-reaching implications of physical shocks. We recognize that improved analytical methods and better use of both conventional and unconvential data may be essential to generate useful probability forecasts of risk of a breadbasket failure and a wide array of associated outcomes.

A recent example, considered an intelligence failure and a prompt for further investment in improved analytic methods, was the failure to recognize the potential impacts of drought and high food prices in Syria immediately preceding the current civil war (Kelley et al. 2015). Some analysts had been warning of the danger of large scale migration, but the broader community overlooked the links between infrastructure (the construction of a dam in Turkey to support agricultural self-sufficiency) and an extreme weather event in Syria (a drought that co-occurred with a global food price spike), with what has become a protracted civil war with extensive civilian casualties. Further impacts of the conflict include the worsening European migration crisis of 2015, extensive political and diplomatic ramifications, and the rise of ISIL.

Risk valuation of hazards through decision-relevant modeling for risk-avoidance, resilience investment, and governance is available for many plausible natural disasters excluding shocks to the food system. The United Nations Office for Disaster Risk Reduction (UNISDR) Global Risk Assessment (GRA) is a probabilistic, open access global multi-hazard risk model with the purpose to estimate country-level risks and inform decision-making. To identify and value the emergence of risks in the food system, models like the GRA would require incorporation of crop modeling, production hazards (e.g. drought) and associated commodity price modeling. From these components the cumulative production losses could be valued, including food insecurity expressed as response cost relative to household income. Further evaluation of systemic risk and global interactions would require understanding and modeling the full structure of the food system, including stocks, distribution, infrastructure, storage, consumption, and financing.

One important step in improved analysis of risk that originates in or is amplified by multiple breadbasket failure will be the proposal and evaluation of loss thresholds by region and commodity that may guide responses of a wide array of types. USAID's FEWS NET has established globally-networked early warning systems for potential onset of famine that depend on systematic within-season monitoring and regular assessment with public report. But this commitment does not extend beyond countries directly at risk. The G20+ countries have established the Agricultural Market Information System (AMIS) to address early warning for the major producer countries and price volatility in the globally-traded major commodities, but this group does not currently address issues beyond the major commodity markets. The opportunity to build on these efforts toward more comprehensive, probability-based and decision-relevant reflections of risk of breadbasket failure will depend on a) the systematic identification of grain-producing regions according to the more inclusive functional criteria above; b) the spatially explicit identification of threshold points: specific points of yield reduction below which effects become relevant, either through food prices or direct impacts on availability; c) the application of fit-for-purpose models drawn from a variety of sources, confronted

"...an important body of work will involve systematically detailing the ways in which policy, infrastructure issues, conflict, increasing population, urbanization or affluence can affect food system shocks."

regularly with data regarding both the extent of extreme events and their frequency. Finally, an important body of work will involve systematically detailing the ways in which policy, infrastructure issues, conflict, increasing population, urbanization or affluence can affect food system shocks.

ESTABLISHING THE SCIENTIFIC FOUNDATION OF POTENTIAL INTERVENTIONS

There have been a number of global food crises in recent history that were sufficiently serious to warrant international response. Following the 1972-1974 Food Crisis, a number of international institutions addressing aspects of the global food system were strengthened (Headey and Fan 2008). In response to crop shortfalls in 2010/2011 following global price spikes in 2007/08, the need for an enhanced international intervention to reduce price volatility and the negative impacts of regional crop failure was recognized. The AMIS Rapid Response Forum was created in 2012 to promote early information exchange, discussion on crisis prevention, responses among policy-makers, and to assist in mobilizing wide and rapid political support for appropriate policy response and actions on issues affecting agricultural production and markets in times of crisis (AMIS 2015). A critical component of any response to intervention is the need for transparent monitoring and early warning of major shortfalls in production or crop failure. An international initiative for global agricultural monitoring in the framework of the Group on Earth Observations (GEOGLAM) was also endorsed by the G20 Agricultural Ministers in 2011, to provide an international consensus on crop conditions with a monthly reporting (Crop Monitor) for major producing countries, and more recently for early warning for countries at risk (Whitcraft, Becker-Reshef, and Justice 2015).

Under a MBBF scenario, international efforts would be needed to help direct global food supplies in order to avoid potential widespread humanitarian disasters. The World Food Program (WFP) is the international agency currently responsible internationally for coordinating food distribution based on humanitarian need, with a focus on mobilization of timely interventions in vulnerability hotspots. However, the WFP is frequently and significantly under-resourced to meet the current food shortages. Headey and Fan (2008) suggest a number of creative ways to improve markets and trade to help mitigate future food crises, for example by formalizing grain reserve arrangements, developing a more secure international trade regime, and establishing binding agreements between a small set of grain traders.

There are a number of ways to strengthen agricultural systems to be more resilient to mitigate against extreme events. For example, at the local scale and over a period of time, farmers could build resilience to drought conditions through soil improvements and greater use of drought resistant crop varieties (Fisher et al. 2015). However, under severe drought conditions, failure of rainfed crops is inevitable, regardless of the variety. Disaster relief insurance could provide a mechanism to build resilience for the farmer against periodic shortfalls in production but widespread catastrophic crop failure would present a major challenge for the insurance industry (Maynard 2015).

As part of a strategy to mitigate price increases, there have been a number of suggestions to strengthen national safety nets, particularly in developing countries, to increase food security and protect farmers and communities from adverse impacts of global price increases (see especially Demeke, Pangrazio, and Maetz 2008).

Irrigation potentially provides an opportunity to increase crop yields and provides a buffer against a lack of rainfall. Currently 20 percent of agricultural land is under irrigation globally, accounting for 40 percent of the global food supply (AQUASTAT 2016). The amount of irrigated land is at an all-time high and expansion has slowed in recent years (Food and Agricultural Organization of the United Nations, Statistics Division 2016). Provided there is sufficient upstream reservoir storage or groundwater, crops can be produced under drought conditions for a period of time. However, this draw down of stored water cannot be sustained indefinitely. Groundwater is regularly overused to support irrigated agriculture in many regions of the world. As groundwater storage declines, competition between users increases and drives up costs and regulatory burdens. More efficient irrigation systems are readily available and should be considered.

LONGER-TERM MITIGATION — ADAPTATION TO DROUGHT?

Helping countries become food sufficient might reduce national expenditure and the dependence on foreign imports, distribute the risk of crop failure, and reduce the importance of the international breadbaskets in the global market. This would be very much in line with the call for achieving food security and promoting sustainable agriculture in the UN Sustainable Development Goal #2 (Griggs et al. 2013) and is clearly a priority for developing nations, for a number of reasons. One clear avenue to increase regional food system resilience would be through the systematic reduction of food waste through the entire supply chain. Similarly, reliance on more local sources of food would further reduce the dependence on the international breadbaskets. But there are potentially significant tradeoffs in terms of land-use and national expenditures if every country were to attempt to become self-sufficient in food, rather than becoming more embedded in a global distribution system that becomes more efficient over time.

The current global food system relies upon a variable distribution of compensatory processes in space and time, with a shortfall in one area being compensated for by a bumper crop in another, or a bad crop one year in a particular region being followed by a good crop the next. However, under the scenario of a persistent MBBF, these mechanisms are likely to fail, requiring a more proactive approach to build resilience across the food system. Developing a realistic modeling framework to explore the impact of interventions in the global food supply under different scenarios of regional crop failure would provide a tool to inform both global and regional decision making processes (Vervoort et al. 2014).

Conclusions

In our analysis of the challenge of responding to multiple breadbasket failures, there are many factors that are simply not known, or not known well enough to underpin effective policy and operational responses. The likelihood of such failures occurring due to extreme weather events, and the degree to which those probabilities might change as the climate system continues to shift, are major features that require much better quantification. The magnitude of the impact of recent extreme events on agricultural productivity can be documented on a case-by-case basis, but the underlying processes that determine the sensitivity of productivity to future and more persistent shocks is poorly modeled. The potential compensatory processes within the food system (e.g.

how storage is used or the effectiveness of trade) are not well understood, and need much better quantification. The monitoring systems for the current food production system, analysis of the policy response options to price increases of different magnitudes, and the ability to simulate multiple future scenarios are crucial and will require significant investment.

> *"... there must be investigations of the entire food system using integrated monitoring and modeling techniques, so that we can gain a system-level understanding of the risks and potential consequences of multiple breadbasket failures."*

These features will remain poorly known without major support for targeted research on each topic. In addition, there must be investigations of the entire food system using integrated monitoring and modeling techniques, so that we can gain a system-level understanding of the risks and potential consequences of multiple breadbasket failures. Mounting such an effort will require the collaborations of climate scientists, agronomists, ecologists, remote sensing experts, economists, political scientists and decision-makers on a scale that is difficult - but altogether necessary given the size and potential consequences of the risk. We call for a coordinated post-disciplinary research agenda to understand the likelihood and the potential impacts of a multiple breadbasket failure on the global food system, and to identify measures that might be taken to ameliorate the potentially devastating consequences. •

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